Flow characteristics in compound channels with and without vegetation

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Flow Characteristics in Compound Channels with and without Vegetation

by

Xin Sun

A Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of Doctor of Philosophy of Loughborough University

Loughborough University

March 2007

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Abstract

The flow characteristics in compound channels with and without vegetation on the floodplain were investigated experimentally and numerically in this thesis. Detailed measurements of velocity and boundary shear stress, using a Pitot tube and an acoustic Doppler velocimeter together with a Preston tube, were undertaken to understand the flow characteristics in compound channels. Eight no-rod cases, two emergent-rod cases and two submerged-rod cases were tested. Unsteady large eddies that occur in the shear layer were explored numerically with Large Eddy Simulation (LES) to identify its generation and its effects on the flow behaviors. Mean flow parameters were predicted using the quasi-2D model by considering the shear effect.

Using the data of depth-averaged velocity and boundary shear stress, the contributions of shear-generated turbulence and bed-generated turbulence to the Reynolds shear stress were identified, the apparent shear stress was calculated using the modified method of Shiono and Knight (1991) and the depth-averaged secondary current force was then obtained. Large eddies were important to the lateral momentum exchange in shallow non-vegetated compound channels and even in deep vegetated compound channels. In the compound channel with one-line rods at the floodplain edge, the secondary current forces were of opposite signs in the main channel and on the floodplain and the bed shear stress was smaller than the standard two-dimensional value of $\gamma HS_0$ due to the vegetation effect, where $\gamma, H, S_0$ are the specific weight of water, water depth and bed slope respectively. In vegetated compound channels, the velocity patterns were different to those and the discharges were smaller than those in non-vegetated compound channels under similar relative water depth conditions. The anisotropy of turbulence was the main contribution to the generation of secondary currents in non-vegetated and vegetated compound channels, but the Reynolds stress term was more important in the vegetated compound channels. Results of cross spectra showed the mechanisms of the turbulent shear generation near the main channel - floodplain junction are due to large eddies in the non-vegetated compound channel and owing to wakes in the vegetated compound channel.

LES results indicated that large eddies caused significant spatial and temporal fluctuations of velocity and water level in the compound channel and the instantaneous values of these flow parameters were significantly higher than the mean values. In vegetated compound channels, the flow moved from the main channel to the floodplain and from the floodplain to the main channel alternately. The characteristic frequencies of the large eddy were less than 1 Hz which was consistent with the experimental data.

The capability of the quasi-2D model to predict the 2D mean flow parameters in compound channels were assessed under different flow conditions and also improved by using the mean wall velocity as the boundary condition and appropriate values of the lateral gradient of the secondary current force. In the vegetated compound channels, new approaches were proposed to treat the drag force in the cases of one-line emergent rods at the floodplain edge and submerged rods on the floodplain.

Key words: Compound channel, Vegetation, Large eddies, Secondary currents, Large Eddy Simulation, Quasi-2D flow prediction.
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**List of Symbols**

- $a_{ij}, a_{2j}$: Acceleration thresholds
- $A$: Cross-sectional area of channel
- $A_1$: Advection of the longitudinal vorticity by the main flow
- $A_2$: Generation of the secondary currents by the anisotropy of turbulence
- $A_3$: Generation of secondary currents by the shear stress
- $A_4$: Viscous term
- $ADV$: Acoustic Doppler Velocimeter
- $A_i$: Projected area
- $A_v$: Average cross-sectional area of $i$ vegetation
- $A_{fp}$: Sub-area above the wooden bed
- $A_f$: Magnitude of the acceleration threshold
- $A_{me}$: Sub-area above the mattress bed
- $A_s$: Total horizontal area of $i$ vegetation
- $A_p$: Total projected area of $i$ vegetation per unit fluid volume
- $B$: Width of the channel
- $B_s$: Vegetation-layer width
- $c_a$: Constant
- $c_f$: Dimensionless friction coefficient
- $c_f$: Mean bed friction coefficient
- $c_{\mu}$: Constant
- $C$: Chazy friction coefficient
- $C_k$: Empirical constant
- $C_s$: Smagorinsky constant
- $C_B$: Bed friction coefficient
- $C_D$: Drag coefficient
- $C_D'$: Apparent drag coefficient
- $C_D$: Bulk drag coefficient
- $C_{di}$: Drag coefficients of the $i$th element
- $C_{sc}$: Interface shear coefficient
- $C_s$: Speed of sound
- $C_r$: Courant number
- $d$: External diameter of the dynamic tube
- $dt$: Time interval
- $d\phi$: Doppler phase shift
- $D$: Rod diameter
$D_k$ Empirical constant
$D_r$ Relative water depth
$D_u$ Empirical constant in the longitudinal direction
$D_v$ Empirical constant in the lateral direction
$D_w$ Empirical constant in the vertical direction
$DNS$ Direct Numerical Simulation
$E_i(f)$ Energy density at frequency $f$
$f$ Frequency in Section 5.7, Flow variable in Section 6.1, Friction factor elsewhere.
$\bar{f}$ Mean flow variable
\[ f' \] Filtered variable
\[ f' \] Fluctuation against the filter variable
$f_i$ Cartesian components of force per unit volume $\bar{f}$
$f'^2$ Variance of flow variable
$f_{fp}$ Friction factor on the floodplain
$f_{mc}$ Friction factor in the main channel
$f_{ADV}$ Operating frequency
$f(x,t)$ Flow variable in the continuous space $\vec{x}$
$\bar{f}(x,t)$ Filtered flow variable by the filter function $G_{\Delta x}(\vec{x})$
$f(x,y,t)$ Flow variable
$F$ Total drag force
$F_i$ Drag force per unit volume
$F_{cf}$ Motor frequency
$F_{dl}$ Drag force in the sub-area
$F_{el}$ Drag force of $i$ vegetation per unit fluid volume
$F_{sl}$ Shear force of $i$ submerged vegetation
$F_r$ Drag force per fluid mass
$F_x$ Force per unit volume in the $x$ direction
$F_y$ Force per unit volume in the $y$ direction
$Fr$ Froude number
$FCF$ Flood Channel Facility, UK
$FFT$ Fast Fourier Transform
$g$ Gravitational acceleration
$h$ Water depth on the floodplain
$H$ Water depth in the main channel, Water depth in Section 2.1, Tank height in Section 3.1
$H_{in}$ Mean water depth in the main channel and on the floodplain
$H_v$ Height of the vegetation
$H_{m0}$ Averaged water depth along the floodplain edge
\( H(y) \) Local water depth at lateral position \( y \)

\( i, j \) Standard tensor indices varying between 1 and 3

\( k \) Turbulence kinetic energy

\( k_s \) Equivalent sand roughness

\( l \) Spacing between two rods

\( l_d \) Turbulence length scale

\( l_m \) Turbulent mixing length

\( l_s \) Sub-grid length scale

\( l_w \) Distance to the wall

\( L \) Length of channel

\( L_r \) Length of the vegetated domain

\( LDA \) Laser Doppler Anemometry

\( LES \) Large Eddy Simulation

\( M \) Node number

\( MEI \) Stems with stiffness value

\( MOC \) Method of Characteristics

\( MURD \) Multidimensional Upwind Residual Distribution

\( n \) Manning coefficient

\( n_e \) Overall Manning coefficient

\( n_v \) Dimensionless vegetation density

\( n_{fw} \) Manning coefficient for the wood bed

\( n_{mc} \) Manning coefficient for the mattress bed

\( N_r \) Total number of elements or rods

\( N_v \) Vegetation density

\( p \) Pressure

\( p \) Wetted perimeter of the channel

\( Q \) Node number

\( Q_p \) Measured discharge

\( Q_F \) Flow rate

\( R \) Hydraulic radius

\( R_i(t) \) Auto-correlation function

\( R_{u,u} \) Longitudinal velocity correlation

\( R_{r,v} \) Lateral velocity correlation

\( R_{w,v} \) Vertical velocity correlation

\( Re \) Reynolds number

\( Re_{rod} \) Rod Reynolds number

\( RANS \) Reynolds-averaged Navier-Stokes (RANS) modelling

\( s \) Bank slope

\( \lbrack S \rbrack \) Filtered-field deformation tensor

\( S_0 \) Bed slope of the channel

\( S_b \) Area of the river bed

\( S_s \) Source term
\( \bar{S}_U \) Strain rate of the large scale eddies

\( S_F \) Shading factor

\( SNR \) Signal to noise ratio

\( T_{sg}, T_{br}, T_{rz}, T_{sc} \) Represent \( \rho g H S_0 / \rho g H S_0, -\tau_v (1 + s^{-2})^{1/2} / \rho g H S_0, \partial [H (\rho \bar{U} \bar{V})] / \partial y / \rho g H S_0, \)

\( \partial [H (\rho \bar{U} \bar{V})] / \partial y / \rho g H S_0 \) respectively

\( TB \) Represents \( T_{sg} + T_{br} + T_{rz} + T_{sc} \)

\( TR_{ai}, TR_{az}, TR_{av} \) Represent \( \tau_{ai} / \rho g H S_0, \tau_{az} / \rho g H S_0, - \left( \rho \bar{U} \bar{V} \right)_d / \rho g H S_0 \) respectively

\( t \) Time

\( t^n, t^{n+1} \) Time n, Time n+1

\( T \) Averaging time period

\( T_s \) Run time of the first fluctuation of velocity \( V \)

\( T_t \) Sub-grid stress tensor

\( SUPG \) Streamline Upwind Peterov-Galekin

\( \bar{u}, \bar{v}, \bar{w} \) Turbulent fluctuations with respect to the mean velocities

\( u' \) Turbulent intensity in the x direction

\( u_i \) Velocity fluctuation in the \( x_i \) direction

\( u_i^2 \) Average turbulent kinetic energy of \( i \) velocity component

\( u_j \) Velocity fluctuation in the \( x_j \) direction

\( \bar{v} \) Turbulent intensities in the y direction

\( v_{\Delta x} \) Characteristic sub-grid velocity

\( w \) Turbulent intensity in the z direction

\( -\bar{u} \bar{v}, -\bar{u} \bar{w}, \bar{v} \bar{w} \) Reynolds shear stress components

\( \bar{U}, \bar{V}, \bar{W} \) Temporal mean velocity components in the \( x, y, z \) directions

\( U(z) \) Local longitudinal velocity at vertical level \( z \)

\( \bar{U} \) Shear velocity

\( U_{\text{max}} \) Maximum longitudinal velocity

\( \bar{U}_c \) Mean flow velocity in the vegetation layer

\( \bar{U}_c \) Maximum longitudinal velocity in the main channel

\( \bar{U}_f \) Longitudinal velocity at the centre on the floodplain

\( U_d \) Depth-averaged longitudinal velocity

\( U_d(y) \) Depth-averaged velocity at \( y \) m from the left wall

\( U', U'_j \) Velocity components in the new \( X'_i, X'_j \) plane

\( U_m \) Bulk velocity determined from measured velocity

\( U_p \) Longitudinal velocity from a Pitot tube

\( U_{d,i}, U_{d,j-1} \) Depth-averaged velocity at \( y = y_i, y_{j-1} \)

\( U_{m,p} \) Bulk velocity determined from the discharge

\( U_{m0} \) Averaged longitudinal velocity along the floodplain edge

\( U_{\text{wall}} \) Mean wall velocity
\( U_{*,\text{wall}} \)  Mean wall shear velocity
\( V_d \)  Depth-averaged lateral velocity
\( V_s \)  Magnitude of the secondary current vector (=\( \sqrt{V^2 + W^2} \))
\( V_{\text{max}} \)  Maximum lateral velocity
\( V_w \)  Water volume of the \( i \) sub-area
\( V_s,_{\text{max}} \)  Maximum magnitude of \( V_s = \sqrt{V^2 + W^2} \)
\( V_w \)  Water volume in the whole channel
\( V_{\text{rw}} \)  Effective water volume in the computation domain
\( x, y, z \)  Cartesian coordinate direction
\( x_i \)  Cartesian coordinates \((i = 1, 2, 3)\)
\( x^* \)  \( \log_{10}\left(\frac{\rho d^2}{\rho v^2}\right) \)
\( X \)  Longitudinal distance from the inlet
\( X_s \)  Longitudinal distance of the first fluctuation of velocity \( V \)
\( X_f \)  Longitudinal distance 300 s after the first fluctuations of velocity \( V \)
\( y^* \)  \( \log_{10}\left(\frac{\rho d^2}{\rho v^2}\right) \)
\( y^+ \)  \( y \)-coordinate normalised by the viscous length \( v/Us_{*,\text{wall}} \)
\( y_{25\%} \)  Lateral position \( y \) where \( \bar{U}(y_{25\%}) = \bar{U}_f + 0.25(\bar{U}_c - \bar{U}_f) \)
\( y_{75\%} \)  Lateral position where \( \bar{U}(y_{75\%}) = \bar{U}_f + 0.75(\bar{U}_c - \bar{U}_f) \)
\( Z \)  Vertical level from the channel bed
\( \alpha_e \)  Velocity correction factor for drag force \( F_{d,l} \)
\( \alpha_s \)  Velocity correction factor for shear force \( F_{s,l} \)
\( \alpha_v \)  Porosity
\( \alpha_r \)  Aspect ratio
\( \alpha_{\tau} \)  Critical aspect ratio
\( \beta \)  Proportionality constant
\( \delta \)  Width of the shear layer
\( \Delta p \)  Pressure difference
\( \Delta t \)  Time step
\( \Delta l \)  Characteristic sub-grid scale
\( \Delta x, \Delta y, \Delta z \)  Grid sizes in the \( x, y, z \) directions
\( \Delta x^+, \Delta y^+, \Delta z^+ \)  Distance in the \( x, y, z \) directions normalised by \( v/U_s \)
\( \Delta \theta \)  Rotation angle
\( \Delta S \)  Mean spacing between two cylinders
\( \xi \)  Normalized \( z \)-coordinate
\( \xi_1 \)  Empirical constant
\( \epsilon_t \)  Eddy viscosity
\( \overline{\epsilon_t} \)  Depth-averaged eddy viscosity relating to \( \tau_{yx} \)
\( \epsilon_{xx} \)  Eddy viscosity relating to \( \tau_{xx} \)
\( \epsilon_{SE} \)  Sub-grid eddy viscosity
Depth-averaged eddy viscosity
Depth-averaged eddy viscosity due to the bed-generated turbulence
Depth-averaged eddy viscosity due to the shear-generated turbulence
Mean sub-grid eddy viscosity
Lateral gradient of the secondary current force per unit length
Time lag
Theoretical overall boundary shear stress
Bed shear stress
Mean bed shear stress
Mean wall shear stress
Micro-timescale
Characteristic time scale of large eddies
Measured overall boundary shear stress
Averaged bed shear stress along the floodplain edge
Depth-averaged apparent shear stress
Reynolds shear stress
Mean wall shear stress on the left wall
Mean wall shear stress on the vertical right wall of the main channel
Mean wall shear stress on the right wall
Reynolds shear stress components
Depth-averaged Reynolds shear stress
Mean wall shear stress
Theoretical overall boundary shear stress
Shear stress due to large eddies
Shear stress due to small eddies
Von Karman constant
Fluid density
Standard two-dimensional bed shear stress
Depth-averaged secondary current
Vegetation density
Dimensionless eddy viscosity due to the bed-generated turbulence
Dimensionless eddy viscosity due to the shear-generated turbulence
Kinematic fluid viscosity
Effective depth-averaged eddy viscosity
Sub-grid eddy viscosity
2D vorticity
Vorticity vector components in the x, y, z directions
Longitudinal vorticity
Chapter 1

Introduction

As a natural valuable asset, the river has attracted almost every civilization. Rivers provide many contributions to human wellbeing: water for household consumption, industry and irrigation; convenient transportation; sustainable energy; scenic landscapes and wildlife habitats. However, the global river environments are being influenced greatly by the increasing urbanization in the developing and developed countries. Worldwide, catastrophic floods make millions of people homeless, cause huge economic loss and destroy, or seriously damage, the environment every year.

After a series of destructive floods, extensive research into the behaviour of natural rivers and manmade channels has been carried out in order to understand and manage floods since the early parts of the last century. To meet the needs of sustainable flood management, the interests of flood research have transferred from understanding of the hydrodynamics in flooding channels to studying the channel conveyance capacity. As most of the natural rivers consist of a deep main channel for the primary flow conveyance and shallow floodplain(s) for auxiliary conveyance during floods (the so-called compound channels), many controlled environments for flood study are built in the form of a compound channel. In the United Kingdom, extensive research on flood control has been conducted using the SERC Flood Channel Facility (SERC-FCF), which consists of a channel 56m long, 10m wide with a discharge capacity of 1.1 m³/s (Shiono & Knight 1991).

Numerous researchers have studied the straight compound channel flows in the past to understand the flow mechanisms both experimentally and numerically (Sellin 1964; Knight & Lai 1985; Shiono & Knight 1991; Naot et al. 1993; Knight & Shiono 1996; Nezu & Nakayama 1997; Bousmar 2002; Prooijen et al. 2005). The strong interaction between the fast main channel flow and the slow floodplain flow causes significant lateral momentum exchange near the junction of the main channel and the floodplain, which makes the flow structures very complex and causes additional flow resistance and then reduces the channel conveyance. In straight compound channels, the three main flow mechanisms are the bed-generated turbulence, free shear turbulence and secondary currents (Shiono & Knight 1991). In the previous studies, one of the
mechanisms is usually thought to be of the most importance. The main contributions of these physical processes to the lateral momentum exchange under different flow conditions are still unclear.

Recently, the river hydraulics in vegetated open channels has become one of the focuses of flood research due to the environmental point of view. River vegetation has traditionally been considered to produce high flow resistance and consequently decrease the channel conveyance capacity when the river is flooding. However, more and more engineers prefer to preserve the natural river vegetation and implement river restoration schemes since the vegetation has advantages for river protection and ecological equilibrium.

During the first stages of the research on hydraulics in vegetated channels, most of the research work was concentrated on the flow resistance in terms of the roughness coefficient or the friction factor due to the vegetation (Li & Shen 1973; Petryk & Bosmajian 1975; Kouwen & Fathi-Moghadam 2000). Increasing efforts are now being made to explore the complex physical processes due to the presence of vegetation. Most of the experimental and numerical investigations of the vegetated channel flows are carried out in the simple channels with emergent and submerged vegetation on the channel bed (Tsujimoto 1992; Nepf 1999; Nepf & Vivoni 2000; Nezu & Onitsuka 2001). Compound channels with vegetation on the floodplain exist widely in nature and investigations of the flow characteristics in these kinds of channels are of practical importance. However, only limited literature is available for the case of compound channels with emergent vegetation on the whole floodplain (Pasche & Rouve 1985; Naot et al. 1996; Rameshwaran & Shiono 2006). The flow characteristics in compound channels with one-line, emergent vegetation and with submerged vegetation on the floodplain have not been reported to date. Some natural compound channels consist of a vegetated main channel and non-vegetated floodplain, but the flow characteristics in these channels have not been extensively investigated.

Recently, the free shear turbulence in the compound channel has been receiving increasing interest from researchers and engineers. Since Sellin (1964) first observed the large-scale turbulence structures near the MC-FP junction in the compound channels, the large eddies in compound channels have been investigated with
experiments using flow-visualisation and Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA) (Tamai et al, 1986; Nezu & Nakayama, 1997). Large Eddy Simulation (LES) has also been applied to predict large eddies in the compound channel. Thomas and Williams (1995) applied LES to compound channel flow, but they only analysed the mean flow characteristics. Bousmar (2002) applied the depth-averaged Sub-Depth-Scale turbulence model of Nadaoka and Yagi (1998) to simulate the unsteady compound channel flow without vegetation. Ifuku and Shiono (2004) developed a 2-D, depth-averaged, LES model and predicted the instantaneous longitudinal and lateral velocities in a 60m-long, FCF, straight compound channel with emergent trees on the floodplain. LES has not been applied to predict the unsteady flow characteristics in the compound channel with one-line emergent vegetation along the floodplain edge and that with submerged vegetation on the whole floodplain. For engineering issues, the quasi-2D model is a very useful tool to predict the lateral distributions of depth-averaged velocity and bed shear stress in straight compound channel. Compared with other 1D, 2D and 3D models, it has the advantages of simplicity, effectiveness and accuracy. It has been successfully applied to predict the 2D flow structures in wide compound channels with and without emergent vegetation on the floodplain (Rameshwaran & Shiono 2006). However, the predictive capability of the quasi-2D model to predict the 2D flow structures in narrow compound channels is still uncertain. In the vegetation case, the drag force due to the vegetation can be introduced into the depth-averaged momentum equation as a source term; thus, the treatment of the drag force is the key to the satisfactory application of the quasi-2D model. In the cases of the compound channel with one-line emergent vegetation on the floodplain and that with submerged vegetation on the whole floodplain, the predictive capability of the quasi-2D model to predict the 2D flow structures also remains uncertain.

Based on the research gaps identified above, the main objectives of this research are to understand and predict the mean and unsteady flow characteristics under certain flow conditions. The detailed research objectives are listed below:
To carry out the velocity and boundary shear stress measurements in the compound channels to study the shear-generated turbulence and secondary currents from the point of depth-averaging.

(2) To understand the turbulent characteristics in the compound channels without vegetation, with one-line emergent vegetation at the floodplain edge and emergent vegetation on the floodplain, and with submerged vegetation on the floodplain.

(3) To explore the unsteady flow characteristics in the compound channels without vegetation, with one-line emergent vegetation at the floodplain edge and submerged vegetation on the floodplain.

(4) To assess and improve the capability of the quasi-2D model to predict the 2D mean flow characteristics in shallow and deep compound channels without vegetation, with one-line emergent vegetation at the floodplain edge and with submerged vegetation on the floodplain.

(5) To give references for the engineering application in flood management by evaluating the maximum water level in the compound channel and treating the drag force term in the quasi-2D model appropriately.

To meet the above research objectives, the following research approaches are adopted. Firstly, different compound channels were designed and constructed to investigate the flow characteristics experimentally. Secondly, LES was then applied to study the unsteady flow characteristics in the compound channels. Thirdly, the quasi-2D model with new approaches was applied to predict the 2D flow structures in these channels for the engineering application.

This thesis consists of eight chapters. Chapter 1 gives a brief introduction to the subject, background and objectives of this research. Chapter 2 outlines a comprehensive review of the literature on the straight compound channels with and without vegetation on the floodplain, which identifies the research prospects for this research. Chapter 3 explains the experimental methodologies adopted in this research, which include the channel bed levelling and channel design, calibrations for the pressure transducer and tests for the Pitot tube and the Preston tube. Velocity measurements with a Pitot tube and a 3D non-intrusive Acoustic Doppler Velocimeter (ADV) as well as boundary shear stress measurement with a Preston tube are also
explained. Chapter 4 shows the results obtained from simple rectangular channels, rectangular and trapezoidal compound channels without vegetation on the floodplain and trapezoidal compound channels with one-line emergent rods along the floodplain edge. Chapter 5 presents the results of turbulence measurements in trapezoidal compound channels without vegetation, with emergent and submerged vegetation on the floodplain. Chapter 6 illustrates the numerical methodologies of LES and numerical investigations of the unsteady flow characteristics in a smooth shallow compound channel, a compound channel with one-line emergent rods along the floodplain edge and a compound channel with submerged rods on the floodplain. Chapter 7 concentrates on the mean flow prediction for the smooth and vegetated compound channel with the quasi-2D model. Chapter 8 summarises the important findings from Chapters 4, 5, 6 and 7 and makes recommendations for future research projects. References of the text quoted from the literature are listed at the end of this thesis.
Chapter 2

Literature Review

The characteristics of flows in straight open channels are mainly reviewed in this chapter. The main aspects of turbulent characteristics are given first. Secondary currents, mean flow and boundary shear stress in the simple open channel are described in Section 2.2. The flow mechanisms, secondary currents, large eddies, mean flow and boundary shear stress in straight, compound channels are summarised in Section 2.3. The drag coefficient, large eddies and other flow behaviours in vegetated channel flows are finally reviewed in Section 2.4. Several uncertainties related to vegetated, compound channel flow are also pointed out in Section 2.4.

2.1 Turbulent characteristics

Almost all geophysical flows that occur in nature are turbulent. Despite the randomness of turbulence, some turbulent characteristics or quantities can be quantified statistically. The characteristic flow parameters are important in both theoretical turbulence research and practical engineering applications. In this section, turbulent intensity, turbulent kinetic energy and Reynolds shear stress are briefly summarized.

2.1.1 Turbulent intensity

Turbulent intensity is defined as the r.m.s. value of velocity fluctuations. The behaviour of turbulent intensity in the open channel has been extensively investigated since the first turbulent measurements were made by Raichlen (1967) using dual-sensor, hot-film anemometers. Beyond a Reynolds number of 4,000, Nezu and Nakagawa (1993) found that the turbulent intensities are independent of the Reynolds number and the Froude number and proposed the following universal expressions:

\[ \frac{u'}{U_*} = D_u \exp(-C_k \xi) \]  \hspace{1cm} (2.1)

\[ \frac{v'}{U_*} = D_v \exp(-C_k \xi) \]  \hspace{1cm} (2.2)

\[ \frac{w'}{U_*} = D_w \exp(-C_k \xi) \]  \hspace{1cm} (2.3)
where $u'$, $v'$ and $w'$ are the turbulent intensities in the longitudinal $x$, lateral $y$ and vertical $z$ directions, respectively; $U_*$ is the shear velocity; $D_u$, $D_v$ and $D_w$ are empirical constants; $\zeta = Z/H$ is the normalized $z$-coordinate; $Z$ is the distance above the channel bed and $H$ is the water depth of the flow.

The above universal expressions were confirmed by turbulent measurements in wide, open channels using Acoustic Doppler Current Profiler (ADVP) and Laser Doppler Anemometer (LDA) by Song et al. (1994), Muste and Patel (1997), and Nezu et al. (1998), but the empirical constants in the expressions vary. However, these expressions are not valid near the channel boundary where the viscous effects exist (Nezu 1977).

Many experimental results have shown $u' > v' > w'$ in open channels (Grass 1971; Steffler et al. 1985; Shi et al. 1999), but $u' > w' > v'$ near the channel wall (Renato 2002).

Turbulence kinetic energy ($k$), defined as $k = \frac{u'^2 + v'^2 + w'^2}{2}$, behaves similarly to turbulence intensity and can be expressed as follows:

$$ k/U_*^2 = D_k \exp(-2C_k \zeta) \quad (2.4) $$

where $D_k$ and $C_k$ are the empirical constants.

2.1.2 Reynolds shear stress

Reynolds shear stress ($\tau_{ij}$) represents the momentum exchange due to turbulent motion. Reynolds shear stress ($\tau_{ij}$) is usually expressed by the eddy viscosity or the mixing length.

Boussinesq (1877) assumed that the Reynolds stress behaves similarly to the viscous shear stress, therefore he developed the eddy viscosity concept, which relates the Reynolds stress ($\tau_{ij}$) to the gradients of mean velocity by Equation 2.5.

$$ \tau_{i,j} = -\rho u_i u_j = \rho \epsilon_i \frac{\partial U_i}{\partial x_j} \quad (2.5) $$
where $\rho$ is the fluid density, $u_i$ and $u_j$ are velocity fluctuations in $x_i$ and $x_j$ directions, respectively, $\varepsilon_i$ is the turbulent or eddy viscosity which is a property of the flow rather than the fluid and is dependent on the state of turbulence.

For steady, uniform, homogeneous flow, the turbulent eddy viscosity can be expressed as follows (Nezu & Nakagawa 1993):

$$\varepsilon_i = \kappa U_Z(1 - \xi)$$  \hfill (2-6)

where $\kappa$ is the Von Karman constant ($\kappa = 0.41$).

Prandtl (1925) assumed that the turbulent fluctuations are proportional to the local velocity gradient, and related the Reynolds stress ($\tau_{i,j}$) to the exchange distance of turbulent eddies and the mean flow quantities. In this concept, Reynolds shear stress is expressed as follows:

$$\tau_{i,j} = \rho \frac{\partial u_i}{\partial x_j} \frac{\partial U_l}{\partial x_j}$$  \hfill (2-7)

where $l_m$ is the turbulent mixing length.

For steady, uniform, homogeneous flow, the turbulent mixing length can be expressed as follows:

$$l_m = \kappa \xi (1 - \xi)^{\frac{3}{2}}$$  \hfill (2-8)

2.2 Simple open channel flow

2.2.1 Secondary currents

2.2.1.1 Generation mechanism

A detailed description of secondary currents is beyond the scope of this work. A brief introduction to secondary currents in simple, straight, open channels is given below. According to their generation mechanisms, the secondary currents in open channels can be categorised into two kinds: the Prandtl's first kind and the Prandtl's second kind (Nezu & Nakagawa 1993).
Secondary currents of the Prandtl's first kind are generated by centrifugal force, which can be observed in the curved or meandering channel, even in laminar flow as well as turbulent flow. Secondary currents of this kind are the so-called pressure- or geometry-driven secondary currents. Secondary currents of the Prandtl's second kind are produced by anisotropic turbulence, which can often be observed in straight channels and ducts. Secondary currents of this kind are the so-called turbulence-driven secondary currents.

The turbulence-driven secondary motions in straight, open channels are governed by Equation 2.9. In Equation 2.9, Term A represents the advection of longitudinal vorticity by the main flow and is equal to zero if no secondary currents exist, Term B represents the generation of the secondary currents by anisotropic turbulence, Term C represents the generation of secondary currents by the shear stress and Term D is the viscosity term which is only important close to the wall.

\[
W \frac{\partial \Omega_x}{\partial z} + V \frac{\partial \Omega_x}{\partial y} = \frac{\partial^2}{\partial z \partial y} \left( \nu^2 - v^2 \right) + \left( \frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2} \right) (-\nu v) + \nu \nu^2 \Omega_x \tag{2.9}
\]

where \( \Omega_x \left( = \frac{\partial W}{\partial y} - \frac{\partial V}{\partial z} \right) \) is the longitudinal vorticity.

Researchers have stated that the secondary currents are generated by various sources. Based on the possible explanations of Prandtl (1953), Brundrett and Baines (1964) evaluated each term in the vorticity equation and concluded that the secondary current is produced by the gradient of the normal stress difference. On the other hand, Einstein and Li (1958) first ascribed the origin of the secondary current in straight, open-channel flow to the gradients of the Reynolds shear stresses, a suggestion also supported by Gessner (1973).

With the advent of measurement and modelling techniques, Nezu and Nakagawa (1984) and Demuren and Rodi (1984) verified experimentally and numerically that Term B and Term C are dominant and opposite in sign. The difference between Term
B and Term C generates the secondary currents in straight, open channels, but Term B is the main generation source of secondary currents (Nezu & Nakagawa 1993).

Secondary currents can be observed by experimental measurement and numerical modelling. Nezu and Rodi (1985a) first accurately measured secondary currents in rectangular open channel flows with a two-component LDA. Tominaga et al. (1989) and Shiono and Knight (1989) measured secondary currents in compound open channel flows with a two-component LDA. The secondary currents can also be numerically solved by using appropriate turbulence models. Launder and Ying (1973) calculated the secondary currents in fully-developed, straight-channel flow with an algebraic stress model. Nato and Rodi (1982) successfully simulated the vorticity generation term \( \bar{w}^2 - \bar{v}^2 \) by introducing an empirical damping function of the turbulence due to the free water surface and the computational results agreed well with the measurements by Nezu and Rodi (1985a). Extensive measurement and calculation results reveal that the secondary currents are also influenced by channel geometry and flow conditions (Tominaga et al. 1989; Nezu & Nakagawa 1993).

Although the magnitudes of the secondary currents are only 1 – 4% of the bulk velocity (Lin & Shiono 1994), the secondary currents play an important role in the hydraulic behaviour in the open channel and this will be discussed in the following sections.

2.2.1.2 Secondary current pattern

Secondary currents have been widely investigated by scientists and engineers worldwide since Thomson (1878) first discovered the importance of secondary motions. Based on extensive experimental observations (Nezu & Rodi 1985a; Nezu & Nakagawa 1993, Imamoto et al. 1993) and numerical calculations (Naot & Rodi 1982), the secondary currents near the free-surface and the bottom exist in almost all simple, open channels and the third mid-depth vortex might occur at the half depth of the channel in narrow, open channels.

According to the experimental and theoretical investigations (Nezu and Rodi 1985b; Nezu et al. 1989; Knight & Lai 1985), the aspect ratio \( \alpha r \) has an obvious effect on hydrodynamic behaviour in open-channel flows. The aspect ratio of a channel is
defined as the ratio between the width of the channel (B) and the depth of the flow (H). Nezu and Nakagawa (1993) proposed the critical value of aspect ratio $\alpha_r$ as 4-5. In narrow, open channels, $\alpha r \leq \alpha r_c$ and the 3-D open channel flow prevails in the whole cross-section of the channel. In wide, open channels, $\alpha r \geq \alpha r_c$, the 2-D open channel flow prevails in most cross-sections of the channel.

Figure 2.1 shows secondary current streamlines in a rectangular open channel under various channel aspect ratios (Naot & Rodi 1982). The free-surface vortex is much stronger than the bottom vortex and is of most significance to the flow behaviour in open channels because it transports high momentum from the water surface to the mid-depth and this momentum exchange causes the velocity-dip phenomenon. The bottom vortex, limited by the corner and bottom bisectors, moves the low momentum fluids from near the walls towards the channel centre.

It can also be seen from Figure 2.1 that the clockwise upper free-surface vortex grows in strength and size and suppresses the lower bottom vortex as the aspect ratio increases. Therefore, the upper free-surface vortex occupies most of the channel and the lower vortex is squeezed into the channel corner. However, the secondary current patterns are almost the same when the aspect ratios are higher than 4. On the other hand, the lower vortex grows in strength and increases in size and eventually dominates the secondary motion as the aspect ratio decreases below 2. When the aspect ratio falls below 1, the upper vortex becomes very weak and breaks up into two or more weaker vortices. Thus the aspect ratio is a key factor in secondary current generation.

2.2.2 Mean velocity

Thomson (1878) first discovered the phenomenon that the maximum velocity occurs below the free water surface. It has been widely recognised that the velocity-dip phenomenon is caused by the secondary currents in open channels, especially in narrow, open channels (Nezu & Nakagawa 1993). For an aspect ratio < 2, the location of the maximum velocity is at around $Z/H = 0.60$ for both subcritical and supercritical flows (Nezu & Nakagawa 1993).
Unlike the isovels in closed channels (Bradshaw 1987), the isovels in open channels bulge towards the sidewalls and the corner due to the presence of secondary currents and these behaviours are not strongly affected by the Froude number (Nezu & Nakagawa 1993). The isovels are more distorted and the velocity-dip phenomena more noticeable for smaller aspect ratios < 4 (Naot & Rodi 1982).

Therefore, the main features of the velocity distribution in simple narrow open channels, \( \alpha r < 5 \), are the depression of the maximum velocity below the water surface, the inclination of isovels near the water surface towards the centre and the bulging towards the sidewalls and corners. Figure 2.2 shows the isovels under various aspect ratios, which agree well with the secondary current patterns as shown in Figure 2.1 (Naot & Rodi 1982).

### 2.2.3 Boundary shear stress

Boundary shear stress is directly related to flow resistance, sediment transport and bank erosion. The overall boundary shear stress \( (\tau_0) \) around the wetted perimeter in the uniform, open-channel flow can be expressed by the following equation:

\[
\tau_0 = \rho g R S_0
\]  

(2.10)

where \( R \) is the hydraulic radius, \( g \) is the gravity acceleration and \( S_0 \) is the bed slope of the channel.

The distribution of boundary shear stress around the wetted perimeter of a channel is dependent on many factors, mainly the shape of the cross-section, boundary roughness and flow conditions. Figures 2.3a and 2.3b show the typical distributions of wall shear stress and bed shear stress in rectangular, open channels under various aspect ratios (Knight et al. 1984). The representative distributions of bed shear stress in trapezoidal open channels under different aspect ratios can be found in Knight et al. (1994). The wavy distributions of boundary shear stress seen in Figures 2.3a ~ 2.3b are caused by secondary currents (Nezu & Nakagawa 1993; Knight et al. 1994; Naot & Rodi 1982; Knight & Patel 1985). Based on extensive experimental data, Knight et al. (1984, 1994) developed empirical expressions to relate the mean wall shear stress
and mean bed shear stress ($\bar{\tau}_b$) to the overall boundary shear stress in rectangular and trapezoidal channels, which are very useful to engineering practice.

2.3 Compound open channel flow

Most natural rivers and man-made channels have floodplains that extend laterally away from the river channel, “so-called compound channels” (Knight & Shiono 1996). To effectively manage the flood and riverbank system, the distributions of velocity and boundary shear stress need to be understood. Since the last century, this has driven many scientists and engineers to carry out extensive studies on the complicated flow behaviours in compound channels (Knight & Demetriou 1983; Fukuoka & Fujita 1989; Shiono & Knight 1991; Rhodes & Knight 1994).

2.3.1 Flow mechanisms

The differences in water depth and bed friction across sections in the compound channel lead to the velocity difference between the main channel and the floodplain(s) and consequently the formation of a shear layer near the junction of the main channel and the floodplain (MC-FP junction). The complex overflow mechanisms in a compound, trapezoidal channel are schematically illustrated in Figure 2.4 (Shiono & Knight 1991). The complex flow structures in compound channels arise from three distinct physical processes, namely, the bed-generated turbulence, free shear turbulence and secondary currents (Shiono & Knight 1991).

Sellin (1964) first identified the existence of vertical vortices at the MC-FP junction, as shown in Figure 2.5, using a flow visualisation technique and explained that these vertical vortices transported the high momentum fluid from the main channel towards the floodplain. Zheleznyakov (1965) called this momentum-exchange phenomenon the “kinematic effect” and showed that the interaction between the main channel flow and the floodplain flow becomes weaker as the water depth increases. The vertical vortices were also observed by other researchers (e.g. Tamai et al. 1986). Large eddies as shown in Figure 2.6 were observed in compound channels by Fukuoda and Fujita (1989). In addition to the vertical vortices, the helical secondary currents exist in the longitudinal direction and also play an important role in the momentum exchange, especially near the MC-FP junction (Shiono & Knight 1989; Tominaga & Nezu 1991).
In the previous studies, one of the above mechanisms is usually thought to be the most important. The individual contribution of these processes to the transverse momentum exchange is still unclear and needs to be quantified and generalized under various channel geometries and flow conditions. The relative water depth ($D_r$), the ratio of water depth on the floodplain ($h$) to that in the main channel ($H$), plays a very important role in the momentum exchange. Strong interaction between the main channel flow and the floodplain flow usually occurs for relative depths $D_r = 0.1 - 0.3$ (Knight & Shiono 1996). However, the low relative water depth leads to very small water depths on the floodplains at the laboratory scale and this obviously makes the experimental work to measure flow parameters difficult. Thus, the data for such small water depths have not been currently available and will be collected in this study.

The momentum exchange near the MC-FP junction causes considerable turbulent shear stress and then produces additional flow resistance, which reduces the channel conveyance capacity (Myers 1978). Apparent shear stress is normally used to reflect the overall effects of the momentum exchange arising from the bed-generated and shear-layer turbulence and secondary currents (Myers 1978; Knight & Demetriou 1983; Shino & Knight 1991). Apparent shear stress can be easily obtained from turbulence measurement data. Based on the bed shear stress data across the section, Shino & Knight (1991) proposed a new approach to calculate depth-averaged, apparent shear stress in the symmetrical, trapezoidal, compound channel. The application of this approach to calculate the apparent shear stress in the asymmetrical compound channel needs to be assessed further. Thus, the calculation method for the apparent shear stress in such cases will be explored in this study.

To numerically investigate complex flow structures in compound channels, a number of 1-D, 2-D and 3-D numerical models have been developed by many researchers (Knight & Shiono 1996). 1-D models can only be used to predict the stage-discharge relationship. 3-D models can give detailed information about flow structures, but they require quite a few empirical constants and the simulations take a long time. For engineering applications, 2-D models seem to be the best way to predict the depth-averaged velocities and bed shear stresses across the section. In the quasi 2-D model of Rameshwaran & Shiono (2006), the friction factors, depth-averaged eddy viscosities ($\overline{v}_t$) and the gradients of the depth-averaged, secondary-current term
(\frac{\partial (H \rho \overline{UV})}{\partial y}) across the section are required. Thus, an investigation of these parameters will be carried out under various flow conditions in this study.

2.3.2 Secondary currents

Secondary currents in compound channels are generated by anisotropic turbulence and their patterns are influenced by many factors, such as the channel geometry and the flow conditions.

Shiono and Knight (1989) undertook secondary current measurements using a Laser Doppler Anemometer (LDA) in the SERC Flood Channel Facility at Hydraulics Research Ltd., Wallingford, England. According to their results, the shape of the cross section influences secondary current patterns in the main channel in the case of a wide, symmetrical, compound channel (See Figure 2.7). For the rectangular compound channel, a larger counter-clockwise secondary current cell exists in the upper region and a smaller, clockwise, secondary current cell exists in the left corner of the main channel. For the trapezoidal compound channel, a smaller, counter-clockwise secondary current cell exists near the MC-FP junction and a larger, clockwise, secondary current cell exists in the main channel. One larger secondary current cell extends across the majority of the floodplain, regardless of the shape of the cross section. Smaller cells also exist in the far corner region of the floodplain. The geometry of the cross section also affects the secondary current patterns in compound channels. Shiono et al. (2003) predicted secondary currents using various numerical models in a narrow, asymmetrical, rectangular compound channel with a vertical sidewall. In the main channel, they identified a larger secondary cell in the upper region and a smaller secondary cell in the left corner. These were also observed by Shiono and Knight (1989). Besides these two secondary cells, a clockwise secondary cell was also identified near the left sidewall of the main channel.

Naot et al. (1993) calculated the rectangular, compound, open-channel flows using the 3-D algebraic stress model (ASM). The calculated secondary currents agreed well with the experimental results of Nezu (1996). The calculated results of secondary currents also indicate that the secondary current patterns are influenced by the geometry of the cross section.
Tominaga & Nezu (1991) investigated the secondary current patterns in rectangular, compound channels. Under high relative water depth $Dr = 0.75$ (Figure 2.8 a), the secondary currents near the free surface prevailed over the main channel vortex and the floodplain vortex was very strong and reached the free surface. Under relative water depth $Dr = 0.50$ (Figure 2.8 b), a pair of secondary currents, called the main-channel vortex and the floodplain vortex, was recognised near the MC-FP junction and the free-surface vortex was also observed in the sidewall region of the main channel. Under low relative water depth $Dr = 0.25$ (Figure 2.8 c), the main channel vortex expanded in the lateral direction and formed a flat vortex in the right side of the main channel. Compared with a smooth floodplain, the rough floodplain with an equivalent sand roughness $k_s' = 2\text{mm}$ has little effect on the secondary current patterns in compound channels. The effects of a rough main-channel bed on the secondary currents in compound channels remain uncertain.

According to Tominaga and Nezu (1991), the maximum magnitude of $V_s = (V^2 + W^2)^{1/2}$ is about 4% of the maximum longitudinal velocity $U_{\text{max}}$ in a compound channel, while for simple, open-channel flow, the maximum magnitude of $V_s = (V^2 + W^2)^{1/2}$ is about 2-3% of the maximum longitudinal velocity $U_{\text{max}}$. The magnitudes of secondary currents at the MC-FP junction in compound channels are usually about 5% of the bulk longitudinal velocity (Naot et al. 1993; Nezu 1996). Although the magnitude is small, the secondary currents can greatly influence the flow behaviours, such as velocity and boundary shear stress, in the open compound channels (Naot et al. 1993).

2.3.3 Large eddies

2.3.3.1 Experimental observations

The velocity shear generates large-scale turbulent structures near the MC-FP junction. Sellin (1964) first observed large vortices at the surface of a compound channel from the photographs of aluminium powder scattered on the water surface taken by a camera moving downstream at a constant speed. The distances between adjacent vortex centres were evaluated by analysing photographs. The frequency of these distances or wavelength was also estimated. Since then, large eddies have been widely investigated using various experimental techniques.
Alavian and Chu (1985) studied the large vortices in a small, experimental, compound-channel flow and found that the bed friction generates the small-scale turbulence, and at the same time exerts a stabilizing influence on the large-scale lateral disturbance.

Tamai et al. (1986) performed a set of comparative experiments to identify the predominant factor on the generation of large eddies in a compound channel flow. They observed that the large eddies are not boiling-like phenomena, but tornado-like vortices generated by the local lateral shear at the MC-FP junction. Their velocity measurement data using a hydrogen bubble method also showed that large eddies are intensively stretched by the existence of the vertical velocity gradient and that a strong upward flow existed along the vortex axis.

Using Particle Imaging Velocimetry (PIV) together with LDA, Nezu and Nakayama (1997) obtained detailed information about the three-dimensional flow structures in a compound channel. Their experiments highlighted time-discontinuities for the helical secondary currents and revealed the strong interaction between the upward flows and the horizontal vortices.

Previous experiments have mainly been concerned with the phenomenon of large eddies in compound channels and have also revealed that large eddies contain most of the turbulent kinetic energy. However, the relationship between the eddy size and the turbulent energy has not been investigated. It is important to understand the eddy structures under various flow conditions, thus this will be investigated in this study.

2.3.3.2 Numerical modelling

Recently, Large Eddy Simulation (LES) has been used to investigate large eddies in compound channel flows. In LES, flow variables are separated into resolved and unresolved parts (Lesieur et al. 2005). The resolved or large-scale quantities control the turbulent diffusion of momentum or mass and they are computed numerically by solving modified conservation equations. The crucial effects of unresolved or small-scale quantities on the resolved ones are modelled with various sub-grid models. The unsteady characteristics of large eddies can be well captured using the LES technique. The flow behaviours can be modelled using LES better than the Reynolds Averaged Navier-Stokes (RANS) approach. In addition, this numerical modelling method does
not require such extensive computational power as Direct Numerical Simulation (DNS). Details of sub-grid models can be found in Lesieur et al. (2005).

The Smagorinsky model is the most widely used sub-grid model. In this model, the Smagorinsky constant $C_s$ may vary with location in the channel, but its value is usually set to 0.1 for general engineering applications. The sub-grid length scale $l_s$ is dependent on the grid spacing and determined by Equation 2.11 (Deardorff 1970). According to Thomas and Williams (1995a), the length scale near the solid wall is reduced and must scale on the usual mixing length $l_w$, where $\kappa$ is the Von Karman constant and $l_w$ is the distance to the wall.

$$l_s = C_s \left(\Delta x \Delta y \Delta z\right)^{1/3} \tag{2.11}$$

In LES, periodic boundary conditions are usually imposed at the inlet and outlet boundaries and slip boundary conditions are usually used at the boundary walls (Thomas & Williams 1995a, Bousmar 2002).

Thomas and Williams (1995a; 1995b) applied 3-D LES with the Smagorinski model to capture the complex flow structures in a compound open channel under Reynolds numbers of approximately 42,000 and 430,000. In their works, the flow variables, mainly the velocities, bed shear stresses and Reynolds shear stresses, are all time-averaged over time period $8H/U_*$ and the unsteady flow behaviours were not presented. The overall simulation results agreed with experimental measurement data from the SERC Flood Channel Facility at Hydraulics Research Ltd, Wallingford, England. The mean velocities were over-predicted by about 8% in the middle of the main channel and this was probably caused by the coarse streamwise mesh resolution. The mesh intervals normalised by $v/U_*$ were $\Delta x^+ \sim 658$, $\Delta y^+ \sim 98$, $\Delta z^+ \sim 240$.

Shi et al. (2001) investigated the effects of the sub-grid model length scale and lateral resolution on the LES results for the compound channel flow. They found that there is no universal value of $C_s$ which satisfies all the range of mesh scales ($\Delta$). Based on Mason's matching function (Mason & Thomson 1992), they modified the length scale function with varied power values. A lateral resolution of $\Delta y^+ < 20$ near the channel
boundaries was suggested. Using a reasonable length scale and lateral resolution, the mean velocity profile was better-predicted than that of Thomas and Williams (1995b).

If a large eddy in a shallow, compound-channel flow is mainly two dimensional, a depth-averaged model will be sufficient to describe this phenomenon with less expensive computation cost. A shallow water flow is characterised by the coexistence of large-scale, 2-D, horizontal eddies with length scales larger than the water depth and small-scale, 3-D turbulence with length scales less than the water depth (Nadaoka & Yagi 1998). Based on this flow structure, Nadaoka and Yagi (1998) developed the SDS-2DH model, which is slightly different to the LES. In this model, the large eddies are computed explicitly by solving the 2-D, shallow-water equations and the effects of the sub-depth scale turbulence (SDS) on the large eddies are implicitly modelled with a $k-l$ turbulence model as expressed in Equation 2.12. In Equation 2.13, the turbulence length scale $l_d$ is calculated by Equation 2.13.

$$v_{SDS} = \frac{c_{\mu} k l^2}{c_d}$$  \hspace{1cm} (2.12)

$$l_d = \xi_l H$$  \hspace{1cm} (2.13)

where $v_{SDS}$ is the turbulence eddy viscosity, $c_{\mu}$ is constant and equal to 0.09, $c_d$ is constant and equal to 0.17, $k$ is the turbulence kinetic energy, $\xi_l$ is a constant and $H$ is the water depth. Nadaoka and Yagi (1998) suggested $\xi_l = 0.01$.

Using the SDS-2DH model of Nadaoka and Yagi (1998), Bousmar (2002) investigated large eddies in compound open channels under different relative water depth conditions. The numerical computation was initiated from an unperturbed uniform flow. The eddy generation in compound channels was qualitatively reproduced and the effects of mesh resolution on the eddy generation were also analysed. The vortex wavelength estimated from the modelling results, agrees well with that from the hydrodynamic stability analysis and that from the experiments. The averaged velocity and bed shear stress profiles are predicted well in the shear layer. In the centre region of the main channel, the velocities are under-predicted for relative water depths $Dr \leq 0.15$ and over-predicted for relative water depths $Dr \geq 0.20$. The
velocities on the floodplain are under-predicted, especially for high relative water depth conditions. The predicted shear stress at the MC-FP junction is similar to that from experiments.

2.3.4 Mean velocity

Mean velocities in compound, open-channel flows have been measured by many researchers (Knight & Lai 1985; Shiono & Knight 1991; Tominaga & Nezu 1991). The distributions of the longitudinal mean velocities are influenced by many factors, such as the shape and geometry of the cross section and relative water depth.

Figure 2.9 shows typical velocity isovels normalised by the maximum longitudinal velocity ($U_{max}$) in a rectangular compound channel under various relative water depth conditions (Tominaga & Nezu 1991). The clockwise secondary currents as shown in Figure 2.8 carry fluid with lower momentum from the wall upwards to the free surface near the MC-FP junction, then the velocities are reduced and consequently the velocity bulging near the MC-FP junction is formed. The velocity bulging near the MC-FP junction is more obvious under moderate and deep relative water depth conditions. Under low relative water depth $Dr = 0.25$ (Figure 2.9c), the isovels do not bulge towards the free surface, but towards the sidewall of the main channel in the same manner as with rectangular open channels. The velocity bulging near the corners of the main channel is similar to that in simple, rectangular channels due to the secondary currents occurring near the corners.

In Figure 2.9, the free-surface vortex moves low-momentum fluid from the left wall towards the upper region of the main channel and causes the velocity-dip phenomenon near the water surface. The bottom vortex causes the velocity reduction in a similar manner to that of the free-surface vortex. The maximum longitudinal velocity appears in the main channel but the location depends on the relative depth and the channel geometry. The velocity-dip phenomenon becomes more remarkable under higher relative water depth conditions.

Knight and Lai (1985) pointed out that the channel geometry has an important effect on the velocity distribution in the compound channel.
2.3.5 Boundary shear stress

The boundary shear stresses in compound, open-channel flows have been widely investigated by researchers and engineers (Myers & Elsawy 1975; Knight & Hamed 1984; Knight & Lai 1985; Tominaga & Nezu 1990; Shiono & Knight 1991). The distribution of boundary shear stress along the wet perimeter of a channel is influenced by many factors, such as the shape of the cross section, the streamwise variation in planform geometry, the lateral and streamwise distributions of boundary roughness and the sediment concentration (Knight et al. 1994).

Figure 2.10 shows a typical distribution of boundary shear stresses along the wet perimeter in shallow, compound, open-channel flows (Yuen 1989). Under small relative water depth conditions $Dr \leq 0.25$, the normalised values of $\overline{\tau_{ww}}/\tau_0$ decrease in the main channel and increase on the floodplain as the relative water depth increases. The wavy distributions of boundary shear stress are caused by the momentum exchange between the faster main channel flow and the slower floodplain flow, together with the complex distribution of secondary current cells (Knight et al. 1994). The three dimensional turbulence characteristics make the boundary shear stress distribution very complex. The bed shear stress ($\tau_b$) differs from the standard two-dimensional value ($\rho g H S_0$) due to the transverse gradient of the apparent shear stress (Shiono & Knight 1991). It has been found that the boundary shear stress on the main channel bed is usually smaller than $\rho g H S_0$ and larger on the floodplain (Shiono & Knight, 1991; Tominaga & Nezu 1991; Knight & Shiono 1996). It has been explained that the difference between $\tau_b$ and $\rho g H S_0$ is caused by the gradients of the depth-averaged Reynolds stress and the secondary current in the lateral direction.

2.4 Vegetated compound open channel flow

2.4.1 Drag coefficient

River vegetation can be mainly classified into two types: rigid (or stiff) and flexible (or deformable) vegetation. Stems with stiffness values ($MEI$) less than 200 $N/m^2$ are considered as flexible vegetation, others are thought of as rigid vegetation (Stephen 1999). The stems of flexible vegetation can be deformed by the flow, while the stems
of rigid vegetation can remain in their original state in the flow. This study is only concerned with rigid vegetation.

According to the definition of Douglas et al. (2001), the drag force per fluid mass \( F_T \) due to rigid vegetation can be given by Equation 2.14. Based on the previous study on vegetation, the drag force due to rigid vegetation is mainly dependent on stem geometry, stem displacement, stem density and flow conditions (Petryk 1969; Fathi-Maghadam & Kouwen 1997; Kouwen & Fathi-Moghadam 2000; Wilson et al. 2003).

\[
F_T = \sum_{i=1}^{N_r} \frac{1}{2} \rho A_i C_{D_i} U_c^2
\]

where \( U_c \) is the mean flow velocity in the vegetation layer, \( A_i \) and \( C_{D_i} \) are projected area and drag coefficients of the \( i \)th element respectively, \( N_r \) is the total number of elements, \( S_b \) is the area of the river bed and \( H \) is the flow depth.

For a single cylinder, the drag coefficient is mainly influenced by the cylinder geometry, cylinder displacement and flow conditions (Douglas et al., 2001). The drag coefficient for a circular cylinder in a two-dimensional flow is about 1.2 within the cylinder Reynolds number range of \( 8 \times 10^3 \) to \( 2 \times 10^5 \) and for its expression under cylinder Reynolds numbers less than \( 10^3 \) can refer to Frank (1999) or Douglas et al. (2001).

For array cylinders, the drag coefficients for different cylinders could be different due to the wake characteristics, which contribute to the sheltering effect (Nepf 1999). Firstly, the downstream cylinder experiences a lower impact velocity due to the velocity reduction caused by the wake. Secondly, the turbulence contributed by the wake delays the point of separation on the downstream cylinder, which results in a lower pressure drop around the cylinder and thus a lower drag. This sheltering effect increases as both the longitudinal and lateral spacing between the cylinders decrease.

The bulk drag coefficient \( \overline{C_D} \) can be expressed by Equation 2.15 (Nepf 1999):

\[
\overline{C_D} = \frac{2F_T}{\lambda U_c^2}
\]
where $\lambda$ is the vegetation density, defined as the projected area per unit volume, and can be given by equation 2.16:

$$\lambda = N_v D = \frac{DH}{\Delta S^2 H} = \frac{D}{\Delta S^2} \quad (2.16)$$

Where $N_v$ is the vegetation density ($m^{-2}$); $\Delta S$ is the mean spacing between two cylinders; $D$ is the cylinder diameter and $H$ is the water depth.

Based on the force balance in uniform flow, the value of $C_D$ for emergent vegetation can be estimated from Equation 2.17 (Nepf 1999; Nikora 2000).

$$\left(1 - \frac{\pi \lambda D/4}{2}ight) C_b U_e^2 + \frac{1}{2} C_D (\lambda D) U_e^2 = (1 - \frac{\pi \lambda D/4}{2}) g h \frac{\partial h}{\partial x} \quad (2.17)$$

where the first left term represents the bed friction force, $C_b$ is the bed friction coefficient which can be determined from the bed shear stress; the second left term represents the drag force due to vegetation; the right term represents the weight component due to gravity.

The bulk drag coefficient usually decreases as the vegetation population density increases. Under cylinder Reynolds numbers 4,000-10,000, Nepf (1999) concluded that the bulk drag coefficient decreases roughly from 1.2 to 0.6 as cylinder density increases from 0.008 to 0.07.

In addition to the drag due to the projected area of vegetation, the shear on the top surface of the submerged vegetation also causes drag force and the effect of the interface shear on the overall bulk drag coefficient needs to be considered. However, this effect has not been studied, thus this effect will be studied here.

2.4.2 Overall flow behaviours

2.4.2.1 Emergent vegetation

Simple, open-channel flow through emergent vegetation has three characteristics: the flow is mainly pressure-driven; the primary source of turbulence production is from the stem wakes and the principal exchange mechanism is longitudinal advection (Nepf
In the emergent case, the turbulence length scale is of the order of the stem diameter. The turbulence intensities increase with the introduction of sparse vegetation due to the wake, but decrease as the vegetation density increases due to the reduced velocity.

In a rectangular partly-vegetated channel, Tsujimoto (1992) measured the turbulence with a micro-propeller and an electromagnetic current meter. Under the water depth of about 4.5cm, the mean velocity decreases from 0.32m/s to 0.22m/s when the vegetation density increases from 1.88m$^{-1}$ to 11.34m$^{-1}$. The velocity difference between the vegetated zone and non-vegetated zone increases as the vegetation density increases. He reported that the Reynolds shear stresses and turbulence intensities for vegetation density 11.34m$^{-1}$ are about 40% higher than those for vegetation density 1.88m$^{-1}$.

Naot et al. (1996) numerically predicted the flow behaviours in a rectangular partly-vegetated channel using an algebraic stress model. The maximum turbulent kinetic energy increases as the vegetation density increases from lower value to median value and then decreases as the vegetation density increases to high values. The locations of the maximum turbulent kinetic energy shift from close to the channel bed at the edge of the vegetation zone to the upper part of the shear layer in the channel interior. They explained that this is caused by the stronger secondary currents at high vegetation densities.

In a compound channel with a vegetated floodplain, a lateral shear layer is generated near the MC-FP junction and the momentum exchange mechanism is similar to that in a compound channel with uniform roughness (Pasche & Rouve 1985). However, the emergent vegetation causes additional flow resistance on the floodplain and then a larger velocity difference and finally a lateral momentum exchange stronger than that in a compound channel with a smooth floodplain under similar relative water depth conditions. This can be clearly seen from the turbulence measurement data and predicted results of Rameshwaran and Shiono (2006).

In most vegetation studies of compound channels, the vegetation was distributed over the whole floodplain. However, little attention has been paid to vegetation along the floodplain edge. One-line vegetation along the floodplain near the MC-FP junction
can absorb noticeable momentum from the mean flow, reduce the local velocity near the edge and finally reduce the bed shear stress near the edge which is helpful in protecting the riverbed. In addition, one-line vegetation along the floodplain can cause less conveyance effect than vegetation over the whole floodplain under similar vegetation densities.

2.4.2.2 Submerged vegetation

In simple, open-channel flow with submerged vegetation, the vertical discontinuity of vegetation results in a strong shear layer around the top of the vegetation which is similar to the free shear layer (Nepf & Vivoni 2000). Turbulence generated in this layer transports the high momentum of the overlying water to the vegetation zone. Therefore, it defines the scales of active turbulence in the channel with the shear length scale being of the order of the vegetation height. In this case, the flow is mainly driven by the shear stress and the momentum-exchange mechanism involves turbulent exchange through large eddies.

The flow behaviours in simple open channels with vegetated beds have been widely investigated by researchers and engineers (Tsujimoto et al. 1992; Naot et al. 1996; Nepf & Vivoni 2000; López & García 2001). Tsujimoto et al. (1992) carried out turbulence measurements in a rectangular channel with rigid vegetation on the bed. The velocity deflection was observed at the interface between the vegetated and the non-vegetated zones. Turbulent intensities and Reynolds shear stresses peak at the interface and their values increase as the water depth above the vegetation zone increases.

In partly vegetated channels or compound channels with vegetated floodplains, the flow behaviours are more complex than those in the smooth open channels (Shimizu & Tsujimoto 1993; Naot et al. 1996; Nezu & Onitsuka 2001). In submerged vegetation cases, both lateral and vertical shear layers exist between the vegetated zone and the non-vegetated zone due to the submerged vegetation. These shear layers generated by the vegetation make the flow behaviours more complex than those in the emergent vegetation cases.

Nezu and Onitsuka (2001) carried out detailed turbulence measurements in partly-vegetated open channels using LDA and PIV techniques. The vegetation was
simulated by bronze cylinder rods with a diameter of 2 mm and a length of 50 mm. The dimensionless vegetation densities, $\lambda d$, were chosen as 0.0625, 0.25 and 1.0. The Froude numbers were set at 0.10, 0.24 and 0.40 under the same water depth of 7cm.

Nezu and Onitsuka (2001) reported that the maximum region of $u'$, $v'$ and $w'$ is at the boundaries between the vegetated and non-vegetated zones. The isovel of $v'$ is similar to that of $u'$. The value of $v'$ increases complicatedly near the water surface at the junction owing to the coherent horizontal vortex, but that of $w'$ does not increase much over the vegetation owing to the depression of the water surface. The position of the maximum vertical Reynolds shear stress $-\overline{uw}$ is at around the vertical interface between the vegetated and non-vegetated zones. The position of the peak lateral Reynolds shear stress $-\overline{uv}$ is at around the lateral interface between the vegetated zone and the non-vegetated zone and the peak value increases with the Froude number. Their results also show that the lateral Reynolds shear stress increases as the vegetation density and the Froude number increase.

The flow characteristics in a compound channel with submerged vegetation on the floodplain have not been reported to date, thus they are investigated in this study.

2.4.3 Large eddies

2.4.3.1 Emergent vegetation

Similar to smooth compound channel flows, large eddies exist in the shear layer in simple partly-vegetated channels and compound channels with emergent vegetation on the floodplains.

Pasche & Rouve (1985) carried out laboratory and field experiments in trapezoidal compound channels and observed the existence of large eddies at the interface between the vegetated floodplain and the smooth main channel using visualization techniques. In this flow, the energy spectra are dominated by a principal peak at frequency 0.125 Hz, which indicates that a periodic vortex is generated in the shear layer.
Tsujimoto (1992) used capacity limnimeters to measure the instantaneous fluctuations of the water surface as well as instantaneous fluctuations of the longitudinal and lateral velocities in a partly-vegetated channel. The measurement results indicate that the intense transverse mixing is caused by the organized and low-frequency fluctuations of the transverse velocity in the shear layer and is maintained by associated water-surface fluctuations. These mechanisms are also clarified by stochastic analyses of simultaneous measurements of velocities and water-surface elevation.

Recently, LES has been applied to simulate large eddies in vegetated open channels. Ifuku and Shiono (2004) developed a 2-D, depth-averaged, LES model and predicted the instantaneous longitudinal and lateral velocities in a 60m-long, Flood Channel Facility (FCF), straight, compound channel with emergent trees on the floodplain. Smagorinsky model was used to determine the sub-grid eddy viscosity. Boundary conditions were discharge at the channel inlet, water depth at the channel outlet and slip condition on the wall. The vegetation effect was taken into account by introducing the drag force term in the governing 2D depth-averaged equation. In TELEMAC-2D, the vegetation was modelled by introducing simple geometry in the mesh and the boundary conditions were similar to those in Ifuku and Shiono (2004).

Strong horizontal eddies were produced near the MC-FP junction (Ifuku & Shiono 2004). The trends of the predicted depth-averaged velocity and bed shear stress agreed with the experimental data obtained from FCF in the United Kingdom (UK), but their values near the MC-FP junction were over-predicted in the main channel side and under-predicted on the floodplain side. The contributions of Reynolds shear stress and the secondary current to the flow resistance were found to be relatively significant in the shear layer.

Nadaoka and Yagi (1998) developed a 2-D, SDS-2DH model to simulate the generation of large eddies in a shallow, rectangular, open channel with a vegetated bank. They found that the bed friction and vegetation drag, acting as sinks of vorticity, play an important role in the development of large eddies and the production of Reynolds shear stress. They also noticed that the equilibrium horizontal eddy size increases with the vegetation-layer width $B_z$. 
Su and Li (2002) modified the LES model of Li and Wang (2000) and used a $k-l$ model to parameterize the sub-grid turbulence. The vegetation effect was also modelled as the internal source of drag force per unit fluid mass and was added into the momentum equation. The predicted results show that large eddies occurred at the interface between the vegetation zone and non-vegetation zone. The numerical results agreed well with the experimental data of Tsujimoto and Kitamura (1992).

2D-LES has not been applied for the compound channel with one-line emergent vegetation along the floodplain edge and it will be studied in this work. Results of LES for vegetated, compound-channel flows using TELEMAC-2D have not been reported till now.

2.4.3.2 Submerged vegetation

Flow through submerged vegetation is characterised as the large-scale coherent eddies which control the turbulence dynamics in the vertical shear layer (Nepf & Vivoni 2000). A typical large eddy consists of a pair of counter-rotating, longitudinal vortices. Sweeps generated by the downdraft between the vortex pair rather than ejections dominate the eddy fluxes (Finnigan 2000).

The vertical discontinuity of vegetation leads to the inflection of vertical velocity profiles at the top of the vegetation and this velocity inflection makes the flow susceptible to Kelvin-Helmholtz instability (Nepf & Vivoni 2000). This instability generates the large-scale, coherent vortices within the mixing layer. Some researchers have identified frequency peaks between 0.1 and 0.6 Hz in the energy spectra of the longitudinal velocity measured within the vegetation canopies (Ackerman & Okubo 1993; Grizzle et al. 1996; Nepf & Vivoni 2000; Nezu & Onitsuka 2001). The advection of these vortices causes the progressive, coherent waving of aquatic vegetation, known as “monami” (Ackerman & Okubo 1993; Tsujimoto 1993).

PIV results from Nezu & Onitsuka (2001) showed that the horizontal large eddies near the free surface are generated by the velocity inflectional instability which increases as the Froude number and vegetation density increase. The space-time correlation analyses show that large eddies control the momentum-exchange between the vegetated and non-vegetated zones by periodic motions. The vertical large eddies due to the lateral shear were not presented.
Compared with LES studies for emergent vegetation cases, LES has not been used to study the flow characteristics in the compound channel with submerged vegetation on the floodplain due to the more complex treatments of drag force and the lack of computational power.

Frohlich and Rodi (2004) carried out LES for the flow around a circular cylinder of finite height 2.5 times the diameter at a Reynolds number of $Re = 43,000$. Using fine mesh, the simulation results obtained with the Smagorinsky model captured the periodic eddy structures quite well and also agreed with the measurements. In particular, the existence of tip vortices and an arch vortex in the average flow downstream of the free end was also demonstrated, but the dependence of the height-to-diameter ratio on the flow simulation was not studied.

Park et al. (2004) evaluated the suitability of high-order accuracy, centred and upwind-biased, compact difference schemes for large eddy simulation (LES) through both static and dynamic analyses. The results from the static analysis give a misleading conclusion that both the aliasing and finite-differencing errors increase as the numerical dissipation increases. The dynamic analysis, however, shows that the aliasing error decreases as the dissipation increases and the finite-differencing error outweighs the aliasing error. It is also shown that there exists an optimal upwind scheme of minimizing the total discretization error because the dissipative schemes decrease the aliasing error but increase the finite-differencing error. Based on LES results for channel flow at $Re = 23,000$ and flow over a circular cylinder at $Re = 3,900$, they found that the conventional, compact, upwind schemes are not suitable for LES, whereas the fourth-order, compact-centred scheme is better for LES, provided that a proper treatment of the nonlinear term is performed.

2.4.4 Mean flow

Extensive velocity measurements have been undertaken in partly-vegetated open channels. For channel flows over a bed covered by rigid vegetation, various empirical expressions have been developed to describe the velocity distributions over the water depth. Inside the vegetation zone, some researchers assumed the longitudinal velocities are uniform (Kouwen et al. 1969) or even zero (Christensen 1985). Most of the velocity expressions inside the vegetation zone are related to the vegetation
density and the constants in the expressions are usually functions of the vegetation density (Tsujimoto et al. 1992; EI-Hakim & Salama 1992; Kutija & Hong 1996; Klopstra et al. 1997). The velocities above the vegetation zone are mainly expressed by a log-law and the characteristic roughness length is usually included in the expression (Kouwen et al. 1969; Nnaji & Wu 1973; Christensen 1985; Temple 1986).

For channels with vegetated corners, the isovels are different to those in smooth compound channels. The maximum velocity occurs in the non-vegetated zone and the velocity-dip occurs near the free surface in the non-vegetated zone, when the ratios of the vegetation height to water depth are relatively low (Shimizu & Tsujimoto 1992).

According to Naot et al. (1996) and Nezu & Onitsuka (2001), the isovels only bulge near the junction between the vegetated and the non-vegetated zones under large vegetation density conditions. This is caused by the secondary currents generated under these vegetation conditions.

Naot et al. (1996) also applied an algebraic stress model to predict the velocity distributions in a compound channel with emergent vegetation on the floodplain. With an increase in the vegetation density, the flow on the floodplain is considerably attenuated and a zone of homogeneous longitudinal velocity is formed and extends to the floodplain under higher vegetation densities. However, no experimental data are available to verify this flow behaviour. To date, the isovels in the compound channel with a submerged floodplain have not been reported. For engineering applications, prediction of the distributions of the depth-averaged velocity using 2D-SKM (Shiono & Knight 1991) in this case has not been explored.

2.4.5 Secondary currents

The secondary currents in vegetated channel flows require more attention and investigation. Compared with smooth channel flows, literature on this topic is currently very limited, especially in the case of compound channels with submerged vegetation on the floodplain.

In channel flows through submerged vegetation, Nepf and Koch (1999) found small-scale vertical secondary currents behind the submerged stem, which play an important role in the vertical transport of sediments and nutrients within an aquatic canopy. The ascending flow is generated by the vertical pressure gradients along the surface of the
stem due to the gradient of the longitudinal velocity. It is controlled by a local balance of the vertical pressure gradient, proportional to $\partial u^2/\partial z$, and the viscous stress and is also influenced by vegetation density and flow velocity. The roughness difference between the walls and the top of the vegetation zone can also cause secondary circulation above the vegetation, but the magnitude of the secondary currents can be even less than 3mm/s (Ghisalberti 2000; Nepf & Vivoni 2000).

Nezu and Onitsuka (2001) measured secondary currents with LDA in a vegetated corner of an open channel and they found that the secondary currents were quite different from those in smooth open channels. Their results show that a large, counterclockwise, secondary circulation exists in the channel (See Figure 2.11)—and they move high-momentum fluid from the non-vegetated zone to the top of the vegetated zone and then into the vegetated zone and finally to the non-vegetated zone. They also found that the secondary currents are generated by an anisotropic turbulence and that the strength of secondary currents near the free surface over the vegetation zone is of appreciable size. The strength of the secondary currents increases as the Froude number increases.

2.4.6 Boundary shear stress

Vegetation in the channel bed increases the total drag by absorbing momentum from the flow and thereby reduces the bed shear stress. In general, the boundary shear stress on the vegetated bed is smaller than that in the non-vegetated bed owing to the drag force on the vegetation. Compared with the extensive turbulence measurements, to date little measurement work has been successfully done on boundary shear stress in the vegetated channel. The distribution of boundary shear stress in the vegetation zone depends on many factors, such as vegetation density, flow conditions and channel geometry (Shimizu & Tsujimoto 1993; Nezu & Onitsuka 2001; Anita & Bruce 2002; Crawley & Nickling 2002; Baptist 2003).

Shimizu & Tsujimoto (1993) tried to measure the boundary shear stresses on the bed in a compound channel and the vegetated corner of a channel, but they did not obtain accurate values due to technical problems. However, they found that the boundary shear stresses on the vegetated bed are smaller than those in the smooth compound channel under similar water depth conditions.
Thompson and Wilson (2002) measured the particle shear with a hot-film anemometer and determined the drag force by using a special instrument in a flume with a length of 7.32 m, a width of 0.38 m and a height of 0.38 m. Four idealized shapes were used to simulate the geometric characteristics of vegetation: cylinders, rectangles, trapezoids with large bases and trapezoids with small bases. Under the conditions of water depths 0.022–0.058 m and vegetation densities of 1–9 m², the experimental results showed that the particle shear partition decreases with an increase in vegetation density and that the particle shear accounted for 13–89% of the total shear. The measurement results agreed well with the theory of Raupach (1992).

In most cases, the flow in the vegetation zone approximately relates to the flow over a rough surface and the behaviour of the bed shear stress of the vegetated bed is similar to that of a rough surface. To indirectly determine the bed shear stress in vegetated channels, two main calculation methods have been developed by a number of researchers. The *force balance method* is used to determine the average bed shear stress on a vegetated channel bed and the *momentum equation method* is used to determine the local bed shear stress on the vegetated channel bed.

For uniform flow in vegetated channels, the bed shear stress can be usually calculated from the relationship derived from the balance of the shear force on the bed, drag force on the vegetation and the weight component of the flow. This force balance method can give the results of mean bed shear stress in vegetated channels phenomenally (Angelina & James 2003).

Extending the continuity equation and steady Reynolds equations for normal, open-channel flow, Nezu and Onitsuka (2001) predicted the lateral distributions of bed shear stresses in the partly-vegetated open channel. The distribution in the channel estimated from Equation 2.21 agreed well with those estimated from the log-law. The bed shear stresses on the non-vegetated bed were larger than those on the vegetated bed. The bed shear stresses near the MCFP region varied greatly and this was caused by the complex momentum-exchange.

In the momentum equation method, the effects of flow and vegetation conditions on the bed shear stress in vegetated channels are embodied. Theoretically, this method
can correctly predict results, but more verification is needed because the drag force term is not easy to determine precisely under complex flow conditions.

It is very important to know wall shear stress in terms of riverbank design since the wall shear stress affects the stability of the riverbank. However, experimental measurements of wall shear stresses in vegetated channels have not been reported to date.
Figure 2.1 Calculated secondary current streamlines in open channels under various width-to-depth ratio conditions (after Nezu & Rodi 1982).

Figure 2.2 Calculated longitudinal velocity contours in open channels under various width-to-depth ratio conditions (after Nezu & Rodi 1982).
Figure 2.3  Distributions of wall shear stress and bed shear stress in open channels (after Knight et al. 1994).

Figure 2.4  Overflow mechanisms in a two-stage compound channel flow (after Shiono & Knight 1991).
Figure 2.5  Large eddies observed at the junction between the main channel and the floodplain of a compound channel (after Sellin 1964).

Figure 2.6  Conceptual visualisation of the momentum exchange between the main channel and the floodplain of a compound channel (after Fukuoka & Fujita 1989).
Figure 2.7 Illustration of secondary currents in compound channels with rectangular and trapezoidal cross-sections (after Shiono & Knight 1989).

Figure 2.8 Secondary current patterns for straight compound channel (after Tominaga & Nezu 1991). (a) $h/H = 0.75$; (b) $h/H = 0.50$; (c) $h/H = 0.25$. 
Figure 2.9  Longitudinal velocity isovels for straight compound channel (after Tominaga & Nezu 1991).

Figure 2.10  Distributions of boundary shear stress in compound trapezoidal channels under various relative water depth conditions (after Yuen 1989).
Figure 2.11 Secondary current patterns for rectangular channels with vegetation corner (after Nezu & Onitsuka 2001).
Chapter 3

Experimental Methodologies

In this section, the experimental methodologies used in this work are explained. Section 3.1 gives a detailed description of the experimental apparatus, which consists of rectangular channels, smooth compound channels and compound channels with vegetated floodplains. Section 3.2 describes the measurement techniques, including flow rate determination, Pitot tube and acoustic Doppler velocimeter for the velocity measurement and a Preston tube for the boundary shear stress measurement.

3.1 Experimental apparatus

3.1.1 Rectangular channels

3.1.1.1 Hydraulic system

To model natural river environments during the experiments, various channels were designed from simple rectangular channels to complex, compound channels with vegetated floodplains. Most experiments were undertaken in a small open channel with a length ($L$) of 12 m and a width ($B$) of 0.306 m and in a large open channel with $L \times B = 8.6m \times 0.915m$ in the hydraulic laboratory at Loughborough University.

The rectangular channel with $L \times B = 12m \times 0.306m$ was made out of Perspex and was mainly used to determine the flow rate chart and test a Preston tube and a Pitot tube. To study the flow development and gain basic knowledge of flow behaviour in open channels, two small rectangular channels with $L \times B = 8.3m \times 0.15m$ and $L \times B = 8.3m \times 0.10m$, as shown in Figure 3.1, were made by placing 5cm wide and 5cm high Perspex prisms in the small rectangular channel. Table 3.1 shows the flow conditions for the rectangular channel experiments. The detailed flow conditions of two representative rectangular cases SR-1 and SR-2 will be shown in Table 4.1.

Figure 3.2 illustrates the hydraulic system of the small rectangular channel. It was filled with tap water through a circular PVC pipe by a centrifugal pump as shown in Figure 3.3a. Before the experiments the water level in the steel outlet tank ($L \times B \times H = 3.00m \times 1.30m \times 0.89m$) was kept constant. The required flow rate, measured by an electromagnetic flow meter (Figure 3.3b), was obtained by changing
the motor speed of the pump. The motor speed of the pump was controlled by adjusting the pump controller (Figure 3.3c) to obtain the required flow rate.

Table 3.1  Flow conditions for rectangular open channels

<table>
<thead>
<tr>
<th>Flow Rate (m³/s)</th>
<th>Channel Width (m)</th>
<th>Water Depth (m)</th>
<th>Re (×10⁴)</th>
<th>Water Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0048-0.0232</td>
<td>0.306</td>
<td>0.047-0.152</td>
<td>0.99-3.92</td>
<td>18.6-21.8</td>
</tr>
<tr>
<td>0.0012-0.009</td>
<td>0.10</td>
<td>0.0295-0.0498</td>
<td>0.65-2.17</td>
<td>20.7-23.8</td>
</tr>
<tr>
<td>0.0013-0.011</td>
<td>0.15</td>
<td>0.0303-0.0365</td>
<td>0.66-2.32</td>
<td>20.5-21.9</td>
</tr>
</tbody>
</table>

To facilitate making the uniform flow under small water depths, an adjustable polymethyl methacrylate weir, as shown in Figure 3.4a, was fabricated and installed at the outlet of the small rectangular channel. The uniform flow was obtained by adjusting the weir height at the outlet of the channel and the water depths were measured by a point gauge, as shown in Figure 3.4b.

3.1.1.2 Channel bed levelling

Bed levelling is of utmost importance to open channel experiments. The bed slope of the small rectangular channel was set to be 1/1,000 by using surveying equipment. The detailed procedures are described below.

Firstly, six sections were chosen in the rectangular channel. The longitudinal distances at the six sections from the inlet are 0, 0.805, 2.513, 4.908, 8.246 and 11.434 m, respectively. Two control points at each section were set to ensure the zero bed slope in the lateral direction. The left point A and right point B were set at 2.8cm away from the left wall and the right wall, respectively. The zero control point was set at 12 m downstream from the inlet.

Secondly, the expected bed levels of 6 sections along the channel were calculated based on a bed slope of 1/1,000.
Thirdly, the measured levels were obtained using the surveying equipment as shown in Figure 3.5 and the bed level difference between the expected and measured bed levels at each section was evaluated.

Fourthly, the screws under the channel sections were slightly and carefully adjusted from the downstream section to the inlet section until the ideal bed levels were obtained. Figure 3.6a shows the bed level profiles of the left side.

Lastly, six new sections were set at an interval of 2 m from the channel inlet to x = 10 m to check whether the bed slope is 1/1,000 or not. After slightly adjusting some screws, the channel was run with flowing water for 12 hours and the channel bed slope was checked again. Figure 3.6b shows the final bed level profiles.

For the large compound channel, the slopes of the main channel bed were 0.002 as shown in Figure 3.7 (Wilkins 2003).

3.1.1.3 Boundary roughness

The bed roughness has an important influence on the flow behaviour. The distributions of boundary shear stress will vary according to the bed roughness. At the beginning of the experiments, there were lots of glue and stickers along the channel bed and the sidewalls, which were used for building the channel, which could obviously influence the distribution of the bed shear stress by changing the local bed roughness (Figure 3.8).

The effect of changes in the bed roughness on the bed shear stress has been observed by a number of researchers. The formation of the internal boundary shear layer as a result of a sudden change of roughness has been studied by Fredsoe et al (1993) and Nezu & Tominaga (1994). They all noted an abrupt increase in the bed shear stress over the bed at the larger roughness section. Although most of the bed roughness heights on the channel boundary were about 1~2mm, their effect on the distribution of boundary shear stress was ambiguous. This indicates that complete cleaning of the channel is of vital importance in obtaining satisfactory measurements. All the glue and stickers on the channel boundary were therefore removed before the experiments.
3.1.1.4 Inlet turbulence

To minimize the effect of inlet turbulence on the flow behaviour downstream, three major units were adopted (Figures 3.9a - 3.9b). Firstly, a 1m long steel inlet tank, as shown in Figure 3.9a, was constructed to minimize the strong turbulence from the outlet of the circular PVC pipe. The cross-section of the 1m long inlet tank changes in dimension from $B \times H = 0.59m \times 1.40m$ to $B \times H = 0.31m \times 0.50m$. Secondly, a 10cm long, 30cm wide and 20cm high Kraft honeycomb with small, uniform, hexagonal holes, as shown in Figure 3.9b, was placed at the entrance to the channel to straighten the flow and prevent large disturbances due to inlet turbulence. The average diagonal length of the hexagonal holes was about 1cm. Thirdly, a 25.5cm long, 30.5cm wide and 2.5cm high float foam plate, as shown in Figure 3.9b, was fixed to the honeycomb by a nylon thread to avoid the wavy water surface propagating downstream.

Figures 3.10a - 3.10c show the depth-averaged velocity profiles and isovel lines at discharge 15 L/s with and without the honeycomb. The isovel lines and depth-averaged velocity profile are totally different with and without the honeycomb. When the honeycomb was used, the velocity pattern is nearly symmetrical and similar to those in the literature. The depth-averaged velocity profile is also symmetrical. This indicates that the honeycomb plays an important role in minimizing the effect of inlet turbulence and the honeycomb was therefore placed at the channel inlet for each experiment.

3.1.2 Smooth compound channels

The schematic figure for the compound channel is shown in Figure 3.11. Table 3.2 lists the geometrical parameters for some compound channels found in the literatures. Notations in Table 3.2 can refer to Figure 3.11.

Based on the geometrical parameters listed in Table 3.2, the rectangular compound channel, as shown in Figure 3.12a, was made by putting PVC plates on the right side of the rectangular channel. To investigate the effects of channel geometry on flow behaviour, the small, trapezoidal, compound channel shown in Figure 3.12b was also made in the rectangular channel. These two compound channels were mainly used to acquire basic knowledge of flow behaviour and to study the effects of large eddies on momentum exchange. To further study the effects of large eddies on momentum
exchange, the larger trapezoidal compound channel shown in Figure 3.12c was constructed in a larger flume. In the large compound channel, it is possible to undertake turbulence measurements with an acoustic Doppler velocimeter (ADV). Table 3.3 lists the geometrical parameters for compound channels used in this study.

**Table 3.2 Geometrical parameters for compound channels in literatures**

<table>
<thead>
<tr>
<th>B1(cm)</th>
<th>Bm(cm)</th>
<th>B4(cm)</th>
<th>D(cm)</th>
<th>Bf/D</th>
<th>Bf/Bm</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>225</td>
<td>75</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>3</td>
<td>Shiono &amp; Knight, 1991</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>0</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>Nezu &amp; Nakayama, 1997</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>0</td>
<td>5</td>
<td>2</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>0.67</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>Tominaga &amp; Nezu, 1991</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>0</td>
<td>2</td>
<td>10</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>0</td>
<td>6</td>
<td>3.33</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

The large compound channel with a bed slope of 1/500 is 8.6 m long, 0.915 m wide and 0.80 m deep. The channel sides were fabricated with slate. Four glass viewing-windows were incorporated on both channel sides. The main channel bed was a grass mattress. The floodplain was wood. The water was circulated between the channel and the ground water tank by an axial pump. The water level was measured with a point gauge. An adjustable weir was installed at the channel outlet to control the water level in the channel. A honeycomb was put at the channel inlet to minimize the effects of inlet turbulence and the diameter of the honeycomb hole was 6 cm.

**Table 3.3 Geometrical parameters for experimental compound channels**

<table>
<thead>
<tr>
<th>Case</th>
<th>B1(cm)</th>
<th>Bm(cm)</th>
<th>B4(cm)</th>
<th>D(cm)</th>
<th>Bf/D</th>
<th>Bf/Bm</th>
<th>Channel type</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>15</td>
<td>12</td>
<td>0</td>
<td>3.6</td>
<td>4.2</td>
<td>1.3</td>
<td>Rectangular</td>
</tr>
<tr>
<td>T1</td>
<td>15</td>
<td>12</td>
<td>3.6</td>
<td>3.6</td>
<td>4.2</td>
<td>1.3</td>
<td>Small Trapezoidal</td>
</tr>
<tr>
<td>T2</td>
<td>36.5</td>
<td>40</td>
<td>15</td>
<td>15</td>
<td>2.4</td>
<td>0.9</td>
<td>Large Trapezoidal</td>
</tr>
</tbody>
</table>
3.1.3 Vegetated compound channels

To acquire basic knowledge of flow behaviour in the vegetated compound channel, three different arrangements of vegetation on the floodplain, one of which is vegetation on the edge of the floodplain, were examined. One-line emergent circular wood rods were placed at $y = 0.163\text{m}$ on the floodplain of the small, trapezoidal, compound channel. The diameter ($D$) and height ($H_r$) of the rods were 9 mm and 100 mm respectively. A special frame, as shown in Figure 3.13a, was designed for holding one-line rods along the floodplain edge. The spacing ($l$) between two rods was 4 cm and this spacing was chosen based on the critical spacing of $l/D = 3.8$ for no interface by the rods suggested by Igarashi (1991).

Two uniformly vegetated floodplains were used to study flow structures under emergent and submerged vegetation conditions. Emergent vegetation was modelled with square blocks, as shown in Figure 3.13b. The blocks were 6 cm long, 6 cm wide and 10 cm high. Submerged vegetation was modelled with concrete cylinders, as shown in Figure 3.13c. The diameter and height of the cylinders were 6 cm and 11 cm respectively. Figure 3.14a shows the block spacing for the emergent vegetation case and Figure 3.14b shows the rod spacing for the submerged vegetation case.

3.2 Measurement techniques

3.2.1 Flow rate

As mentioned in section 3.1.1.1, the flow rate can be measured by an electromagnetic flowmeter in the small channel. The flow rate ($Q_F$) is directly related to the frequency of the motor of the pump, providing that the water level in the tank remains relatively constant. It is more convenient to obtain the flow rate with the relationship between the flow rate and the motor frequency ($F_c$) than to obtain it by reading the flowmeter. Thus, the flow rate calibration was done in the main rectangular channel, and the calibration curve was obtained from Equation 3.1.

$$Q_F = 0.023 \ln(F_c) - 0.0457$$  (3.1)

The channel discharge for the large compound channel was determined by weighing the water mass per unit time.
3.2.2 Pitot tube

3.2.2.1 Basic principle

Although the Pitot tube only measures the longitudinal velocity, it can give conclusive results if it is correctly used (Rhodes & Knight, 1994). As described in section 3.1.1.1, the main purpose of velocity measurement in the small channels is to obtain isovel line patterns and depth-averaged velocity profiles. Hence, the conventional Pitot tube, as shown in Figure 3.16a, was used in the small channel. A point gauge as shown in Figure 3.16b and a horizontal ruler as shown in Figure 3.16c were used to control the vertical and lateral movements of the Pitot tube. The diameter of the inner tube of the Pitot tube with 4 holes (Φ0.75mm) is 2.2 mm. The Pitot tube was placed against the flow direction to measure the pressure difference between the stable and dynamic pressures. By connecting the L-shaped Pitot tube to the low-range pressure transducer, the pressure difference (Δp) can be obtained from the output of the transducer. The flow velocity (U_p) can be determined by applying Bernoulli's equation (Equation 3.2),

\[
U_p = \sqrt{\frac{2\Delta p}{\rho}}
\]

where \( \rho \) is the fluid density.

A reference reading was required before every experiment to allow the background pressure difference to be considered. The reference reading was taken five minutes after the Pitot tube was submerged in a beaker. Then, the submerged Pitot tube in the beaker was moved to the channel, the beaker was leaned against the channel bed carefully and the submerged Pitot tube was transferred from the beaker into the flowing water in the experimental channel. The Pitot tube must be submerged during the transfer process. The reverse of this procedure was performed when a reference reading was taken at the end of the experiment. If the difference between the start and end reference readings was higher than 5 %, the experiments were repeated. This procedure was also used for the Preston tube.
3.2.2.2 Calibration for the pressure transducer

As mentioned in section 3.2.2.1, the pressure difference \((\Delta p)\) is required to determine the velocity and is normally obtained using a pressure transducer. Careful calibration of the pressure transducer is important to obtain accurate measurements.

A LPM5480, low-range, pressure transducer was used to obtain the pressure difference \((\Delta p)\) in this work. Two compartments in the pressure transducer are separated by a diaphragm which flexes with the change in differential pressure. The displacement of the diaphragm due to a pressure difference can be converted into a voltage. The voltage \((V)\) and the pressure difference \((\Delta p)\) were calibrated by changing the water level from 10mm to 50mm in a calibration tank as shown in Figure 3.17 using a digital calliper. The calibration data were obtained and shown in Figure 3.18. Equation 3.3 is the calibration equation.

\[
\Delta P = 68.913V - 3.5209 \tag{3.3}
\]

3.2.2.3 Test for the Pitot tube

As the diaphragm in the low-range pressure transducer is elastic, it takes a certain period of time to respond to the correct pressure difference. The main purposes of the test are to determine the proper response time and record time.

It takes some time for the pressure transducer to respond when the Pitot tube is moved from one position to another. In order to define a response time, the experiments were performed in the rectangular channel under a water depth of 3.54 cm. Figures 3.19 and 3.20 show the velocity profiles after three lateral movements and four vertical movements, respectively. The velocities become stable after one minute for the seven movement cases. This indicates that the response time can be chosen as one minute.

Figure 3.21 shows the averaged velocity profiles after four movements using a one-minute response time. From Figure 3.21, the averaged velocities do not change much as the recording time is longer than one minute. Therefore, the recording time can be chosen to be more than one minute.
The velocity measurements in the rectangular channel were conducted using a one-minute response time and recording time. The velocities were measured repeatedly at $x/R = 306$ in case SR-1. Figures 3.22a and 3.22b show the isovel lines for the two measurements. The isovel lines in Figures 3.22a and 3.22b are nearly the same and both flow patterns are nearly symmetrical about the centre line. Figure 3.23 shows the velocity profiles over the water depth for the two measurements at the centre. The velocity profiles in Figure 3.23 coincide well. Figures 3.22 and 3.23 demonstrate the consistency of repeated measurements using the one-minute response time and recording time.

3.2.3 Acoustic Doppler velocimeter

3.2.3.1 Basic principles

An acoustic Doppler velocimeter (ADV) as shown in Figure 3.24a, manufactured by Nortek, was used to measure three components of velocity in the large, compound-channel flow. The acoustic Doppler velocimeter (ADV) uses the Doppler shift principle to measure velocity by transmitting short pairs of sound pulses, listening to their echoes and measuring the change in pitch or frequency of the returned sound (Nortek, 2004).

The ADV consists of one transmitter, four receivers, as shown in Figure 3.24b, and one signal-processing module. The transmitter transmits acoustic pulses into water. These pulses are then reflected from the small, suspended particles in the water and the reflected signals are received by the four receivers. The acoustic signal received by each receiver is used to calculate the Doppler phase shift ($d\phi$), which is proportional to the velocity component along the bisector of the transmitted and received beams. The beam velocities $v_i$ ($i = 1, 2, 3$) are computed using the Doppler phase shift relation as expressed in Equation 3.4 and the velocities in the local Cartesian coordinate system ($u_r$) can then be converted from the radial velocities using a transformation matrix which is calibrated by the manufacturer (McLelland & Nicholas 2000).

$$v_i = \frac{C_n d\phi}{4\pi f_{ADV} dt}$$  (3.4)
where \( c_s \) is the speed of sound, \( f_{ADV} \) is the operating frequency (10 MHz), \( d\phi \) is the signal phase change and \( dt \) is the measurement time interval.

Compared with a laser Doppler anemometer, the ADV is relatively low in cost and easy to use. The sampling volume is located at least 5 cm below the transmitter and the flow being measured is then less influenced by the ADV probe. The ADV can measure three components of velocity in a small sampling volume (Kraus et al 1994, Lane et al. 1998). However, the capability of the ADV to resolve turbulence quantities has been a subject of debate among researchers (Nikora & Goring 1998, McLelland & Nicholas 2000, Garcia et al. 2005). Voulgaris and Trowbridge (1998) stated that the main sources of measurement errors are sampling errors (\( \sigma_r^2 \)) generated by the ADV hardware, Doppler noise due to the motion of acoustic reflectors in the sampling volume (\( \sigma_\gamma^2 \)) and errors due to the shear in the sampling volume (\( \sigma_u^2 \)). The effects of configuration parameters on minimizing the measurement errors were investigated in this study.

### 3.2.3.2 Recording time and velocity range

The experiment tests were carried out in the small compound channel to define the recording time. The sampling point was located at 5 m downstream from the channel inlet, 0.10 m away from the left channel wall and 0.01 m above the main channel bottom. The water depth in the main channel was 0.07 m. The mean local velocity measured by a Pitot tube (\( U_0 \)) was 0.232 m/s and the mean shear stress (\( U_* \)) was 0.019 m/s.

Unlike the Pitot tube, the response time of ADV is very short and usually less than 1 second (McLelland & Nicholas 2000). To avoid the possible vibration of the ADV holder, the response time for velocity measurement was chosen as 30 seconds when the ADV was moved from one position to another. Figures 3.25a ~ 3.25c show the effects of recording time on the measured results for averaged velocity, turbulent intensity and Reynolds shear stress. It is easy to see from Figure 3.25, that the values of these parameters remain almost the same when the recording time increases to 2 minutes. Thus the recording time for ADV was chosen as 2 minutes.
The ADV has six nominal velocity ranges as shown in Table 3.4.

### Table 3.4 Maximum velocities in various nominal velocity ranges

<table>
<thead>
<tr>
<th>Nominal velocity range (m/s)</th>
<th>0.03</th>
<th>0.10</th>
<th>0.30</th>
<th>1.00</th>
<th>2.50</th>
<th>4.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum horizontal velocity (m/s)</td>
<td>0.26</td>
<td>0.44</td>
<td>0.94</td>
<td>1.88</td>
<td>3.28</td>
<td>5.25</td>
</tr>
<tr>
<td>Maximum vertical velocity (m/s)</td>
<td>0.08</td>
<td>0.13</td>
<td>0.27</td>
<td>0.54</td>
<td>0.94</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Velocity data were collected for 2 minutes at three nominal velocity ranges using 11 sampling frequencies between 2 and 200 Hz. Figures 3.26 – 3.28 show the averaged velocities \((U, V, W)\), turbulent intensities and Reynolds stresses using nominal velocity ranges \(\pm 0.03\), \(\pm 0.10\) and \(\pm 0.30\) m/s, respectively. Most of the measurement results are not reasonable when the lower range of \(\pm 0.03\) m/s is used. For example, the measured longitudinal velocities \((U)\) are only 0.5 \(U_0\), the measured turbulent intensities \((\hat{u})\) are nearly 7 \(U_*\), and finally the Reynolds shear stresses \((uw)\) are around -6 \(U_*\). The values of \(u_i\) and \(uw\) are quite different from the values at similar positions in the open channel flow obtained by Nezu and Nakagawa (1993). These results indicate that the nominal velocity range \(\pm 0.03\) m/s is not suitable for this case.

Most results of using ranges \(\pm 0.10\) and \(\pm 0.30\) m/s are similar, but the turbulent intensities \((\hat{v}'\)) using range \(\pm 0.30\) m/s are obviously larger than those using range \(\pm 0.10\) m/s at higher frequencies (> 50 Hz). McLelland & Nicholas (2000) also showed that the measurement errors increase with the velocity range and sampling frequency. Thus, the nominal velocity range \(\pm 0.10\) m/s is the best range for this case.

Based on the above results, the nominal velocity range should be set to cover the range of the velocities expected during the data collection and the best velocity range needs to be selected by trial test.

#### 3.2.3.3 Sampling frequency

From Figure 3.26, it can be seen that the sampling frequency does not influence the mean velocity measurements using the velocity range \(\pm 0.10\) m/s. However, Figure
3.27 shows that the sampling frequency influences the turbulent intensities. The turbulent intensities $u_i$ increase as the sampling frequency increases, but peak at around 150 Hz and do not increase further. This means all the turbulent structure for this case can be captured using a sampling frequency of 150 Hz. It is interestingly noticed in the literature that the most used sampling frequency is 25 Hz for ADV (Lane et al. 1998, Sarker 1998, Bousmar 2002). In this test case (Figure 3.27), the ratios of turbulent intensities $u'$, $v'$ and $w'$ at 25 Hz to those at 150 Hz were 0.86, 0.88 and 0.90, respectively. This means that major part of the turbulent energy can be obtained by using a sampling frequency of 25 Hz.

Turbulent intensities at different sampling frequencies can be obtained by integrating the energy spectrum, which will be further described in section 5.7.1. As turbulent measurements were only performed in the large compound channel, the effect of sampling frequency on the turbulent intensity was further studied in the large channel under a relative water depth of 0.50. The sampling point was located at 6.45 m downstream from the channel inlet, 0.46 m away from the left channel wall and 0.178 m above the main channel bed. The sampling frequency was 100 Hz. The measured turbulent intensities $u'$, $v'$ and $w'$ at this point were 7.03, 6.56 and 4.13 (cm/s)$^2$.

Figures 3.29 and 3.30 show the cumulative turbulent intensities contributing to the total intensities under different frequencies. It can be seen from these two figures that the turbulent intensities increase quickly within the range 0 ~ 10 Hz and then increase slowly until a frequency of 50 Hz. Nearly 100% of the turbulent intensity is covered by using a sampling frequency of 50 Hz. In this study, 100 Hz was then chosen for the turbulent measurements using ADV to ensure covering most turbulent frequencies.

3.2.3.4 Sampling volume of ADV

The cylindrical sampling volume with a diameter of 6 mm is located 5 cm below the centre of the transmitter. The height of the sampling volume is adjustable in the range of 1.0 ~ 9.1 mm. Theoretically, increasing the sampling volume size can improve the spatial averaging because the total sample numbers that are used for the velocity calculation are increased (Nortek 2004). However, if the sampling volume size is too large, the measured velocity might be biased towards the local point velocity and
small eddy information might not be captured, especially in a small channel. In this study, the height of the sampling volume was chosen as 2.5 mm.

During the measurements, the transmitting length was set to 1.8 mm. The signal-to-noise ratio (SNR) is an indicator of the relative strength of the received signal and a higher SNR indicates that the velocity measurement is more reliable. Usually, an SNR value of 20 can ensure good measurements (Nortek 2004). The values for SNR were almost all higher than 20 during the large channel experiments and this indicates that the noise effect is suppressed by that of the echo signal.

Based on the above considerations, the height of the sampling volume and the transmitting length can be chosen as 2.5 mm and 1.8 mm respectively. The sampling volume is 70.65 mm$^3$.

Velocity measurement results using ADV were compared against those using a Pitot tube in the small compound channel. The configuration settings for ADV were: nominal velocity range ±0.10 m/s, sampling frequency 100 Hz, sampling volume height 2.5 mm, transmitting length 1.8 mm with the power level set to 'High'. Six sampling points were selected. Figure 3.31 shows the velocity data measured by ADV and the Pitot tube. In Figure 3.31, $y$ represents the distance from the left channel wall, 0.2-ADV and 0.2-Pitot represent the data from ADV at 0.2 cm above the main channel bed and data from the Pitot tube at 0.2 cm above the main channel bed respectively. It can be seen from Figure 3.31 that the velocities measured by ADV almost agree with those measured by the Pitot tube.

### 3.2.3.5 Small tank

Using ADV with a 3-D down-looking probe, the velocity near the water surface cannot be measured directly due to the limitation of a 5 cm distance between the transmitter and the sampling point. To overcome this, a special small cylindrical tank of 8.4 cm diameter, as shown in Figure 3.24a, was designed and placed on the water surface to measure the velocities below the water surface. This is the first application of using ADV with a 3-D down-looking probe to measure velocity near the water surface.
The cylindrical tank was made out of Perspex with a depth of 6 mm. Several transparent materials were tried to seal the tank bottom. No signal was detected by ADV when a Perspex plate with a depth of 6 mm and thick plastic film were used. This might indicate that most of the acoustic energy from the transmit sensor or (and) from the receiver sensors was absorbed by the thick materials. A thin film was proved to be the best material for making the tank bottom. The thin film was stuck to the Perspex wall with superglue. To avoid the sudden water level jump near the small tank and to minimize the flow disturbance around the tank, the film extended about 2 cm in the front and back of the flow direction to make a smooth flow.

The height of the small tank was set as 8 cm, which was 3 cm larger than the minimum distance between the sampling point and the transmitter head. The main purpose of setting this height was to ensure that the sensor head was submerged during the measurements. Moreover, the tank on the water surface cannot be too large because a large tank would pose holding difficulties.

The capability of using the small tank to measure the velocities near the water surface was investigated in the large compound channel. Some representative test results are presented in Figures 3.32a ~ 3.32f. The water depth in the main channel was 20 cm. Velocities at z = 0 ~ 15 cm were measured with ADV in the channel directly and velocities at z = 16 ~ 20 cm were measured with ADV in the tank on the water surface.

In Figure 3.32a, the velocity U profile was not continuous at z = 17 cm which might be caused by the boundary interference. Lane et al (1998) studied the boundary interference and identified the zone where the noise might mask the velocity signal. Velocities decreased quickly between Z=190 and Z=200mm and this is because a boundary layer had developed below the water tank. In Figures 3.32c~3.32d, the turbulence intensities decreased gradually as the distances from the channel bottom increased to 150 mm. Higher turbulence intensities $u^2$ and $w^2$ occurred around Z = 17 cm which corresponded to the sharp changes of velocity U and W in this zone. In Figures 3.32e ~ 3.32f, higher Reynolds stresses were also related to the velocity profiles.
These results indicate that the small water tank can be used to measure velocity near the water surface, except in the zones which are 0–1 cm and around 3 cm below the water surface.

3.2.3.6 Data analysis

The Vectrino software creates a binary data file that can be converted to an ASCII format file. Explore V software from Nortek was used to analyse the measurement data in the ASCII format. To minimize measurement errors, the noisy data were removed by four methods, namely, correlation score threshold, signal to noise ratio (SNR), velocity threshold and spike filtering. The removed data were linearly interpolated.

The correlation score is expressed as a percentage, where 100 represents a perfect correlation and 0 represents no correlation. Perfect correlation indicates that all the water particles move in the same manner. The correlation score threshold replaces velocity data for which the correlation scores are lower than the threshold value. The correlation score threshold was set at 70 during the measurements as suggested by Nortek (2004).

Signal to noise ratio (SNR) is defined by Equation 3.5 and can be used to estimate the relative strength of the velocity signal and the noise signal. The SNR threshold was set at 20 during the measurements.

\[
SNR = 20 \log_{10} \left( \frac{Amplitude_{signal + noise}}{Amplitude_{noise}} \right) 
\]  
(3.5)

Velocity threshold is expressed as a level of the standard deviation of each velocity component. The velocity threshold was set at 3.

Spikes can be identified as the local acceleration. For each successive triplets of sample, the local accelerations can be expressed by Equations 3.6a ~ 3.6b. The sign change in the accelerations indicates the presence of spikes, while the magnitude \( A_{ij} \) can be expressed by Equation 3.7. The spikes are filtered using the acceleration threshold of three times of gravity acceleration \( g \).
where \( j = x, y, z \) and \( dt \) is the sampling rate.

\[
A_U = \sqrt{\sum_{j=1}^{3} (a_{1j} - a_{2j})^2}
\]  

(3.7)

For most of the measurement data, the above four thresholds were used.

3.2.3.7 Velocity corrections

It is very difficult to make the alignment of the probe to the flow direction and the Z direction exactly normal to the channel bed. These alignment problems were also encountered using LDA and velocities need to be corrected (i.e., Nezu & Rodi 1986).

The velocities were corrected by rotating the coordinate system through a small angle and the correction method used in this work is given next.

For vector \((U_i, U_j)\) on the \(X_i - X_j\) plane, the new vector \((U_i', U_j')\) on the new \(X_i' - X_j'\) plane can be calculated by Equations 3.8a ~ 3.8d.

\[
C = \sqrt{U_i^2 + U_j^2}
\]  

(3.8a)

\[
\alpha = \arctg \left( \frac{U_i}{U_j} \right)
\]  

(3.8b)

\[
U_i' = C \cos(\alpha + \Delta \theta)
\]  

(3.8c)

\[
U_j' = C \sin(\alpha + \Delta \theta)
\]  

(3.8d)

where \( \Delta \theta \) is the rotation angle.
With the carefully tested Pitot tube and ADV, the velocities across the sections can be measured accurately using the measurement grids as shown in Figure 3.33.

3.2.4 Preston tube

3.2.4.1 Basic principles

The measurement of boundary shear stress is of vital importance to practical issues like the bed form evolvement and riverbank erosion. Such data can provide a physical insight into the complex flow phenomena in open channels.

The conventional Preston tube method developed by Preston in the 1950's, which is probably the simplest and cheapest indirect measurement technique, has been widely used in the field of fluid mechanics. The boundary shear stress \( \tau_b \) can be obtained from the differential pressure \( \Delta p \) between the dynamic and static pressures in the Preston tube at the boundary. If the Preston tube is accurately calibrated, it gives a measurement accuracy of \( \pm 6\% \) when the pressure gradient parameter \( \Delta \) \( (= \frac{|dp/dx|\nu}{\rho U^2}) \) is in the range \(-0.007 < \Delta < 0.015\) (Patel 1965).

The Preston tube used in this work is shown in Figure 3.34. The diameters of the static and dynamic pressure pipes are 3.00mm and 2.72mm, respectively. There are four circular holes with diameters of 0.54mm.

The offset value of the Preston tube was determined before each experiment by putting the tube into a plastic beaker. Then the Preston tube was moved into flowing water in the channel and fixed on a special holder.

3.2.4.2 Calibration method

The main difficulty of applying the Preston tube method is how to obtain the most appropriate calibration equation for a given Preston tube diameter.

Based on Preston's suggestion of the non-dimensional relationship between \( \Delta p \) and \( \tau_b \) (Preston1954), Patel (1965) proposed the following relationships:

\[
y' = 0.50x' + 0.037, \quad y' < 1.5
\]  

(3.9a)
\[ y^* = 0.8287 - 0.1381x^* + 0.1437x^{*2} - 0.0060x^{*3}, 1.5 < y^* < 3.5 \quad (3.9b) \]

\[ x^* = y^* + 2 \log_{10}(0.95y^* + 4.10), 3.5 < y^* < 5.3 \quad (3.9c) \]

where \( x^* = \log_{10}\left(\frac{d}{\sigma_0 x_0}\right) \), \( y^* = \log_{10}\left(\frac{d}{\sigma_0 x_0}\right) \) and \( d \) is the external diameter of the dynamic tube.

Bechert (1995) proposed a more general calibration equation expressed below,

\[ \tau^* = 28.44(\Delta p^*)^3 + 6.61 \times 10^{-6}(\Delta p^*)^{3.5}, 2.5 < x^* < 9.0 \quad (3.10) \]

where \( \tau^* = \frac{\tau_{b}}{d^2} / \left(\rho v^2\right) \) and \( \Delta p^* = \frac{\Delta p}{d^2} / \left(\rho v^2\right) \)

where \( \rho \) and \( v \) can be determined by Equation 3.11 and 3.12.

\[ \rho = 0.00008889T^3 - 0.01T^2 + 0.0830159T + 999.8048 \quad (3.11) \]

\[ v = 10^{-6}\left[1.14 - 0.031(T - 15) + 0.00068(T - 15)^2\right] \quad (3.12) \]

Based on the boundary shear stresses calculated using Patel’s and Bechert’s methods (e.g., Sutardi & Ching, 2001), Patel’s method was much less dependent on the diameter under ranges of 1.46–5.54 mm and it gives more accurate results. Many researchers in the hydraulics field have used Patel’s method. Therefore, Patel’s method was adopted in this work.

The tests were carried out to find an appropriate response time, recording time and the effects of tube displacements and water temperature on the measurements.

When the Preston tube is moved from one position to another, it will take some time to correctly respond to the measurement system. An accurate boundary shear stress also depends on the length of the recording signal. Two series of tests were conducted. One was setting a proper response time and a recording time and the other was extending the recording time without a response time.
In most cases, the water temperature changes owing to the heat from the pump. A six-hour continuous measurement of the boundary shear stress was conducted at one point on the channel bed to check the temperature effect.

3.2.4.3 Test results

Figures 3.35a ~ 3.35c show the response time results of six movements using three minutes as the recording time. Although the response time for every movement was not always the same, it takes about two minute to settle the output of the system. This indicates that the appropriate response time for measuring boundary shear stress can be chosen as two minutes.

Using two minute as the response time, the relationship between the recording times and the boundary shear stresses for each movement was illustrated in Figure 3.36. In Figure 3.36, the boundary shear stresses reach stable values three minutes later for movements M1–M4 and almost one minute later for movements M5–M6. When the Preston tube was moved from a position of smaller boundary shear stress to a position of larger boundary shear stress, the measured boundary shear stress remained as the previous value within the two minute response time and then it was increased to the current larger value correctly. When the Preston tube was moved from a position of larger boundary shear stress to a position of smaller boundary shear stress, the measured boundary shear stress was decreased from the larger previous value to the current smaller one after two minute response time. As a result, there was a crossover at just two minutes in Figure 3.36. For general applications, a three-minute recording time is an appropriate value for getting satisfactory measurements of boundary shear stress.

The water temperature was recorded every hour. The temperature increased from 20.7°C to 21.8°C in six hours. Figure 3.37 shows that the boundary shear stresses were not influenced if the water temperature changed by about 1 degree centigrade.

With a carefully used Preston tube, the boundary shear stress in open channels can be measured accurately. During the measurements, the lateral intervals on the channel bed were about 1.5 cm and the vertical intervals were about $\frac{1}{7}$ H.
Figure 3.1  Rectangular open channels.

Figure 3.2  Schematic representation of the hydraulic system for the small channel.
Figure 3.3  Flow rate control system for the small channel. (a) Centrifugal pump; (b) Electromagnetic flow meter; (c) Pump controller.

Figure 3.4  Water level control units. (a) Adjustable weir; (b) Point gauge.
Figure 3.5  Surveying equipment for channel bed levelling.

Figure 3.6  Bed level profiles of the main rectangular channel. (a) Left side; (b) Left and right sides.
Figure 3.7  Bed level profiles of the large compound channel.

Figure 3.8  Effect of bed roughness on the boundary shear stress.

Figure 3.9  Main units for disturbing the inlet turbulence. (a) Inlet tank; (b) Kraft honeycomb and float foam plate.
Figure 3.10  Effect of honeycomb on the velocity distributions at aspect ratio 2.9. (a) Depth-averaged velocity with and without honeycomb; (b) Isovels without honeycomb; (c) Isovels with honeycomb.
Figure 3.11  Schematic representation of a compound open channel.

Figure 3.12  Experimental smooth compound channels. (a) Small rectangular compound channel; (b) Small trapezoidal compound channel; (c) Large trapezoidal compound channel.
Figure 3.13 Vegetated compound channels. (a) One-line emergent rods at the floodplain edge; (b) Emergent rods on the floodplain; (c) Submerged rods on the floodplain.

Figure 3.14 Rod spacing for large vegetated compound channel. (a) Emergent rods; (b) Submerged rods.
Figure 3.15  Calibration curve for the pump controller.

Figure 3.16  Pitot tube. (a) Pitot tube and pressure transducer; (b) Point gauge; (c) Horizontal ruler.
Figure 3.17  Calibration tank for the pressure transducer.

Figure 3.18  Calibration curve for the pressure transducer.

\[ P = 68.913V - 3.5209 \]

\[ R^2 = 0.998 \]
Figure 3.19  Velocity and response time (Lateral movements).

Figure 3.20  Velocity and response time (Vertical movements).

Figure 3.21  Velocity and recording time (Lateral and vertical movements).
Figure 3.22  Isovels at x/R = 306 in case SR-1. (a) Run 1; (b) Run 2.

Figure 3.23  Velocity distributions along the water depth.

Figure 3.24  ADV and its probe geometry. (a) ADV; (b) ADV Probes.
Figure 3.25  Time-averaged measurement data using various recording times.  
(a) Velocity; (b) Turbulent intensity; (c) Reynolds stress.

Figure 3.26  Time-averaged velocity data using various nominal velocity ranges.  
(a) U; (b) V; (c) W.
Figure 3.27  Time-averaged turbulent intensity data using various nominal velocity ranges. (a) $u'/U$; (b) $v'/U$; (c) $w'/U$.

Figure 3.28  Time-averaged Reynolds stress data using various nominal velocity ranges. (a) $uv/U^2$; (b) $uw/U^2$; (c) $vw/U^2$.
Figure 3.29  Relationship between energy density and frequency.

Figure 3.30  Relationship between contribution \( \frac{u_i(f)}{u_i} \) and frequency.

Figure 3.31  Measured velocities by ADV and Pitot tube.
Figure 3.32 Measurement results along the water depth using the small tank. (a-b) Averaged velocities; (c-d) Turbulent intensities; (e-f) Reynolds stresses.
Figure 3.33  Measurement grids for velocity using a Pitot tube and ADV. (a) Small compound channel; (b) Large compound channel.

Figure 3.34  Preston tube on the channel bed.
Figure 3.35  Boundary shear stress and response time. (a) Movements M1 ~ M2; (b) Movements M3~ M4; (c) Movements M5 ~ M6.

Figure 3.36  Boundary shear stress and recording time.
Figure 3.37 Boundary shear stress and water temperature.
Chapter 4

Small Compound Channel Experiments

In this chapter, the major results of the small compound channel flow experiments are presented. Sections 4.1 and 4.2 show the experimental conditions and flow development. Section 4.3 summarises the characteristics of the mean flow in the non-vegetated, compound channel whilst section 4.4 describes the method of calculating the depth-averaged eddy viscosity $\overline{e_i}$ by considering the effects of bed-generated turbulence and lateral shear and also illustrates the depth-averaged Reynolds shear stresses $\overline{(r_{ii})}$ under various flow conditions. Section 4.5 introduces the calculation results of the depth-averaged apparent shear stress $\overline{(r_{ai})}$. Section 4.6 gives the calculation results of the depth-averaged secondary current $(-\rho\overline{UV})_d$ and the maximum lateral velocity $V_{max}$. Sections 4.7 and 4.8 present the calculation results of the contributions to the depth-averaged apparent shear stress and bed shear stress respectively. Section 4.9 presents the mean flow pattern and shear layer analyses in the compound channel with emergent rods on the floodplain. Section 4.10 summarises the results and discussions for the small, compound-channel flow.

4.1 Experimental conditions

Nine experiments were conducted in the 9.7m long channel with a variety of cross-section shapes. Detailed channel geometry parameters are described in section 3.1. Cases SR-1 ~ SR-2 are rectangular channel cases under different aspect ratio conditions. Cases SRC-1 ~ SRC-3 are rectangular compound channel cases under different relative depth conditions. Cases STC-1 ~ STC-3 are trapezoidal compound channel cases under similar relative depth conditions to those in cases SRC-1 ~ SRC-3. Case STC-4 is the trapezoidal compound channel case with one-line emergent rods near the MC-FP edge.

Detailed experimental conditions are listed in Table 4.1. $H$ is the water depth in the rectangular channel or in the main channel. $B$ is the channel width. $R$ is the hydraulic radius. $U_m$ is the mean bulk velocity. $U_\ast (=\sqrt{gRS_o})$ is the friction velocity, $g$ is the
gravitational acceleration and $S_0$ is the bed slope. $Re = 4RU_m/v$ is the Reynolds number, $v$ is the kinematic fluid viscosity. $n = \left( \frac{2\frac{1}{3}}{R^2S_0^\frac{1}{2}} \right)/U_m$ is the Manning coefficient.

The velocities and boundary shear stresses were measured with a Pitot tube and a Preston tube, respectively. Velocity measurement grids and boundary shear stress measurement points have been described in section 3.2.3 and 3.2.4 respectively. Based on the velocity measurement data, the depth-averaged velocity ($U_d(y)$) at $y$ m from the left channel wall and measured bulk velocity ($U_m$) were calculated by Equations 4.1 and 4.2 respectively. The bulk velocity ($U_{m,p}$) was determined from the measured discharge ($Q_p$) using Equation 4.3. The different percentages of the bulk velocities ($=100\ast(U_m-U_{m,p})/U_{m,p}$) for all experiments were within 3%. The measured overall boundary shear stress ($\tau_B$) for a compound channel was calculated using Equation 4.4. The theoretical overall boundary shear stress ($\tau_0$) was determined using Equation 4.5. The different percentages of the overall boundary shear stresses ($=100\ast(\tau_B-\tau_0)/\tau_0$) for all experiments were within 4%, except in Case STC-4.

### Table 4.1 Experimental Conditions for the Small Channel

<table>
<thead>
<tr>
<th>Case</th>
<th>$H$(m)</th>
<th>$B$(m)</th>
<th>$R$(m)</th>
<th>$U_m$(m/s)</th>
<th>$U_s$(m/s)</th>
<th>$Re$</th>
<th>$n$</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-1</td>
<td>0.0354</td>
<td>0.150</td>
<td>0.0240</td>
<td>0.2303</td>
<td>0.0153</td>
<td>22109</td>
<td>0.0114</td>
<td>Rectangular</td>
</tr>
<tr>
<td>SR-2</td>
<td>0.0486</td>
<td>0.100</td>
<td>0.0246</td>
<td>0.3044</td>
<td>0.0155</td>
<td>29953</td>
<td>0.0088</td>
<td></td>
</tr>
<tr>
<td>SRC-1</td>
<td>0.0466</td>
<td>0.306</td>
<td>0.0222</td>
<td>0.2428</td>
<td>0.0148</td>
<td>21561</td>
<td>0.0103</td>
<td>Compound (s=0)</td>
</tr>
<tr>
<td>SRC-2</td>
<td>0.0561</td>
<td>0.306</td>
<td>0.0281</td>
<td>0.3075</td>
<td>0.0166</td>
<td>34563</td>
<td>0.0095</td>
<td></td>
</tr>
<tr>
<td>SRC-3</td>
<td>0.0703</td>
<td>0.306</td>
<td>0.0361</td>
<td>0.3555</td>
<td>0.0188</td>
<td>51334</td>
<td>0.0097</td>
<td></td>
</tr>
<tr>
<td>STC-1</td>
<td>0.0475</td>
<td>0.306</td>
<td>0.0223</td>
<td>0.2287</td>
<td>0.0148</td>
<td>20400</td>
<td>0.0110</td>
<td>Compound (s=1)</td>
</tr>
<tr>
<td>STC-2</td>
<td>0.0575</td>
<td>0.306</td>
<td>0.0289</td>
<td>0.2917</td>
<td>0.0168</td>
<td>33720</td>
<td>0.0102</td>
<td></td>
</tr>
<tr>
<td>STC-3</td>
<td>0.0723</td>
<td>0.306</td>
<td>0.0374</td>
<td>0.3477</td>
<td>0.0191</td>
<td>52016</td>
<td>0.0102</td>
<td></td>
</tr>
<tr>
<td>STC-4</td>
<td>0.0745</td>
<td>0.306</td>
<td>0.0386</td>
<td>0.2138</td>
<td>0.0194</td>
<td>33011</td>
<td>0.0175</td>
<td></td>
</tr>
</tbody>
</table>
\[ U_d(y) = \frac{1}{H(y)} \int_0^y U dZ \]

\[ U_m = \frac{\int_0^y U_d(y) H(y) dy}{\int_0^y H(y) dy} \]

\[ U_{m,p} = \frac{Q_p}{A} \]

\[ \tau_b = \frac{1}{P} \int \tau_0 dP \]

\[ \tau_0 = \rho g RS_0 \]

where \( H(y) \) is the local water depth at \( y \) m from the left channel wall; \( Z \) is the vertical level from the channel bed; \( U \) is the local velocity; \( B \) is the width of the channel; \( A \) is the cross-section area; \( P \) is the wet perimeter; \( \tau_b \) is the local boundary shear stress and \( \rho \) is the fluid density.

4.2 Flow development

It takes some distance for the flow to become fully developed. In controlled hydraulic environments, the development length is usually influenced by the inlet condition. To get correct flow information about uniform flow, flow measurement must be undertaken at the proper location where the flow is fully developed. The measurement section needs to be chosen reasonably before formal measurements.

In this channel, only the longitudinal velocity component can be obtained using a Pitot tube. The velocity patterns are the same at various locations where the flow is fully developed. The cross-section isovels along the channel were therefore used to investigate the flow development and determine the proper measurement section. Flow development was initially investigated in the rectangular straight channel and further studied in the rectangular straight compound channel.
The section location was expressed as the distance ratio \( (X/R) \) of the longitudinal distance from the inlet \( (X) \) to the hydraulic radius \( (R) \). The relative water depth \( Dr \) for a compound channel usually ranges from 0 to 0.6 (i.e., Tominaga & Nezu 1991, Knight & Shiono 1996). The relative water depth, \( Dr \), is the ratio between the water depth on the floodplain to that in the main channel, i.e. \( Dr = h/H \), where \( h \) is the water depth on the floodplain. Table 4.2 lists the distance ratios of \( X/R \) at \( X = 7.47 \) m of the rectangular compound channel under four relative water-depth conditions. Based on the above distance ratio ranges, five cross sections were selected along the 15 cm wide and 5 cm deep rectangular channel and four cross sections were selected along the rectangular compound channel.

Figures 4.1a ~ 4.1e show the distributions of the normalized longitudinal velocity \( (U/U_m) \) at five cross sections along the rectangular channel in case SR-1. The aspect ratio \( (= B/H) \) of this case is 4. At \( X/R = 85 \) (Figure 4.1a), the positions of the isovel of 1.14 is at around \( Z/H = 0.75 \) and the velocity pattern is not symmetrical. As the flow progresses downstream (Figure 4.1b), the positions of the maximum isovel of 1.21 and the isovel of 1.14 move down to around \( Z/H = 0.8 \) and \( Z/H = 0.6 \) respectively, but its lateral position shifts slightly from the centre line of the channel. At \( X/R = 176 \) (Figure 4.1c), the lateral position of the isovel of 1.14 moves around the centre line of the channel and the isovels become nearly symmetrical about the centre of the channel. As the flow develops further (Figures 4.1d ~ 4.1e), the positions of maximum velocity are at around \( Z/H = 0.80 \) in the centre of the channel, the velocity-dip near the free surface can be observed and the velocity pattern is symmetrical. Also, the isovels slightly bulge towards the channel corners. As summarized by Nezu and Nakagawa (1993), these flow features are caused by the secondary currents. The velocity patterns in Figures 4.1d ~ 4.1e are similar to the patterns calculated with a 3D numerical model by Naot and Rodi (1982) and the measured ones by Nezu and Rodi (1985). The above results indicate that the flow is fully developed at \( X/R \geq 176 \) in case SR-1.

Figures 4.2a ~ 4.2d show the distributions of normalized longitudinal velocity \( (U/U_m) \) at four cross sections along the rectangular compound channel in case SRC-3. At \( X/R = 50 \) (Figure 4.2a), the isovels do not bulge towards the channel walls, the
area of maximum velocity is wide in the main channel and only slight bulging near the corners of the main channel can be seen. As the flow develops downstream (Figure 4.2b), bulging near the junction of the main channel and the floodplain becomes visible and the maximum-velocity area is reduced. At $X/R = 150$ (Figure 4.2c), bulging near the junction and the corners can be clearly seen and the position of the maximum isovel of $1.25$ moves down from around $Z/H = 0.7$ at $X/R = 100$ to around $Z/H = 0.6$ at $X/R = 150$. As the flow progresses further (Figure 4.2d), the velocity pattern does not change much and is similar to that of Tominaga and Nezu (1991). This indicates that the flow is fully developed at $X/R \geq 150$ in case SRC-3.

Table 4.2  Distance ratios at $X = 7.47$ m under various relative water depths

<table>
<thead>
<tr>
<th>Dr</th>
<th>0.20</th>
<th>0.35</th>
<th>0.50</th>
<th>0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H(m)$</td>
<td>0.045</td>
<td>0.055</td>
<td>0.072</td>
<td>0.144</td>
</tr>
<tr>
<td>$R(m)$</td>
<td>0.021</td>
<td>0.028</td>
<td>0.037</td>
<td>0.065</td>
</tr>
<tr>
<td>$X/R$</td>
<td>353</td>
<td>270</td>
<td>202</td>
<td>115</td>
</tr>
</tbody>
</table>

Figures 4.3a and 4.3b show the velocity distributions over the water depth at $Y/B = 0.5$ in case SR-1 and $Y/B = 0.3$ in case SRC-3 respectively. In Figure 4.3, $U_*$ is the bed shear velocity and $Z^+$ is the z-coordinate normalised by the viscous length ($v/U_*$), where $v$ is the kinematic viscosity. For the fully-developed open channel flow, the velocity distribution over the water depth follows the log law except near free surface, which can be expressed as $U/U_* \propto 2.5\ln Z^+$ (Nezu and Nakagawa 1993). In case SR-1, the velocity profiles at $X = 5.63$ m and $X = 6.76$ m are almost the same and their linear relationships between $2.5\ln Z^+$ and $U/U_*$ were better than those at other two positions. This indicates that the flow is fully developed from $X = 5.63$. In case SRC-3, the velocity profile difference between $X = 5.4$ m and $X = 7.2$ m is smaller than that between $X = 5.4$ m and $X = 3.6$ m. Also the linear relationship between $2.5\ln Z^+$ and $U/U_*$ can be seen from $X = 5.4$ m, except near the water surface. This indicates that the flow is almost fully developed at $X = 7.2$ m.
Measurement sections were set at 6.76 m, 7.47 m and 8.60 m downstream from the channel inlet for cases SR-1, SR-2 and SRC-1 – STC-3 respectively. The distance ratios in cases SR-1 and SR-2 are both higher than 176. The distance ratios in cases SRC-1 – SRC-3, STC-1 – STC-2 are all higher than 150. According to Tominaga and Nezu (1991), a fully developed flow was established at 7.5 m downstream from the channel inlet and the distance ratio was 150. The overall boundary shear stress is close to that determined using Equation 4.5. During these experiments, the different percentages for the overall boundary shear stresses were all within 4% as described in section 4.1.

The above results indicate that distance ratios of 176 for the rectangular channel and 150 for the compound channel can be used as empirical criteria to determine the measurement section for these small channels.

The characteristics of the fully-developed non-vegetated channel flow will be presented and discussed in sections 4.3 – 4.9. The vegetation effects on the flow behaviour in the compound open channel will be discussed in section 4.10.

4.3 Mean flow

As described in section 4.2, the distributions of normalized longitudinal velocity \((U/U_m)\) in case SR-1 are similar to those of Naot and Rodi (1982) and Nezu and Rodi (1985). In case SR-2 (Figure 4.4), the velocity pattern is slightly different from that in case SR-1 (Figure 4.1e). The slower velocity near the free surface in the upper centre region is more obvious in case SR-2 than in case SR-1. The aspect ratio in case SR-2 is 2, which is smaller than its value of 4 in case SR-1. This indicates that the velocity-dip phenomenon becomes more noticeable as the aspect ratio decreases.

According to Nezu and Rodi (1985), the velocity-dip phenomenon in rectangular channel flow is directly influenced by the secondary currents. Imamoto et al (1993) showed two typical vortices of secondary currents in the narrow, open channel. Strong upper secondary currents carry low-momentum fluid from the channel corner up towards the water surface and secondary currents change their moving direction from the wall towards the centre of the channel. Once secondary currents reach the centre line, they move the high-momentum fluid from the upper region downwards to the
corner and the bed bisector. Nezu et al. (1985) further pointed out that secondary currents in a narrow, open channel become stronger as the aspect ratio decreases. So the velocity-dip is more noticeable in case SR-2 than in case SR-1.

Figures 4.5a ~ 4.5c show the normalized velocity \( \left( U/U_n \right) \) patterns in rectangular compound channel cases. The relative water depths in cases SRC-1, SRC-2 and SRC-3 are 0.22, 0.35 and 0.48, respectively. In the shallow case SRC-1 (Figure 4.5a), the velocity isovel lines bulge towards the walls and corners of the main channel in the same manner as the rectangular, open channel and velocity-dip phenomenon can be seen in the main channel. No clear bulging near the junction of the main channel and the floodplain (MC-FP junction) can be seen, but steep velocity gradients can be seen in this region. These flow phenomena are similar to those of Tominaga and Nezu (1991). Under this flow condition, the main channel flow can be roughly thought of as narrow channel flow and secondary currents near the water surface might be much stronger than those near the MC-FP junction.

As the relative water depth increases to 0.35 in case SRC-2, the velocity-dip phenomenon becomes more noticeable in the main channel, as shown in Figure 4.5b. The velocity bulging near the MC-FP junction begins to appear in case SRC-2. Based on the complex flow mechanism illustrated by Shino and Knight (1991), the velocity bulging can be explained by secondary currents near the MC-FP junction. The secondary currents carry low-momentum fluid from the wall upwards towards the water surface near the MC-FP junction. As a result, the velocity is decelerated near the MC-FP junction and consequently the velocity-bulging is formed.

In the deep case, SRC-3 (Figure 4.5c), three flow characteristics can be recognised. The velocity isovel lines bulge towards the channel corners and up towards the water surface near the MC-FP junction. The velocity-dip is more remarkable and the velocity gradients are smaller than those in cases SRC-1 and SRC-2. The position of maximum velocity moves down to \( Z/H \approx 0.6 \) near the centre line of the main channel. The above flow behaviour is similar to that in Tominaga and Nezu (1991).

Figures 4.6a ~ 4.6c show the normalized velocity \( \left( U/U_n \right) \) isovel lines in trapezoidal, compound-channel cases. The relative water depths in cases STC-1, STC-2 and STC-
3 are 0.23, 0.37 and 0.50, respectively. The velocity patterns in the left side of the main channel are similar to those in cases SRC-1 ~ SRC-3, but on the sloping wall of the main channel, the velocity patterns in the right side of the main channel and near the MC-FP junction change slightly. The velocity bulging pattern in the right bisector of the main channel and near the MC-FP junction is weaker than that in cases SRC-1 ~ SRC-3. The velocity bulging in these regions is similar to that of Shiono and Knight (1989). The velocity gradients are also smaller than those in cases SRC-1 ~ SRC-3.

Figures 4.7a ~ 4.7b show the depth-averaged velocity distributions under different relative water depth conditions in the rectangular and trapezoidal compound channels respectively.

The above results show that the flow structures measured in this study more or less agree with the existing ones in the literature, so the data measured seems to be fine.

4.4 Reynolds Shear Stress

4.4.1 Calculation method

Turbulence measurements were not performed in the small channel experiments and the Reynolds shear stresses could not be calculated, so only the depth-averaged Reynolds shear stress $\bar{\tau}_{xy}$ will be analysed, in this section, based on some assumptions. The main purpose of this analysis is to investigate the effects of large eddies in the shear layer on the Reynolds shear stress, which can be used as a parameter to characterise the lateral momentum exchange.

The depth-averaged Reynolds shear stress $\bar{\tau}_{xy}$ is related to the depth-averaged eddy viscosity $\langle \varepsilon \rangle$ and the velocity gradient $\left( \frac{\partial U_g}{\partial y} \right)$ and can be calculated using Equation 4.6,

$$\bar{\tau}_{xy} = \rho \langle \varepsilon \rangle \frac{\partial U_g}{\partial y}$$

(4.6)

where $\rho$ is the fluid density.
Several models have been used to determine the eddy viscosity in the literature. The normally used model is the constant viscosity model where the dimensionless eddy viscosity ($\lambda$) is constant across the section. Shiono and Knight (1991) and Abril and Knight (2004) stated that the value of $\lambda$ is constant in the main channel but a function of the relative water depth on the floodplain. Using the mixing layer approach, Alavian and Chu (1985) proposed a model by taking the effects of both the bed-generated turbulence and shear-generated turbulence into account and. Recently, Prooijen et al (2005) adopted the eddy viscosity concept and proposed a similar model to that by Alavian and Chu (1985). These eddy viscosity models were developed from experimental data and therefore they are expected to be applicable only in similar experimental conditions. In this work, the model by Prooijen et al. (2005) was used.

According to Wormleaton (1988), both bottom turbulence and transverse shear contribute to the eddy viscosity. The depth-averaged eddy viscosity ($\overline{\varepsilon_{ib}}$) due to the bottom turbulence can be modelled with Equation 4.7a (Shiono & Knight 1991). The depth-averaged eddy viscosity ($\overline{\varepsilon_{is}}$) due to the transverse shear can be modelled with Equation 4.7b (Prooijen et al. 2005).

\begin{equation}
\overline{\varepsilon_{ib}} = \lambda_{ib} \left( \frac{f}{8} \right)^{1/2} U_d H
\end{equation}

\begin{equation}
\overline{\varepsilon_{is}} = \frac{H_m}{H} (\beta \delta) \left| \frac{\partial U_d}{\partial y} \right|
\end{equation}

where $\lambda_{ib}$ is the dimensionless depth-averaged eddy viscosity; $U_d$ is the depth-averaged longitudinal velocity; $f$ is the friction factor; $H_m$ is the mean value of the water depth in the main channel and on the floodplain; $\beta$ is the proportionality constant and $\delta$ is the width of the shear layer. In this work, the value of $\lambda_{ib}$ was chose as 0.07 (Rameshwaran & Shiono 2006) and the value of $\beta$ was chose as 0.08 (Prooijen et al. 2005).
Figure 4.8a shows the determination of the width of the shear layer ($\delta$). The distance between the position $Y_{25\%}$, where $\overline{U}(y_{25\%}) = \overline{U}_f + 0.25(\overline{U}_e - \overline{U}_f)$ and $Y_{75\%}$, where $\overline{U}(y_{75\%}) = \overline{U}_f + 0.75(\overline{U}_e - \overline{U}_f)$, determines half the shear layer width

$$\delta = 2|y_{75\%} - y_{25\%}|$$  \hspace{1cm} (4.8)

where $\overline{U}_e$ and $\overline{U}_f$ are the maximum velocity in the main channel and the velocity at the centre on the floodplain.

From the depth-averaged longitudinal velocity $U_d$ shown in Figure 4.7, the shear width $\delta$ was further determined from Equation 4.8 and presented in Figure 4.8b. It can be seen that the shear width decreases with an increase of the relative water depth in both rectangular and trapezoidal channel cases. In cases SRC-1 and STC-1, the shear widths are almost the same and this indicates that the sloping side wall of the main channel does not influence the shear width under shallow water depth conditions. In the other four deeper cases, the shear widths in the rectangular compound channel are larger than those in the trapezoidal compound channel under similar relative water depths. The magnitude of shear width corresponds well to the steepness of the velocity gradient.

The depth-averaged eddy viscosity ($\overline{\varepsilon_i}$) can be expressed by Equation 4.9. In Equation 4.9, both the bed-generated turbulence and shear-generated turbulence are taken into account in the eddy viscosity.

$$\overline{\varepsilon_i} = \overline{\varepsilon_{ib}} + \overline{\varepsilon_{us}}$$  \hspace{1cm} (4.9)

Based on the longitudinal velocity data shown in Figures 4.5 and 4.6, the depth-averaged longitudinal velocity $U_d$ was calculated using Equation 4.1.

Using the calculated data for the depth-averaged velocity ($U_d$) in Figure 4.7 and the measured data of bed shear stress in Figure 4.9, the friction factor ($f$) can be calculated using Equation 4.10.
As shown in Figure 4.10, the bed shear stress ($\tau_b$) differs from the standard two-dimensional value ($\rho g H S_0$) and this difference is caused by transverse gradients of the apparent shear stress arising from secondary currents and lateral shear stresses (Shiono & Knight 1991). As shown in Figure 4.11, the overall values of Manning coefficient ($n$) for various cases are almost 0.01. In these non-vegetated compound channel cases, the Manning coefficients are all about 0.01 and the equivalent sand grain roughness height ($k_s$) can be determined as 0.3 mm. The friction factors for various cases were calculated with Equation 4.11. Figures 4.12a ~ 4.12f show the values of the measured and predicted friction factors for various cases. In the trapezoidal cases, the predicted friction factors roughly agree with the measured ones. In the rectangular cases, the friction factors were not properly predicted with Equation 4.11, especially in the main channel and this could be caused by the right vertical main channel wall. The strong secondary currents near the MC-FP junction make the flow structures three-dimensional, but Equation 4.11 is based on the two-dimensional assumption.

\[ f = \frac{8\tau_b}{\rho U_d^2} \]  

(4.10)

\[ f = \left[ -2\log\left( \frac{3.02\nu}{\sqrt{128gH^3S_0}} + \frac{k_s}{12.3H} \right) \right]^{-2} \]  

(4.11)

The dimensionless depth-averaged eddy viscosity ($\overline{\lambda}_t$) normalized by $U_sH = \left( \frac{f}{8} \right)^{\frac{1}{2}} U_dH$ is composed of two components: a contribution due to the bed turbulence ($\overline{\lambda}_{tb}$) and a contribution due to the transverse shear ($\overline{\lambda}_u$). $\overline{\lambda}_t$ can be determined using Equation 4.12.

\[ \overline{\lambda}_t = \overline{\lambda}_{tb} + \overline{\lambda}_u = 0.07 + \frac{H_m (\beta \delta)^3}{H} \left( \frac{\partial U_d}{\partial y} \right) \left( \frac{f}{8} \right)^{\frac{1}{2}} U_dH \]  

(4.12)
Velocity gradient \( \frac{\partial U_d}{\partial y} \) is calculated from two adjacent, depth-averaged velocities and expressed in Equation 4.13:

\[
\frac{\partial U_d}{\partial y} = \frac{U_{d,i} - U_{d,i-1}}{dy}
\]  

(4.13)

where \( U_{d,i} \) and \( U_{d,i-1} \) are depth-averaged velocities at \( y = y_i \) and \( y = y_{i-1} \).

In Equation 4.13, the depth-averaged velocity was calculated with Equation 4.1 and the local velocity was measured at the local point as shown in Figure 3.33a. The lateral intervals between two adjacent points were 0.9 cm on the right sloped main channel wall and 1.5 cm in other parts of the channel. Under certain channel and flow conditions, the depth-averaged velocity can be assumed as the function of the lateral distance \( y \) from the left channel wall. The lateral intervals are smaller than those used by Shiono and Knight (1991) and accurate enough to calculate the velocity gradient.

Eddy viscosity, dimensionless eddy viscosity and Reynolds shear stress were calculated using the above methods based on raw experimental data for velocity, water depth and bed shear stress.

4.4.2 Results and discussions

4.4.2.1 Eddy viscosity

Figures 4.13a and 4.13b show the lateral distributions of the depth-averaged eddy viscosity \( \bar{\varepsilon}_r \) in rectangular and trapezoidal compound channel cases respectively. In Figure 4.13a, solids "0", "Δ" and "□" represent calculated eddy viscosities taking into account the bed-turbulence contribution only whilst voids "0", "Δ" and "□" represent the calculated eddy viscosities taking both the bed-turbulence and shear contributions into account. In Figure 4.13b, the eddy viscosities were calculated taking the bed-turbulence and shear contributions into account.

The depth-averaged eddy viscosity \( \bar{\varepsilon}_r \) is only from the bed-turbulence when the shear contribution to the eddy viscosity is not considered. Under this assumption, the
values of $\bar{\epsilon}_i$ in each case are relatively constant in the main channel and on the floodplain, but their values increase as the relative water depth increases (Figure 4.13a). This can be explained by the definition of the eddy viscosity from bed-turbulence ($\bar{\epsilon}_{ib}$). The eddy viscosity from bed turbulence ($\bar{\epsilon}_{ib}$) can also be defined as $\bar{\epsilon}_{ib} = \frac{\lambda_{ib} H \sqrt{\tau_b}}{\rho}$ by rearranging Equation 4.7a. As the relative water depth ($Dr$) increases, the bed shear stress ($\tau_b$), as shown in Figure 4.9a, and water depth ($H$) increase, and then the eddy viscosity ($\bar{\epsilon}_{ib}$) increases.

Seen from Figure 4.13a, the depth-averaged eddy viscosities ($\bar{\epsilon}_i$) are larger considering the shear contribution than those without considering the shear contribution, especially under shallow water conditions. It can also be seen that the eddy viscosities ($\bar{\epsilon}_i$) peak at the MC-FP junction. Figures 4.14a and 4.14b further show the relative magnitudes of dimensionless eddy viscosities $\bar{\lambda}_i$, $\bar{\lambda}_u$ and $\bar{\lambda}_{ib}$. The maximum ratios of $\bar{\epsilon}_i / \bar{\epsilon}_{ib}$ in cases SRC-1, SRC-2 and SRC-3 are 28, 4 and 1, respectively. Table 4.3 shows the averaged eddy viscosities ($\bar{\epsilon}_i$) for the main channel and floodplain in cases SRC-1 ~ SRC-3. These results indicate that the shear contribution to the eddy viscosity is very important in the shear layer, especially on the floodplain under low relative water depth conditions, i.e. $Dr = 0.2$.

From Figure 4.13b, the eddy viscosities ($\bar{\epsilon}_i$) in the trapezoidal compound channels behave in a similar manner to those in rectangular compound channels. However, the magnitudes of $\bar{\epsilon}_i$ are smaller than those in the rectangular cases due to the reduced velocity gradient of $\partial U_d / \partial y$, especially under shallow water conditions. As shown in Figure 4.14a, the maximum ratios of $\bar{\lambda}_i / \bar{\lambda}_{ib}$ in cases STC-1, STC-2 and STC-3 are 10, 3 and 1, respectively. From Figure 4.14b, the maximum magnitudes of $\bar{\lambda}_u$ in cases STC-1, STC-2 and STC-3 are 9, 2 and 0.2 times larger than those of $\bar{\lambda}_{ib}$, respectively. Table 4.4 lists the mean values of the eddy viscosity in trapezoidal compound cases STC-1 ~ STC-3. The information from Table 4.4 is similar to that from Figures 4.13 and 4.14.
The above results of eddy viscosity show that the lateral shear in a rectangular compound channel is more significant than that in a trapezoidal compound channel under similar relative water depth conditions, especially under lower shallow-water conditions, i.e. \( Dr = 0.2 \). These results also indicate that the assumption of \( \lambda_{uv} = 0.07 \) across the section of a compound channel is not correct, especially under shallow water conditions. In 2D modelling, the values of the dimensionless eddy viscosity \( (\lambda_{uv}) \) must be properly selected by considering the shear effects to give satisfactory flow predictions.

### Table 4.3  Mean values of the eddy viscosity in cases SRC-1 ~ SRC-3 \((10^{-5} \text{ m}^2/\text{s})\)

<table>
<thead>
<tr>
<th></th>
<th>Dr</th>
<th>0.07</th>
<th>0.07 shear</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRC-1</td>
<td>0.23</td>
<td>5.36</td>
<td>6.69</td>
</tr>
<tr>
<td>SRC-2</td>
<td>0.36</td>
<td>7.25</td>
<td>8.24</td>
</tr>
<tr>
<td>SRC-3</td>
<td>0.49</td>
<td>9.47</td>
<td>9.95</td>
</tr>
<tr>
<td><strong>Floodplain</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRC-1</td>
<td>0.23</td>
<td>0.86</td>
<td>6.37</td>
</tr>
<tr>
<td>SRC-2</td>
<td>0.36</td>
<td>2.09</td>
<td>4.16</td>
</tr>
<tr>
<td>SRC-3</td>
<td>0.49</td>
<td>4.52</td>
<td>4.82</td>
</tr>
</tbody>
</table>

#### 4.4.2.2 Reynolds shear stress

Based on the data presented in Figures 4.7a and 4.13a, the depth-averaged Reynolds shear stresses \( \overline{\tau_{xy}} \) in rectangular, compound channel cases SRC-1 ~ SRC-3 were calculated by using Equation 4.6. Based on the data presented in Figures 4.7b and 4.13b, values for \( \overline{\tau_{xy}} \) in trapezoidal cases STC-1 ~ STC-3 were also calculated. The distributions of \( \overline{\tau_{xy}} \) in rectangular and trapezoidal compound channel cases are presented in Figure 4.15. The shear contribution to the eddy viscosity was considered in all the calculations.

It is clearly seen from Figure 4.15 that the depth-averaged Reynolds shear stresses dip around the MC-FP junction in all six cases, but the dip values of Reynolds shear stress increase as the relative water depth decreases for both the rectangular and trapezoidal...
compound channel cases. It can also be seen that the magnitudes of Reynolds shear stress are usually larger in the rectangular compound channel than those in the trapezoidal compound channel under similar relative water depth conditions. These results correspond well with those for the eddy viscosity.

Table 4.4 Mean values of the eddy viscosity in cases STC-1 – STC-3 (10^-5 m^2/s)

<table>
<thead>
<tr>
<th></th>
<th>Dr</th>
<th>( \bar{\nu}_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main channel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STC-1</td>
<td>0.24</td>
<td>7.57</td>
</tr>
<tr>
<td>STC-2</td>
<td>0.37</td>
<td>7.97</td>
</tr>
<tr>
<td>STC-3</td>
<td>0.50</td>
<td>9.93</td>
</tr>
<tr>
<td><strong>Floodplain</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STC-1</td>
<td>0.24</td>
<td>4.24</td>
</tr>
<tr>
<td>STC-2</td>
<td>0.37</td>
<td>3.18</td>
</tr>
<tr>
<td>STC-3</td>
<td>0.50</td>
<td>4.75</td>
</tr>
</tbody>
</table>

It can also be seen from Figure 4.15 that the depth-averaged Reynolds shear stress is nearly zero where the depth-averaged velocity, as shown in Figures 4.7a and 4.7b, peaks in each case. The depth-averaged Reynolds shear stresses increase from the MC-FP junction towards the left channel wall and the right channel wall. According to Nezu and Nakagawa (1993), the magnitude of the Reynolds shear stress \( \tau_{xy} \) near the wall approaches the mean wall shear stress. Some calculated, depth-averaged, Reynolds shear stresses on the main channel wall differ from the measured mean wall shear stresses as shown in Table 4.5 and this could be caused by the determination of the velocity gradient \( \partial U_x / \partial y \) on the wall.

Table 4.5 Measured mean wall shear stresses in compound channels (N/m²)

<table>
<thead>
<tr>
<th>Wall</th>
<th>SRC-1</th>
<th>SRC-2</th>
<th>SRC-3</th>
<th>STC-1</th>
<th>STC-2</th>
<th>STC-3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main channel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRC-1</td>
<td>0.2293</td>
<td>0.2708</td>
<td>0.3509</td>
<td>0.2419</td>
<td>0.2795</td>
<td>0.3519</td>
</tr>
<tr>
<td>SRC-2</td>
<td>0.0199</td>
<td>0.0732</td>
<td>0.1970</td>
<td>0.1050</td>
<td>0.1442</td>
<td>0.2239</td>
</tr>
<tr>
<td><strong>Floodplain</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRC-1</td>
<td>0.2334</td>
<td>0.2769</td>
<td>0.3512</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Sloped Junction Wall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.5 Apparent shear stress

4.5.1 Calculation method

The depth-averaged momentum equation for steady, uniform flow in the streamwise
direction can be expressed by Equation 4.14 (Shiono & Knight 1991),

$$\rho g HS_0 - \tau_b (1 + s^{-2})^{1/2} = \frac{\partial}{\partial y} \left\{ H \left[ (\rho \overline{UV})_d - \overline{\tau_{xy}} \right] \right\}$$  \hspace{1cm} (4.14)

A depth-averaged apparent shear stress ($\overline{\tau_{as}}$), which is expressed in Equation 4.15,
was introduced to consider the effects of the secondary current and the turbulence on
the lateral shear (Shiono & Knight 1991). In a symmetrical, trapezoidal, compound
channel, the depth-averaged apparent shear stress ($\overline{\tau_{as}}$) is assumed to be zero at the
centre of the main channel, so the depth-averaged apparent shear stress ($\overline{\tau_{as}}$) can be
calculated from the centre of the main channel by Equation 4.15 (Shiono & Knight
1991),

$$\overline{\tau_{as}}(y) = -\left[ (\rho \overline{UV})_d - \overline{\tau_{xy}} \right] = - \frac{1}{H} \int \left[ \rho g HS_0 - \tau_b (1 + s^{-2})^{1/2} \right] dy$$  \hspace{1cm} (4.15)

where $y$ is the lateral coordinate; $H$ is the local water depth; $s$ is the bank slope.

In this study, an asymmetrical, trapezoidal, compound channel, as illustrated in Figure
3.11, was used and the $y$ coordinate starts from the left channel wall towards the right
channel wall. In this case, the boundary shear stress on the left channel wall needs to
be taken into account to calculate the depth-averaged apparent shear stress. Based on
Equation 4.15, the apparent shear stress ($\overline{\tau_{as}}$) is zero where the depth-averaged
velocity ($U_d$) peaks. In this study, the apparent shear stress ($\overline{\tau_{as}}$) at $y = 0$ is equal to
the mean wall shear stress on the left wall ($\overline{\tau_{ml}}$). On the right wall ($y = B$), the
magnitude of the apparent shear stress ($\overline{\tau_{as}}$) is equal to the mean wall shear stress on
the right wall ($\overline{\tau_{mr}}$), but it is negative, namely, $\overline{\tau_{as}}(y = B) = -\overline{\tau_{mr}}$. This is because the
value of $-\left( \rho \overline{UV} \right)_d$ at $y = B$ is zero. The Reynolds shear stress $\overline{\tau_{xy}}$ at $y = B$ is negative
due to the velocity gradient \( \frac{\partial U_y}{\partial y} \) in the \( y \) direction. During the following calculations, the above boundary conditions will be imposed.

For the asymmetrical, trapezoidal, compound channel, the depth-averaged shear stress \( \bar{\tau}_{ar} \) can be calculated using Equation 4.16:

\[
\bar{\tau}_{ar}(y) = \left[ -\int_0^\gamma \left( \rho g H(y) S_0 - \tau_b \left( 1 + s^2 \right)^{1/2} \right) dy + H \bar{\tau}_{wm} \right] / H(y) \quad (4.16)
\]

For the asymmetrical, rectangular, compound channel, the depth-averaged shear stress \( \bar{\tau}_{ar} \) in the main channel can also be calculated using Equation 4.16. To calculate the depth-averaged apparent shear stress on the floodplain, the mean wall shear stress on the vertical right wall of the main channel needs to take into further account. Equation 4.17 can be used to calculate the depth-averaged shear stress \( \bar{\tau}_{ar} \) on the floodplain.

\[
\bar{\tau}_{ar}(y) = \left[ -\int_0^\gamma \left( \rho g H(y) S_0 - \tau_b \left( 1 + s^2 \right)^{1/2} \right) dy + H \bar{\tau}_{wm} \right] / H(y) \quad (4.17)
\]

where \( \bar{\tau}_{wm} \) is the mean wall shear stress on the vertical right wall of the main channel.

4.5.2 Results and discussions

Figure 4.16a shows the lateral distributions of the calculated apparent shear stresses \( \bar{\tau}_{ar} \) in cases SRC-1 ~ SRC-3 and STC-1 ~ STC-3. It can be seen that the apparent shear stress decreases from the left wall, reaches the lowest negative value at the MC-FP junction and then increases towards the right wall. From Figure 4.16b, the peak magnitudes in rectangular cases SRC-1, SRC-2 and SRC-3 are -0.67, -0.36 and -0.32 N/m², respectively. The peak magnitudes in trapezoidal cases STC-1, STC-2 and STC-3 are -0.56, -0.33 and -0.21 N/m², respectively. Figure 4.16b shows that the peak magnitudes of the apparent shear stresses in the trapezoidal cases are smaller than those in the rectangular cases under similar relative water depth conditions. This indicates that the lateral shear is weaker in the trapezoidal cases than in the rectangular cases under similar relative water depth conditions. It can also be seen that the peak magnitude of the apparent shear stress decreases as the relative water depth...
increases, especially in the low relative water depth range, and this indicates that the lateral shear is weaker under conditions of greater water depth.

4.6 Secondary current

4.6.1 Calculation method

As can be seen from Equations 4.14 and 4.15, the apparent shear stress \( \overline{\tau_{ar}} \) arises from the secondary current and the turbulence. Based on Equations 4.14 and 4.15, the secondary current contribution can be calculated from Equation 4.18:

\[
-\left( \rho \overline{UV} \right)_d = \overline{\tau_{ar}} - \overline{\tau_{ys}}
\]  

(4.18)

Figure 4.17 shows the calculated secondary currents \(-\left( \rho \overline{UV} \right)_d\) in rectangular and trapezoidal compound channel cases.

According to Prooijen et al. (2005), for a trapezoidal compound channel, the lateral velocities in the main channel \( V_{max,mc} \) and on the floodplain \( V_{max,fp} \) are expressed by Equations 4.19a and 4.19b respectively. For a rectangular compound channel, the lateral velocity on the floodplain is also expressed by Equation 4.19b, but the lateral velocity in the main channel is expressed by a new approach. As shown in Figure 4.18, the secondary current is stronger in the upper part than in the lower part of the main channel, but their magnitudes at the vertical level of the floodplain are the same. If the lateral velocity in the upper part of the main channel is expressed by Equations 4.19c, then the lateral velocity in the lower part of the main channel can be expressed in a similar equation but using a reduction factor \( = Z/(H - h) \) and an opposite value of the maximum velocity in Equation 4.19c, which is expressed in Equation 4.19d.

The depth-averaged secondary current term \(-\left( \rho \overline{UV} \right)_d\) in the main channel and on the floodplain can also be calculated by Equations 4.20a and 4.20b respectively. Combing with Equation 4.18, the maximum lateral velocity can be further determined. For a trapezoidal compound channel, the value of maximum lateral velocity in the main channel and on the floodplain can be determined by Equations 4.21a and 4.21b respectively. Using the new concept described above, for a rectangular channel, the value of maximum lateral velocity in the main channel and on the floodplain can also
be determined by Equations 4.21c and 4.21b respectively. The value of maximum lateral velocity varies with the lateral position $y$.

$$ V(Z) = -V_{\text{max,mc}} \cos \left( \pi \frac{Z}{H} \right) $$

(4.19a)

$$ V(Z) = -V_{\text{max,fp}} \cos \left( \pi \frac{Z - (H - h)}{h} \right) $$

(4.19b)

$$ V(Z) = -V_{\text{max,mc}} \cos \left( \pi \frac{Z - (H - h)}{h} \right), H - h \leq Z \leq H $$

(4.19c)

$$ V(Z) = \frac{Z}{H - h} V_{\text{max,mc}} \cos \left( \pi \frac{Z}{H - h} \right), 0 \leq Z \leq H - h $$

(4.19d)

$$ - \left( \overline{\rho UV} \right)_{d} = - \frac{\int_{0}^{l} \rho U(Z) V(Z) dZ}{H} $$

(4.20a)

$$ - \left( \overline{\rho UV} \right)_{d} = - \frac{\int_{l-h}^{l} \rho U(Z) V(Z) dZ}{h} $$

(4.20b)

$$ V_{\text{max,mc}} = \frac{H (\tau_{as} - \tau_{ys})}{\int_{0}^{l} \rho U(Z) \cos \left( \pi \frac{Z}{H} \right) dZ} $$

(4.21a)

$$ V_{\text{max,fp}} = \frac{h (\tau_{as} - \tau_{ys})}{\int_{l-h}^{l} \rho U(Z) \cos \left( \pi \frac{Z}{h} \right) dZ} $$

(4.21b)

$$ V_{\text{max,mc}} = \frac{H (\tau_{as} - \tau_{ys})}{\int_{0}^{l-h} \frac{Z}{H - h} \rho U(Z) \cos \left( \pi \frac{Z}{H - h} \right) dZ + \int_{l-h}^{l} \rho U(Z) \cos \left( \pi \frac{Z - (H - h)}{h} \right) dZ} $$

(4.21c)

where $Z$ is the distance from the main channel bed; $H$ is the water depth in the main channel; $h$ is the water depth on the floodplain; $U(Z)$ is the local streamwise velocity measured by a pitot tube.
In cases SRC-1 ~ SRC-3, the value of the secondary current $-(\rho\overline{UV})_d$ decreases from the main channel towards the floodplain near the MC-FP junction, attains a negative peak at the junction edge and then increases from the edge towards the right wall, irrespective of relative water depth conditions. These observations are similar to those of Tominaga and Nezu (1991). This can be explained by the secondary current structures in the rectangular compound channel. Based on the turbulence measurement data of Tominaga and Nezu (1991), major secondary current cells can be illustrated in Figure 4.18. Based on the work of Shiono and Knight (1991) and Omran and Knight (2006), the typical distributions of the streamwise velocity (U) and the lateral velocity (V) can be illustrated in Figure 4.19. Figures 4.19a, 4.19b, 4.19c and 4.19d show the U and V distributions in the main channel, near the left, main-channel wall, near the junction in the main channel side and on the floodplain, respectively. The U distribution on the floodplain is assumed to be similar to that in the main channel.

It can be seen from the velocity distributions shown in Figure 4.19 that the sign and magnitude of $-(\rho\overline{UV})_d$ are mainly determined by U and V in the upper zone of the channel. This is because the magnitudes of U and V are generally larger than those in other parts of the channel. On the floodplain, values for U are positive over the depth, V is positive in the upper parts and negative in the lower parts, so $\overline{UV}$ is positive in the upper part and negative in the lower part, the sum of $\overline{UV}$ in the upper part is larger than the absolute sum of $\overline{UV}$ in the lower part and this leads to the negative $-(\rho\overline{UV})_d$ on the floodplain. The magnitudes of U and V decrease from the junction towards the left floodplain wall, so the values of $-(\rho\overline{UV})_d$ decrease from the junction towards the floodplain wall. This analysis is also applicable to the variations of $-(\rho\overline{UV})_d$ in the main channel. For example, the magnitude of negative V near the junction in the main channel is larger than that in other locations, positive $-(\rho\overline{UV})_d$ is possible near the junction in the main channel side and the magnitude of $-(\rho\overline{UV})_d$ becomes smaller from the junction towards the centre of the main channel. The larger positive V makes $-(\rho\overline{UV})_d$ negative near the left main channel wall.
Compared with Figure 4.15, the value of $-\left(\rho \overline{U'V'}\right)_d$ in each rectangular case is larger than $\overline{\tau_{yy}}$ on the floodplain, but smaller than $\overline{\tau_{yy}}$ near the MC-FP junction and near the left main channel wall. This indicates that the secondary current is more important than the turbulent shear on the floodplain, but is less important near the MC-FP junction.

It can also be seen that $-\left(\rho \overline{U'V'}\right)_d$ profiles in the trapezoidal cases STC-1 ~ STC-3 behave in a similar manner to that in the rectangular channel cases. In trapezoidal, compound-channel cases STC-1 ~ STC-3, the value of $-\left(\rho \overline{U'V'}\right)_d$ also attains a positive peak at around $y = 0.138 \ m$ and a negative peak at around $y = 0.158 \ m$. The negative peak at the junction edge was also observed by Shiono and Knight (1991).

The value of $V_{\text{max}}$ was determined using Equation 4.19. Figure 4.20 shows the lateral distributions of $V_{\text{max}}$ in rectangular and trapezoidal, compound-channel cases. Except at the channel walls, the maximum value of $V_{\text{max}}$ occurs near the MC-FP junction and this agrees with the experimental observations (i.e. Tominaga & Nezu 1991). The ratios of $V_{\text{max}}/U_{\text{max}}$ for rectangular cases SRC-1, SRC-2 and SRC-3 are 3.4 %, 1.9 % and 2.6 %, respectively. The ratio of $V_{\text{max}}/U_{\text{max}}$ for case SRC-3, relative water depth $Dr = 0.49$, is approaching the value of 4 % reported by Tominaga and Nezu (1991). The ratios $V_{\text{max}}/U_{\text{max}}$ for trapezoidal cases STC-1, STC-2 and STC-3 are 2.0 %, 1.9 % and 1.6 %, respectively. Under relative water depths 0.2 and 0.5, the ratios of $V_{\text{max}}/U_{\text{max}}$ were larger in the rectangular channel than in the trapezoidal channel and this indicates that the secondary currents are stronger in the rectangular channel than in the trapezoidal one under. This is because turbulence intensities in three directions are stronger in a rectangular channel than in a trapezoidal one because of the wall slope in the shear layer zone as shown in Shiono and Knight (1989). The generation term of secondary currents in Equation 2.9 is then larger in the rectangular channel than in the trapezoidal one.

Prooijen et al. (2005) assumed the transverse velocity ($V$) profile to be half-cosine and calculated $V_{\text{max}}$ at the edge of the MC-FP junction for one FCF case of relative water
depth 0.15, but they found the calculated $V_{\text{max}}$ was one order of magnitude greater than the experimental one. They assumed the longitudinal velocity (U) profile to be logarithmic and the value of $-\left(\rho \overline{U'V'}\right)_d$ was to be that of $\tau_{xx}$, so these two assumptions might be the main sources of their calculation error.

4.7 Boundary shear stress

4.7.1 Friction factor

The local values of the friction factors have been illustrated in Figure 4.12. From Figures 4.12a and 4.12f, the friction factor decreases with the relative depth, $Dr$, increases, especially on the floodplain. This indicates that the bed friction effect becomes weaker as the water depth increases. It can also be seen that the friction factor $f$ is relatively constant in the main channel and on the floodplain under larger relative water depth conditions. Under $Dr \approx 0.20$, the peak values of the friction factor occur at different positions in the rectangular and trapezoidal cases and this could be caused by the secondary currents on the floodplain. The peak positions for cases SRC-1 and STC-1 are at around $y = 0.22$ m and 0.29 m respectively. In case SRC-1, one clockwise, secondary current cell is generated on the left floodplain and one counterclockwise secondary current cell is generated because of the corner effect on the right floodplains. Under shallow water conditions, the clockwise secondary current might be suppressed by the turbulent shear near the MC-FP junction, so the counterclockwise secondary current extends towards the MC-FP junction, this moves the high-momentum fluid near the surface towards the channel bed and this leads to a larger friction factor on the left floodplain. In case STC-1, the turbulent shear is weaker than in case SRC-1, so a large secondary current cell might exist on the floodplain and extend to the whole floodplain. This leads to the peak position near the right floodplain wall.

According to Shiono and Knight (1991), $f \propto \text{Re}^{-\frac{1}{4}}$, and therefore the ratio $f_{fp} / f_{mc}$ will depend on $Dr^{-\frac{3}{7}}$. Based on the experimental data presented in Figure 4.12, the average friction factors on the main channel bed $f_{mc}$ and the floodplain $f_{fp}$ can be
calculated. The relationships between $f_{mc}$ and $f_{fp}$ in the rectangular and trapezoidal cases can be expressed by Equations 4.22 and 4.23, respectively.

\[
f_{fp} / f_{mc} = 1.4390 Dr^{3/7} - 0.4531 \quad (4.22)
\]

\[
f_{fp} / f_{mc} = 0.7371 Dr^{3/7} + 0.2433 \quad (4.23)
\]

### 4.7.2 Contributions to boundary shear stress

As shown in Figure 4.10, the boundary shear stresses differ from the two-dimensional value ($\rho g H S_0$). The bed shear stresses are smaller than $\rho g H S_0$ in the main channel and larger than $\rho g H S_0$ on the floodplain. Equation 4.14 indicates that the difference is caused by the depth-averaged Reynolds shear stress and secondary current gradients in the lateral direction. To examine the contributions of different forces to the boundary shear stress, the normalised gradients of the Reynolds shear stress ($\frac{\partial (H \tau_{xy})}{\partial y} / \rho g H S_0$) and the secondary current term ($\frac{\partial (H (- \rho U V))}{\partial y} / \rho g H S_0$) were calculated and are presented in Figures 4.21 and 4.22. In these figures, $T_s$ represents $\frac{\rho g H S_0}{\rho g H S_0}$, $T_{bs}$ represents $- \frac{\tau_b (1 + s^{-2})^{1/2}}{\rho g H S_0}$, $T_{rs}$ represents $\frac{\partial (H \tau_{xy})}{\partial y} / \rho g H S_0$ and $T_{sc}$ represents $\frac{\partial (H (- \rho U V))}{\partial y} / \rho g H S_0$. The shear effect on the Reynolds stress is considered in these analyses.

Figures 4.21a, 4.21b and 4.21c show the force contributions under the assumption of $\lambda_{nb} = 0.07$ in rectangular, compound-channel cases. In case SRC-1, Term $T_{rs}$ is negative and Term $T_{sc}$ is nearly zero at $0.04 < y < 0.12$ m, so the bed shear stress is smaller than $\rho g H S_0$. Near the MC-FP junction, Term $T_{rs}$ increases sharply, attains a positive peak at the junction edge, then decreases to be around zero at $0.19 < y < 0.27$ m. Term $T_{sc}$ decreases towards the junction edge, attains a negative peak at the junction edge, then increases to be positive around $y = 0.18$ m on the floodplain. The
magnitudes of Term $T_{rr}$ are around negative 40% in the main channel, but around positive 380% at the junction edge. The magnitudes of Term $T_{sc}$ are generally smaller than those of Term $T_{rr}$ and this indicates that the turbulent shear is more important than the secondary current to the bed shear stress. As a result, the bed shear stress is smaller than $\rho g H S_0$ in the main channel but larger than $\rho g H S_0$ on the floodplain.

Terms $T_{rr}$ and $T_{sc}$ in the deeper cases, SRC-2 and SRC-3, behave in a similar manner to those in case SRC-1, but their magnitudes are smaller than those in case SRC-1 because the turbulent shear becomes weaker as the relative water depth increases. As a result, the difference between $\rho g H S_0$ and $\tau_b$ on the floodplain becomes smaller as the relative water depth increases. It can also be seen that the magnitudes of Terms $T_{rr}$ and $T_{sc}$ are larger near the sidewalls. As the relative water depth increases, the velocity gradient $\partial U/\partial y$ is steeper near the walls and the Reynolds shear stress is therefore larger. Meanwhile, the corner effects become more significant as the water depth increases and this generates stronger secondary currents near the walls, hence the magnitudes of $T_{sc}$ are larger in the deeper cases.

Figures 4.22a ~ 4.22c show the force contributions in three trapezoidal, compound-channel cases under the assumption that $\lambda_{w} = 0.07$. The overall trends of Terms $T_{rr}$ and $T_{sc}$ are similar to those in the rectangular cases, but they are more complex near the MC-FP junction than in the rectangular cases. This could be caused by the different secondary current structures over the sloped-wall region.

As can also be seen from Figures 4.21 and 4.22, the magnitudes of $T_{sc}$ in the main channel are almost zero except for the junction region and near the wall region, but they are positive and remain relatively constant on the floodplain. This indicates that the depth-averaged velocity on the floodplain will be under-predicted using the SKM model (Shiono & Knight 1991) unless secondary current effects are considered.

For each case, the magnitudes of $TB$ are nearly zero in the main channel and on the floodplain, except for the junction region and near the sidewalls. The non-zero $TB$
could be caused by the several secondary current cells and the eddy viscosity model used. This method requires further improvement in the future to better predict the depth-averaged apparent stress, Reynolds stress and the secondary current across the section in the compound channel.

4.8 Vegetated compound channel flow

4.8.1 Mean velocity and bed shear stress

To investigate the vegetation effects on the flow pattern and also gain basic knowledge of vegetated compound channel flow, 237 circular wooden rods were used to model the vegetation and placed at \( y = 0.163 \text{ m} \) (\( Y/B = 0.53 \)) along the floodplain. The lateral position of the MC-FP junction is \( y = 0.156 \text{ m} \) (\( Y/B = 0.51 \)). The diameter and height of the rods are 9 mm and 100 mm respectively. The distance between each rod is 40 mm. The relative water depth in this case is 0.52, which is similar to that in case STC-3. Velocity and boundary shear stress were measured at the cross section \( x = 7.47 \text{ m} \).

Figure 4.23 shows the normalised velocity \( (U/U_m) \) pattern across the section in STC-4 case. The measurement section was located at the centre between two emergent rods. It is clear that there are two high velocity zones, which are located in the main channel and on the floodplain. In the main channel, the maximum velocity zone exists around \( Y/B = 0.15 \) and \( Z/H = 0.55 \) and the peak velocity is \( 1.40 U_m \). The velocity-dip phenomenon is very obvious and this may be caused by the momentum transfer due to secondary currents. Based on the previous section of secondary currents in the trapezoidal compound channel, one large and strong, counter-clockwise secondary circulation might exist in the right side of the main channel and one small, clockwise secondary circulation might exist near the left wall of the main channel. The velocity decreases from \( 1.40 U_m \) around \( Y/B = 0.15 \) to \( 0.60 U_m \) at the MC-FP junction and this indicates the strong shear layer in the right side of the main channel. On the floodplain, the flow pattern is opposite to that in the main channel, but its velocity is smaller. A large, clockwise secondary circulation in the left side of the floodplain and a small, counter-clockwise secondary circulation near the right side of the floodplain might exist.
Figure 4.24 shows the distributions of the depth-averaged velocity and bed shear stress under a relative water depth $Dr = 0.5$. The velocity pattern in the emergent rod case is totally different from that in the no rod case, STC-3. The velocity is smaller in the emergent rod case, STC-4, than in the no rod case, STC-3, at the same position whilst the channel discharge in the rod case is about 67\% of that in the no rod case. The velocity gradient ($\partial U/\partial y$) is steeper near the MC-FP junction in the rod case than in the no rod case and stronger shear layers are generated in the main channel and on the floodplain. The bed shear stress is also smaller in the rod case than that in the no rod case at the same location. This indicates that the emergent rods greatly reduce the channel discharge under similar water depth conditions and this is not good for the relief of flooding. However, the bed shear stress is much smaller in the rod case than in the no rod case, especially near the rods, and this is good for riverbed protection.

Figure 4.25 shows the lateral distributions of $(\rho g HS_0 - \tau_b)/\rho g HS_0$ in the emergent rod case, STC-4, and in the no rod case, STC-3, for a relative water depth $Dr = 0.5$. In the rod case, the measured bed shear stress is smaller than the standard two-dimensional value $\rho g HS_0$ everywhere in the channel. From the point of force balance, this is due to the drag force. In the no rod case, the measured bed shear stress on the left floodplain is higher than $\rho g HS_0$ and this has been explained in the previous section.

In the rod case STC-4 (Figure 4.26), the friction factors are slightly larger in the main channel and on the floodplain than those in the non-vegetated case STC-3. This indicates that the emergent rods increase the flow resistance noticeably.

### 4.8.2 Eddy viscosity and Reynolds shear stress

As mentioned in Section 4.8.1, there are two shear layers in the compound channel with one-line emergent rods along the edge of the MC-FP junction. The eddy viscosity was calculated by considering the shear effect and using the assumption that $\overline{\lambda_{nb}} = 0.07$. 


Using the same method described in Section 4.4.1, the shear layer widths in the main channel and on the floodplain are 0.0832 m and 0.0829 m respectively. These shear layer widths in the rod case STC-4 are larger than their value of 0.033 m in the no rod case STC-3 and this is caused by the steeper velocity gradient \( \partial U/\partial y \) in the rod case. Figure 4.27a shows the eddy viscosity across the section in cases STC-4 and STC-3. In case STC-4, the eddy viscosity increases from the centre of the main channel to the MC-FP junction and decreases sharply approaching the rods. On the floodplain, the eddy viscosity increases from the rod position to the centre of the floodplain. This is because the eddy viscosity is not only dependent on \( \partial U/\partial y \), but also dependent on other parameters, such as \( U, H \) and \( f \). In the no rod case STC-3, the eddy viscosity remains relatively constant both in the main channel and on the floodplain, but it decreases from the main channel to the floodplain. The difference of eddy viscosity between the rod case and the no rod case is also caused by the multiple factors that determine the eddy viscosity. The shear effects on the eddy viscosity can be clearly seen from the dimensionless eddy viscosity, as shown in Figure 4.27b. In the no rod case STC-3, the values of \( \lambda_{v}/\lambda_{b} \) are nearly zero, even near the MC-FP junction, and this is due to the smaller velocity gradients. In the rod case STC-4, the maximum values of \( \lambda_{v}/\lambda_{b} \) reach about 4 in the main channel and 2.5 on the floodplain. This indicates that the shear contribution to the eddy viscosity is also important in the rod case, even under the deep-water condition.

Using \( \lambda_{b} = 0.07 \), Reynolds shear stress \( (\tau_{xy}) \) was calculated from the data presented in Figures 4.24 and 4.26. Figure 4.28a shows the distributions of depth-averaged Reynolds shear stress, apparent shear stress and secondary current normalised by \( \rho gH S_{0} \) in case STC-4. The secondary current \( - \langle \rho U V \rangle_{d} \) was calculated by using Equation 4.18. For comparison, Figure 4.28b shows the normalised forces in the non-vegetated case STC-3. In Figures 4.28a and 4.28b, \( TR_{as}, TR_{rs} \) and \( TR_{se} \) represent \( \tau_{as}/\rho gH S_{0}, \tau_{xy}/\rho gH S_{0} \) and \( - \langle \rho U V \rangle_{d}/\rho gH S_{0} \), respectively.

From Figure 4.28a, the sign of \( TR_{rs} \) corresponds well with the velocity gradient \( \partial U/\partial y \). In the main channel, the value of \( TR_{rs} \) decreases from zero where the peak velocity exists towards the MC-FP edge and attains a negative peak of -1.5 at \( y = \)
0.147 m. On the floodplain, it increases from zero at $y = 0.17$ m, attains a positive peak of 0.3 at $y = 0.23$ m and then decreases to be negative near the right wall. From Figure 4.28b, under similar water-depth conditions, it attains a negative peak of -0.5 near the MC-FP edge and remains negative on the floodplain. This indicates that the emergent rods generate strong shear layers in the main channel and on the floodplain, even under deep relative water depth conditions.

4.8.3 Apparent shear stress

The method of Shibno and Knight (1991) will be modified to calculate the apparent shear stress in a vegetated compound channel and this is also a new application. In vegetated, compound-channel flow, the depth-averaged momentum equation can be given as follows:

$$\left(\rho g S_0 - F_i\right)H - zb \left(1 + \frac{1}{s^2}\right)^{\frac{1}{2}} = \frac{\partial}{\partial y} \left[H \left\{\left(\rho U V\right)_d - \tau_{xy}\right\}\right]$$

(4.24)

where $F_i$ is the drag force per unit volume and is zero outside the area affected by the drag force.

According to Igarashi (1984), the affecting area of a circular, emergent rod is around $4D \times 4D$, where $D$ is the diameter of the rod. In case STC-4, the diameter of the rod is 0.009 m and the rods are located at $0.158 \leq y \leq 0.167$ m, so the affecting area was roughly chosen at $0.12 \leq y \leq 0.201$ m. The drag effect becomes weaker as the distance from the rod centre increases, so the drag force is assumed to peak at the rod centre, $y = 0.163$ m, and decrease from the rod centre to $y = 0.12$ m and $y = 0.201$ m. The total drag force ($F$) in the channel was calculated from Equation 4.25. In traditional volume averaging, the drag force is assumed to be uniform in the whole water volume. This is easy to calculate, but it is not accurate enough. In this study, the drag force was assumed to be distributed linearly in the affecting area as illustrated in Figure 4.29a. The affecting area was divided into several small sub-areas. The drag force in the sub-area ($F_{di}$) was calculated using the assumption illustrated in Figure 4.29a and the drag force per unit volume in the sub-area ($F_i$) was calculated from Equation 4.26. Figure 4.29b presents the calculation results of $F_{di}$ and $F_i$. 

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\[ F = \frac{1}{2} N_r \rho C_D D h U_c^2 \]  

(4.25)

where \( N_r \) is the total number of rods (\( =237 \)), \( C_D \) is the drag coefficient (\( =1 \)), \( D \) is the diameter of the rod (\( =0.009 \) m), \( h \) is the water depth on the floodplain (\( =0.0385 \) m) and \( U_c \) is the averaged streamwise velocity (\( =0.1679 \) m/s) within \( 0.12 \) m \( \leq y \leq 0.201 \) m.

\[ F_t = \frac{F_d}{V_{wl}} \]  

(4.26)

where \( V_{wl} \) is the water volume of the \( i \) sub-area.

The apparent shear stresses in the main channel and on the floodplain were calculated from the left wall and the right wall respectively. Mean wall shear stresses on the left and right channel walls were used as boundary conditions. For example, the apparent shear stress in the main channel can be calculated by using Equation 4.27,

\[
\overline{\tau_w}(y) = -\frac{1}{H} \int\left[ \rho (g S_0 - F_t) H - \tau_b \left( 1 + \frac{1}{S^2} \right)^{\frac{1}{2}} + H \overline{\tau_{wl}} \right] dy
\]  

(4.27)

From Figure 4.28a, in the main channel, the apparent shear stress decreases from the left wall towards the sloped wall of the main channel, however, once it attains a negative peak of -1.0 at \( y = 0.138 \) m, its magnitude increases again. On the floodplain, the apparent shear stress increases from a negative value of -1.5 near the MC-FP edge, attains a positive peak of 1.3 at \( y = 0.20 \) m and then decreases to a negative value near the right wall. In the non-vegetated case STC-3 (Figure 4.28b), the apparent shear stress attains a negative peak of -0.2 at \( y = 0.156 \) m and then increases slightly towards the right wall. This further indicates that the lateral shear is stronger in the emergent rod case than that in the non-vegetated case under similar deep water conditions.
4.8.4 Secondary current

The secondary current \(-\frac{\rho U V}{\rho g HS_0}\) varies in a similar manner to that of the apparent shear stress \(\frac{\tau_{\alpha i}}{\rho g HS_0}\). From Figures 4.28a and 4.28b, it can also be seen that the magnitudes of secondary current \(-\frac{\rho U V}{\rho g HS_0}\) are larger in the emergent rod case, STC-4, than in the non-vegetated case STC-3, especially near the rods. The negative and positive peak values of \(-\frac{\rho U V}{\rho g HS_0}\) are -1.5 and 1.0 for the rod case. The negative and positive peak values of \(-\frac{\rho U V}{\rho g HS_0}\) are -0.7 and 0.2 for the non-vegetated case. Moreover, \(-\frac{\rho U V}{\rho g HS_0}\) behaves in a more complex manner in the emergent rod case. The stronger secondary currents could be caused by the large eddies near the MC-FP junction and the strong wakes around the rods.

Figure 4.30 shows the maximum lateral velocity \(V_{max}\) profiles in cases STC-4 and STC-3. From Figure 4.30, the \(V_{max}\) in the rod case, STC-4, is generally much larger than that in the no rod case STC-3. The maximum ratios of \(V_{max}/U_{max}\) for the rod case and the no rod case are 0.45 and 0.03 respectively. The sign of \(V_{max}\) changes near the rods and this could be caused by the wakes or eddies around the rods.

Based on the measured streamwise velocity and calculated results of \(-\frac{\rho U V}{\rho g HS_0}\), the typical vertical profiles of the lateral velocity \(V\) can be roughly estimated. The proposed vertical profiles in the main channel and on the floodplain were illustrated by Figures 4.31 and 4.32 respectively.

4.8.5 Contributions to boundary shear stress

As shown in Figure 4.25, the boundary shear stresses are smaller than the two-dimensional value \(\rho g HS_0\) across the section in the rod case STC-4. Figures 4.33a and 4.33b show the contributions to the boundary shear stress in cases STC-4 and STC-3 respectively. In Figures 4.33a and 4.33b, \(T_s\) represents \(\frac{\rho g HS_0 - F}{\rho g HS_0}\), \(T_{z_s}\) represents \(-\frac{\tau_b(1 + s^{-2})}{\rho g HS_0}^{\frac{1}{2}}\), \(T_{r_s}\) represents \(\frac{\partial(H\tau_{rs})}{\partial y}\) and \(T_{z_c}\) represents...
\[ \frac{\partial}{\partial y} \left( -\frac{\rho U V}{g} \right) \]

TB represents \( T_{g} + T_{bs} + T_{rs} + T_{rc} \). The shear effect on the Reynolds stress is considered in these analyses.

The overall contributions are well-balanced in the main channel, except near the rods, i.e. at \( y = 0.156 \, m \) and \( y = 0.171 \, m \). The remarkable difference between the rod case and the no rod case exists in the junction region because of the non uniform flow condition near the rods. The drag force due to the emergent rods causes steep velocity gradient and then strong lateral shear near the MC-FP junction, this makes the behaviours of \( \frac{\partial \left( H \tau_{y} \right)}{\partial y} \), \( \frac{\partial \left( -\rho U V \right)}{\partial y} \) very complex and then the behaviour

\[ - \frac{\tau_b \left( 1 + s^{-2} \right)^{\frac{1}{2}}}{g H S_0} \]

4.9 Summary

Narrow, rectangular, open-channel flow is characterised by the strong velocity-bulging towards the corners whilst the maximum velocity occurs around the centre region \((Z/H = 0.60)\) of the channel. The velocity-dip becomes remarkable as the aspect ratio (=B/H) decreases. These flow behaviours described in the literature were also confirmed in this work.

The distance ratio \((X/R)\) of the longitudinal distance from the inlet \((X)\) to the hydraulic diameter \((R)\) can be used to select the measurement section for a fully developed flow in open channel experiments. In these experiments, the appropriate distance ratios \((X/R)\) for flow development are 176 in the rectangular channel and 150 in the compound channel respectively.

Non-vegetated, compound, open-channel flow is characterized by the velocity-bulging near the MC-FP junction and the corners due to the momentum transfer via secondary currents. In this study, velocity-bulging near the MC-FP junction was demonstrated to be stronger under large relative water depth conditions, especially in the rectangular compound channel.
The lateral shear in the shear layer zone was found to play an important role in the momentum exchange in the non-vegetated, compound open channel, especially under shallow relative water depth conditions. The shear layer width, $\delta$, decreases as the relative water depth increases and the value of $\delta$ is larger in the rectangular compound channel than that in the trapezoidal compound channel. The dimensionless, depth-averaged eddy viscosity ($\overline{\lambda_u}$) peaks at the MC-FP junction and the peak value decreases as the relative water depth increases. For the rectangular compound channel, the peak ratios of $\overline{\lambda_u}/\overline{\lambda_{ib}}$ under relative water depths of 0.22, 0.35 and 0.48 are 29, 3 and 0.2 respectively. For the trapezoidal compound channel, the peak ratios of $\overline{\lambda_u}/\overline{\lambda_{ib}}$ under relative water depths of 0.23, 0.37 and 0.50 are 9, 2 and 0.2 respectively. The Reynolds shear stress ($\overline{r_{yx}}$) behaves in a similar manner to that of the dimensionless, depth-averaged eddy viscosity ($\overline{\lambda_u}$).

The apparent shear stress ($\tau_{as}$) arises from the Reynolds shear stress ($\overline{r_{yx}}$) and the secondary current ($-\rho \overline{U'V'}_d$). The method of Shiono and Knight (1991) was used to calculate the apparent shear stresses in the trapezoidal compound channel. This method was modified to calculate the apparent shear stresses in the rectangular compound channel using appropriate boundary conditions. The apparent shear stress peaks near the MC-FP junction, and the ratio of the apparent shear stress to $\rho g H S_0$ decreases as the relative water depth increases, which indicates that the lateral shear becomes weaker under deep-water conditions. The peak value of $\tau_{as}$ is smaller in the trapezoidal, compound channel cases than that in the rectangular cases under similar, relative water-depth conditions.

The secondary current ($-\rho \overline{U'V'}_d$) was calculated from the apparent shear stress and Reynolds shear stress. The calculated ($-\rho \overline{U'V'}_d$) and $V_{max}$ profiles roughly agree with the measurements in the literature, but they are more complex near the MC-FP junction. The magnitudes of ($-\rho \overline{U'V'}_d$) and $V_{max}$ are also large near the MC-FP junction, even in shallow cases, and this indicates that the secondary current also plays an important role in the momentum exchange near the MC-FP junction in the compound channel.
In non-vegetated, compound-channel cases, the bed shear stresses are smaller than $\rho g H S_0$ in the main channel and larger on the floodplain and this is caused by the gradients of the Reynolds shear stress ($\partial H \bar{\tau}_{xy} / \partial y$) and secondary current ($\partial H \bar{\rho U V} / \partial y$). The values of $\partial H \bar{\tau}_{xy} / \partial y$ and $\partial H \bar{\rho U V} / \partial y$ are much larger near the MC-FP junction than those outside this region and this indicates that the effect of $\partial H \bar{\rho U V} / \partial y / \rho g H S_0$ can be neglected outside the MC-FP junction region in 2D modelling.

The emergent rods make the flow pattern totally different from that in the compound channel without rods on the floodplain under similar, relative water-depth conditions. In the compound open channel with one-line emergent rods along the floodplain, the flow is characterized by two shear layers in the main channel and on the floodplain separately. For relative water depth $Dr \approx 0.5$, the shear layer widths in the main channel and on the floodplain in the rod case are both about 0.083 m and the shear layer width in the nonvegetated case is only 0.033 m. The maximum values of $\bar{\lambda}_{\text{ch}} / \bar{\lambda}_{\text{ch}}$ in the main channel and on the floodplain are about 4 and 2.5 respectively. Compared with the non-vegetated compound channel, the channel discharge and bed shear stress are reduced remarkably in the compound channel with emergent rods along the floodplain under similar relative water depth conditions.

By distributing the drag force linearly in the affecting area, the depth-averaged, apparent shear stress and the secondary current were properly calculated. The apparent shear stress, Reynolds shear stress and secondary current peak near the MC-FP junction in the rod case and their peak values are larger than those in the non-vegetated case, and they behave with greater complexity near the MC-FP junction than those in the non-vegetated compound channel owing to the large eddies and wakes around the rods.
Figure 4.1  Isovels of normalised velocity $U/U_m$ along the rectangular channel Case SR-1). (a) $X/R = 85$; (b) $X/R = 127$; (c) $X/R = 176$; (d) $X/R = 235$; (e) $X/R = 282$. 
Figure 4.2  Isovels of normalised velocity $U/U_m$ along the compound channel for Case SRC-3. (a) $X/R = 50$; (b) $X/R = 100$; (c) $X/R = 150$; (d) $X/R = 210$. 
Figure 4.3 Normalised velocity \((U/U_*)\) distributions over the water depth at \(Y/B = 0.5\) in case SR-1 and at \(Y/B = 0.3\) in case SRC-1. (a) Case SR-1; (b) Case SRC-3.

Figure 4.4 Isovels of normalised velocity \((U/U_m)\) at \(X/R = 185\) (Case SR-2).
Figure 4.5  Isovels of normalised velocity $U/U_m$ in rectangular compound channel cases. (a) SRC-1; (b) SRC-2; (c) SRC-3.

Figure 4.6  Isovels of normalised velocity $U/U_m$ in trapezoidal compound channel cases. (a) STC-1; (b) STC-2; (c) STC-3.
Figure 4.7 Lateral distributions of depth-averaged velocity $U_d$. (a) Rectangular compound channel cases; (b) Trapezoidal compound channels cases.

Figure 4.8 Width of shear layer $\delta$ in various compound channel cases. (a) Definition sketch for determination of $\delta$; (b) Values of $\delta$ in various cases.
Figure 4.9  Lateral distributions of bed shear stress $\tau_b$. (a) Rectangular compound channel cases; (b) Trapezoidal compound channel cases.

Figure 4.10  Lateral distributions of $\rho g H S_0 - \tau_b$ for six cases.
Figure 4.11  Overall values of Manning coefficient in various cases

(a)

(b)

(c)

(d)

(e)

(f)

Figure 4.12  Lateral distributions of measured and predicted friction factor. (a) Case SRC-1; (b) Case SRC-2; (c) Case SRC-3; (d) STC-1; (e) STC-2; (f) STC-3.
Figure 4.13  Lateral distributions of $\bar{\varepsilon}_i$ in compound channels. (a) Rectangular cases; (b) Trapezoidal cases.

Figure 4.14  Lateral distributions of $\bar{\lambda}_t/\bar{\lambda}_{tb}$ in compound channels and peak $\bar{\lambda}_u/\bar{\lambda}_{tb}$ under various relative water depth conditions. (a) $\bar{\lambda}_t/\bar{\lambda}_{tb}$; (b) Peak value of $\bar{\lambda}_u/\bar{\lambda}_{tb}$.
Figure 4.15  Lateral distributions of Reynolds stress in compound channels.

Figure 4.16  Lateral distributions of apparent stress in compound channels and dip apparent stresses in various relative water depth conditions. (a) Apparent shear stress; (b) Dip value of apparent shear stress.

Figure 4.17  Lateral distributions of secondary current term $-(\rho \overline{UV})_d$ in compound channels.
Figure 4.18  Secondary current cells in a rectangular compound channel.

Figure 4.19  Typical distributions of U and V in different locations of a rectangular compound channel. (a) Main channel; (b) Near left wall; (c) Near junction; (d) Floodplain.

Figure 4.20  Lateral distributions of $V_{max}$ in compound channels.
Figure 4.21 Contributions of different forces to the difference of $\rho g H S_0 - \tau_b$ in rectangular compound channel cases. (a) Case SRC-1; (b) SRC-2; (c) SRC-3.
Figure 4.22 Contributions of different forces to the difference of $\rho g H S_0 - \tau_b$ in trapezoidal compound channel cases. (a) Case STC-1; (b) Case STC-2; (c) Case STC-3.
Figure 4.23  Isovels of normalised velocity $U/U_m$ in emergent rod case STC-4.

Figure 4.24  Lateral distributions of depth-averaged velocity and bed shear stress in vegetated and non-vegetated channels under $Dr = 0.5$.

Figure 4.25  Lateral distributions of $(\rho g H S_0 - \tau_b)/\rho g H S_0$ under $Dr = 0.5$.

Figure 4.26  Lateral distributions of friction factor under $Dr = 0.5$.  

$\rho g$
Figure 4.27  Lateral distributions of eddy viscosity $\overline{\epsilon}$, and $\overline{\lambda_{ii}/\lambda_{ib}}$ in vegetated and non-vegetated channels under $Dr = 0.5$. (a) Eddy viscosity $\overline{\epsilon}$; (b) $\overline{\lambda_{ii}/\lambda_{ib}}$.

Figure 4.28  Distributions of normalised forces in vegetated and non-vegetated channels under $Dr = 0.5$. (a) Case STC-4; (b) Case STC-3.
Figure 4.29  Distributions of drag force in the affecting area. (a) Drag force per unit length; (b) Drag force per unit volume.

Figure 4.30  Lateral distributions of $V_{\text{max}}$ in cases STC-4 and STC-3.
Figure 4.31  Vertical distributions of $\overline{U}$, $\overline{V}$ and $-\left(\rho\overline{UV}\right)_d$ at $y = 0.12$ m in the main channel. (a) $\overline{U}$; (b) $\overline{V}$; (c) $-\left(\rho\overline{UV}\right)_d$.

Figure 4.32  Vertical distributions of $\overline{U}$, $\overline{V}$ and $-\left(\rho\overline{UV}\right)_d$ at $y = 0.186$ m on the floodplain. (a) $\overline{U}$; (b) $\overline{V}$; (c) $-\left(\rho\overline{UV}\right)_d$. 
Figure 4.33 Contributions of different forces to the difference of $\rho g HS_0 - \tau_s$ in cases STC-4 and STC-3. (a) Case STC-4; (b) Case STC-3.
Chapter 5

Large Compound Channel Experiments

In this chapter, based on the turbulence measurement data undertaken in the large compound channel, the turbulent characteristics of flow in compound channels with and without vegetation on the floodplain are presented. Section 5.1 describes the mean flow and Section 5.2 explores the secondary currents in the compound channels. In Section 5.3, vorticity distributions and vorticity balance are further analysed to explain the generation of secondary currents under various flow conditions. In Sections 5.4 and 5.5, the turbulent intensities, turbulent kinetic energy and Reynolds shear stress are illustrated. In Section 5.6, the depth-averaged Reynolds shear stress, eddy viscosity and secondary currents are presented. In Section 5.7, velocity correlation and energy spectra are presented. In Section 5.8, the contribution of large eddies to the momentum exchange are discussed. Section 5.9 summarises the results for the large, compound-channel flow.

5.1 Mean Flow

Turbulent characteristics for five cases were investigated in this section. In cases LC-1 and LC-2, there were no rods on the floodplain and the relative water depths were 0.41 and 0.5 respectively. In cases LC-3 and LC-4, there were submerged rods on the floodplain and the relative water depths were 0.44 and 0.52 respectively. In case LC-5, there were emergent rods on the floodplain and the relative water depth was 0.22. The detailed flow conditions for the five cases are listed in Table 5.1.

<table>
<thead>
<tr>
<th>Case</th>
<th>H(m)</th>
<th>R(m)</th>
<th>$U_m$(m/s)</th>
<th>$U_*(m/s)$</th>
<th>Re</th>
<th>n</th>
<th>Vegetation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC-1</td>
<td>0.255</td>
<td>0.125</td>
<td>0.7808</td>
<td>0.0495</td>
<td>390847</td>
<td>0.0146</td>
<td>No</td>
</tr>
<tr>
<td>LC-2</td>
<td>0.312</td>
<td>0.146</td>
<td>0.7892</td>
<td>0.0535</td>
<td>461225</td>
<td>0.0155</td>
<td>submerged</td>
</tr>
<tr>
<td>LC-3</td>
<td>0.27</td>
<td>0.132</td>
<td>0.5767</td>
<td>0.0509</td>
<td>305509</td>
<td>0.0633</td>
<td>submerged</td>
</tr>
<tr>
<td>LC-4</td>
<td>0.312</td>
<td>0.151</td>
<td>0.5695</td>
<td>0.0544</td>
<td>344559</td>
<td>0.0743</td>
<td>Emergent</td>
</tr>
<tr>
<td>LC-5</td>
<td>0.192</td>
<td>0.091</td>
<td>0.5301</td>
<td>0.0421</td>
<td>192018</td>
<td>0.0367</td>
<td>Emergent</td>
</tr>
</tbody>
</table>
5.1.1 Non-vegetated floodplain

Figure 5.1 shows the isovel lines of the longitudinal mean velocity ($U$) normalised by the cross-sectional average velocity ($U_m$) for cases LC-1 ~ LC-5. In case LC-1 (Figure 5.1a), strong bulging in the velocity contour lines is observed from the bottom around $Y/B = 0.2$ in the main channel. According to Nezu and Nakagawa (1993), the velocity bulging is caused by the secondary currents in open channels. Figure 5.2 shows the secondary current patterns for these cases. In case LC-1, the velocity bulging is caused by two main secondary circulations as shown in Figure 5.2a. The reason for the bulging is that the clockwise secondary currents carry fluid with lower momentum from the bed to higher momentum regions and also move fluid with higher momentum from the upper centre region down to the right corner of the main channel. These large clockwise circulations were also observed in the symmetrical, trapezoidal, compound channel by Shiono and Knight (1989). Tominaga and Nezu (1991) also observed the small counter-clockwise circulations near the left corner of the main channel in the deep, rectangular, compound-channel experiments, but these circulations are stronger in case LC-1 than theirs. As a result, the velocity contour lines' bulge more strongly in this case. According to Nezu and Nakagawa (1993), the secondary currents are stronger in narrower channels because of the stronger corner effects. In this case, the aspect ratio ($= B/H$) is 3.6 and is higher than that in the case of Tominaga and Nezu (1991), hence the velocity isovel lines bulge strongly near the left corner.

Figure 5.1a also indicates that the velocity isovel lines bulge strongly around $Y/B = 0.2$ than around the junction of the main channel and the floodplain (MC-FP). This can be explained by the strengths of the secondary currents in these regions, where the secondary currents are stronger near the bed around $Y/B = 0.2$ than at the MC-FP junction as shown in Figure 5.2a.

As shown in Figure 5.1b, in case LC-2, strong bulging can also be recognised around $Y/B = 0.2$, which is directly influenced by the momentum exchange due to strong secondary currents near the bed of the main channel. From Figure 5.1b, weak bulging exists near the MC-FP junction and the velocity-dip phenomenon occurs near the free surface in the main channel. From Figures 5.1b and 5.2b, the velocity patterns also
agree well with the secondary current patterns in case LC-2. This further confirms that the velocity distributions are also influenced by the secondary currents in this case.

5.1.2 Vegetated floodplain

Comparing the rod case LC-3 of Figure 5.1c with the no-rod case LC-1 of Figure 5.1a, the velocities on the vegetated floodplain become much smaller than those for the non-vegetated floodplain. This is because the submerged rods exert additional drag force on the water flow on the floodplain, increase the flow resistance on the floodplain and consequently decrease the velocities on the floodplain. As a result of the self-adjustment process, the velocity gradient in the transverse direction at the MC-FP junction becomes steeper than that in the no rod case LC-1.

In case LC-3 (Figure 5.1c), the bulging near the main channel bed becomes slightly weaker than that in case LC-1 and its position moves further towards the left wall of the main channel. The velocity-dip is remarkable near the free surface in the main channel and this is caused by the secondary currents near the free surface as shown in Figure 5.2c. Unlike case LC-1, the velocity-bulging is not clear at the MC-FP junction and this is caused by the opposite secondary motions from the main channel and the floodplain, as shown in Figure 5.2c. No references are currently available on velocity patterns in compound open channels with submerged vegetation on the floodplain. Nezu and Onitsuka (2001) observed the flow behaviour in a rectangular open channel with partly-covered, submerged vegetation on a simple channel bed and found the velocity isovel lines bulge considerably toward the upper region of the vegetation. The flow behaviour is obviously more complex in the compound open channel with submerged vegetation on the floodplain than in the simple open channel.

In the deeply-submerged rod case LC-4 (Figure 5.1d), the velocity patterns are greatly different from those in cases LC-2 and LC-3 and this can be explained by the various secondary current patterns in these cases. As shown in Figure 5.2d, the secondary currents near the free surface moves fluid with higher momentum from the main channel to the floodplain, hence the velocity-dip cannot be seen in case LC-4. The strong, clockwise, junction vortex on the floodplain side causes the velocity-bulging near the MC-FP junction and the lateral shift of the bulging position. This junction
vortex might be caused by the secondary currents and the three dimensional rod wakes.

In cases LC-3 and LC-4, the velocity-bulging near the MC-FP junction might also be explained by the concept of an imaginary compound channel. Based on the measurement results, the velocities below the rod top on the floodplain are much lower than those in other parts of the channel and can be assumed to be zero, hence the region below the rod top can be assumed to be part of the imaginary floodplain bed and an assumed compound channel is configured. The vertical positions of the imaginary floodplain bed are at the top of the submerged rods and the imaginary MC-FP edge is located 1cm away from the actual MC-FP edge. In case LC-3, the water depth on the imaginary floodplain is 2cm, the relative water depth of the imaginary compound channel is 0.07 (0.02/0.27). In case LC-4, the water depth on the imaginary floodplain is 5cm and the imaginary relative water depth is 0.16 (0.05/0.31). The velocity-dip phenomenon near the water surface in the main channel becomes less remarkable in case LC-4 than in case LC-3 because the relative water depth of the imaginary compound channel in case LC-4 is higher than that in case LC-3. The lateral position of velocity bulging in the actual channel is located just at the imaginary MC-FP junction and this explains the position shift of the velocity-bulging in case LC-4.

Figure 5.1e shows the isovel lines of the longitudinal mean velocity ($U$) normalised by the cross-sectional average velocity ($U_m$) in case LC-5. The emergent rods cause much smaller velocities near the MC-FP junction and on the floodplain. From Figure 5.1e, the isovels bulge slightly toward the sloped main channel bed near the MC-FP junction and this is caused by the secondary currents as shown in Figure 5.2e. Compared with the previous four cases, the bed vortex is the weakest in case LC-5. Among the five cases, the Reynolds number is the smallest and the bed-generated bed turbulence is the weakest in case LC-5. This also indicates that the bed vortex becomes stronger as the relative water depth increases in this narrow compound channel.

The velocity patterns, especially near the water surface and MC-FP junction, in case LC-5 are different to those noted by Shiono and Knight (1989) under similar relative
water depths. Shiono and Knight (1989) obtained their velocity results in a wide, symmetrical, trapezoidal, compound channel with a non-vegetated floodplain. This indicates that the emergent rods on the floodplain play a very important role in altering the velocity distributions and also in producing characteristic secondary currents.

It can also be seen from figures 5.1a – 5.1e that the velocity patterns in case LC-5 are different to cases LC-1 – LC-4. This indicates that the rods on the floodplain complicate the velocity distributions.

5.2 Secondary Currents

Secondary currents play an important role in momentum exchange and hence directly influence the longitudinal velocity distributions in open channels. As described in Section 3.2.3.7, the measured velocities are usually resolved by rotating the coordinate system to obtain the velocities in the required directions. The rotation angles for the five cases are listed in Table 5.2.

<table>
<thead>
<tr>
<th></th>
<th>LC-1</th>
<th>LC-2</th>
<th>LC-3</th>
<th>LC-4</th>
<th>LC-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-y</td>
<td>-1.3</td>
<td>0.75</td>
<td>0.5</td>
<td>0.5</td>
<td>-1.0</td>
</tr>
<tr>
<td>x-z</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.5</td>
<td>-0.3</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

For uniform flow, the cross-sectional secondary currents satisfy the continuity equation. However, the velocities near the sidewalls and free water surface cannot be measured due to the measurement limit of ADV. The measurement results for the secondary currents cannot be strictly checked by using this method. In spite of the above drawback, the secondary current patterns can be roughly recognised from Figure 5.2.

In cases LC-1 and LC-2 (Figures 5.2a and 5.2b), a pair of bottom vortices is generated around $Y/B = 0.2$ in the main channel. As described in section 5.1.1, these secondary currents move fluid with lower momentum from the bed up to the centre of the main
channel and move fluid with higher momentum down to the corners of the main channel. The velocity-bulging (Figures 5.1a and 5.1b) coincides well with the secondary current patterns in this region (Figures 5.2a – 5.2b). The secondary current patterns are not very clear near the MC-FP junction, but it seems that there is a clockwise circulation in this region. In a wide, trapezoidal, compound channel, Shiono and Knight (1989) showed that there is a large, clockwise circulation in the main channel and there is a pair of vortices near the MC-FP junction. In cases LC-1 and LC-2, the channel is a relatively narrow, trapezoidal, compound channel, which makes the secondary current patterns different to those found in Shiono and Knight (1989).

Tominaga and Nezu (1991) used the ratio of the maximum magnitude of \( V_s = \left( V^2 + W^2 \right)^{1/2} \) to the maximum streamwise velocity \( U_{max} \), \( V_{s,\text{max}} / U_{max} \), to characterise the magnitude of the secondary currents. From Figures 5.2a and 5.2b, the ratios of \( V_{s,\text{max}} / U_{max} \) in no rod cases LC-1 and LC-2 are both about 3%, while the ratio of \( V_{s,\text{max}} / U_{max} \) near the water surface is larger in case LC-2.

In cases LC-3 and LC-4 (Figures 5.2c and 5.2d), a large, clockwise vortex is clearly recognised in the main channel and this clockwise vortex changes its rotation direction near the MC-FP edge due to the strong wakes around the rods. In the shallow, submerged case LC-3 (Figure 5.2c), the secondary current patterns near the MC-FP junction are not clear and this might be caused by the rod wakes in this region. In the deep, submerged case LC-4 (Figure 5.2d), the clockwise, secondary currents near the MC-FP junction can be easily identified. Nezu and Onitsuka (2002) observed the large secondary circulations in partly-vegetated, rectangular channels, but they did not report the vortex near the junction between the non-vegetated and vegetated zones. This shows that the submerged rods on the floodplain make the flow behaviour much more complex. It can be clearly seen that the ratios of \( V_{s,\text{max}} / U_{max} \) in submerged cases LC-3 and LC-4 are larger than 10%, especially near the MC-FP junction and the main channel bed regions, which are much larger than those in the no rod cases LC-1 and LC-2. This indicates that the submerged rods on the floodplain increase the anisotropy of turbulence and consequently strengthen the secondary currents in the vegetated compound channel.
In the emergent case LC-5 (Figure 5.2e), a large counter-clockwise vortex can be clearly identified in the main channel and this secondary current pattern matches well with the velocity patterns shown in Figure 5.1e. Owing to the ADV measurement near the water surface, insufficient velocity data make it hard to see the secondary current patterns on the floodplain.

According to Nezu and Nakagawa (1984), secondary currents in uniform, rectangular channels are generated by the anisotropy of turbulence and the strength of the secondary current is normally expressed by the gradient of the normal stress difference $\frac{\partial (\bar{w}^2 - \bar{v}^2)}{\partial y \partial z}$. The higher the value of the gradient of the normal stress difference, $\frac{\partial (\bar{w}^2 - \bar{v}^2)}{\partial y \partial z}$ the stronger the secondary current. In other words, stronger secondary currents exist where the $(\bar{v}^2 - \bar{w}^2)$ isovel lines are denser.

Figures 5.3a - 5.3e show the magnitudes of the term $(\bar{v}^2 - \bar{w}^2) / U_z^2$ in cases LC-1 - LC-5 respectively. In the no rod cases LC-1 and LC-2 (Figures 5.3a and 5.3b), the denser isovel lines exist around $Y/B = 0.2$ near the bottom region in the main channel. The peak magnitudes of $(\bar{v}^2 - \bar{w}^2) / U_z^2$ in cases LC-1 and LC-2 are 2.9 and 3.0 respectively. In the submerged-rod cases LC-3 and LC-4 (Figures 5.3c and 5.3d), the densest $(\bar{v}^2 - \bar{w}^2) / U_z^2$ isovel lines exist between the MC-FP junction and the rods. The peak magnitudes of $(\bar{v}^2 - \bar{w}^2) / U_z^2$ in cases LC-3 and LC-4 are 7.0 and 5.7 respectively. In the emergent-rod case LC-5 (Figure 5.3e), the denser $(\bar{v}^2 - \bar{w}^2) / U_z^2$ isovel lines not only exist between the MC-FP junction and the rods, but also extend to the free surface region in the main channel. The peak magnitude of $(\bar{v}^2 - \bar{w}^2) / U_z^2$ in case LC-5 is 4.3 near the rods. In all the five cases, the dense isovel lines of $(\bar{v}^2 - \bar{w}^2) / U_z^2$ correspond well to the strong secondary currents in these regions which causes noticeable velocity-bulging and velocity-dip phenomena.

The results of $(\bar{v}^2 - \bar{w}^2) / U_z^2$ confirm that the anisotropy of turbulence is the main generation mechanism of the secondary current in the straight compound channel, even when the vegetation effect exists. Moreover, under similar relative water-depth conditions, the vegetation increases the anisotropy of turbulence in the compound
channel; as a result, the secondary current in the vegetated channel is stronger than that in the no rod one.

It should be noted that the magnitudes of the secondary currents are only several percent of the mean longitudinal velocities and it is very difficult to measure them accurately, even when using a sophisticated Laser Doppler Anemometer (LDA). During the velocity measurements, much noise was experienced using ADV. The SNR (signal-noise ratio) values were higher than 20 and this indicates that the effect of the boundary is suppressed by the echoes from particles in the water. The possible sources of the noise come from the nominal velocity range and steep velocity gradient in the sampling volume, especially in the strong shear layer zone. If the practical velocities are much lower or higher than the set nominal velocity range, much noise is introduced. As suggested by Nortek (2004), the measured vertical velocity (w) has the lowest uncertainty. There are noticeable uncertainties with respect to the transverse velocity (v) because the longitudinal velocity (u) and the transverse velocity (v) have the same velocity range, but v is usually less than 10% of u. Despite this, all results seem to agree with those in the literature.

5.3 Vorticity

5.3.1 Vorticity equation

Vorticity analyses are used to explain the secondary current profiles in section 5.2. For steady and incompressible flow, the generation mechanisms of secondary currents can be understood by analysing the longitudinal vorticity equation (Equation 5.1).

\[
\begin{align*}
U \frac{\partial \Omega_1}{\partial x} + V \frac{\partial \Omega_1}{\partial y} + W \frac{\partial \Omega_1}{\partial z} - \Omega_1 \frac{\partial U}{\partial x} - \Omega_2 \frac{\partial U}{\partial y} - \Omega_3 \frac{\partial U}{\partial z} &= \\
\frac{\partial}{\partial x} \left( \frac{\partial \Omega}{\partial z} - \frac{\partial \Omega}{\partial z} \right) + \frac{\partial^2}{\partial y \partial z} \left( \frac{\partial w}{\partial z} - \frac{\partial v}{\partial z} \right) - \left( \frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2} \right) \frac{\partial w}{\partial z} + \\
v \left( \frac{\partial^2 \Omega}{\partial x^2} + \frac{\partial^2 \Omega}{\partial y^2} + \frac{\partial^2 \Omega}{\partial z^2} \right) + \frac{g}{\rho_r} \frac{\partial \rho}{\partial y}
\end{align*}
\]

where the three component vorticity vectors are:
As reviewed in Chapter 2, the secondary currents in a straight channel are generated by the non-homogeneity (or anisotropy) of turbulence. For uniform straight compound channel flow, terms \( \frac{\partial \Omega_1}{\partial x}, \frac{\partial U}{\partial x}, \frac{\partial}{\partial x} \left( \frac{\partial \nu}{\partial z} - \frac{\partial \omega}{\partial y} \right) \) and \( \frac{\partial \Omega_1}{\partial x} \) are zero and \( \Omega_2 \frac{\partial U}{\partial y} = -\Omega_2 \frac{\partial U}{\partial z} \) (Nezu 2005), Equation 5.1 can be further simplified to Equation 5.3 if the fluid density is constant.

\[
\begin{align*}
\nu \frac{\partial \Omega_1}{\partial y} + \nu \frac{\partial \Omega_1}{\partial z} &= \frac{\partial^2}{\partial y \partial z} \left( \frac{\partial \nu}{\partial z} - \frac{\partial \omega}{\partial y} \right) - \left( \frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial y^2} \right) \nu \nu + \\
\text{A1} & \quad \text{A2} & \quad \text{A3} \\
\nu \left( \frac{\partial^2 \Omega_1}{\partial y^2} + \frac{\partial^2 \Omega_1}{\partial z^2} \right) &= \text{A4}
\end{align*}
\]

In the above equation, Term A1 represents the advection of the longitudinal vorticity by the main flow. Term A2 represents the generation of the secondary currents by the anisotropy of turbulence, while Term A3 represents the generation of secondary currents by the shear stress. Term A4 is the viscous term, which is only important close to the wall.

### 5.3.2 Vorticity distributions

Before analysing vorticity balance, a brief description of the vorticity field is given below. The longitudinal vorticity fields in the five cases are presented in Figures 5.4a – 5.4e. The values of the vorticity are multiplied by 100 and divided by \( (U_m/H) \). A positive value represents a clockwise circulation of the secondary current while a negative value represents a counter-clockwise circulation. Due to ADV measurement, vorticity fields near the free surface and the right and left walls cannot be calculated.

In case LC-1 (Figure 5.4a), there is a negative vorticity with a value of -20 and a positive vorticity with a value of 20 around \( Y/B = 0.2 \) near the main channel bottom,
which indicates that there are counter-clockwise and clockwise secondary cells in this region. The values of vorticity near the MC-FP junction are negative in the main channel side and this indicates there are counter-clockwise secondary cells in this region. Due to ADV measurement, the vorticity fields on the floodplain cannot be calculated for this case. The general information obtained from Figure 5.4a coincides well with the secondary current patterns shown in Figure 5.2a. In case LC-2 (Figure 5.4b), both the junction vortex and the bottom vortex can be easily identified because more data are available.

In the shallow, submerged case LC-3 (Figure 5.4c), most values of the vorticity are positive in the main channel and this indicates that there is a clockwise secondary cell in the main channel. There is a negative vorticity field near the water surface in the main channel, which indicates that there is a counter-clockwise secondary cell. The positive vorticity fields with values of 40 and 60 exist at the MC-FP edge and the sloped wall of the main channel respectively. The negative vorticity field with a value of -10 exists near the water surface. The vorticity fields in case LC-3 indicate that the secondary currents are more complicated near the MC-FP junction than those in the no rod case LC-1 and this is caused by the submerged rods on the floodplain. In the deep, submerged case of LC-4 (Figure 5.4d), the secondary cells are similar to those in the shallow, rod case LC-3.

In the emergent-vegetated case LC-5 (Figure 5.4e), most of the values of the vorticity are negative in the main channel, except for a small region around $Y/B = 0.3$ near the main channel bed and the sloped middle bank, which indicates that there is a large counter-clockwise secondary cell in the main channel. This information also agrees well with the secondary current patterns shown in Figure 5.3e. The results of the longitudinal vorticity in the five cases indicate that the measured secondary current patterns are roughly reasonable under these flow conditions.

5.3.3 Vorticity balance

In this section the vorticity balance is carried out to explore the contribution of each term in Equation 5.3 to the generation of secondary currents for the five cases. Thus, each term in the longitudinal vorticity equation was calculated and shown in Figures
5.5 ~ 5.9 for cases LC-1 ~ LC-5. The values of each term in the longitudinal vorticity equation are multiplied by 100 and divided by \( \left( \frac{U_m}{H} \right)^2 \).

Figures 5.5a ~ 5.5d show the magnitude distributions of terms A1, A2, A3 and A4 respectively in the longitudinal vorticity equation in case LC-1. Figure 5.5a shows that the values of term A1 are higher around \( Y/B = 0.2 \) near the bed of the main channel, where the secondary currents are stronger, than in other areas of the channel. This is because term A1 is directly related to the secondary velocities and vorticity gradients and the magnitude is high where the secondary currents are strong and vorticity gradients are steep. The contributions of the anisotropy of turbulence A2, Reynolds shear stress A3 and viscous term A4 to the generation of secondary currents can be evaluated using their respective normalised values. The magnitudes of Term A2 are much larger near the bottom and sidewall of the main channel than in other areas and are about 40% of \( \left( \frac{U_m}{H} \right)^2 \). The magnitudes of term A2 in the centre are very small and are less than 10% of \( \left( \frac{U_m}{H} \right)^2 \). The magnitudes of term A3 are also larger near the centre bottom and sidewall of the main channel, but less than 10% of \( \left( \frac{U_m}{H} \right)^2 \). The magnitudes of term A4 are much smaller as compared with terms A2 and A3 and are less than 0.1% of \( \left( \frac{U_m}{H} \right)^2 \). The above data indicate that the anisotropy of turbulence is the dominant driving force of secondary motion. The Reynolds shear stress term is less important than the anisotropy of turbulence and the viscous term is negligible.

From Figures 5.6a ~ 5.6d, the magnitudes of terms A1, A2 and A3 are slightly larger in case LC-2 than those in case LC-1, especially near the bed and the sloped wall of the main channel, because the relative water depth in case LC-2, which, at 0.50, is larger than that in case LC-1. In other areas, the magnitudes of each term in cases LC-1 and LC-2 are almost the same because the difference of relative water depth between the two cases is not large.

In the submerged rod case LC-3 (Figures 5.7a ~ 5.7d), the magnitudes of term A1 are larger near the sloped wall of the main channel than in other areas, which indicates that the advection of secondary currents is stronger in this region. The magnitudes of term A2 are larger near the MC-FP junction and around \( Y/B = 0.16 \) near the main
channel bed. The magnitudes of term A3 are slightly smaller than those of term A2 near the MC-FP junction in the main channel side, while, in case LC-1, the magnitudes of terms A3 are much smaller than those of term A2 near the MC-FP junction. The above information indicates that stronger secondary currents are generated near the MC-FP junction, and that the shear stress term is more important for the generation of secondary currents in case LC-3 than in case LC-1.

In the deep, submerged-rod case LC-4 (Figures 5.8a - 5.8d), the overall trend of the magnitude distributions of the four terms are similar to those in the shallow, submerged-rod case LC-3 case and this indicates that the secondary currents are generated in a similar manner in cases LC-3 and LC-4. However, the magnitudes of term A2 in case LC-4 are larger than those in case LC-3 near the MC-FP junction in the main channel side, which indicates that in case LC-4 stronger secondary currents are generated in this region than for case LC-3 because the water depth is larger in case LC-4.

In case LC-5 (Figures 5.9a - 5.9d), the magnitudes of term A2 are larger than other terms in the channel and this indicates that the anisotropy of turbulence is also the dominant mechanism for generating secondary currents in the compound channel with emergent rods on the floodplain.

Based on the above results, the anisotropy of turbulence (term A2) is the dominant origin of secondary currents in the compound channel and the shear stress (term A3) is more important in the compound channel with submerged vegetation on the floodplain than in the non-vegetated compound channel. It was also seen that the secondary current pattern is directly related to the magnitude distributions of \( (v'^2 - w'^2) \). Nezu and Onitsuka (2002) investigated the secondary currents in partly-vegetated rectangular channels and suggested that the anisotropy of turbulence \( (v'^2 - w'^2) \) increases with the Froude number, but the contributions of different terms to the generation of secondary currents were not analysed. In cases LC-3 ~ LC-5, the Froude numbers are 0.38, 0.33 and 0.39 respectively. As described in Section 5.2, the magnitudes of \( (v'^2 - w'^2) \) differ greatly in these five cases. It seems that this suggestion is not totally applicable to vegetated compound channel flows due to the more complicate mechanisms in compound channels with roughened floodplains.
5.4 Turbulent Intensities and kinetic energy

5.4.1 Case study on turbulent intensities

Turbulent intensities $u'$, defined as the r.m.s. values of velocity fluctuations, are very important for the analysis of flow structures. Higher turbulent intensities mean that stronger shear forces exist. Data for case LC-1 are only used to analyse the vertical and lateral distributions of turbulent intensities.

Figures 5.10a and 5.10b show the vertical distributions of turbulent intensities at $y = 0.31 \ m$ and $y = 0.73 \ m$ respectively. As the turbulence is dissipated away from the channel bed, the turbulent intensities decay gradually. Stronger shear produces higher turbulent intensities near the boundaries. It can be seen that the turbulent intensities show an exponential decay with the vertical distance from the channel bed and the best-fitting expressions of turbulent intensities at $y = 0.31 \ m$ and $y = 0.73 \ m$ are shown in Equations 5.4a ~ 5.4f. The estimated semi-empirical coefficients differ from those of Nezu and Nakagawa (1993) because the compound-flow conditions in this study are different from the wide-flow conditions of Nezu and Nakagawa (1993).

\[
\begin{align*}
    u'/U_* &= 2.73 \exp(-1.29 \xi), \ R^2 = 0.98, \ y = 0.31 m \\
    v'/U_* &= 2.43 \exp(-1.25 \xi), \ R^2 = 0.98, \ y = 0.31 m \\
    w'/U_* &= 1.17 \exp(-0.80 \xi), \ R^2 = 0.82, \ y = 0.31 m \\
    u'/U_* &= 1.30 \exp(-0.87 \xi), \ R^2 = 0.99, \ y = 0.73 m \\
    v'/U_* &= 1.23 \exp(-1.09 \xi), \ R^2 = 0.96, \ y = 0.73 m \\
    w'/U_* &= 0.43 \exp(-0.04 \xi), \ R^2 = 0.44, \ y = 0.73 m
\end{align*}
\]  

(5.4a) (5.4b) (5.4c) (5.4d) (5.4e) (5.4f)

where $u'$, $v'$ and $w'$ are the longitudinal, lateral and vertical turbulent intensities respectively, $U_*$ is the shear velocity, $\xi = Z / H$, $Z$ and $H$ are the vertical distance and water depth above the channel bottom.
Figures 5.11a - 5.11c show the lateral distributions of turbulent intensities ($u'$, $v'$ and $w'$) at different vertical positions in case LC-1. In Figure 5.11, "—, ▲, Δ, ■ and □" represent "Z = 0.193m, Z = 0.16m, Z = 0.1m, Z = 0.043m and Z = 0.01m" respectively. The turbulent intensities increase from around $y = 0.07 \, m$, and attain the first local peak at around $y = 0.17 \, m$, then they decrease to the local lowest value at around $y = 0.34 \, m$, then they increase to the local peak value around the MC-FP junction and decrease from the junction edge towards the right channel wall. The position of the lowest turbulent intensities coincides well with the position of the maximum velocity, which is similar to others in the literature. The two peak positions of turbulent intensities, one near the main channel bed and the other near the MC-FP junction, coincide well with the strong vortices in the compound channel as shown in Figure 5.2a. In each local peak region, the strong momentum exchange causes remarkable turbulent velocity fluctuations and consequently the turbulent intensities reach the local highest value.

Figures 5.11a - 5.11c also show that $u' > v' > w'$ for almost all the points, but that the ratios $v'/u'$ and $w'/u'$ vary with position. For turbulent intensities at $y=0.31m$ in the main channel, the average values of $v'/u'$ and $w'/u'$ are 0.93 and 0.52 respectively. For turbulent intensities at $y=0.73m$ on the floodplain, the average values of $v'/u'$ and $w'/u'$ are 0.90 and 0.42 respectively. The ratio $v'/u'$ is larger than 0.55, but the ratio $w'/u'$ is smaller than the value of 0.71 suggested by Nezu and Nakagawa (1993). This is because the investigated channel is relatively narrow under the experimental conditions.

5.4.2 Distributions of turbulent intensities

Figures 5.12 ~ 5.14 provide an overview of the turbulent intensities $u'$, $v'$ and $w'$ in the five cases, normalised by the average shear velocity $U_*$ ($=\sqrt{gRS_0}$).

Figures 5.12a ~ 5.12e show the longitudinal, turbulent-intensity profiles in cases LC-1 ~ LC-5 respectively. In the without-vegetation cases LC-1 and LC-2 (Figures 5.12a and 5.12b), it is noticeable that the highest value of 2.20 occurs around $Y/B=0.2 ~ 0.25$ near to the bed of the main channel due to the strong bed-generated
turbulence. Other high values occur close to the sloped wall of the main channel and near to the MC-FP junction. These results are different from those in compound channels with uniform roughness and this can be explained by the shear strength generated under different conditions. For the investigated channel, the bed of the main channel was made with a rough vegetation lining and the floodplain was made with a smooth wood plate and this channel configuration leads to a small velocity difference between the main channel and the floodplain and consequently to weaker shear near the MC-FP junction. Stronger shear occurs around \( Y/B = 0.2 \sim 0.25 \) near the main channel bed rather than near to the MC-FP junction and, consequently, larger velocity fluctuation exists in this region. The values of turbulent intensity \( u' \) are even smaller near the MC-FP junction in case LC-2 than those in case LC-1.

In the shallow, submerged case LC-3 (Figure 5.12c), the highest value of 4.50 occurs near the MC-FP junction. Other high values occur close to the sloped wall and the bed of the main channel. This is because the submerged rods exert huge flow resistance to the floodplain flow and this leads to a significant velocity difference between the main channel and the floodplain and consequently strong shear near the MC-FP junction. In the deep submerged case LC-4 (Figure 5.12d), the distributions of the longitudinal turbulent intensity are similar to those in case LC-3, but the magnitudes are smaller than those in case LC-3.

In the emergent case LC-5 (Figure 5.12e), the highest value of 4.00 occurs near the MC-FP junction. Other high values also occur close to the bed of the main channel.

Figures 5.13a ~ 5.13e show the lateral turbulent intensity profiles in cases LC-1 ~ LC-5 respectively. The patterns of turbulent intensity \( v' \) are similar to those of turbulent intensity \( u' \) as shown in Figures 5.12a ~ 5.12e, but the highest values of \( v' \) are lower than those of \( u' \). In the without-vegetation cases LC-1 and LC-2, the peak value of \( v^2 \) occurs around \( Y/B = 0.2 \) near the bed of the main channel and the highest values are 2.00 and 1.80 respectively. In the vegetation cases of LC-3 ~ LC-5, the peak value of \( v^2 \) occurs near the MC-FP junction and the highest values are 3.20, 2.80 and 2.25 respectively.
Figures 5.14a ~ 5.14e show the vertical turbulent-intensity profiles in cases LC-1 ~ LC-5 respectively. In cases LC-1 and LC-2, the peak value of the vertical turbulent intensity \( w' \) occurs around \( Y/B = 0.2 \) in the main channel, which corresponds to the strong bottom-vortex in this region. The highest value of \( w' \) is 0.90 in case LC-1 and 0.80 in case LC-2. In the submerged-rod cases LC-3 and LC-4, the turbulent intensity \( w' \) also decreases from the MC-FP junction to other areas. The highest values of \( w' \) in cases LC-3 and LC-4 are 2.20 and 1.60 respectively. In the emergent-rod case LC-5, the highest value of \( w' \) is 0.90 near the MC-FP edge.

From Figures 5.12 ~ 5.14, turbulent intensities \( u', v' \) and \( w' \) behave in a similar manner. It can be seen that the bed roughness has an important effect on the distributions of turbulent intensities in the compound channel and the rough grass mattress leads to peak turbulent intensities occurring near the main channel bed rather than near the MC-FP junction. The submerged rods on the floodplain cause significant velocity difference between the main channel and the floodplain. Strong shear, and consequently strong momentum exchange, occurs near the MC-FP junction where the turbulent intensities peak. In the submerged-rod cases, the peak turbulent intensities are about 1.5 ~ 2.0 times those in the non-vegetated cases. In the emergent-rod case, the rough main channel bed and the emergent rods lead to strong shear near the main channel bed and the MC-FP junction, also strong momentum exchange causes the turbulent intensities to peak in these regions.

The characteristics of the turbulence intensity are reflected in the distinctive differences between the velocity fluctuations in the five cases. Figures 5.15, 5.16 and 5.17 show typical velocity data set in the main channel and at the floodplain edge for \( U, V \) and \( W \) respectively. For cases LC-1 ~ LC-4, the sampling point in the main channel was located at \( Y = 0.25 \) m and \( Z = 0.19 \) m and the sampling point at the floodplain edge was located at \( Y = 0.55 \) m and \( Z = 0.19 \) m. For case LC-5, the vertical position of the sampling point was \( Z = 0.18 \) m.

From Figures 5.15 ~ 5.17, three characteristics of the velocity fluctuations can be recognised. Firstly, owing to the stronger momentum exchange at the floodplain edge, the velocity fluctuation, especially the lateral velocity \( V \), is larger than in the main channel and this corresponds well to the larger turbulent intensities at the floodplain...
edge. Secondly, the submerged rods cause larger velocity fluctuations in cases LC-3 and LC-4 than that in the non-vegetated LC-1 and LC-2 cases, especially at the floodplain edge. Thirdly, the emergent rods cause larger velocity fluctuations at the floodplain edge in case LC-5, especially for the streamwise velocity $U$.

5.4.3 Distributions of turbulent kinetic energy

Figure 5.18 shows the turbulent kinetic energy distributions normalised by $U^2$ for the five cases. As turbulent intensity $u'$ makes the dominant contribution to turbulent kinetic energy $k$, the distributions of turbulent kinetic energy $k$ are similar to those of turbulent intensity $u'$.

In case LC-1 (Figure 5.18a), the turbulent kinetic energy ranges from 5.00 $U^2$ near the centre bottom to 0.95 $U^2$ near the free water surface. In case LC-2 (Figure 5.18b), the turbulent kinetic energy ranges from 4.50 $U^2$ near the centre bottom to 0.5 $U^2$ near the free surface on the floodplain.

In the vegetation cases LC-3 ~ LC-5 (Figures 5.18c ~ 5.18e), the turbulent kinetic energy mainly decreases from the MC-FP junction to the main channel and also decreases from the bed and the right corner of the main channel to outside the junction area. This indicates that both the bed-generated turbulence and shear-generated turbulence are important to the energy production under these flow conditions. The maximum values of turbulent kinetic energy are 12.80 $U^2$, 9.00 $U^2$ and 5.80 $U^2$ near the MC-FP junction in cases LC-3, LC-4 and LC-5 respectively. The minimum values of turbulent kinetic energy are 2.00 $U^2$, 1.00 $U^2$ and 1.00 $U^2$ in the main channel for cases LC-3, LC-4 and LC-5 respectively. Nezu and Onitsuka (2001) undertook turbulent measurements in a rectangular channel with submerged vegetation in the channel corner. The water depths in the channel and above the top of the vegetation were 7 cm and 2 cm respectively and the nominal, relative water-depth was 0.29 (= 2/7). They reported that the maximum values of turbulent kinetic energy under Froude numbers 0.10, 0.24 and 0.40 were 22, 24 and 26 times $U^2$ respectively. In their study, the minimum values of $k/U^2$ were around 1.0 ~ 2.0. In this study, the relative water depths were larger than that of Nezu and Onitsuka (2001), so the
maximum values of $k/U^2$ for submerged cases LC-3 and LC-4 were smaller than those of Nezu and Onitsuka (2001).

5.5 Reynolds Shear Stresses

Reynolds shear stresses $\tau_{xy} (\equiv -\rho \overline{vw})$, $\tau_{yx} (\equiv -\rho \overline{uw})$ and $\tau_{zz} (\equiv -\rho \overline{uw})$ represent the vertical transfer of lateral momentum and the lateral and vertical transfers of longitudinal momentum respectively. Reynolds shear stress $\tau_{yz}$ is directly related to the lateral gradient of the longitudinal velocity ($\partial U/\partial y$), also $\tau_{zz}$ is directly related to the vertical gradient of the longitudinal velocity ($\partial U/\partial z$) whilst $\tau_{yz}$ is directly related to the vertical gradient of lateral velocity ($\partial V/\partial z$). Figures 5.19 - 5.21 give an overview of the Reynolds shear stresses normalised by $\rho U^2$.

5.5.1 Lateral transfer of longitudinal momentum

Figures 5.19a - 5.19e show the distributions of the normalised Reynolds shear stress $\tau_{yz}/\rho U^2$ in cases LC-1 ~ LC-5 respectively. In case LC-1 (See Figure 5.1a), most velocity gradients, $\partial U/\partial y$, are negative in the zones $0.07 < y < 0.19 \, m$ and $y > 0.31 \, m$ and positive in the zone $0.19 < y < 0.31 \, m$. The zones of the negative and positive $\tau_{yz}/\rho U^2$ correspond to the zones of the negative and positive velocity gradients $\partial U/\partial y$ respectively. The absolute values of $\tau_{yz}/\rho U^2$ around $Y/B = 0.2$ near the bed of the main channel are larger than those near the MC-FP junction. In case LC-2 (Figure 5.19b), the normalised Reynolds shear stresses $\tau_{yz}/\rho U^2$ vary in a similar manner to those in case LC-1 because the relative water depths of both cases are not much different.

In the shallow, submerged case LC-3 (Figure 5.19c), the absolute values of $\tau_{yz}/\rho U^2$ are very high near the MC-FP junction because strong shear flow and wakes are generated by the submerged rods in this region. The normalised Reynolds shear stress decreases from the MC-FP junction to the main channel and floodplain. In the deep submerged case LC-4 (Figure 5.19d), the distributions of $\tau_{yz}/\rho U^2$ are similar to those in case LC-3, however, the magnitudes are smaller than those in case LC-3. This
indicates that the strength of the lateral shear decreases as the relative water depth increases. The absolute values of $\tau_{yx}/\rho U^2$ near the bed of the main channel are much smaller as compared with the MC-FP junction because the difference in velocity gradients is smaller than that near the MC-FP junction.

In the shallow, emergent case LC-5 (Figure 5.19e), the normalised Reynolds shear stresses are larger near the MC-FP junction than near the bed of the main channel due to the stronger shear near the MC-FP junction. However, the magnitudes are smaller than those in the submerged cases of LC-3 and LC-4 and this indicates that the shear strength is weaker in case LC-5 than in cases LC-3 and LC-4.

In the non-vegetated cases LC-1 and LC-2 (Figures 5.19a and 5.19b), the magnitude of the Reynolds shear stress $\tau_{yx}$ decreases away from $Y/B = 0.20$ towards other areas and the peak value increases as the relative water depth decreases. In the submerged-rod cases LC-3 and LC-4 (Figures 5.19c and 5.19d) and the emergent-rod case (Figure 5.19e), the magnitude of $\tau_{yx}$ decreases away from the MC-FP junction towards other areas and the peak value increases as the relative water depth decreases.

**5.5.2 Vertical transfer of longitudinal momentum**

Figures 5.20a - 5.20e show the distributions of normalised Reynolds shear stress $\tau_{yx}/\rho U^2$ in cases LC-1 - LC-5 respectively. In case LC-1 (Figure 5.20a), almost all the values of $\tau_{yx}/\rho U^2$ at $z < 0.043$ m are positive because almost all the values of $\partial U/\partial z$ are positive. Large values of $\tau_{yx}/\rho U^2$ occur near the main channel bed and the MC-FP junction due to the strong shear from bed-generated turbulence and shear-generated turbulence respectively. Close to the bed of the main channel, the values of $\tau_{yx}/\rho U^2$ are about 0.8 which indicates that the magnitude of the Reynolds shear stress $\tau_{yx}$ approaches that of the bed shear stress on the channel bed. The zero shear stress zone seems to exist where $0.8 < z/H < 1.0$ where $\partial U/\partial Z = 0$. In case LC-2, zero shear stress appears at about $z/H = 0.8$ throughout the main channel. The magnitudes of $\tau_{yx}/\rho U^2$ are slightly smaller than those in case LC-1. It can also be seen that the maximum values for Reynolds shear stress $\tau_{yx}$ near the MC-FP junction
are only $0.24 \rho U^2$ because the velocity isovels are almost parallel and the values of $\partial U/\partial Z$ are then small.

In the shallow submerged vegetation case LC-3 (Figure 5.20c), the highest magnitude of $\tau_{xz} / \rho U^2$ occurs near the MC-FP junction, other large magnitudes of $\tau_{xz} / \rho U^2$ occur close to the bed of the main channel and zero magnitude of $\tau_{xz} / \rho U^2$ occurs near the water surface. Negative $\tau_{xz}$ was also observed near the sloping wall of the main channel and this might be caused by the wakes. The wakes move high-velocity fluid down to the sloped wall and this could cause higher $U$ velocity at a lower vertical position near the sloped wall. These distributions of $\tau_{xz}$ also show the good relationship between $\tau_{xz}$ and $\partial U/\partial Z$. In the deep, submerged case LC-4 (Figure 5.20d), the distribution of $\tau_{xz}$ is similar to that in case LC-3, but the shear stress at the mid-depth of the MC-FP edge is higher than that in case LC-3 and this could be caused by the different three-dimensional wake structures under various water depth conditions.

In the emergent case LC-5 (Figure 5.20e), the Reynolds shear stresses $\tau_{xz}$ are large near the main channel bed and the right bisector of the main channel. Positions of zero shear stress are mainly located in the upper parts around $Y/B = 0.15$ and $Z/H = 0.70$ where the maximum $U$ velocity exists.

In the non-vegetated cases LC-1 and LC-2 (Figures 5.20a and 5.20b), the Reynolds shear stresses $\tau_{xz}$ decrease from around $Y/B = 0.20 \sim 0.25$ near the main channel bed towards the water surface. In the submerged-rod cases LC-3 and LC-4 (Figures 5.20c and 5.20d), the submerged rods have different effects on the distribution of $\tau_{xz}$ at various water depths. In the shallow case LC-3, $\tau_{xz}$ decreases from the main channel bed towards the water surface, it also decreases from peak positive value near the main channel bed to a negative value near the MC-FP junction. In the deep case LC-4, $\tau_{xz}$ decreases from the MC-FP junction towards the main channel and the floodplain. In the shallow, emergent-rod case LC-5 (Figure 5.20e), the distribution of
\( \tau_{yx} \) is not influenced by the emergent rods and behaves in a similar manner to that in the non-vegetated cases LC-1 and LC-2, but the \( \tau_{zx} \) isovels are smoother.

### 5.5.3 Vertical transfer of lateral momentum

Figures 5.21a - 5.21e show the distributions of normalised Reynolds shear stress \( \tau_{yx}/\rho U_*^2 \) in cases LC-1 - LC-5. In the non-vegetated cases LC-1 and LC-2 (Figures 5.21a and 5.21b), the magnitudes of \( \tau_{yx}/\rho U_*^2 \) are very small; the highest value is 0.19 near the sloping wall of the main channel. The values of \( \tau_{yx} \) are much smaller as compared with \( \tau_{yx} \) and \( \tau_{zx} \) which indicates that the vertical transfers of lateral momentum are much weaker than the other two kinds of momentum transfer.

In the submerged rod cases LC-3 and LC-4 (Figures 5.21c and 5.21d), large values of \( \tau_{yx}/\rho U_*^2 \) occur near the sloping bank of the main channel and the MC-FP junction due to the strong shear generated by the wakes in these regions. Their magnitudes are of the order of \( \tau_{zx}/\rho U_*^2 \) and this indicates that the wakes are totally three-dimensional.

In the emergent rod case LC-5 (Figure 5.21e), the highest magnitude of \( \tau_{yx}/\rho U_*^2 \) is about 0.4 near the MC-FP junction. The vertical transfer of lateral momentum is weaker in case LC-5 as compared with the submerged cases LC-3 and LC-4.

### 5.6 Depth-averaged parameters

#### 5.6.1 Depth-averaged velocity

Figure 5.22 shows the depth-averaged longitudinal velocity distributions of cases LC-1 - LC-5. The depth-averaged velocity \( U_d \) was determined using Equation 5.5,

\[
U_d = \frac{\int U dz}{H} \tag{5.5}
\]

Where \( U \) is the local longitudinal velocity, \( H \) is the local water depth and \( z \) is the vertical distance above the channel bed.
In cases LC-1 and LC-2, there are distinct dips around \( Y/B = 0.2 \) in the depth-averaged velocity distributions due to the strong bottom vortex previously described in section 5.1.1. It can also be seen that the velocity curve becomes slightly smoother as relative water depth increases. This is because the effect of bed friction becomes weaker as the water depth increases and then the velocity difference between the main channel and the floodplain decreases as relative water depth increases. Figure 5.23 further shows the Manning coefficient for the grass mattress decreases as the water depth increases.

In cases LC-3 and LC-4, the velocity curves are steeper near the MC-FP junction as compared to those of cases LC-1 and LC-2 and this is because the velocity on the floodplain is significantly reduced by the submerged rods, as explained in Section 5.1.2. There are tiny dips around \( Y/B = 0.16 \) and the positions of the velocity dips shift slightly towards the left wall. The depth-averaged velocities peak above the submerged rods on the floodplain for which there are two possible explanations. Firstly, there are decreases in the water depth above the rods, which cause local velocity peaks. This can be seen from Figures 5.24a and 5.24b which show the longitudinal and lateral water level profiles around one rod on the floodplain. Secondly, the measurements were carried out between two longitudinal rods and one lateral rod. The rods make the mean velocities very low below the rod top surfaces and these low velocities contribute to the lower depth-averaged velocities.

In case LC-5, the emergent rods also increase the flow resistance on the floodplain and, as a result, increase the velocity difference between the main channel and the floodplain. As the channel in LC-5 is wider than in the other four cases, there is no velocity dip in the main channel and this could be because the corner effect is weak under this shallow-water condition.

### 5.6.2 Depth-averaged eddy viscosities

The depth-averaged Reynolds shear stress, \( \overline{\tau_{yx}} \), was calculated from the data presented in Figure 5.19 using Equation 5.6a,

\[
\overline{\tau_{yx}} = \frac{1}{H} \int_0^H \tau_{yx} \, dz
\]

(5.6a)
The depth-averaged eddy viscosity, $\bar{\varepsilon}_i$, was calculated from Equation 5.6b,

$$\bar{\varepsilon}_i = \frac{\tau_{yx}}{\rho \partial U_d / \partial y}$$  \hspace{1cm} (5.6b)

The dimensionless depth-averaged eddy viscosity ($\bar{\lambda}_i$) and the dimensionless eddy viscosity due to the transverse shear were calculated from Equations 5.6c and 5.6d respectively,

$$\bar{\lambda}_i = \frac{\bar{\varepsilon}_i}{U_s H}$$  \hspace{1cm} (5.6c)

$$\bar{\lambda}_u = \frac{H \left( \beta \delta \right)^2 \left| \frac{\partial U_d}{\partial y} \right|}{U_s H}$$  \hspace{1cm} (5.6d)

where $U_s$ is the shear velocity ($= \sqrt{gR S_0}$), other parameters are same to those in Section 4.4.1.

The local eddy viscosity, $\varepsilon_{zz}$, was calculated using Equation 5.7a,

$$\varepsilon_{zz} = \frac{\tau_{zz}}{\partial U / \partial z}$$  \hspace{1cm} (5.7a)

The depth-averaged eddy viscosity, $\bar{\varepsilon}_{zz}$, was calculated using Equation 5.7b,

$$\bar{\varepsilon}_{zz} = \frac{1}{H} \int_0^H \varepsilon_{zz} \, dz$$  \hspace{1cm} (5.7b)

Figure 5.25 shows the distributions of depth-averaged Reynolds shear stress $\bar{\tau}_{yx}$ in all the five cases. In the non-vegetated cases LC-1 and LC-2, $\bar{\tau}_{yx}$ local peaks around $y = 0.16 \, m$, $y = 0.22 \, m$ and $y = 0.42 \, m$ correspond to the large velocity gradients in the lateral direction. The Reynolds shear stresses are relatively low near the MC-FP junction as compared to those in the literature (i.e. Shiono & Knight 1991).
In the submerged-rod cases LC-3 and LC-4, $\tau_{yx}$ peaks near the MC-FP junction. The highest magnitudes of $\tau_{yx}$ are about -6.5 in case LC-3 and -5.0 in case LC-4. The submerged rods greatly change the patterns of $\tau_{yx}$ as compared with the non-vegetated cases and these results from the stronger shear near the MC-FP junction generated by the rod effects. Although there are tiny peaks in the main channel, considerably high Reynolds shear stresses occur near the MC-FP junction in cases LC-3 and LC-4. As the water depth increases, the depth-averaged Reynolds shear stress decreases slightly. Under similar relative water-depth conditions, the peak magnitude of $\tau_{yx}$ in the submerged-rod case is about 6 times that in the non-vegetated case and this indicates that the submerged rods on the floodplain generate a stronger shear layer near the MC-FP junction.

In the shallow, emergent case LC-5, the depth-averaged Reynolds shear stresses $\tau_{yx}$ are relatively small in the main channel and peak near the MC-FP junction. These patterns are similar to those in non-vegetated, shallow, compound channels because the emergent rods don't change the flow patterns much under this relative water depth.

Figure 5.26 shows the dimensionless depth-averaged eddy viscosity profiles of $\lambda_\tau$ and $\lambda_\upsilon$ under different flow conditions. In Figure 5.26, $\lambda_\tau$ was determined with Equation 5.6c using the measured data of $\tau_{yx}$ and $U$, and $\lambda_\upsilon$ was calculated with Equation 5.6d using the measured data of $U$. It can be seen from Figures 5.26 that the dimensionless depth-averaged eddy viscosities $\lambda_\tau$ and $\lambda_\upsilon$ increased from the right main channel bisector to the edge of the MC-FP junction due to the increased shear strength. In most cases, the magnitudes of $\lambda_\tau$ and $\lambda_\upsilon$ are similar near the MC-FP junction and this indicates that large eddies play a dominant role in the lateral shear near the near the MC-FP junction. The depth-averaged eddy viscosity $\bar{\varepsilon}_{xz}$, and the depth-averaged eddy viscosity $\bar{\varepsilon}_r$, are of the same order, which indicates that the vertical exchange of the longitudinal momentum is also important and this might be due to the three-dimensional wakes in the submerged rod cases.
5.6.3 Depth-averaged secondary current

The depth-averaged, secondary current term, $-\rho(UV)_d$, was calculated from Equation 5.8,

$$-\rho(UV)_d = -\frac{\rho}{H} \int_0^H UV dz \quad (5.8)$$

Figure 5.27 shows the distributions of the depth-averaged secondary current term $-\rho(UV)_d$ in different cases. The positions of the bump in cases LC-1 ~ LC-5 are $Y/B = 0.35, 0.30, 0.52, 0.52$ and $0.28$ respectively. In the submerged cases of LC-3 and LC-4, it is noticeable that the signs of the term $-\rho(UV)_d$ change where the submerged rod exists on the floodplain and this could be caused by the wakes in this region.

5.7 Energy spectrum

5.7.1 Introduction

According to Hinze (1975), turbulence is composed of various sized eddies, which can be expressed by an energy spectrum. A distribution of energy between frequencies is usually called an energy spectrum. The energy spectrum can give valuable information on the contribution of eddies to the turbulent kinetic energy. The turbulent intensity $u^t$ can be obtained by integrating the energy spectrum through the entire frequency ($f$) domain,

$$u^t = \left( \int E_i(f) df \right)^{\frac{1}{2}} \quad (5.9)$$

where $E_i(f)$ is the energy density at frequency $f$.

The energy spectrum $E_i(f)$ can be obtained by two methods. The first method is by applying the Fast Fourier Transform (FFT) to the temporal series of instantaneous velocities. The second method is by applying the Fast Fourier Transform (FFT) to the velocity correlation function.
An auto-correlation function $R_i(t)$ at a fixed point is the velocity correlation function normalised by $u_i^2$:

$$R_i(t) = \frac{u_i(t)u_i(t+\tau)}{u_i^2}$$

(5.10)

where $u_i^2$ is the average turbulent kinetic energy of $i$ component, $t$ is the time and $\tau$ is the time lag.

Taylor (1938) first pointed out that the velocity correlation function $Q_i(\tau)$ and energy spectrum function $E_i(f)$ can be expressed by Fourier cosine transforms of each other as in Equations 5.11a - 5.11b.

$$Q_i(\tau) = \int f E_i(f) \cos(2\pi f \tau) df$$

(5.11a)

$$E_i(f) = 4 \int Q_i(\tau) \cos(2\pi f \tau) d\tau$$

(5.11b)

This second method is used to obtain the energy spectrum in this study.

In general, the energy spectrum can be divided into three distinct sub-ranges. The first sub-range is the energy production range, in which the turbulent kinetic energy is produced by large, energy-containing eddies. The second sub-range is the inertial sub-range, in which the turbulent kinetic energy production rate is in equilibrium with its dissipation rate. In this sub-range, the energy spectral behaviour follows the Kolmogoroff law ($-5/3$ law). The third sub-range is the viscous sub-range, in which the turbulent kinetic energy is finally dissipated into heat.

5.7.2 Velocity correlation

Velocity correlation can give some valuable information on eddy scales. Based on its definition, the velocity correlation function is one when the time lag ($\tau$) is zero. If the velocity correlation function curve decreases rapidly from one to zero, the velocity has good correlation only within the smaller time lag range, which indicates that the turbulence is mainly composed of small eddies. On the other hand, if the velocity
correlation function curve drops slowly from one to zero, the turbulence is mainly composed of large eddies. Moreover, if the velocity correlation function curve oscillates about the axis of time lag $\tau$, there exists some periodicity in the flow pattern. This concept can be applied to roughly evaluate the relative sizes of the eddies in the turbulence.

Velocity data at the vertical position of $Z = 0.19 \, m$, which is 0.04 $m$ above the floodplain, are used to analyse the velocity correlation and the energy spectrum in cases LC-1 ~ LC-5. This is based on the following two considerations. Firstly, to ensure the ADV transducers are submerged during the measurements, the safe minimum water depth should be larger than 5 cm, which is required for ADV, because the water surface fluctuated by around 1 cm during the experiments. Secondly, the main works were on the deep-water depth cases, in which the minimum water depth on the floodplain was 0.055 $m$. For the shallow, emergent-rod case LC-5, velocity data at $Z = 0.18 \, m$ was used and the data were obtained using a small tank on the water surface. The lateral positions of the measurement points range from $Y = 0.25 \, m$ to $Y = 0.58 \, m$ and the interval between two points is 0.03 $m$. Figures 5.28 ~ 5.32 show the velocity correlation curves in the cases LC-1 ~ LC-5.

Figures 5.28a ~ 5.28c show the respective longitudinal, lateral and vertical velocity auto-correlation curves in case LC-1. In the longitudinal velocity correlation $R_{u,u}$ curves (Figure 5.28a), the curve of $Y = 0.25 \, m$ drops fastest, whereas the curve of $Y = 0.55 \, m$ drops slowest and oscillates about the axis of time lag. The information in Figure 5.28a indicates that there are large eddies at $Y = 0.55 \, m$ at the MC-FP junction, and there are small eddies at $Y = 0.25 \, m$, where the velocity is the maximum locally in the main channel. In the lateral velocity correlation $R_{v,v}$ curve (Figure 5.28b), the curves of different lateral positions are almost the same and so there are no obvious horizontal, large eddies at this vertical plane. In the vertical correlation $R_{w,w}$ curve (Figure 5.28c), the curve of $Y = 0.25 \, m$ drops rapidly from one to zero when compared with the other curves. The information about the vertical velocity correlation function might indicate that the vertical eddy sizes might be slightly larger near the MC-FP junction than those near the centre of the main channel.
Figure 5.29 shows the velocity correlation curves in case LC-2. The longitudinal velocity correlation curves (Figure 5.29a) also drop slower as the lateral position moves from the centre of the main channel to the MC-FP junction. The lateral and vertical velocity correlation curves (Figures 5.29b - 5.29c) are also similar to those in case LC-1.

Figure 5.30 shows the velocity correlation curves in case LC-3. In the longitudinal velocity correlation curves (Figure 5.30a), the curve of $Y = 0.49 \, m$ oscillates with a period of 3 seconds. The information from $R_{u,u}$ indicates that the strongest shear might exist at $Y = 0.49 \, m$ in the case of vertical level $Z = 0.19 \, m$. In the lateral velocity correlation curves (Figure 5.30b), the curve of $Y = 0.49 \, m$ decreases slower than the other curves and the oscillation is similar to that in $R_{u,u}$ curve. The vertical velocity correlation curves are similar at different lateral positions (Figure 5.30c). Compared with the LC-1 case, the periodicity of large eddies is more obvious in case LC-3 under similar relative water depths. The above information indicates that there are some horizontal large eddies in this case and that the eddy sizes decrease from the MC-FP junction to the centre of the main channel.

Figure 5.31 shows the velocity correlation curves in case LC-4. In the $R_{u,u}$ curves (Figure 5.31a), the curve of $Y = 0.49 \, m$ also drops slowest and there is a modulation around $\tau = 1.3s$. In the $R_{v,v}$ curves (Figure 5.31b), the curves of different lateral positions are similar and the weak modulation exists around $\tau = 0.8s$. In the $R_{w,w}$ curves (Figure 5.31c), the curve of $Y = 0.49 \, m$ oscillates about the axis of time lag and there is a modulation around $\tau = 0.6s$. Compared with the LC-3 case, the oscillation is more pronounced in the vertical direction.

Figure 5.32 shows the velocity correlation curves in case LC-5. In the $R_{u,u}$ curves (Figure 5.32a), the curve of $Y = 0.55 \, m$ drops much slower than the other curves and oscillates greatly about the axis of time lag. In the $R_{v,v}$ curves (Figure 5.32b), oscillations can just be recognised at $Y = 0.55 \, m$. In the $R_{w,w}$ curves (Figure 5.32c), there are very weak oscillations at $Y = 0.55 \, m$. This information indicates that
horizontal large eddies exist in the LC-5 case and large eddy sizes are dominant at the MC-FP junction.

In conclusion, the velocity correlation function gives valuable information about the flow pattern in a different way and this information coincides with the hydraulic behaviours in various cases. Large oscillations occur at the MC-FP junction in the LC-5 case, relatively large oscillations occur at the MC-FP junction in cases LC-3 and LC-4 and few large oscillations occur at the MC-FP junction in cases LC-1 and LC-2.

5.7.3 Energy spectra

In this section, the energy spectrum was calculated by applying the Fast Fourier Transform (FFT) to the velocity correlation function \( Q_\tau (\tau) \). The FFT algorithms were performed with ExploreV software from Nortek. Figures 5.33 ~ 5.37 show the energy spectrum in cases LC-1 ~ LC-5 respectively.

Figures 5.33a ~ 5.33c show the respective energy spectra for the longitudinal, lateral and vertical velocities in case LC-1. In Figure 5.33a, each \( u \) energy spectrum log-log curve peaks between 0.1 and 1 Hz. The frequencies corresponding to each peak decrease with the lateral distance, which indicates that the eddy sizes become larger towards the MC-FP junction. At the peak frequency, the spectrum magnitude increases with the lateral distance from the left wall of the main channel and this indicates that the \( u \) velocity fluctuation becomes stronger and consequently the values for the turbulent intensity \( u' \) are larger towards the MC-FP junction. Information from the \( v \) spectrum (Figure 5.33b) and the \( w \) spectrum (Figure 5.33c) is similar to that from the \( u \) spectrum, but the peak magnitudes of the \( v \) spectrum are smaller than those of the \( u \) spectrum and the peak magnitudes of the \( w \) spectrum are also smaller than those of the \( v \) spectrum. This information from the energy spectra coincides with the turbulence analyses in the previous sections.

Figure 5.34 shows the energy spectra in the LC-2 case. The spectrum patterns are similar to those in case LC-1, in which the flow pattern is similar to that in LC-1 case. It should be noted that, although Tukey's weighting function was used to smooth the spectrum, the spectrum curves in the high frequency zones are still noisy and this
might be due to the data quality. In general, the noise increases as the sampling frequency increases while using ADV.

Figure 5.35 shows the energy spectra in case LC-3. In Figure 5.35a, the peak frequencies of each spectrum curve are within 0.1 ~ 1.0 Hz and the spectrum magnitude increases with the lateral distance. Compared with the LC-1 case (Figure 5.33a), the spectrum magnitude is larger and the magnitude difference between $Y = 0.25 \ m$ and $Y = 0.55 \ m$ becomes more noticeable. This is because the shear is stronger in case LC-3 than in LC-1. For the $v$ spectrum (Figure 5.35b) and the $w$ spectrum (Figure 5.35c), the spectrum magnitude also increases with the lateral distance and the magnitude difference between the centre of the main channel and the MC-FP junction is noticeable. The magnitude of the $w$ spectrum for $Y = 0.49 \ m$ is higher than the other four $w$ spectrum curves. This is possibly due to the three dimensional nature of the wakes near the MC-FP junction.

Figure 5.36 shows the energy spectra in case LC-4. The spectrum patterns are similar to those in case LC-3. However, the magnitudes of the $u$ spectrum and the $w$ spectrum in low frequency zones at $Y = 0.49 \ m$ are larger than those at $Y = 0.55 \ m$. This indicates that, in the compound channel with submerged rods on the floodplain, the shear centre shifts slightly towards the main channel as the water depth increases.

In case LC-5 (Figure 5.37), the peak frequencies of each spectrum curve are within 0.1 ~ 0.5 Hz and the spectrum magnitude also increases with the lateral distance. This indicates that the frequency range of the energy-containing ($w^2$) eddies is wider than those of the $u^2$ and $v^2$ energy-containing eddies, so the horizontal large eddies contribute more to the turbulent kinetic energy in this case.

5.8 Eddy contributions to momentum exchange

5.8.1 Cross energy spectra

To study the momentum exchange in the shear layer, the cross energy spectra were calculated using the fluctuation data of $u'$, $v'$ and $w'$. Figures 5.38 ~ 5.42 show the respective cross energy spectra and phase relationships in cases LC-1 ~ LC-5.
Figure 5.38a shows the $u'$, $v'$ spectra and the $u'v'$ cross spectra and Figure 5.38b shows the phase relation between $u'$ and $v'$ in the no rod case LC-1. In Figure 5.38a, both the $u'v'$ cross spectra and the $v'$ spectrum peak in the low frequency zone ($0.5 < f < 1$ Hz) and both peak frequencies are almost the same. The peak magnitudes of the $u'v'$ cross spectra and the $v'$ spectrum are also of the same order. While, the $u'$ spectrum peaks around $f = 0.15$ Hz and its peak magnitude is about 4 times those in the $u'v'$ cross spectra and the $v'$ spectrum. These spectra results indicate that the $u'v'$ cross spectra is more sensitive to $v'$. In Figure 5.38b, the phase relation between $u'$ and $v'$ gives approximately 0 in this low frequency zone, whereas it is random in the high frequency zone. This information indicates that the lateral shear is generated by the large horizontal eddies and the contribution to the Reynolds shear stress $\tau_{xy}$ is mainly related to the motion of low frequency eddies. From Figure 5.38d, the phase relation between $u'$ and $w'$ gives approximately $\pm \pi$ in the low frequency zone, which indicates that the vertical shear is generated by the bed-generated turbulence and the contribution to the Reynolds shear stress $\tau_{xz}$ is mainly related to the motion of low frequency eddies. From Figures 5.38a and 5.38c, the $u'v'$ spectra and $u'w'$ spectra are of the same order in the low frequency zone and this indicates that both lateral and vertical momentum-exchange are both important in this case.

In the deep, no rod case LC-2 (Figure 5.39), the phase relation between $u'$ and $v'$ is about 0 in the low frequency zone ($0.4 < f < 0.8$ Hz) and the relation between $u'$ and $w'$ is $\pm \pi$. The above phase relationships are same to those in case LC-1, which indicates that the production mechanism of the shear is the same to that in case LC-1. The peak frequency $f$ is lower and the peak magnitudes of the energy spectra and the cross spectra are also lower as compared with case LC-1, possibly indicating that the peak frequency is just one characteristic low frequency, but not the decisive parameter to describe and quantify the momentum exchange.

In the submerged rod case LC-3, Figure 5.40a shows a good correlation between the $u'v'$ spectra and $v'$ spectrum and Figure 5.40b shows the $\pm \pi$ phase relation between $u'$ and $v'$. This indicates that the lateral shear is generated by the wakes and the
contribution to the Reynolds shear stress $\tau_{xy}$ is mainly related to the low frequency motion of the wakes ($0.2 < f < 0.7$ Hz). Figure 5.40c shows that the fluctuation of the vertical velocity $w$ is very weak. The phase relation between $u'$ and $w'$ is around 0 in the low frequency zone, which indicates that the vertical shear is possibly generated by the wakes and the contribution to the Reynolds shear stress $\tau_{xy}$ is mainly related to the motion of the wakes. The peak magnitude of $u'v'$ is about 3 times of that of $u'w'$, but both of them are larger than those in cases LC-1 and LC-2. These results indicate that the momentum exchange is stronger in the lateral direction than in the vertical direction in case LC-3 whilst the momentum exchange is stronger in the lateral direction than in case LC-1, as well as in the vertical direction.

In the deep, submerged case LC-4 (Figure 5.41), the low frequency falls in the range of $0.2 < f < 0.75$ Hz. In the low frequency zone, the phase relation between $u'$ and $v'$, and that between $u'$ and $w'$ are similar to those in case LC-3, which indicates that the shear around the rods is also generated by the wakes. The peak magnitude of $u'v'$ is nearly 10 times of that of $u'w'$. The peak magnitude of $u'v'$ in case LC-4 is about 0.6 times of that in case LC-3, indicating that the momentum exchange is weaker in the LC-4 case due to the increased water depth.

In the emergent-rod case LC-5 (Figure 5.42), both the $u'v'$ and $u'w'$ cross spectra peak around $f = 0.27$ Hz. In the low frequency zone, the phase relation between $u'$ and $v'$ is $\pm \pi$, and the phase relation between $u'$ and $w'$ is 0. This indicates that the production mechanism of the shear around the emergent rods is same to that around the submerged rods.

5.8.2 Eddy contributions to momentum exchange

As discussed in section 5.8.1, the momentum exchange in compound channel flow is mainly done by the low frequency motion. The characteristic frequency and the contributions of low frequency motion to the momentum exchange are investigated in this section.
5.8.2.1 Determination of characteristic frequency

Based on the Fourier Transform relation between the energy spectrum and the velocity auto-correlation, Hinze (1975) obtained the following interesting results expressed in Equations 5.12 and 5.13.

\[ E = \int_0^\infty R_u(t) dt = \lim_{f \to 0} \frac{E_u(f)}{4u'^2} \]  

\[ \tau_E = \left[ \frac{1}{2u'^2} \left( \frac{\partial u(t)}{\partial t} \right)^2 \right]_t = \left[ \frac{1}{2} \left( \frac{\partial^2 R_u(t)}{\partial t^2} \right) \right]_t \right]^{0.5} = \left[ \frac{1}{2\pi^2} \int f^2 E_u(f) df \right]^{0.5} \]  

From Equation 5.12, \( \tau_E \) has a time dimension (s) and is directly related to the low frequency (\( f \to 0 \) Hz), hence, \( \tau_E \) can be regarded as a characteristic time scale of turbulence related to the low frequency motion. Larger eddies correspond to fluctuations at low frequencies, so \( \tau_E \) can be further regarded as a characteristic time scale of larger eddies, which is usually known as the macro-timescale.

From Equation 5.13, it is obvious that \( \tau_E \) also has a time dimension (s) and is a measure of the most rapid changes that occur in the fluctuations of \( u(t) \). Smaller eddies correspond to fluctuations of high frequencies, so \( \tau_E \) can be further regarded as a characteristic time scale of smaller eddies which is usually known as the micro-timescale. The characteristic frequencies can be calculated from \( \tau_E \) and \( \tau_E \).

As large eddies are important to the generation of Reynolds stress, only the macro-timescale and characteristic frequency are discussed in this section. It should be noted that Equation 5.12 was not used in this study because its accuracy remains uncertain on the following grounds:

1) Taylor's frozen-turbulence hypothesis was used to calculate the energy spectrum by applying FFT to velocity auto-correlation (Hinze 1975).
2) Homogeneous and isotropic turbulence was assumed while the turbulence in this study is anisotropic.
Peak frequency and energy percent methods were used to determine the characteristic frequency of the large eddies. Details of these two methods will be described in Sections 5.8.2.2 ~ 5.8.2.3.

5.8.2.2 Peak frequency method

For the peak frequency method, the peak frequency is estimated from the \( v \) energy spectra because the lateral momentum exchange is dominant in compound channel flows and this is also one of the objectives of this research work. As described in section 5.7.1, turbulent kinetic energy is produced due to large energy-containing eddies. For simplification, the peak frequency was used as the characteristic frequency.

Figure 5.43 shows the peak frequencies at different positions in cases LC-1 ~ LC-5. The average characteristic frequencies in these cases are 0.93, 0.90, 0.42, 0.52 and 0.29 Hz respectively. These results indicate that the submerged rods on the floodplain produce a strong shear layer, even under large relative water depth conditions, which is reflected in the average characteristic frequency. In the shallow emergent-rod case LC-5, the strong shear layer is most significant since the characteristic frequency is decreased to 0.29 Hz, which is the lowest among all the cases.

To analyse the contributions of large eddies to the momentum transfer, a low-pass filter was used to remove the high-frequency data from the raw measurement data. For this method, the average characteristic frequency was used as the filtering frequency. Figures 5.44a ~ 5.44e show the percentage ratio of the filtered mean values to the raw mean values of \( u'^2 \), \( v'^2 \), \( w'^2 \), \( uv' \) and \( uw' \) respectively in the five cases.

In the non-vegetated cases LC-1 and LC-2 (Figures 5.44a and 5.44b), the ranges of contribution percentages of large eddies to \( u'^2 \), \( v'^2 \), \( w'^2 \), \( uv' \) and \( uw' \) are 5 ~ 20, 2 ~ 10, 2 ~ 10, 5 ~ 17.5 and 0 ~ 17.5 % respectively. The contributions become noticeable near the MC-FP junction and this indicates that there are larger eddies near the MC-FP junction.

In the vegetated cases LC-3 ~ LC-5 (Figures 5.44c ~ 5.44e), the range of contribution percentages of large eddies to \( u'^2 \), \( v'^2 \), \( w'^2 \), \( uv' \) and \( uw' \) are 5 ~ 15, 2 ~ 5, 2 ~ 4, 2.5 ~
15 and 0 ~ 15 % respectively. In general, the contributions become noticeable near the MC-FP junction and this is similar to the situation in the non-vegetated cases (Figures 5.44a ~ 5.44b).

It can be seen that the calculated contribution depends on the filtering frequency. In fact, the energy-containing eddies have a range of low frequencies. The peak frequency is not high enough to represent and cover the low frequency range.

5.8.2.3 Energy percent method

For the energy percent method, the percentage of cumulative turbulent intensity \( u'_c \) to the total turbulent intensity \( u' \) was used to determine the characteristic frequency of large eddies because \( u'^2 \) makes up most of the turbulent kinetic energy. The values of the characteristic percentage were chosen as 70 %, 80 % and 90 % in this study.

Figures 5.45a ~ 5.45e present the lateral frequency distributions characterising large eddies for cases LC-1 ~ LC-5. Under medium and large relative water depth conditions (Figures 5.45a ~ 5.45d), the characteristic frequency decreases from the left main channel, attains the lowest value around \( Y = 0.43 \sim 0.49 \) m and then increases slightly towards the edge of the MC-FP junction, regardless of the energy percentage. This indicates that the eddies are of high frequencies in the main channel and low frequencies near the MC-FP junction where strong shear layer exists. The results for the position of the lowest frequency also indicate that the shear centre is not at the MC-FP edge, but is slightly shifted towards the main channel. The characteristic frequency of the large eddy decreases as the energy percentage decreases and this is consistent with the definition of the energy spectra.

For an energy percentage of 70%, the lowest characteristic frequencies in cases LC-1 ~ LC-4 are 4.6, 6.0, 3.0 and 2.3 Hz respectively. This indicates that the characteristic frequency of the energy-containing eddies increases as the relative water depth increases in the no rod cases, but the characteristic frequency does not change much with the relative water depth in the submerged cases. In the main channel outside the shear layer zone, the characteristic frequency is similar in the no rod and submerged-rod cases. In the shear layer zone, the characteristic frequency is lower in the submerged-rod case than in the no rod case under similar relative water depth
conditions and this indicates that the submerged rods on the floodplain generate larger eddies near the MC-FP junction than in the non-vegetated compound channel.

In the shallow, emergent-rod case LC-5 (Figure 5.45e), the characteristic frequency is almost constant in the main channel, but decreases sharply from $Y = 0.49$ m to the MC-FP edge. For an energy percentage of 70%, the characteristic frequency decreases from about 13 Hz in the main channel to about 4.5 Hz at the MC-FP edge. This indicates that the strong shear layer might be limited to a narrow area near the MC-FP junction.

In the rod cases (Figures 5.45c - 5.45e), it seems there is a tendency that the eddies move and grow from near the rods towards the main channel side in the MC-FP junction region, which is caused by the wakes.

Using the energy percentage of 70%, the characteristic frequency was used as the filtering frequency to filter the small eddies whose frequency is higher than the characteristic frequency in each case. Figures 5.46 ~ 5.50 show the raw and filtered temporal variations of velocities $U$ and $V$, together with the Reynolds shear stress $uv$, for cases LC-1 ~ LC-5. Figure 5.51 shows the Reynolds shear stresses and their contributions of large eddies at the MC-FP edge in LC-1 ~ LC-5 cases. The vertical positions of the sampling points are described in Section 5.7.2. Under relative water depths $Dr = 0.4$ and 0.5, the respective contribution percentages of large eddies are 27% and 8% higher in the submerged-rod cases than in the non-vegetated cases. This indicates that large eddies contribute more to the Reynolds shear stress in the rod cases, especially under shallow water conditions.

5.9 Summary

In compound channels with submerged rods on the floodplain, the velocity patterns were different to those and the discharges were smaller than those in non-vegetated compound channels under similar relative water depth conditions.

The secondary currents influenced the velocity patterns in non-vegetated and vegetated compound channels. The secondary currents were stronger in the vegetated compound channels than in the non-vegetated compound channels under similar
relative water depth conditions. From the results of vorticity analyses, the anisotropy of turbulence was the main contribution to the generation of secondary currents in non-vegetated and even vegetated compound channels, but the Reynolds stress term was more important in the vegetated compound channels.

The turbulent intensities, turbulent kinetic energy and Reynolds shear stresses $\tau_{yx}$ and $\tau_{zx}$ peak near the MC-FP junction in the vegetated compound channels, but peak near the main channel bed in the non-vegetated compound channels. The peak magnitude of $\tau_{yx}$ was larger than that of $\tau_{zx}$ indicating that the lateral transfer of the longitudinal momentum was stronger than the vertical transfer of the longitudinal momentum. The peak magnitude of $\tau_{yx}$ was only slightly smaller than that of $\tau_{zx}$ indicating that the shear stress generated by the secondary currents was also important in the submerged rod case. The Reynolds shear stresses became slightly smaller as the relative water depth increased from 0.4 to 0.5.

Results of cross spectra showed the mechanisms of the turbulent shear generation near the MC-FP junction are due to large eddies in the non-vegetated compound channel and owing to wakes in the vegetated compound channel.
Figure 5.1 Normalised longitudinal velocity ($U/U_m$) distributions. (a) Case LC-1; (b) Case LC-2; (c) Case LC-3; (d) Case LC-4; (e) Case LC-5.
Figure 5.2 Rotated secondary current patterns \((v/U_m, w/U_m)\). (a) Case LC-1; (b) Case LC-2; (c) Case LC-3; (d) Case LC-4; (e) Case LC-5.
Figure 5.3  Anisotropy of turbulence $\frac{\sqrt{v^2 - w^2}}{U^2}$.  (a) Case LC-1; (b) Case LC-2; (c) Case LC-3; (d) Case LC-4; (e) Case LC-5.
Figure 5.4  Longitudinal vorticity \( \left( 100\Omega_i/(U_m/H) \right) \) profiles. (a) Case LC-1; (b) Case LC-2; (c) Case LC-3; (d) Case LC-4; (e) Case LC-5.
Figure 5.5  Longitudinal vorticity balance for Case LC-1. (a) Advection term A1; (b) Anisotropy term A2; (c) Shear stress term A3; Viscous term A4.
Figure 5.6 Longitudinal vorticity balance for Case LC-2. (a) Advection term A1; (b) Anisotropy term A2; (c) Shear stress term A3; Viscous term A4.
Figure 5.7 Longitudinal vorticity balance for Case LC-3. (a) Advection term A1; (b) Anisotropy term A2; (c) Shear stress term A3; Viscous term A4.
Figure 5.8 Longitudinal vorticity balance for Case LC-4. (a) Advection term A1; (b) Anisotropy term A2; (c) Shear stress term A3; Viscous term A4.
Figure 5.9  Longitudinal vorticity balance for Case LC-5. (a) Advection term A1; (b) Anisotropy term A2; (c) Shear stress term A3; Viscous term A4.
Figure 5.10  Vertical distributions of turbulent intensities for Case LC-1. (a) In the main channel; (b) on the floodplain.

Figure 5.11  Lateral distributions of turbulent intensities for Case LC-1. (a) $u'/U_*$; (b) $v'/U_*$; (c) $w'/U_*$. 
Figure 5.12 Normalised turbulent intensity ($u'/U_*$) profiles. (a) Case LC-1; (b) Case LC-2; (c) Case LC-3; (d) Case LC-4; (e) Case LC-5.
Figure 5.13  Normalised turbulent intensity \( \tfrac{v'}{U_c} \) profiles. (a) Case LC-1; (b) Case LC-2; (c) Case LC-3; (d) Case LC-4; (e) Case LC-5.
Figure 5.14 Normalised turbulent intensity ($w'/U_*$) profiles. (a) Case LC-1; (b) Case LC-2; (c) Case LC-3; (d) Case LC-4; (e) Case LC-5.
Figure 5.15  Temporal variations of U velocity data for LC-1 ~ LC-5 cases. (a) Case LC-1; (b) Case LC-2; (c) Case LC-3; (d) Case LC-4; (e) Case LC-5.
Figure 5.16  Temporal variations of V velocity data for LC-1 – LC-5. (a) Case LC-1; (b) Case LC-2; (c) Case LC-3; (d) Case LC-4; (e) Case LC-5.
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Chapter 6

Large Eddy Simulation with TELEMAC

As described in Chapters 4 ~ 5, the shear effects on the lateral momentum exchange are significant in the shallow, non-vegetated, compound channel and even in the deep compound channel with a vegetated floodplain. The periodic large eddies play an important role in the lateral momentum exchange under such flow conditions. To explore the unsteady flow characteristics in the compound channel, a large eddy simulation (LES) was performed with TELEMAC.

Section 6.1 describes the numerical methodology for LES with TELEMAC. Section 6.2 investigates the generation of large eddies and the sensitivity of influencing factors. Section 6.3 presents the main simulation results of smooth, compound, open-channel flows. Sections 6.4 and 6.5 illustrate the main simulation results for compound, open-channel flows with emergent and submerged vegetation on the floodplain. Section 6.6 summarises the LES results of compound open channel flows.

6.1 Numerical methodology

In this section, the numerical methodologies for TELEMAC-2D used in this work are explained. Section 6.1.1 briefly presents the governing equations Large Eddy Simulation (LES). Section 6.1.2 describes the TELEMAC modelling system. The description mainly concerns the 2D Saint-Venant equations, mesh generation, initial and boundary conditions, numerical schemes and the data analysis method. Section 6.1.3 illustrates the simulation methods and simulation cases in this work.

6.1.1 LES governing equations

The essence of LES is the separation of variables like velocity, temperature, pollutant and other scalars into resolved and unresolved parts (Lesieur et al. 2005). The resolved or large-scale quantities controlling the turbulent diffusion of momentum or mass are computed numerically using modified conservation equations. The unresolved or sub-grid quantities are not directly computed, but modelled with various sub-grid models. The main advantages of LES is that it can capture the unsteady effects of the modelled flow better than the Reynolds Averaged Navier-
Stokes (RANS) approach and yet does not require such extensive computational
dpower as Direct Numerical Simulation (DNS).

The LES equations were described in detail by Lesieur et al. (1997) and Lesieur et al. (2005). For simplification, the spatial discretization is assumed as cubic and the scale characteristic of the grid mesh is assumed as $\Delta l$ in LES. A filter of width $\Delta l$ was used to eliminate the sub-grid scales. Mathematically, the flow variable $f(x,t)$ in the continuous space $\tilde{x}$ is converted to the filtered flow variable $\tilde{f}(\tilde{x},t)$ by the filter function $G_{\Delta l}(\tilde{x})$ as follows:

$$\tilde{f}(\tilde{x},t) = \int f(y,t) G_{\Delta l}(\tilde{x} - \tilde{y},t) d\tilde{y} = \int f(x-y,t) G_{\Delta l}(y) dy$$ (6.1)

The flow variable $f$ is composed of a filtered variable and fluctuations ($f = \tilde{f} + f'$).

After applying the filter to continuity and momentum equations for the incompressible flow, the LES equations can be obtained as follows:

$$\frac{\partial u^+}{\partial x_i} = 0$$ (6.2)

$$\frac{\partial u^+}{\partial t} + \frac{\partial}{\partial x_j} \left( u^+ u^+ \right) = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{1}{\rho} \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial u^-}{\partial x_j} + \frac{\partial u^-}{\partial x_i} \right) + T_g \right) + f_i$$ (6.3)

where $T_g$ as expressed in Equation 6.4 is the sub-grid stress tensor responsible for momentum exchange between the filtered and sub-grid eddies.

$$T_g = \overline{u^+_i u^+_j} - \overline{u^+_i} \overline{u^+_j}$$ (6.4)

Analogous to the framework of the Reynolds stress equations for the RANS equations, the sub-grid stresses are also, in most cases, expressed in terms of eddy
viscosity and dynamic viscosity. The most widely used sub-grid model is the Smagorinsky model developed by Smagorinsky (1963). Similar to the mixing length concept in RANS equations, Smagorinsky proposed that the sub-grid eddy viscosity $\varepsilon_{se}$ is proportional to the characteristic sub-grid scale $\Delta l$ and to a characteristic sub-grid velocity $v_{\Delta}$ as expressed by Equation 6.5,

$$v_{\Delta} = \Delta l |\overline{S}|$$  \hspace{1cm} (6.5)

In Equation 6.5, $\Delta l$ and $|\overline{S}|$, filtered-field deformation tensor, can be expressed by Equations 6.6a and 6.6b respectively.

$$\Delta l = \sqrt{\Delta x \Delta y}$$  \hspace{1cm} (6.6a)

where $\Delta x$ and $\Delta y$ are the grid sizes in the $x$ and $y$ directions respectively.

$$|\overline{S}| = \sqrt{2S_{yy} S_{yy}}$$  \hspace{1cm} (6.6b)

where

$$\overline{S_{yy}} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)$$  \hspace{1cm} (6.7)

The sub-grid eddy viscosity $\varepsilon_{se}$ can then be determined using the Smagorinsky model in the following form:

$$\varepsilon_{se} = (C_s \Delta l)^2 |\overline{S}|$$  \hspace{1cm} (6.8)

where $C_s$ is the Smagorinsky constant and is normally 0.1.

In this work, large eddy simulation was performed with TELEMAC and the Smagorinsky model was used to calculate the LES eddy viscosity. In most cases, the
Smagorinsky constant $C_s$ is assumed as 0.1, but in TELEMAC, it can be set as various values using a subroutine.

### 6.1.2 TELEMAC modelling system

#### 6.1.2.1 2-D Saint-Venant equations

The TELEMAC modelling system is a set of finite-element-based computer codes for numerical simulations of free surface flows. Since its development by the National Hydraulics Laboratory of Electricité de France (EDF) in the 1960's, it has been successfully applied to research and practice in almost all aspects of hydrodynamics worldwide by more than 60 organizations including Hydraulic Research Wallingford, UK; National Research Council, Canada and several universities (Hervouet & Van Haren 1996, Hervouet 2000, Rameshwaran & Shiono 2003). Now it has become one of the main standard codes in the hydrodynamic modelling field. In this work, the TELEMAC-2D module was mainly used to predict the 2-D flow structures in the compound channel by solving the 2-D Saint-Venant equations.

The 2-D Saint-Venant equations are derived from the Navier-Stokes equations under the following assumptions and approximations.

Firstly, the vertical acceleration caused by the pressure is assumed to balance gravity, and the vertical velocity is then neglected in the Saint-Venant equations.

Secondly, it is assumed that there will be no transfer of water either through the bottom or from the free surface.

Thirdly, the rule of Leibnitz is mainly used for the derivation of the Saint-Venant equations. Equation 6.9 gives an example of deriving $\frac{\partial}{\partial x} \int_{z_f}^{z} F(x, y, z) dz$.

$$\frac{\partial}{\partial x} \int_{z_f}^{z} F(x, y, z) dz = \int_{z_f}^{z} \frac{\partial F(x, y, z)}{\partial x} dz + \frac{\partial (x, y, z)}{\partial x} \frac{\partial Z}{\partial x} - F(x, y, z) \frac{\partial Z_f}{\partial x} \tag{6.9}$$

where $x$ is the Cartesian coordinate, $F(x,y,z)$ is the flow variable, $Z$ is the free surface elevation, $Z_f$ is the bottom elevation and the water depth $H$ is defined as $Z-Z_f$. 

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Using the above assumptions and approximations, continuity and momentum equations for the incompressible flow can be averaged vertically to obtain the 2-D Saint-Venant equations as expressed in Equations 6.10 – 6.12. In the 2-D Saint-Venant equations, the two new components of depth-averaged velocities $U_d$ and $V_d$ are produced by depth averaging and defined by Equation 6.13.

\[
\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(HU_d) + \frac{\partial}{\partial y}(HV_d) = 0 \tag{6.10}
\]

\[
\frac{\partial (HU_d)}{\partial t} + \frac{\partial}{\partial x}(HU_d U_d) + \frac{\partial}{\partial y}(HU_d V_d) = -Hg \frac{\partial z}{\partial x} + HF_x + \text{div}(HV_e \nabla(U_d)) \tag{6.11}
\]

\[
\frac{\partial (HV_d)}{\partial t} + \frac{\partial}{\partial x}(HU_d V_d) + \frac{\partial}{\partial y}(HV_d V_d) = -Hg \frac{\partial z}{\partial x} + HF_y + \text{div}(HV_e \nabla(V_d)) \tag{6.12}
\]

\[
U_d = \frac{1}{H} \int_{z_f}^{z} u dz \quad \text{and} \quad V_d = \frac{1}{H} \int_{z_f}^{z} v dz \tag{6.13}
\]

where $x$ and $y$ are the longitudinal and lateral directions respectively, $F_x$ and $F_y$ are the forces per unit volume in the $x$ and $y$ directions respectively, and $V_e$ is the effective depth-averaged eddy viscosity.

### 6.1.2.2 Mesh generation

In TELEMAC, the finite-element, unstructured, triangular mesh is generated by a pre-processing software called MATISSE. The bathymetric and coastline data files in the sinusx format are generated first by running data2mat.exe. In MATISSE, the channel geometry is then built automatically once bathymetric data and coastline data are imported. The mesh can be generated by setting compute criteria once the coastline is connected and has been defined as a contour line type. The mesh can be refined locally with required element sizes in the areas of interest, such as the junction of the main channel and the floodplain and steep sloped banks, and the mesh in other areas can be coarse. Various element sizes will avoid the spurious topographical interpolation and also make the computation less expensive.
For channels with emergent vegetation, the emergent vegetation in the mesh can be generated by using the function for creating simple geometry in the "Geometric lines" mode and defining the rod lines as contour lines. For channels with submerged vegetation, the vegetation has to be generated from the bathymetric data file and the vertical vegetation has to be replaced by steep sloped ones. This replacing treatment will pose a difficulty when refining the local element sizes.

The resolution of the mesh size can be determined based on the Courant number concept. During the simulations, the Courant number \((Cr)\) was set within the range 0.1 ~ 0.4 to ensure stable computation. The initial grid size criteria \((\Delta l_x)\) in the longitudinal direction can be roughly determined by Equation 6.14 using a Courant number of 0.25 and a time step of 0.01s. Using the criteria of \(\Delta l_x\), triangular mesh will be generated with MATISSE software and the actual values of grid size in the longitudinal direction might differ from \(\Delta l_x\). The Courant number \((Cr)\) for each time step is calculated automatically with TELEMAC based on the actual value of grid size in the longitudinal direction. The actual time step can be adjusted manually and set as a constant value during the simulation according to the actual Courant number \((Cr)\).

\[
\Delta l_x = \frac{U_m \Delta t}{Cr}
\]

where \(U_m\) is the mean streamwise velocity and \(\Delta t\) is the time step.

The mesh resolution influences the simulation results (Hardy et al. 1999) and this effect will be discussed later in this chapter.

6.1.2.3 Boundary and initial conditions

The boundaries of an open channel flow consist of inlet, outlet, sidewalls, bottom and free surface. The boundary conditions need to be specified along these boundaries. The boundary condition file is generated by MATISSE, which gives information on the inlet, outlet and wall conditions. As an initial condition, the free water surface was set parallel to the channel bed.
At the inlet, the constant flow rate is given and the unknown free water depth is set as zero. At the outlet, the constant water level is given and the unknown free flow rate is set as zero. On the channel bed and sidewalls, the slip (friction) boundary condition is usually used because this condition does not require very fine mesh near the walls and the influence of boundary layer is limited to the region near the side walls (Nadaoka & Yagi 1998). For the narrow channel in this work, the non-slip boundary condition was also used to compare the results of using different boundary conditions on the sidewalls.

Slip and non-slip boundary conditions can be imposed by MATISSE. Slip boundary condition can be expressed by Equation 6.15 (Nadaoka & Yagi 1998). For non-slip boundary condition, the longitudinal velocity $U$ and lateral velocity $V$ on the wall are zero.

$$\frac{\partial U}{\partial y} = 0, \ V = 0, \text{ on the wall} \quad (6.15)$$

For two dimensional flow, the bed friction is usually given by Equation 6.16a. The friction factor $c_f$ is rarely used and it is usually replaced by Chazy coefficient $c$, Manning coefficient $n$ or equivalent roughness height $k_r$. Equations 6.16b - 6.16d show these the Chezy's law, Manning's law and Nikuradse's law in TELEMAC-2D respectively. The friction coefficients are to be specified as constant values in the steering file or to be specified as various values by modifying the "STRCHE" or "CORSTR" subroutines.

$$\tau = \frac{1}{2} \rho c_f \sqrt{U \overline{U}} \quad (6.16a)$$

$$c = \sqrt{\frac{2g}{c_f}} \quad (6.16b)$$

$$c = 7.831 \log \left( 12 \frac{H}{k_r} \right) \quad (6.16c)$$
where $\tau$ is the bed shear stress vector, $\rho$ is the fluid density, $c_f$ is the friction factor, $\vec{U}$ is the velocity vector and $H$ is the water depth.

6.1.2.4 Advection scheme

In TELEMAC-2D, the solution algorithm is based on the operator-splitting technique and its detailed description can be found in Hervouet and Haren (1996). The solution algorithm includes two steps: the discretization of the advection terms and the discretization of the diffusion terms. The first step starts from solving the non-conservative 2-D Saint-Venant equations in depth and velocity. The discretization of the advection scheme can be treated with various advection schemes and the Method of Characteristics (MOC) is the default scheme in TELEMAC (Hervouet and Haren 1996; Janin et al. 1997). The latter is treated using the finite element variational method (Janin et al. 1997).

Based on studies carried out by Hervouet and Haren (1996), Janin et al. (1997), Morvan (2002) and Rameshwaran and Shiono (2003), the Method of Characteristics (MOC), streamline Upwind Peterov-Galekin (SUPG) formulation and MURD scheme are summarised here. In the MOC scheme, the flow variable $f$ at time $t^{n+1}$ at the node $M$ is assumed to be equal to that at time $t^n$ at the node $Q$ obtained by retracing backwards the trajectory from point $M$ by going back in time interval $dt$. The MOC is the fastest scheme to discretize the advection problem, but it induces large advection error due to the linear interpolation, which is not good for mass conservation. In the SUPG scheme, each term of a conservative equation can be treated by using test functions bent in the flow direction. The additional diffusion stabilising term in the SUPG scheme gives more weight to the element moving forward and greatly enhances the mass conservation. The MURD scheme is similar to, but more stable than the SUPG scheme.

The above investigations were all made using RANS modelling. In this work, the effects of the MOC, SUPG and MURD schemes on the LES results have not been investigated to date and therefore are investigated here.
6.1.2.5 Data analysing method

For RANS modelling, the steady, uniform flow is achieved if the slope of the free surface is equal to that of the channel bed and the default value of the variable difference between two time steps is $10^{-4}$ in TELEMAC. The data at the final time step can be used for analysis.

For LES, the simulation is unsteady and the mean data are obtained by time-averaging and time-space averaging methods. In the smooth cases, for flow variable $f(x,y,t)$, the mean value $\overline{f}$ and variance $f'^2$ were calculated with the time-space averaging method (Bousmar 2002) and are expressed by Equations 6.17a and 6.17b respectively, while in the vegetated cases they were calculated by Equations 6.18a and 6.18b respectively.

\[ \overline{f}(y) = \frac{1}{T} \frac{1}{L} \sum f(x,y,t) \quad (6.17a) \]

\[ f'^2(y) = \frac{1}{T} \frac{1}{L} \sum [f(x,y,t) - \overline{f}(y)]^2 \quad (6.17b) \]

\[ \overline{f}(y) = \frac{1}{T} \sum f(y,t) \quad (6.18a) \]

\[ f'^2(y) = \frac{1}{T} \sum [f(y,t) - \overline{f}(y)]^2 \quad (6.18b) \]

where $f$ is the flow variable, $x$ and $y$ are the longitudinal and lateral directions respectively, $t$ is the time, $T$ is the total time period for averaging and $L$ is the length of the computation domain.

In this work, the value of $T$ was chosen as 50s, the values of $L$ for cases STC-1, FCF020201 and LC-2 were chosen as 1 m ($x = 8 - 9$ m), 10 m ($x = 45 - 55$ m) and 1 m ($x = 6.4 - 7.4$ m) respectively.
6.1.3 Simulation cases

In this work, 2D-LES simulations were carried out for four smooth-channel cases, one emergent vegetation case and one submerged vegetation case.

Large eddy generation and unsteady flow characteristics were first studied for the small, smooth, compound channel with a relative water depth of 0.24. The detailed channel geometry and flow conditions of the shallow case STC-1 are listed in Tables 3.3 and 4.1, respectively. To study the impact of the mesh resolution on the LES results, three meshes of different resolutions were generated and are presented in Figure 6.1. To simplify simulation and save time, fine mesh MS2 was used first. In mesh MS2, the longitudinal mesh resolution is uniformly 0.02 m and the lateral mesh resolutions are 0.0052 m near the MC-FP junction and 0.0075 m in other areas. Further sensitivity tests were undertaken using the finer mesh MS1. The mesh details for various simulation cases are listed in Table 6.1.

After the above simulations, LES was performed for the large-scale smooth flume at the UK Flood Channel Facility (FCF) with a relative water depth of 0.15. The detailed channel geometry and flow conditions of the shallow case FCF020201 can be found in Shiono and Knight (1991). Figure 6.2 shows the mesh for case FCF020201.

To study the flow characteristics in the compound channel with one-line emergent vegetation along the floodplain edge, 2D-LES was performed for case STC-4. The detailed channel geometry and flow conditions of case STC-4 are listed in Table 3.3 and Table 4.1, respectively. Finer mesh MS4, as shown in Figure 6.3a for a one-metre domain, was first generated to study the flow plunge around the rods. Coarser mesh MS5, as shown in Figure 6.3b, was then used for the whole compound channel. For comparison, 2D-LES was also performed for the smooth STC-3 with Dr = 0.50 using mesh MS1.

To study the flow characteristics in the compound channel with submerged vegetation on the floodplain, 2D-LES was performed for the LC-4 case. The detailed channel geometry and flow conditions of case LC-4 are listed in Table 3.3 and Table 5.1, respectively. To study the effects of mesh resolution on the LES results of the submerged case, LES was first performed under relative water depth \( Dr = 0.51 \) in the
large, trapezoidal, compound channel and Figures 6.4a–g show the meshes for the test case LTCT. Based on the preliminary test results, the appropriate mesh resolution was used to generate the mesh for case LC-4 as shown in Figure 6.5. For comparison, 2D-LES was also performed for the smooth LC-2 with Dr = 0.50 using mesh ML3 as shown in Figure 6.6. Experimental data from Shiono and Knight (1991) were used to verify the LES results for case FCF020201. Experimental data collected in this work were used to verify the LES results of other cases.

### Table 6.1 Mesh details for various LES simulation cases

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### 6.2 LES for the smooth, compound-channel flow

#### 6.2.1 Eddy evolution

As suggested by Tamai et al. (1986) and Chu et al. (1991), large eddy generation is a dynamic process due to the shear instability of a lateral velocity profile with an
inflection point and is influenced by bed friction and other flow conditions. To obtain basic knowledge about large eddy generation, a large eddy simulation was first performed for case STC-1 using Mesh MS2. For meshes MS1 and MS3, the longitudinal mesh resolutions are 0.01 m and 0.03 m respectively, and the lateral mesh resolutions are same as those of mesh MS2. The simulation time for the evolution test was t = 463 s. To make simulation simple, the method of characteristic (MOC) was first used for the advection of velocity and water depth variables whilst a slip boundary condition was imposed on the sidewalls.

Figure 6.7 shows the velocity field for case STC-1 from t = 30 s to t = 150 s. Figure 6.8 gives the velocity field in a moving frame with the MC-FP junction velocity. The MC-FP junction velocity was obtained by averaging the velocities from the position where large eddies were generated to the channel outlet at the MC-FP junction edge. Figure 6.9 depicts the vorticity (Ω = ∂v/∂x − ∂u/∂y) field. In Figures 6.8 ~ 6.9, the x axis represents the actual distance from the channel inlet. The evolution of eddy generation can be described by these figures.

At t = 30 s (Figure 6.7a), the velocity field is uniform and no fluctuations are visible. At t = 50 s (Figure 6.7b), some weak flow meandering appears around the MC-FP junction at about 8.5 m downstream from the inlet. The location of meandering velocity moves upstream as the simulation time increases. It can also be seen that the periodic flow meandering appears from around x = 6 m at t = 100 s and x = 5.2 m at t = 150 s (Figures 6.7c ~ 6.7d).

Corresponding to the wavy velocity fields, the periodic large eddies can be clearly identified from the subtracted velocity fields (Figure 6.8). At t = 30 s, no eddies can be seen. At t = 50 s, small weak eddies are visible at around x = 8 m and large strong eddies are generated from around x = 8.6 m. Large eddies appear from around x = 6.4 m at t = 100 s and around x = 5.2 m at t = 150 s.

Large eddies in the shear layer are characterised as the vorticity. The locations of large eddies coincide well with those of the velocity fluctuations, so the vorticity fields near the outlet of the channel are studied to see the eddy generation. As seen from Figure 6.9, high positive vorticity values occur at the MC-FP junction at t = 30 s, but no fluctuations can be seen, which indicates that the shear layer is limited to a
narrow sheet at the junction at this stage. At $t = 50 \text{ s}$, remarkable fluctuations of vorticity can be seen from around $x = 8 \text{ m}$ and the fluctuation zone occupies most of the channel width, which indicates that the shear layer begins to develop. As the run time increases, the vortices begin to merge into larger ones and this can be seen from Figures 6.9c and 6.9d. This agrees with the statement given by Bousmar (2002) that the final growth of large eddies is restricted by the sidewalls in the compound channel flows.

From the above results, large eddies are first generated downstream and then move upstream. It can also be seen that there is a minimum length and a time period for large eddy generation, but the detailed values of these in general cannot be determined since they depend on the flow and simulation conditions.

Once large eddies are generated, the appreciable fluctuations of velocities, free water surfaces, water depths and vortices can be easily recognised. Figures 6.10a ~ 6.10e show the 2D perspective profiles of longitudinal velocity $U$, lateral velocity $V$, vorticity, water depth and free surface at the MC-FP junction between $t = 450 \text{ s}$ and $t = 455 \text{ s}$ for case STC-1. It is clear that these variables begin to fluctuate from around $x = 5 \text{ m}$ which coincides well with the results for the velocity and vorticity fields. This confirms that a minimum length of $5 \text{ m}$ is required for large eddy generation under this simulation condition. Compared with other parameters, the oscillation of the lateral velocity $V$ at the junction edge is easier to identify, so the lateral velocity $V$ at the junction edge was chosen as an indirect parameter for identifying large eddies.

Figure 6.11 shows the streamwise advection of large eddies between $t = 450 \text{ s}$ and $t = 453 \text{ s}$ for case STC-1. The core of large eddies moves from $x = 8.375 \text{ m}$ at $t = 450 \text{ s}$ to $x = 8.825 \text{ m}$ at $t = 453 \text{ s}$, so the mean relative advection speed of large eddies is $0.15 \text{ m/s}$. The mean velocity at the interface between $t = 450 \text{ s}$ and $t = 453 \text{ s}$ is $0.135 \text{ m/s}$. It can be seen that large eddies move at a speed of about $0.285 \text{ m/s}$.

6.2.2 Flow fluctuations

6.2.2.1 Spatial distributions

For fully-developed, uniform flow without large eddies, the flow variables, such as velocity and free surface, remain relatively constant in the channel. In the cases of
channel flows with large eddies, the flow variables vary periodically with time and space and the local values of flow variables differ from those from RANS modelling. The maximum local velocity and bed shear stress can be estimated from the LES results and the safety factor can then be selected to consider the maximum values of water level and bed shear stress for use in engineering design along with the proper measures for effective, practical, river management. This might be one of the important considerations when applying LES to practical engineering issues. Figures 6.12a ~ 6.12e show the spatial distributions of longitudinal velocity, lateral velocity, vorticity, free surface and bed shear stress at $t = 450$ s in case STC-1. In Figure 6.12, the velocity and bed shear stress are normalised by the measured bulk velocity $U_m$ and the measured overall boundary shear stress respectively. The effects of large eddies on the hydraulic behaviour can be described as follows.

In Figure 6.12a, obvious wavy distributions of velocity $U$ can be recognised near the MC-FP junction. Three high-velocity zones can also be seen near the sidewall of the main channel and three low-velocity zones occur near the sidewall of the floodplain. In Figure 6.12b, positive and negative velocity zones exist alternately around the MC-FP junction and this indicates that there are periodic motions in this region. It can be seen that the maximum values of $U/U_m$ and $V/U_m$ reach 1.50 and 0.18 respectively. The parameter of $UV$ is important for engineering issues. Figure 6.12c shows the spatial distributions of $UV$. Positive and negative values of $UV$ exist alternately near the MC-FP junction, which is similar to the distribution of $V$ as shown in Figure 6.12b, and the value of $UV/U^2$ falls in the range of $-20$ ~ $15$. It can also be seen that the magnitude of $UV$ at the junction edge is slightly smaller than that away the junction edge and this is because the magnitude of velocity $V$ is larger on the floodplain than in the main channel near the MC-FP junction.

In Figure 6.12d, there are three high-vorticity cores at the MC-FP junction edge and the longitudinal locations of these cores coincide well with those where the peak and low values of velocity $U$ exist. This can be explained by reference to the velocity gradient $\left(\frac{\partial U}{\partial y}\right)$. At the longitudinal location where the peak and low velocity zones...
exist, the velocity gradient \( \frac{\partial U}{\partial y} \) at the junction edge is higher than that in other areas, the shear is then stronger than that in other areas. At the same time, the shear strength is positively related to the value of vorticity.

In Figure 6.12e, the regions of low free surfaces roughly correspond to those of high-vorticity cores. Nadaoka and Yagi (1998) also observed this phenomena and suggested that it is caused by the horizontal large eddies.

The bed shear stress \( \tau_b \) is calculated from velocities, water depth and Manning coefficient \( \tau_b = \rho g n^2 \left( U^2 + V^2 \right) h^{1/3} \). Among these variables, velocity \( U \) is much larger, especially in the main channel, so the bed shear stress is more influenced by velocity \( U \). In other words, the bed shear stress varies in the same manner as velocity \( U \) and this can be seen from Figure 6.12a and 6.12f.

The variations of vorticity, velocity, bed shear stress and water depth will be further analysed in Sections 6.2.2.2 - 6.2.2.3.

### 6.2.2.2 Variations of variables along the MC-FP junction

The variations of variables along the MC-FP junction are shown in Figure 6.13 together with the subtracted velocity field and vorticity field at \( t = 450 \) s.

In Figure 6.13a, the high-vorticity zones correspond to the cores of large eddies around the MC-FP junction and this indicates that the shear is stronger in the core region of large eddies than in other parts of the flow domain. Figure 6.13b shows the vorticity variations in detail along the MC-FP junction. The peak locations of vorticity approximately correspond to the longitudinal positions of eddy cores. The value of the vorticity normalised by \( 100h/U_{m0} \) ranges from around 5 to around 20 along the edge, where \( h \) and \( U_{m0} \) are the averaged values of water depth and longitudinal velocity along the edge of \( 7 \text{m} < x < 9 \text{m} \). The positive sign of \( 100\Omega h/U_{m0} \) indicates that there is a counter-clockwise circulation along the edge, which is consistent with the sign shown in Figure 6.13a. The wavy distribution of normalised vorticity indicates that the shear strength varies along the edge, which corresponds to the lateral distribution
of longitudinal velocity as shown in Figure 6.12a. These results further confirm that
the vorticity can be used to identify the existence of large eddies.

Figure 6.13c shows the longitudinal variations of longitudinal velocity $U$; lateral
velocity $V$ and bed shear stress $\tau_b$. In Figure 6.13c, the velocity and bed shear stress
are normalised by the averaged longitudinal velocity ($U_{m0}$) and bed shear stress ($\tau_{m0}$)
along the edge to show the variation along the edge. The variation range of $U/U_{m0}$,
$V/U_{m0}$ and $\tau_b/\tau_{m0}$ are $85 \sim 120\%$, $-30 \sim 15\%$ and $60 \sim 140\%$ respectively. The
trend of the normalized bed shear stress is similar to that of the normalized
longitudinal velocity and this has been explained in Section 6.2.2.1. It can be seen that
the bed shear stress varies more than the longitudinal velocity and this is because the
bed shear stress has a relationship to the square of the longitudinal velocity.

Figure 6.13d shows the variation of the secondary current term ($\rho UV$) normalised by
the averaged bed shear stress ($\tau_{m0}$). The value of the secondary current term ($\rho UV$)
ranges from around $-60 \tau_{m0}$ to $30 \tau_{m0}$. Compared with the variation of the lateral
velocity as shown in Figure 6.13c, the secondary current term varies in a similar
manner to that of the lateral velocity $V$ and this indicates that the lateral velocity is
decisive to the secondary current term.

As shown in Figure 6.13e, the water depth normalised by the averaged water depth
along the edge ($H_{m0}$) varies in the same manner as the velocity $U$, but its variation
range is limited to $94 \sim 106\%$.

6.2.2.3 Time series of variables

Figure 6.14 further shows the time series of the longitudinal velocity ($U$), the lateral
velocity ($V$), bed shear stress ($\tau_b$), the secondary current term ($\rho UV$) and water depth
($H$) at an interface point $8.6 \text{ m}$ downstream from the inlet. In this figure, the velocity
is normalised by the time-averaged longitudinal velocity ($U_{m0}$), the bed shear stress
and the secondary current term are normalised by the time-averaged bed shear stress
and the water depth is normalised by the time-averaged water depth.
From Figure 6.14a, the variation ranges of $U/U_m\theta$, $V/V_m\theta$, and $\tau_b/\tau_m\theta$ are 80 ~ 120 %, -25 ~ 15 % and 64 ~ 133 % respectively, which are a little different to those of the spatial variation range as shown in Figure 6.13c. From Figure 6.14b, the value of the secondary current term ($\rho UV$) ranges from around -60 $\tau_m\theta$ to 30 $\tau_m\theta$, which is the same as the spatial variation range as shown in Figure 6.13d. From Figure 6.14c, the variation range of $H/H_m\theta$ is 96 ~ 104 % which is 2 % smaller than the spatial one as shown in Figure 6.13e. Based on these results, in the smooth, compound-channel case, the spatial variation range of the flow variable is similar to the temporal one.

In Figure 6.14a, the three local positions of low velocity $U$ can be recognised to occur at $t = 451$ s, $t = 454.3$ s and $t = 458.5$ s. The two corresponding time intervals of adjacent positions of low velocity $U$ are 3.3 s and 4.2 s and the two characteristic frequencies can be determined as 0.30 Hz ($=1 / 3.3$ s) and 0.24 Hz ($=1 / 4.2$ s). The average characteristic frequency is 0.27 Hz. These results indicate that the large eddies downstream under this flow condition are low frequency.

### 6.2.3 Sensitivity analyses of eddy generation

#### 6.2.3.1 Generation problem and analysing method

Large eddy simulation was performed for case STC-2 using the same numerical method as with case STC-1. However, large eddies were not generated until $t = 450$ s. The necessary run-time for eddy generation depends on the various cases. Bousmar (2002) suggested that the minimum time step should be 50,000, so the minimum run time for case STC-2 could be 250 s using time step 0.005 s in this case. Thomas & Williams (1995) suggested the necessary time can be $23H/U_\ast$, where $H$ is the water depth in the main channel and $U_\ast$ is the average shear velocity, so the minimum run time for case STC-2 could be 79 s. To investigate large eddy generation, a series of sensitivity tests for case STC-1 were carried out using TELEMAC-2D. Numerical conditions for tests a ~ c are listed in Table 6.2.

As shown in Section 6.2.1, large eddies can be easily seen from the velocity field in a moving frame with the MC-FP junction velocity. The effect of the time step was first evaluated by using this method.
As explained in Section 6.2.1, the velocity V profiles at the MC-FP junction can also be used to identify large eddies. To simplify the analysis, the effects of other factors were evaluated with this method. The main criteria were selected as the run time ($T_s$) and the longitudinal distance ($X_s$) of the first fluctuation of velocity V and the longitudinal distance ($X_f$) of the final fluctuations of velocity V. The final run time was selected as 300 s or more after the run time of the first fluctuation of velocity V.

### Table 6.2 Sensitivity test conditions for case STC-1

<table>
<thead>
<tr>
<th>Test series</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Step(s)</td>
<td>0.0025, 0.005, 0.001</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>Mesh</td>
<td>MS2</td>
<td>MS1, MS2, MS3</td>
<td>MS1</td>
</tr>
<tr>
<td>Boundary condition</td>
<td>Slip</td>
<td>Slip</td>
<td>Non Slip</td>
</tr>
<tr>
<td>Advection scheme</td>
<td>MOC</td>
<td>MOC</td>
<td>MOC, SUPG</td>
</tr>
</tbody>
</table>

#### 6.2.3.2 Results

Figure 6.15 shows the velocity fields in a moving frame with the MC-FP junction velocity for the time step test. For tests b - c, the results of $T_s$ and $X_s$ are shown in Figure 6.16 and the results of $X_f$ are shown in Figure 6.17.

From Figure 6.15, large eddies were generated from around $x = 2.5 \text{ m}$ at run time $t = 525 \text{ s}$, using smaller time steps of 0.0025 s and 0.005 s. Using a larger time step of 0.01 s, large eddies were generated from around $x = 5.25 \text{ m}$ at $t = 525 \text{ s}$. This indicates that the smaller time step encourages eddy generation. In the following tests, smaller time steps were used to keep the Courant number around 0.1 - 0.2.

In Figures 6.16a - 6.16c, the values of $T_s$ for three meshes are all 40 s, the values of $X_s$ using meshes MS1, MS2 and MS3 are 6 m, 7 m and 7 m respectively and the values of $X_f$ at $t = 450 \text{ s}$ using meshes MS1, MS2 and MS3 are 4.2 m, 4.5 m and 5.5 m respectively. At $t = 450 \text{ s}$, the wavy profiles of the lateral velocity V can all be seen.
using different meshes and the periodic patterns can be identified. Moreover, the V pattern using the finer mesh MS 1 is more regular than when using the other two meshes. The characteristic frequency using mesh MS 1 is slightly smaller than for the other two meshes and this indicates that the flow structure can be better captured using the finer mesh MS 1. Bousmar (2002) also reported that the finer mesh is better for large eddy simulation. In the following tests, the finer mesh (MS1) was then used.

The effects of boundary condition on eddy generation can be seen from Figures 6.16c and 6.16d and Figures 6.17c and 6.17d. Although the same fine mesh resolution was used, the value difference in $X_s$ and $T_s$ can be clearly seen under slip and non-slip boundary conditions. The value of $X_s$ is $9 \text{ m}$ under non-slip conditions (Figure 6.16d), which is $3 \text{ m}$ longer than under slip conditions. The value of $T_s$ under non-slip conditions is also $160 \text{ s}$ later than under the slip conditions (Figure 6.16d). The magnitudes of $V$ are also smaller during the eddy generation under non-slip boundary conditions. This indicates that the slip boundary condition is better for eddy generation near the MC-FP junction than the non-slip boundary condition when the other numerical simulation conditions are the same.

From Figures 6.16d and 6.16e, using the SUPG scheme, the values of $X_s$ and $T_s$ are $5 \text{ m}$ and $160 \text{ s}$ smaller than using the MOC scheme. The values of $X_f$ using the SUPG scheme is around $2 \text{ m}$, which is $5 \text{ m}$ smaller than using the MOC scheme. The magnitudes of $V$ using the SUPG scheme is the largest among all the tests. This indicates that the SUPG scheme encourages the eddy generation.

6.2.3.3 Discussions

Large eddies are usually generated under strong lateral velocity gradient and weak bed friction conditions (Chu et al. 1991). Eddy generation is a dynamic process influenced by many factors and large eddies can also be destroyed. It will take some time and a significant length for large eddies to be generated in compound channels and the proper running times and development lengths vary with cases. Numerically, periodic boundary conditions (PBC) with random disturbance at the inlet are usually applied to LES. However, the technique of imposing these boundary and initial
conditions is currently not available in TELEMAC. The running time and development length for eddy generation could be longer than using other LES codes.

The effects of mesh resolution on the eddy generation can be explained from the point of view of an energy cascade. If a larger mesh size is used, more energy will be dissipated as the sub-grid turbulence and less energy will be contained by large eddies. Meanwhile, large eddies are generated from smaller scale to larger ones gradually and some of them will be destroyed by other factors, it will take more time and longer distances to develop the eddies with characteristic length-scales larger than the grid sizes.

The effects of boundary conditions on the eddy generation can also be explained from the viewpoint of energy dissipation. If the slip boundary condition is imposed on the sidewalls, most energy will be dissipated due to the lateral shear near the MC-FP junction. On the contrary, under the non-slip condition, energy will be dissipated due to the lateral shear near the MC-FP junction and the sidewalls, so less energy will be lost near the MC-FP junction and this indicates that the shear near the MC-FP junction will be weaker than under the slip condition. In other words, large eddies are easier to generate under the slip boundary condition.

As described in Section 6.1.2.4, the MOC scheme is more advective and can induce more advection error. The characteristics of the MOC scheme make this scheme less effective in solving diffusive terms and in predicting lateral momentum exchange. The development length of eddy generation is usually larger than using other advection schemes. SUPG is less diffusive, which encourages eddy generation, and so large eddies can be generated in a shorter time period and computation length than using other advection schemes. Also the effects of the SUPG scheme on eddy generation are very clearly seen in Figures 6.16d and 6.16e and 6.17d and 6.17e.

The time step influences the stability of the numerical computation. A small time step is good for the stable numerical computation and for the gradual development of eddies. Under larger time-step conditions, it usually takes a longer time for the generation of larger eddies because larger eddies are formed by the merging of smaller eddies.
6.2.4 LES results of case STC-1

For the smooth, compound-channel case STC-1, Figures 6.18 and 6.19 show the LES results using the slip and the non-slip boundary conditions respectively. In Figure 6.18, the effect of the mesh resolution on the LES results is illustrated. In Figure 6.19, the effect of the advection scheme on the LES results is shown.

6.2.4.1 Mesh resolution

Figure 6.18a shows the distributions of the longitudinal velocity \(U\) normalised by the measured bulk velocity \(U_m\) using three mesh resolutions. It can be clearly seen that the predicted longitudinal velocity is independent of the mesh resolution in this case. The predicted velocity \(U\) profiles differ from the experimental ones. Predicted longitudinal velocities from LES are larger at \(0 < y < 0.09 \text{ m}\) and smaller at \(0.09 < y < 0.306 \text{ m}\) than the experimental ones. Under relative water depth 0.25, the velocity prediction error is similar to that of Ifuku and Shiono (2004). In this case, the MC-FP junction is located at \(y = 0.156 \text{ m}\). Bousmar (2002) also found the predicted longitudinal velocities from 2D-LES were underestimated on the floodplain and suggested that this is due to the development of helical secondary currents. As shown in Section 4.1, the measurement error was within 3%. The larger simulation error could come from the imposing of slip wall condition because the wall effect is relatively important in the narrow channels and the 2D numerical code usually works well in the wide channel cases, i.e. the aspect ratio of \(B/H\) is larger than 10. Another possible reason for the velocity prediction error in Figures 6.18 ~ 6.19 is that the lateral shear is under-predicted and the insufficient shear could be caused by the Smagorinsky model. Appropriate Smagorinsky constant requires further investigation.

Figure 6.18b shows the profiles of \(UV\) normalised by \(U^2\) using various mesh resolutions. Using the three meshes, the magnitude of \(UV\) ranges from \(-1.5 U^2\) to \(1.5 U^2\), but the trend of \(UV\) for Mesh MS1 was the closest to that of Shiono and Knight (1991) and this indicates that the mesh resolution has a big effect on the flow simulation. Finer mesh is required to capture the correct flow structures for this case.
Figures 6.18c and 6.18d show the shear stress ($\tau_{LE}$) due to large eddies and the shear stress ($\tau_{SE}$) due to the small eddies respectively. $\tau_{LE}$ and $\tau_{SE}$ are calculated with Equations 4.19a and 4.19b respectively.

$$
\tau_{LE} = \frac{1}{T} \frac{1}{L} \sum \left( U - \bar{U} \right) \left( V - \bar{V} \right) \quad \text{or} \quad \tau_{LE} = \frac{1}{T} \sum \left( U - \bar{U} \right) \left( V - \bar{V} \right) \tag{4.19a}
$$

$$
\tau_{SE} = \rho \varepsilon_{SE} \frac{\partial \bar{U}}{\partial y} \tag{4.19b}
$$

where $\varepsilon_{SE}$ is the mean sub-grid eddy viscosity.

Both kinds of shear stresses dip at the MC-FP junction indicating the strongest shear. The magnitude of $\tau_{LE}$ using 1cm mesh resolution are larger than those using coarser meshes and this can be explained by the captured characteristic eddy sizes. Using finer mesh resolutions, the characteristic size of captured large eddies covers a wider range and all the large eddies of various characteristic sizes contribute to $\tau_{LE}$, so the magnitude of $\tau_{LE}$ is larger. It can also be seen that the magnitude of $\tau_{SE}$ are smaller than 0.1 $U^2$ using various mesh resolutions. Using mesh MS1, the magnitude of $\tau_{LE}$ is about 10 times of $\tau_{SE}$. This indicates that the effect of the sub-grid eddies can be neglected in LES under this shallow-water condition, which makes the LES simpler.

Figure 6.18e shows that the predicted bed shear stress profiles are also similar to the predicted profiles of the longitudinal velocity.

Figure 6.18f shows that there is a good correlation between the free surface and the vortices, especially using the small grid size of 1cm. Large variation of the free surface can be seen near the MC-FP junction where large eddies are generated. Using larger grid size, the filter size is larger and eddies of larger sizes might be captured and then the flow variation is stronger. This indicates that the mesh size influences the variation of free surface.

As shown in Table 6.3, the mass balance values for various meshes are between 0.4% ~ 2.2%. The mass balance value is defined as the percent of the ratio of the predicted
discharge to the prescribed discharge. Although the flow is uniform, the mass balance values are higher than the normal criterion of ±1 % for RANS modelling.

Table 6.3  Mass balance values under various numerical conditions

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Slip-1cm-MOC</th>
<th>Slip-2cm-MOC</th>
<th>Slip-3cm-MOC</th>
<th>Non-slip-1cm-MOC</th>
<th>Non-slip-1cm-SUPG</th>
</tr>
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<td>Mass Balance</td>
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<td>Values (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6.2.4.2 Boundary condition

Using mesh MS1 and the MOC advection scheme, the effect of the slip and the non-slip boundary conditions on the LES results can be seen from Figures 6.18 and 6.19. The predicted longitudinal velocity using the non-slip boundary condition as shown in Figure 6.19a agrees with the experimental data better than using the slip boundary condition as shown in Figure 6.18a. Predicted bed shear stress varies in a similar manner to the predicted longitudinal velocity.

Figures 6.18c and 6.19c show that the magnitude of the shear stress due to the large eddies is only slightly larger using the slip boundary condition than using the non-slip boundary condition. The peak magnitudes of $\tau_{LE}$ at the MC-FP junction are -0.71 $U^2$ using the slip boundary condition and -0.58 $U^2$ for the non-slip condition. This is because the shear is weaker in using the non-slip boundary condition than using the slip boundary condition. From Figures 6.18b and 6.19b, the magnitude ranges of $UV$ using the slip and non-slip boundary conditions are similar.

Based on the above results, the flow prediction in case STC-1 is better using the non-slip boundary condition than using the slip boundary condition.

6.2.4.3 Advection scheme

Using mesh MS1 and the non-slip boundary condition, the effect of the advection scheme is further investigated. Figure 6.19a shows that the longitudinal velocity is better predicted in the main channel and $y < 0.2$ m on the floodplain using the SUPG
scheme than using the MOC scheme. As the main channel conveys the major portion of the channel discharge, the velocity is better predicted using the SUPG scheme than using the MOC scheme.

Figure 6.19c shows that the peak magnitude of the predicted $\tau_{le}$ using the SUPG scheme is about two times larger than that using the MOC scheme. Figure 6.19d shows that the magnitudes of the predicted $\tau_{se}$ using the SUPG and the MOC schemes are almost the same. The shear stresses due to the large eddies and the small eddies consist of the apparent shear stress. The sum of $\tau_{le}$ and $\tau_{se}$ at the MC-FP junction using the SUPG scheme better matches the calculated value of Reynolds stress as shown in Figure 4.14. The magnitude ranges of $UV$ using the SUPG and the MOC schemes are similar.

Figure 6.19e shows that the bed shear stress is better predicted near the MC-FP junction and this indicates that the flow characteristics due to large eddies can be better captured by using the SUPG scheme.

Figure 6.19f shows that the time-averaged free surface fluctuates also across the section and the variation is stronger for SUPG scheme than for MOC scheme. Table 6.3 shows that the mass balance is better for SUPG scheme than for MOC scheme. This coincides with the statements in Section 6.1.2.4. Using MOC scheme, the mass balance is better for the non-slip condition than for the slip condition in this case.

In conclusion, the above results indicate that the SUPG scheme is better than the MOC scheme in this case. The SUPG scheme is used in the following LES cases.

6.2.5 LES results for the smooth FCF case 020201

For the FCF case 020201, the channel is wide and the sidewalls have little effect on the numerical simulation results (Bousmar 2002), so the slip boundary condition was used in this case. To obtain the mean value of the flow variable, the computation length was selected as 10 m ($x = 45 - 55m$) and the time period was selected as 50 s ($t = 450 - 500 s$).
Figure 6.20a shows that the mean values of U are larger in the main channel and smaller on the floodplain than the experimental data which is similar to Bousmar (2002). The slope of the predicted U profile near the MC-FP junction is steeper than that from experimental data and this indicates that less momentum-exchange took place in LES for this case. The predicted bed shear stress profile as shown in Figure 6.20b is similar to that of the longitudinal velocity.

Figure 6.20c shows the shear stresses due to large eddies and small eddies and measured Reynolds shear stresses. The space-time averaging of velocities u and v gives good predictions of the shear stresses. The highest values of $\tau_{LE}$ appeared close to the MC-FP junction. Although the predicted and measured values are slightly different, they are of the same magnitude.

6.3 LES for the vegetated, compound-channel flow
6.3.1 Emergent vegetation case
6.3.1.1 Spatial flow fluctuations

Unlike the smooth compound channel, large eddy generation was first concerned with the wake generation around the emergent rods and above the submerged rods and then on the eddy generation in the main channel and on the floodplain.

To study the wake generation for the emergent-rod case STC-4, a fine mesh of uniform grid size 0.005 m as shown in Figure 6.3a was constructed for a small computation domain with a length of 1 m. Figures 6.21a - 6.21d show the velocity fields between $t=0.1$ s and $t=3$ s. When the flow goes through the rods, wakes are formed near the rods (Figure 6.21a) and the wavy velocity field is visible near the rods (Figures 6.21b). As the simulation runs (Figures 6.21c - 6.21d), the flow goes alternately from the main channel to the floodplain and from the floodplain to the main channel.

Figures 6.22a - 6.22g show the instantaneous profiles of the velocity vector, vorticity, velocity, bed shear stress and free surface at $t=495$ s for case STC-4. Figure 6.22a shows the meandering-flow pattern becomes regular in the main channel, around the rods and on the floodplain (Figure 6.22a). From Figures 6.22a and 6.22c, the higher
velocity $U$ occurs in the centre regions of the main channel and the floodplain, while the lower velocity $U$ occurs around the emergent rods and near the wall regions.

Figure 6.22d shows that positive and negative values for velocity $V$ occur alternately and this indicates the existence of periodic motions, but the highest magnitude of velocity $V$, which corresponds to the strongest shear, occurs at the central parts of the main channel and the floodplain as well as around the rods. In the smooth case STC-1, the highest magnitude of velocity $V$ only occurs at around the MC-FP junction.

Figure 6.22b shows the spatial distribution of the vorticity. Positive and negative vorticities occur alternately along the rods and this corresponds to the flow moving pattern in this region. In the left main channel and on the right floodplain, the vorticity is positive which corresponds to the distributions of $U$ and $V$. On the contrary, in the right main channel and on the left floodplain, the vorticity is negative.

Figure 6.22e shows that the secondary current term $UV$ varies in a similar manner to the velocity $V$, so the distribution of this term in the emergent case STC-4 is different to that in the smooth case STC-1. However, the secondary current term $UV$ varies in a similar manner to that of the velocity $V$ and this indicates that the velocity $V$ is also decisive for the secondary current term, which is the same as for the smooth case STC-1. Figure 6.22f shows that the bed shear stress is higher in the centre regions of the main channel and the floodplain and lower around the rods. This indicates that the emergent rods also make the bed shear stress distribution different to that in the smooth case STC-1 and this difference is caused by the drag effect.

Figure 6.22g shows that the fluctuation of the free surface is also different to that in the smooth case STC-1. In this emergent case, the lower and higher values of the free surface occur alternately in the centre region of the main channel and the floodplain, as well as around the rods, while in the smooth case STC-1, the lower and higher values of the free surface only occur alternately around the MC-FP junction edge.

In conclusion, the emergent rods along the MC-FP greatly influence the 2D flow pattern and make the flow characteristics totally different to those in the smooth compound channel.
6.3.1.2 Temporal flow fluctuations

Figures 6.23 and 6.24 show the respective time series of the longitudinal velocity (U) and the lateral velocity (V) across the section 8.6 m downstream from the inlet. In these figures, the velocity is normalised by the local time-averaged longitudinal velocity ($U_{m0}$). From Figure 6.23, the variation range of $U/U_{m0}$ decreases from 33 ~ 183 % at $y = 0.015$ m, reaches the lowest range of 86 ~ 122 % at $y = 0.075$ m, then increases and reaches the highest range of -10 ~ 400 % at $y = 0.171$ m, then decreases again and reaches the lower range of about 65 ~ 135 % at $0.231 < y < 0.306$ m. The trend of the variation of $U/U_{m0}$ is reasonable in physics. Near the sidewall of the main channel, the wall effect generates a narrow shear zone and the shear strength decreases as the magnitude of the velocity gradient $\partial U/\partial y$ decreases gradually as the lateral distance ($y$) increases, so the fluctuation of U becomes lower as $y$ increases. In the centre region of the main channel, the velocity reaches its maximum and the magnitude of $\partial U/\partial y$ approaches zero, so the shear is zero and the fluctuation of U is the lowest. As $y$ increases from the centre region of the main channel towards the MC-FP junction, the magnitude of $\partial U/\partial y$ increases gradually and the shear becomes stronger, so the fluctuation of U becomes higher towards the MC-FP junction. Near the rods, the strong wake is generated and the fluctuation of U becomes the highest. As $y$ increases further, the magnitude of $\partial U/\partial y$ decreases, the shear becomes weaker and then the fluctuation of U becomes lower. The trend of the variation of the $V/U_{m0}$ as shown in Figure 6.24 is similar to that of $U/U_{m0}$.

Based on the time series data for the velocity U, the characteristic time scale can be determined using the same method described in Section 6.2.2.3. The time scales at various lateral locations are similar and the mean time scale is 2.32 s. The characteristic frequency is 0.431 Hz. Based on the time series data of the velocity V, the results are almost the same and the characteristic frequency is 0.435 Hz. These frequencies are consistent with those in the literature as reviewed in Chapter 2.

6.3.1.3 Mean parameters

Figure 6.25 shows the LES results of mean parameters at $x = 8.6$ m, where the experimental measurements were undertaken, for the emergent rod case STC-4 and
the no-rod case STC-3. In Figure 6.25, the velocity $U$ is normalised by the measured bulk velocity $U_m$, the secondary current term ($-\rho UV$), the shear stresses due to large eddies ($\tau_{LE}$) and small eddies ($\tau_{SE}$) and the bed shear stress ($\tau_b$) are normalised by the measured overall boundary shear stress ($\tau_{b0}$).

In Figure 6.25a, the predicted $U$ profile for the rod case STC-4 does not agree well with the experimental one, but the predicted $U$ profile for no rod case STC-3 agrees better with the experimental one. The disagreement of velocity $U$ in case STC-4 could be caused by the imposing of the non-slip boundary condition. In case STC-4, the emergent rods were modelled with vertical walls and the non-slip boundary condition was imposed on these rods, so the velocity near the rods is very small and even approaches zero, as a result, the velocities in the centre regions of the main channel and the floodplain are larger than the measured ones. It can also be seen from Figure 6.25a that the slope of the velocity profile near the rods is steeper than the measured one, which indicates less momentum exchange in LES.

Figure 6.25b shows the profiles of $-\rho UV$ normalised by $\tau_{b0}$ in cases STC-4 and STC-3. In the main channel, the secondary current term ($-\rho UV$) decreases linearly from the left wall to around $y = 0.12$ m, which indicates that a large, clockwise, secondary cell might exist in this region. The secondary current term ($-\rho UV$) decreases sharply from $y = 0.12$ m towards the rods and arrives at a negative peak of $-41 \tau_{b0}$ at the MC-FP junction, then it increases and arrives at a positive peak of $23 \tau_{b0}$ at $y = 0.171$ m, then decreases sharply again from $y = 0.171$ m to 0.20 m. The sharp change of $-\rho UV$ in the region $0.12$ m < $y$ < $0.20$ m is caused by the strong eddies and the wakes together. On the floodplain, the secondary current term ($-\rho UV$) decreases linearly from around $y = 0.20$ m to the right wall, which indicates that a large, counter-clockwise secondary cell might exist in this region. The peak values of $-\rho UV$ are much bigger than those in the no-rod case STC-3 and in other literature (i.e. Shiono & Knight 1991), which indicates that there are stronger eddies and wakes around the rods.
Figure 6.25c shows that the profiles of the shear stress ($\tau_{LE}$) due to the large eddies normalised by $\tau_{bo}$ in cases STC-4 and STC-3 are similar to those of $-\rho UV$. The trends of $\tau_{LE}$ are caused by the shear due to large eddies and wakes. The negative value of $\tau_{LE}$ in the main channel side and the positive value of $\tau_{LE}$ in the floodplain side indicate that there are two shear layers generated in this case. The peak magnitudes of $\tau_{LE}$ near the rods indicate that the shear strength reaches the maximum around the rod position, like an imaginary wall. The value of $\tau_{LE}$ in case STC-3 is nearly zero and this indicates that the shear due to the large eddies is very weak in this case.

Figure 6.25d shows the profiles of the shear stress ($\tau_{SE}$) due to the small eddies normalised by $\tau_{bo}$ in cases STC-4 and STC-3. The magnitudes of $\tau_{SE}$ are much smaller than those of $\tau_{LE}$ as shown in Figure 6.25c, except near the wall regions where the velocity gradient $\partial U/\partial y$ is steep.

Figure 6.25e shows that the predicted bed shear stress ($\tau_b$) varies in a similar manner to that of the predicted velocity $U$.

### 6.3.2 Submerged vegetation case

#### 6.3.2.1 Effect of mesh resolution on LES results

As explained in Section 6.1.2.2, the vertical walls of submerged rods are usually replaced by steeply sloping ones with the angle between the wall and the bed being in excess of 85°. This wall treatment technique imposes mesh generation difficulties. To better generate large eddies, the steepness of the sloped sides has to be investigated before final 2D-LES simulation.

One submerged square rod with a width of 6 cm and a height of 10 cm was put near the MC-FP junction on the floodplain of the large compound channel as shown in Figure 3.12c. The water depth on the floodplain was 0.16m. Seven different meshes, as shown in Figure 6.4, were generated for LES. In the test LES simulations, an MOC scheme was used with a time step of 0.0025 s. Figures 6.26 and 6.27 show the velocity fields and streamwise profiles of the free surface around the submerged rod at
t = 80 s. The velocity fields and the free surface profiles did not change much after t = 80 s, so the results at t = 80 s are presented here.

Figures 6.26a ~ 6.26c show that the velocity vectors behind the submerged rod are random, even when very fine meshes were used on the top of the rod. Figure 6.26d shows the random velocity vector behind the rod using mesh M5d as shown in Figure 6.5. Figure 6.22f also shows the random velocity vector behind the rod. This is because the mesh resolutions around the rod in these five meshes differ greatly, which causes unstable numerical computations.

Figures 6.26e ~ 6.26g show the velocity vectors behind the submerged rod using meshes M5e ~ M5g. The velocity vectors are random only in a very small area behind the submerged rod, especially using mesh M5g. As the water depths above and below the rod top are 5 cm and 10 cm respectively, the longitudinal velocity (U) is much higher above the rod top than below the rod top, so the random vector could exist in a very small area behind the rod. In these two meshes, the mesh resolutions decrease gradually from outside the rod to on the rod surface, which enables stable simulation.

Figures 6.27a ~ 6.27c show the longitudinal profiles of the free surface using seven different meshes. Meshes M5a and M5c give the largest deviation of the free surface profile; the other four meshes give similar free surface profiles. As shown in these three figures, the free surface increases slightly in front of the submerged rod due to the flow being blocked by the submerged rod, and it decreases sharply above the rod behind the rod and then increases again. The wakes behind the submerged rod lead to local backwater (Ferziger 2001) and these wakes could reduce the longitudinal velocity behind the rods and increase the water level again. The trends of predicted free surface profiles are similar to the experimental profile, but the magnitude differences between the simulated and experimental data are obvious above and behind the submerged rods. The mesh M5g gives the smallest difference among the seven meshes.

Based on the above primary results, among the seven different meshes, mesh M5g gave the best prediction of the results hence the mesh resolution of mesh M5g was then used to generate the mesh for case LC-4.
6.3.2.2 Spatial flow fluctuations

Figure 6.28 shows the instantaneous profiles of the velocity vector, velocity $u$, velocity $V$, vorticity and free surface using the SUPG scheme at $t = 602.5$ s, which is the time 350 s after the eddy generation, in the submerged-rod case LC-4.

Figure 6.28a shows the meandering velocity vector fields in the main channel and on the floodplain occupied by the submerged rods. When the flow approaches the submerged rods, it is separated into several parts, some flow moves through the rod surface whilst some of the flow changes its direction and moves through the gap between two rods. The flow moves from the left to the right of the rod and from the right to the left of the rod alternately and this flow movement pattern forms the meandering velocity vector fields on the floodplain. Figure 6.28a shows that the magnitudes of the velocity vector above and just behind the submerged rods are much larger than in the other areas around the rods, and Figure 6.28b further shows that the longitudinal velocities are larger above the rods than in the other areas around the rods. This velocity difference is caused by the rod effect. In one submerged-rod test, the free surface increases in front of the rod and decreases above and behind the rod. As a result, the longitudinal velocity $U$ decreases in front of the rod and increases above and behind the rod. In the submerged-rod case LC-4, the free surface varies in a similar but more complex manner to the single-rod case, which can be seen from the free surface profile as shown in Figure 6.28e. From Figure 6.28e, the free surface over the rods is relatively lower than outside the rods, which is similar to the results for the single submerged-rod case.

Corresponding to the velocity vector near the rods, the vorticity values (Figure 6.28d) around the rods vary greatly and these are resulted from the rod wakes. The wakes can be easily seen from the lateral velocity profile as shown in Figure 6.28c, as the positive and negative lateral velocities existing alternately around the rods.

6.3.2.3 Temporal flow fluctuations

Figures 6.29 and 6.30 show the respective time series of the normalised longitudinal velocity ($U/U_{m0}$) and the normalised lateral velocity ($V/U_{m0}$) across the section 6.4m downstream from the inlet. $U_{m0}$ is the time-averaged longitudinal velocity. In
case LC-4, the experimental measurements were carried out at 6.4 m downstream from the channel inlet.

From Figure 6.29, the variation range of $U/U_{m0}$ increases gradually from 93 - 108% at $y = 0.1 \text{ m}$ to 85 - 115% at $y = 0.40 \text{ m}$, and increases rapidly to 70 - 144% at the MC-FP junction ($y = 0.55 \text{ m}$), then increases to the highest range of 58 - 149% above the submerged rod at $y = 0.725 \text{ m}$. The trend of the variation of $U/U_{m0}$ is reasonable in physics. The longitudinal velocity $U$ peaks at around $y = 0.10 \text{ m}$, so the weakest shear occurs here and the fluctuation of $U$ is the lowest in the channel. The velocity gradient $\partial U/\partial y$ increases gradually as the lateral distance ($y$) increases, so the fluctuation of $U$ becomes higher as $y$ increases. It can be seen from Figures 6.29e and 6.29f that the fluctuation of $U$ at $y = 0.72 \text{ m}$ becomes the highest in the channel and this is caused by the strong wakes generated above the rods. As $y$ increases further, the fluctuation of $U$ becomes lower and this is because the wakes become weaker away from the rods. The variation of the velocity $V$, as shown in Figure 6.30, is similar to that of velocity $U$.

Using the same method described in Section 6.2.2.3, the characteristic time scale and frequency were determined as 2.80 s and 0.36 Hz based on the time series data of the velocity $U$. Based on the time series data of the velocity $V$, the results are almost the same and the characteristic frequency is 0.42 Hz. These frequencies are also consistent with those in the literature as reviewed in Chapter 2.

### 6.3.2.4 Mean parameters

Figure 6.31 shows the LES results for the mean parameters for the submerged-rod case, LTC-4, and the smooth case, LC-2, under a relative water depth $Dr = 0.50$. In these figures, the velocity $U$ is normalised by the measured bulk velocity whilst the secondary current term ($\rho UV$), the shear stresses due to the large eddies ($\tau_{LE}$) and the shear stress due to the small eddies ($\tau_{SE}$) are each normalised by the measured overall boundary shear stress ($\tau_{bo}$).

Figure 6.31a shows the lateral distributions of longitudinal velocity $U$ for cases LC-2 and LC-4. For case LC-4, the velocity is well predicted in the main channel and the trend of the predicted velocity on the floodplain is similar to the experimental one. For
case LC-2, the velocities were better predicted in the main channel, but slightly overestimated on the floodplain and this could be due to the unpredicted secondary currents under deep conditions.

Figure 6.31b shows that the secondary current term ($\rho UV$) in the submerged-rod case LC-4 is similar to that in the no-rod case LC-2 in the left main channel and on the right floodplain, but it is different near the MC-FP junction region and the submerged rods. The peak magnitude near the rods is as large as $2.5 \tau_{bo}$ in case LC-4, which is four times larger than that in case LC-2. This indicates that the submerged rods have an important effect on the secondary currents and mainly influence them near the rods.

Figure 6.31c shows the distributions of the shear stress ($\tau_{LE}$) due to the large eddies in cases LC-4 and LC-2. For case LTC-4, the shear stress $\tau_{LE}$ is well predicted, although the magnitude near the MC-FP junction is slightly smaller than the measured one. For case LTC-2, the values of $\tau_{LE}$ using the MOC scheme were almost zero and this indicates that there were no recognised large eddies in this case.

Figures 6.31d shows the lateral distributions of $\tau_{LE}$ and $\tau_{SE}$ in case LC-4. In this case, the shear stress due to the small eddies is much smaller than that due to the large eddies and this indicates that the effect of the small eddies on the shear stress can be neglected in this submerged-rod case.

### 6.4 Summary

Large eddy generation was systematically investigated in this chapter. Large eddies are associated with significant fluctuations of velocity, vorticity and free surface or water depth. The mesh resolution, advection scheme and boundary conditions have an important role in generating large eddies. Fine mesh resolution, SUPG scheme and the slip boundary condition encourage large-eddy generation. The effects of large eddies on hydraulic behaviours such as wavy distributions of velocity, free surface and bed shear stress were also analysed and the maximum value of the flow parameter was larger than the mean value.
Large eddy simulations with TELEMAC-2D were performed for case STC-1 and the simulation results under various numerical conditions were compared. As a result, mesh resolution and advection schemes were found to greatly influence the LES results. LES results for the FCF case 020201 agreed well with the experimental data.

Compared with the smooth, deep case, the shear effects in the emergent-rod case were underestimated by LES with TELEMAC-2D, but the main hydraulic behaviours were well captured. The hydraulic behaviours in a compound channel with submerged rods on the floodplain were satisfactorily predicted using LES with TELEMAC-2D. The predicted values for the depth-averaged velocity and the shear stress due to large eddies using the SUPG scheme agreed well with the experimental data.

From the above analysis and conclusions, LES with TELEMAC-2D can be used to predict the 2D unsteady flow characteristics in large channels.
Figure 6.1  Meshes for case STC-1. (a) Mesh MS1 of resolution 1cm; (b) Mesh MS2 with resolution 2cm; (c) Mesh MS3 of resolution 3cm.

Figure 6.2  Mesh FCF4 for case FCF 020201.
Figure 6.3   Meshes for case STC-4. (a) Fine mesh of resolution 0.5cm; (b) Coarse mesh.
Figure 6.4  Meshes M5a–M5g for one submerged rod case LTCT. (a) Mesh M5a; (b) Mesh M5b; (c) Mesh M5c; (d) Mesh M5d; (e) Mesh M5e; (f) Mesh M5f; (g) Mesh M5g.
Figure 6.5  Mesh M6 for submerged rod case LC-4.

Figure 6.6  Mesh M7 for non-vegetated case LC-2.
Figure 6.7  Velocity fields between 30 s and 150 s for STC-1 case. (a) 30s; (b) 50s; (c) 100s; (d) 150s. Horizontal axis represents the longitudinal distance $x$ from the channel inlet. Vertical axis $y$ represents the lateral distance from the left channel wall.
Figure 6.8 Velocity fields in a moving frame between 30 s and 150 s for STC-1 case. (a) 30s; (b) 50s; (c) 100s; (d) 150s. Horizontal axis represents the longitudinal distance $x$ from the channel inlet. Vertical axis $y$ represents the lateral distance from the left channel wall.
Figure 6.9 Vorticity fields between 30 s and 150 s for STC-1 case. (a) 30 s; (b) 50 s; (c) 100 s; (d) 150 s. Horizontal axis represents the longitudinal distance $x$ from the channel inlet. Vertical axis $y$ represents the lateral distance from the left channel wall.
Figure 6.10 2D profile perspective graphs of U, V and Ω at the MC-FP junction between t = 450 s and t = 455 s for STC-1 case. (a) velocity U; (b) Velocity V; (c) Vorticity; (d) Free Surface; (e) Water Depth.
Figure 6.11  Velocity fields in a moving frame between 450 s and 453 s for STC-1 case. (a) 450s; (b) 451s; (c) 452 s; (d) 453s. Horizontal axis represents the longitudinal distance $x$ from the channel inlet. Vertical axis $y$ represents the lateral distance from the left channel wall.
Figure 6.12  Spatial distributions of $U$, $V$, $\Omega$, free surface and bed shear stress at $t = 450$ s for case STC-1. (a) Velocity $U/U_m$; (b) Velocity $V/U_m$; (c) Vorticity; (d) Free Surface; (d) Bed Shear Stress $\tau_b/\tau_{bm}$. Horizontal axis represents the longitudinal distance $x$ from the channel inlet. Vertical axis $y$ represents the lateral distance from the left channel wall.
Figure 6.13  Variations of velocity U, velocity V, vorticity, bed shear stress and water depth at MC-FP junction at t = 450 s for STC-1 case. (a) Vector in a moving frame and vorticity; (b) $100\Theta h / U_{m0}$; (c) $U / U_{m0}$, $V / U_{m0}$, $\tau_b / \tau_{m0}$; (d) $\rho UV / \tau_{m0}$; (e) $H / H_{m0}$. 
Figure 6.14  Temporal variations of velocity, bed shear stress, water depth and secondary current term at point A (8.6, 0.156) between 450 s and 463 s. (a) $U/U_{m0}$, $V/U_{m0}$, $\tau_b/\tau_{m0}$; (b) $\rho UV/\tau_{m0}$; (c) $H/H_{m0}$. 
Figure 6.15  Velocity fields in a moving frame at $t = 525$ s for case STC-1. (a) Time step 0.0025s; (b) Time step 0.005s; (c) Time step 0.01s. Horizontal axis represents the longitudinal distance $x$ from the channel inlet. Vertical axis $y$ represents the lateral distance from the left channel wall.
Figure 6.16 V variations at the start period of eddy generation under various simulation conditions. (a) 3cm, Slip, MOC, 40s; (b) 2cm, Slip, MOC, 40s; (c) 1cm, Slip, MOC, 40s; (d) 1cm, Non Slip, MOC, 20s; (e) 1cm, Non Slip, SUPG, 40s.
Figure 6.17 V variations at 300s after eddy generation under various simulation conditions. (a) 3cm, Slip, MOC, 450s; (b) 2cm, Slip, MOC, 450s; (c) 1cm, Slip, MOC, 450s; (d) 1cm, Non Slip, MOC, 450s; (e) 1cm, Non Slip, SUPG, 450s.
Figure 6.18  LES simulation results of different mesh resolutions for case STC-1. (a) $U/U_m$; (b) $UV/U^2$; (c) $\tau_{LE}/\rho U^2$; (d) $\tau_{SE}/\rho U^2$; (e) $\tau_u/\tau_0$; (f) Free surface.
Figure 6.19  LES simulation results of different advection scheme for case STC-1. (a) $U/U_m$; (b) $UV/U^2$; (c) $\tau_{LE}/\rho U^2$; (d) $\tau_{SE}/\rho U^2$; (e) $\tau_b/\tau_0$; (f) Free surface.
Figure 6.20  LES simulation results for FCF case 020201. (a) Depth-averaged velocity; (b) Bed shear stress; (c) Reynolds shear stress.
Figure 6.21  Velocity fields around emergent rods in case STC-4. (a) 0.2 s; (b) 1 s (c) 2 s; (d) 3 s. Horizontal axis represents the longitudinal distance x from the channel inlet. Vertical axis y represents the lateral distance from the left channel wall.
Figure 6.22  Instantaneous profiles of velocity vector, vorticity, velocity $U$, velocity $V$, $UV$, bed shear stress and free surface at $t = 495$ s for case STC-4. (a) Velocity vector; (b) Vorticity; (c) Velocity $U$; (d) Velocity $V$; (e) Secondary current term $UV$; (f) Bed shear stress; (g) Free surface.
Figure 6.23 Variations of longitudinal velocity $U/U_{m0}$ across the section for Case STC-4. (a) $Y = 0.015 - 0.060$ m; (b) $Y = 0.075 - 0.120$ m; (c) $Y = 0.1306 - 0.1710$ m; (d) $Y = 0.1860 - 0.2310$ m; (e) $Y = 0.2460 - 0.2910$ m.
Figure 6.24 Variations of lateral velocity $V/U_{m0}$ across the section for Case STC-4. (a) $Y = 0.015 \sim 0.060$ m; (b) $Y = 0.075 \sim 0.120$ m; (c) $Y = 0.1306 \sim 0.1710$ m; (d) $Y = 0.1860 \sim 0.2310$ m; (e) $Y = 0.2460 \sim 0.2910$ m.
Figure 6.25  2D-LES simulation results of cases STC-4 and STC-3. (a) $U/U_m$ ; (b) $-\rho UV/\tau_{b0}$ ; (c) $\tau_{LE}/\tau_{b0}$ ; (d) $\tau_{SE}/\tau_{b0}$ ; (e) $\tau_b/\tau_{b0}$ .
Figure 6.26   Longitudinal profiles of the velocity field using different meshes for the test submerged-rod case. (a) Mesh M5a; (b) mesh M5b; (c) Mesh M5c; (d) mesh M5d; (e) Mesh M5e; (f) mesh M5f; (g) mesh M5g. Horizontal axis represents the longitudinal distance \( x \) from the channel inlet. Vertical axis \( y \) represents the lateral distance from the left channel wall.
Figure 6.27 Longitudinal profiles of the free surface using different meshes for the test submerged-rod case. (a) Meshes M5a ~ M5c; (b) Meshes M5d ~ M5e; (c) Meshes M5f ~ M5g.
Figure 6.28 Instantaneous profiles of velocity vector, vorticity and free surface at $t = 602.5$ s for submerged rod case LC-4. (a) Velocity vector; (b) Velocity U; (c) Velocity V; (d) Vorticity; (e) Free surface. Horizontal axis represents the longitudinal distance $x$ from the channel inlet. Vertical axis $y$ represents the lateral distance from the left channel wall.
Figure 6.29 Variations of longitudinal velocity $U/U_0$ in case LC-4. (a) $Y = 0.10 \sim 0.16$ m; (b) $Y = 0.22 \sim 0.28$ m; (c) $Y = 0.34 \sim 0.40$ m; (d) $Y = 0.47 \sim 0.51$ m; (e) $Y = 0.55 \sim 0.59$ m; (f) $Y = 0.63 \sim 0.73$ m; (g) $Y = 0.81 \sim 0.85$ m.
Figure 6.30 Variations of longitudinal velocity $V/U_{m0}$ in case LC-4. (a) $Y = 0.10 - 0.16$ m; (b) $Y = 0.22 - 0.28$ m; (c) $Y = 0.34 - 0.40$ m; (d) $Y = 0.47 - 0.51$ m; (e) $Y = 0.55 - 0.59$ m; (f) $Y = 0.63 - 0.73$ m; (g) $Y = 0.81 - 0.85$ m.
Figure 6.31  2D-LES simulation results of cases LC-4 and LC-2. (a) $U/U_m$ ; (b) $UV/U^2$ ; (c) $\tau_{LE}/\rho U^2$ ; (d) $\tau_{LE}/\rho U^2$, $\tau_{SE}/\rho U^2$. 
Chapter 7
Quasi-2D Flow Prediction for Vegetated, Compound, Open Channels

In this chapter, the main results of a quasi-2D flow model are presented. Section 7.1 introduces the quasi-2D flow model. Sections 7.2 and 7.3 show the flow prediction results of the non-vegetated and vegetated compound channels. Section 7.4 summarises the quasi-2D flow prediction for the compound channel.

7.1 Governing equations and solutions

7.1.1 Governing equations

Based on the momentum equation given by Shiono and Knight (1991), the momentum equation in the longitudinal direction for steady, uniform flow in the compound, open channel is given by Equation 7.1

\[
\rho \left[ \frac{\partial \bar{U} \bar{V}}{\partial y} + \frac{\partial \bar{U} \bar{W}}{\partial z} \right] = \frac{\partial}{\partial y} (\rho \bar{\mu} \bar{V}) + \frac{\partial}{\partial z} (\rho \bar{\mu} \bar{W}) - \rho g S_o + S_x
\]  

(7.1)

where \( x, y, z \) are the longitudinal, lateral and vertical directions respectively; \( \bar{U}, \bar{V}, \bar{W} \) are the temporal mean velocity components (m/s) in the \( x, y, z \) directions respectively; \( u, v, w \) are turbulent fluctuations of velocity (m/s) with respect to the mean velocities; \( \rho \) is the density of water; \( g \) is the gravitational acceleration; \( S_o \) is the bed slope of the channel and \( S_x \) is the source term.

Providing \( \bar{W}(H) = \bar{W}(0) = 0 \), Equation 7.1 can be transformed into Equation 7.2 by integrating over the water depth,

\[
\frac{\partial}{\partial y} \left[ H(y)(\rho \bar{U} \bar{V})_d \right] = (\rho g S_o - S_x)H(y) - \tau_b \sqrt{1 + s^{-2}} + \frac{\partial(H(y)\bar{\tau}_{yx})}{\partial y}
\]  

(7.2)

where \( \tau_b \) is the bed shear stress; \( H(y) \) is the local water depth; \( (\rho \bar{U} \bar{V})_d = \frac{1}{H(y)} \int_0^{H(y)} \rho \bar{U} \bar{V} dz \) and \( \bar{\tau}_{yx} = \frac{1}{H(y)} \int_0^{H(y)} (\rho \bar{\mu} \bar{V}) dz \).

The bed shear stress \( \tau_b \) can be determined from Equation 7.3,
\[ \tau_b = \frac{f}{8} \rho U_d^2 \]  

(7.3)

where \( f \) is the local friction factor, \( U_d \) is the depth-averaged longitudinal velocity and \( s \) is the bank slope (1: \( s \) - vertical : horizontal).

The depth-averaged Reynolds shear stress \( \overline{\tau_{xy}} \) can be related to the depth-averaged eddy viscosity \( (\overline{\epsilon_r}) \) and the velocity gradient \( (\partial U_d / \partial y) \) by Equation 7.4,

\[ \overline{\tau_{xy}} = \rho \overline{\epsilon_r} \frac{\partial U_d}{\partial y} \]  

(7.4)

As described in Section 4.4.1, when the contributions of bed-generated turbulence and shear-generated turbulence to the eddy viscosity \( (\overline{\epsilon_r}) \) are both considered, the depth-averaged Reynolds shear stress \( (\overline{\tau_{xy}}) \) can be expressed by Equation 7.5,

\[ \overline{\tau_{xy}} = \rho \left[ \alpha_{\text{ib}} \left( \frac{f}{8} \right) U_d H(y) + \frac{H_m}{H(y)} (\beta \delta)^2 \left( \frac{\partial U_d}{\partial y} \right) \right] \frac{\partial U_d}{\partial y} \]  

(7.5)

where \( \alpha_{\text{ib}} \) is the depth-averaged dimensionless eddy viscosity due to bed-generated turbulence, \( H(y) \) is the local water depth, \( H_m \) is the mean value of water depths in the main channel and on the floodplain, \( \beta \) is the proportionality constant (≈0.08), \( \delta \) is the width of the shear layer.

Substituting Equation 7.3 and 7.5 into 7.2 gives,

\[ \frac{\partial}{\partial y} \left[ H(y) \left( \rho \overline{U V} \right)_d \right] = (\rho g S_0 - S_x) H(y) - \frac{f}{8} \rho \sqrt{1 + \frac{1}{s^2} U_d^2} \]

\[ + \frac{\partial}{\partial y} \left\{ \rho H(y)^2 \left[ \alpha_{\text{ib}} \left( \frac{f}{8} \right)^2 U_d + \frac{H_m}{H(y)^2} (\beta \delta)^2 \left( \frac{\partial U_d}{\partial y} \right) \right] \frac{\partial U_d}{\partial y} \right\} \]  

(7.6)

Rameshwaran and Shiono (2006) developed the numerical solution to the above nonlinear equation and predicted the two-dimensional flow structures in the compound channels with and without emergent vegetation on the floodplain. In this study, the
predictive capability of this numerical solution is further assessed against experimental data for a compound open channel with submerged vegetation on the floodplain.

### 7.1.2 Source term for vegetated flow

For the non-vegetation case, the source term $S_x$ is zero and Equation 7.6 takes a similar form to that of Shiono and Knight (1991).

For the emergent vegetation case, the source term $S_x$ in Equation 7.6 is drag forces per unit water volume, which results from various vegetations, and can be modelled with Equation 7.7:

$$S_x = \sum F_{ei} = \sum \frac{1}{2} \rho (C_D S_F A_p) \alpha_d U_d^2$$

(7.7)

where $F_{ei}$ is the drag force of $i$ vegetation per unit fluid volume, $C_D$ is the drag coefficient, $S_F$ is the shading factor, $A_p$ is the total projected area of $i$ vegetation per unit fluid volume.

For the submerged case, the source term $S_x$ in Equation 7.6 is composed of the drag force $\sum F_{ei}$ due to the projected area and the interface shear force $\sum F_{si}$ due to the vegetation top area. Figure 7.1 illustrates the drag force and interface shear force on a submerged circular rod. The shear force $\sum F_{si}$ can be expressed in a similar way to the drag force $\sum F_{ei}$. Velocity correction factors $\alpha_e$ and $\alpha_s$ were introduced to relate the characteristic velocities to the drag force $\sum F_{ei}$ and the shear force $\sum F_{si}$ respectively. The drag force $\sum F_{ei}$ and the shear force $\sum F_{si}$ can be expressed by Equations 7.8 and 7.9 respectively:

$$\sum F_{ei} = \sum \frac{1}{2} \rho (C_D S_F A_p) \alpha_s U_d^2$$

(7.8)

$$\sum F_{si} = \sum \rho (C_s A_s) \alpha_s U_d^2 = 2 \left( \frac{C_s}{C_D} \frac{A_s}{A_p} \frac{1}{S_F} \right) (\alpha_s^2) \sum F_{ei}$$

(7.9)
where $C_{sc}$ is the interface shear coefficient and $A_s$ is the total horizontal area of $i$ vegetation.

For simplification, the source term $S_x$ in the submerged case can be expressed by introducing an apparent drag coefficient $C_D'$ as follows,

$$S_x = \frac{1}{2} \rho (C_D' S_F A_F) U_d^2$$

$$C_D' = C_D + 2 \left( \frac{C_s A_s}{C_D A_F S_F} \right) \left( \frac{\alpha_s}{\alpha} \right)^2$$

### 7.1.3 Input model parameters

In order to solve Equation 7.6 for depth-averaged velocity $U_d$, the channel geometry, boundary conditions, drag coefficient $C_D$ or apparent drag coefficient $C_D'$, shading factor $S_F$, porosity $\alpha_s$, local friction factor $f$, eddy viscosity and advection term $\Gamma$ are required as input data.

#### 7.1.3.1 Channel geometry and boundary conditions

Channel bed levels across the section and water depth in the main channel are required as channel geometry and initial conditions.

In the past, velocity was set to zero at walls for the boundary conditions; however, this does not give an accurate velocity near the wall. To avoid this weakness, a new concept for the calculation of the mean wall velocity ($U_{wall}$) is introduced. The $y$-coordinate $y^*$ normalised by the viscous length $v/U_{wall}$ was set to 30 in order to determine the mean wall velocity (Nezu & Nakagawa 1993). The mean wall velocity can be determined using the measured data of mean wall shear stress ($\tau_{wall}$) by the use of Equation 7.11.

$$U_{wall} = 2.5(\ln(30)+5.5)U_{*,wall}$$

where $U_{*,wall}$ is the mean wall shear velocity ($=\sqrt{\tau_{wall}/\rho}$).
7.1.3.2 Vegetation parameters

To account for the blockage effects on the flow by the vegetation, the porosity $\alpha_v$ was introduced and determined by using Equation 7.12. In this study, the porosity $\alpha_v$ for the submerged-rod experiments is 0.906.

$$\alpha_v = 1 - \sum (N_v A_v)_i$$  \hspace{1cm} (7.12)

where $A_v$ is the average cross-sectional area of $i$ vegetation and $N_v$ is the vegetation density.

As described in Section 3.1, the vegetation on the floodplain was idealised by the use of vertical smooth rods. For a smooth circular rod with diameter $D$, the experimental drag coefficient $C_D$ is a function of the rod Reynolds number $Re_{rod} (= U_d D / \nu)$. For the range of rod Reynolds numbers in these experiments ($2000 \leq Re_{rod} \leq 20000$), the drag coefficient $C_D$ is about 1.0.

In a rod array, the drag coefficient $C_D$ for a single rod is influenced by the wakes formed around all the rods. Nepf (1999) showed that the wake effect on the drag coefficient decreases as the lateral and longitudinal array spacing between the rods increases. Based on Nepf’s results, the bulk drag coefficient ($C_D \times S_F$) is about 1.0 for sparse emergent rod distributions in which the dimensionless vegetation density $n_v (= D^2 / \Delta S^2)$ is less than 0.01. The bulk drag coefficient ($C_D \times S_F$) for dense rod distributions is about 0.6 in which $n_v (= D^2 / \Delta S^2)$ is about 0.1. For the experiments in this study, both the longitudinal and the lateral rod spacings range from $2D$ to $4D$ and the dimensionless vegetation density $n_v (= D^2 / \Delta S^2)$ is 0.094. The bulk drag coefficient ($C_D \times S_F$) can be approximately set as 0.6. However, the apparent drag coefficient $C_D$ for the submerged rod distributions has not been reported.

7.1.3.3 Friction factor

The roughness height $k_s$ is used to determine the bed friction factor across the channel in the numerical solution. The Manning coefficient $n$ was firstly obtained
from the experimental data for the straight trapezoidal compound channel. The equivalent roughness height \( k_s \) was then calculated from the relationship expressed in Equation 7.13 (Ackers 1991):

\[
n = \frac{k_s^{1/6}}{\left[8.25\sqrt{g}\right]}
\]  

(7.13)

For the small channel, the Manning coefficients in cases STC-1 \( \sim \) STC-3 are all about 0.01 and the equivalent roughness height \( k_s \) is 0.0003m.

For the large compound channel flow, the overall Manning coefficient was firstly determined with Manning Equation. The Manning coefficient for the mattress main channel bed was estimated as 0.02 from Figure 5.23 and the Manning coefficient for the wood floodplain was determined with Equation 7.14 as proposed by Cox (1973). The values of the roughness height across the section were then determined with Equation 7.13.

\[
n_{fp} = \frac{n_e A - n_{mc} A_{mc}}{A_{fp}}
\]  

(7.14)

where \( n_{fp} \) is the Manning coefficient for the wood channel bed, \( n_e \) is the overall Manning coefficient, \( A \) is the total area of the cross section, \( n_{mc} \) is the Manning coefficient for the mattress main channel bed, \( A_{mc} \) is the sub-area above the mattress main channel bed and \( A_{fp} \) is the sub-area above the wood channel bed.

The Colebrook – White equation is used to calculate the local friction factor \( f \) for a smooth bed at any location in a cross-section with water depth \( H \):

\[
\frac{1}{\sqrt{f}} = -2 \log \left( \frac{3.02}{Re \sqrt{f} + \frac{k_s}{12.3H}} \right)
\]  

(7.15)

where \( Re \) is the local Reynolds number defined as \( Re = 4U_d H / \nu \).

Using \( U_* = \sqrt{gH S_0} \) and \( f = 8U_*^2 / U_d^2 \), Equation (7.15) can take the following form:
The modified Colebrook – White equation is used to calculate the local friction factor $f$ for a rough floodplain with water depth $H$ (Rameshwaran & Shiono 2006):

$$ f = -2 \log \left( \frac{3.02 \nu}{\sqrt{128 g H^3 S_0}} + \frac{k_s}{12.3 H} \right) $$

(7.16)

$$ f = \left[ -2 \log \left( \frac{3.02 \nu}{\sqrt{128 g H^3 S_0}} + \frac{k_s}{12.3 H} \right) \right]^2 $$

(7.17)

7.1.3.4 Depth-averaged eddy viscosity and advection term

To calculate the depth-averaged eddy viscosity $\overline{\epsilon}$, only the dimensionless eddy viscosity ($\overline{\lambda_{eb}}$) due to the bed-generated turbulence is required as the input eddy viscosity data for this numerical solution. The value of $\overline{\lambda_{eb}}$ was set to 0.0683 in this numerical solution.

For small channel cases, different values of $\Gamma / \kappa_{pg} H S_0$ in the main channel and on the floodplain were tested and their appropriate values were determined from the best-predicted velocity profiles. For large channel cases, different values of $\Gamma / \kappa_{pg} H S_0$ in the main channel and on the floodplain were also calibrated with the measured values.

7.2 Flow prediction for the non-vegetated compound channel

In this section, the predictive capability of the quasi-2D flow model for five non-vegetated cases is investigated. In the small, trapezoidal, compound-channel cases, the relative water depths for cases STC-1 ~ STC-3 are 0.22, 0.35 and 0.5 respectively. In the large, trapezoidal, compound-channel cases LC-1 and LC-2, the relative depths for cases LC-1 and LC-2 are 0.41 and 0.50 respectively. The detailed flow conditions of these five cases were described in Sections 4.1 and 5.1.

7.2.1 Wall velocity

Wall effects are very important to the flow behaviour, especially in narrow channels. In numerical modelling, fine grids near walls are normally required to properly
describe the velocity distribution. To simplify flow prediction, the wall effects are treated by imposing the mean wall velocity as the boundary condition.

The mean wall velocity can be calculated from the mean wall shear stress or obtained from velocity measurements. For compound channel flow, the complex flow mechanisms make it difficult to generalise the distribution of wall shear stress. The mean wall velocities were calculated using the method described in section 7.1.3.1. Table 7.1 shows the calculated and measured mean wall velocities in the seven cases.

**Table 7.1** Comparisons of mean wall velocities for non-vegetated channel cases

<table>
<thead>
<tr>
<th>Calculation</th>
<th>STC-1</th>
<th>STC-2</th>
<th>STC-3</th>
<th>LC-1</th>
<th>LC-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left wall</td>
<td>0.215</td>
<td>0.231</td>
<td>0.259</td>
<td>0.464</td>
<td>0.500</td>
</tr>
<tr>
<td>Right wall</td>
<td>0.147</td>
<td>0.166</td>
<td>0.207</td>
<td>0.403</td>
<td>0.432</td>
</tr>
</tbody>
</table>

Using calculated and measured mean wall velocities and assuming that $\Gamma/\alpha_p g H S_0 = 0$, the prediction results of velocity and bed shear stress for cases STC-1 ~ STC-3 are shown in Figures 7.2 ~ 7.5. In Figures 7.2 and 7.3, "▲" and "△" represent the predicted variables without considering the shear contribution to the eddy viscosity, "◇" and "◇" represent the predicted variables taking the shear contribution to the eddy viscosity into account, "Log-law" represents the predicted variable using the calculated wall velocities, "Measured" represents the predicted variable using the measured wall velocities, "★" represents the measured variable and "—" represents the channel bed level. In case STC-1 (Figure 7.2a), the predicted, depth-averaged, velocity profiles using calculated wall velocities are almost the same as those using measured wall velocities. In cases STC-2 and STC-3, the prediction results using calculated and measured wall velocities are also nearly the same.

From Figures 7.2a ~ 7.2c, all the depth-averaged velocities near the MC-FP junction in cases STC-1 ~ STC-3 are well predicted when the shear contribution to the eddy viscosity is considered. Moreover, for the shallow case STC-1, the velocities across
the section are predicted satisfactorily. In Physics, the lateral shear is the main contribution to the momentum exchange near the MC-FP junction and the shear increases as the relative water depth decreases. In other words, this quasi-2D numerical modelling is capable of predicting the depth-averaged velocities in compound channel flow when the log-law wall boundary conditions are properly imposed.

Figures 7.3a ~ 7.3c illustrate that the bed shear stresses across the section are also well predicted when the shear effect on the momentum exchange is taken into account and the wall velocities are used as boundary conditions. Figures 7.2 and 7.3 confirms that when the calculated wall velocities at y^+ = 30 are used, the 2D flow structures are reasonably well predicted.

7.2.2 Flow prediction for the small channel

Figures 7.2a ~ 7.2c show that depth-averaged velocities become smaller if the shear effects due to large, horizontal eddies is thought to influence the lateral momentum exchange. This is because the large, horizontal eddies are generated by the lateral shear and cause some energy loss from the mean flow. As a result, the mean flow velocity decreases and its decrease depends on the flow condition.

From Figures 7.2a ~ 7.2c, the velocity difference between “Δ”curves and “0” curves becomes smaller as the relative water depth increases, because the shear strength in the compound channel decreases as the relative water depth increases.

In the shallow case STC-1 (Figure 7.2a), the depth-averaged velocities are well predicted across the section. In the median case STC-2, the velocities in the main channel are under-predicted. In deep case STC-3, the velocities in the shear layer and on the floodplain are under-predicted. As reviewed in Chapter 2, the secondary current is significantly large under large water depth conditions, thus the contribution of secondary currents needs to be carefully considered under large water depth conditions. In the shallow case, the effect of secondary currents on the velocity prediction is weaker than the strong shear effect.

Based on the predicted velocities as shown in Figures 7.2a ~ 7.2c, the bed shear stresses in cases STC-1 ~ STC-3 were predicted and are shown in Figures 7.3a ~ 7.3c.
It can be seen that the predicted results agree well with the measurements. Some of the bed shear stresses near the MC-FP junction are over-predicted, mainly in deeper cases, but the overall trends are satisfactorily predicted.

Using the calculated values of \( \frac{\partial (H \rho \overline{UV})_d}{\partial y} / \rho g H S_0 \) as shown in Figure 4.21, the depth-averaged velocities and bed shear stresses for cases STC-1 ~ STC-3 were further predicted with the quasi-2D model and are presented in Figures 7.4 ~ 7.5 together with the prediction results assuming \( \frac{\partial (H \rho \overline{UV})_d}{\partial y} / \rho g H S_0 = 0 \) and the measurement results. Table 7.2 lists the prediction errors for discharge in these cases using different prediction conditions.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>STC-1</th>
<th>STC-2</th>
<th>STC-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated wall velocity, No secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow, No shear contribution</td>
<td>3.8</td>
<td>-2.0</td>
<td>-0.4</td>
</tr>
<tr>
<td>Calculated wall velocity, No secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow, Shear contribution</td>
<td>0.8</td>
<td>-4.1</td>
<td>-1.7</td>
</tr>
<tr>
<td>Measured wall velocity, No secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow, No shear contribution</td>
<td>3.5</td>
<td>-1.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Measured wall velocity, No secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow, Shear contribution</td>
<td>0.3</td>
<td>-3.1</td>
<td>-0.9</td>
</tr>
<tr>
<td>Measured wall velocity, Calculated secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow, No shear contribution</td>
<td>-3.2</td>
<td>-2.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Measured wall velocity, Calculated secondary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow, Shear contribution</td>
<td>-5.6</td>
<td>-3.8</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Figures 7.4 ~ 7.5 show that the secondary current terms are more important to the flow prediction under higher relative water depth condition. For the shallower cases of STC-1 ~ STC-2, the calculated depth-averaged secondary current terms are roughly correct except the deep case STC-3. This error might be caused by the depth-averaged concept itself. For the deep case STC-3, the flow belongs to the narrow channel flow
and there are some errors while using the depth-averaged concept. Table 7.2 shows that the errors of predicted discharge were within -6 ~ 4.5 %, which were similar to those of Rameshwaran and Shiono (2006).

To further evaluate the predictive capability of the quasi-2D model, the results of the Large Eddy Simulation (LES) of TELEGAC-2D are presented in Figures 7.6a and 7.6b. The streamwise velocity at \( y = y_i \) was obtained by time-averaging. The averaging time period is 50-seconds. \( y_i \) is the lateral position where the measurements were carried out. Using the non-slip boundary condition, the velocities are over-predicted around the centre of the main channel and under-predicted in the other areas. For this case, the quasi-2D model is better than 2D-LES of TELEGAC.

### 7.2.3 Flow prediction for the large channel

Using calculated mean wall velocities and various values of \( \Gamma/\alpha_p g HS_0 \) and roughness height \( k_r \), the predicted depth-averaged velocity for cases LC-1 and LC-2 are shown in Figures 7.7 and 7.8 respectively. These predicted results were acquired by considering the shear contribution to the eddy viscosity. In Figures 7.7 and 7.8, “Δ” represents the predicted variable assuming \( \Gamma/\alpha_p g HS_0 = 0 \), “○” represents the variable using \( \Gamma/\alpha_p g HS_0 = 0.25 \) in the main channel and \( \Gamma/\alpha_p g HS_0 = -0.20 \) on the floodplain, “★” represents the predicted variable using fit values of \( \Gamma/\alpha_p g HS_0 \), “*” represents measured data and “—” represents the channel bed level. The values of \( \Gamma/\alpha_p g HS_0 = 0.25 \) in the main channel and \( \Gamma/\alpha_p g HS_0 = -0.20 \) on the floodplain are referenced from Rameshwaran and Shiono (2006).

Figures 7.7 ~ 7.8 show that the predicted depth-averaged velocity profiles do not agree with the measured ones when the value of \( \Gamma/\alpha_p g HS_0 \) is assumed as zero. This is because the secondary currents are significant in the deep, compound channel as noted in Chapter 2 and the effect of secondary currents on the flow prediction needs to be considered. When values of \( \Gamma/\alpha_p g HS_0 = 0.25 \) in the main channel and \( \Gamma/\alpha_p g HS_0 = -0.20 \) on the floodplain for the FCF compound channel were used (Rameshwaran & Shiono 2006), the predicted velocity profiles are not satisfactory, either. This could be caused by differences in the secondary current characteristics in
various compound channels. For FCF cases, the compound channel was considered to be a wide channel whilst the compound channel in this study is considered to be a narrow channel, in which the ratio of the total width $B$ to the water depth $H$ is around 3. The best fitting values of $\Gamma/\alpha p g HS_0$ for different cases are listed in Table 7.3. Using these fitting values of $\Gamma/\alpha p g HS_0$, the predicted discharges are within $\pm 3\%$ accuracy. In this study, the signs of $\Gamma/\alpha p g HS_0$ are more complex than in the FCF cases and this is caused by the narrow channel geometry. Most of the magnitudes of $\Gamma/\alpha p g HS_0$ are larger than those in the FCF cases and this is because the secondary currents are more significant in narrower channels.

Figures 7.9 - 7.10 show the prediction results of the bed shear stress and the Reynolds shear stress in these two non-vegetated cases using the fitting values of $\Gamma/\alpha p g HS_0$. The bed shear stresses decrease sharply from $Y = 0.40$ m to around $Y = 0.42$ m because the roughness heights decrease greatly due to the change of the bed material. The peak magnitudes of predicted depth-averaged Reynolds stress using the quasi-2D model coincide well with those from the measured data in the MC-FP junction area. The Reynolds stress in case LC-2 is slightly smaller than that in LC-1. This is reasonable in physics because the shear decreases as the relative water depth increases in compound channel flow.

<table>
<thead>
<tr>
<th>$Y$(m)</th>
<th>0</th>
<th>0.40</th>
<th>0.49</th>
<th>0.55</th>
<th>0.91</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case LC-1</td>
<td>-0.50</td>
<td>-0.30</td>
<td>0.55</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>Case LC-2</td>
<td>-0.50</td>
<td>0.00</td>
<td>0.60</td>
<td>0.65</td>
<td>0.50</td>
</tr>
</tbody>
</table>

**Table 7.3** Best fitting values of $\Gamma/\alpha p g HS_0$ in cases LC-1 ~ LC-2

7.3 Flow prediction for the compound channel with emergent vegetation

In case STC-4, the one-line emergent circular rods were placed along the MC-FP junction. The relative water depth is 0.52 and the detailed flow conditions are listed in Table 4.1. The flow prediction for the compound channel with this rod alignment has not been studied to date.
For the vegetation case, how to treat the drag force in the quasi-2D model is the key to the accurate prediction of the velocity and boundary shear stress. In the compound channel with emergent rods on the whole floodplain, the drag force is usually treated by overall averaging over the whole floodplain. In this one-line, emergent-rod case, this method does not give accurate flow prediction results, so a new method is introduced. In this study, the total drag force is treated as equivalent to the local bed friction force. For the equivalent transferring method, the drag force is assumed to be exerted on the region of the bed where the rods are put and hence the relationship in Equation 7.19 follows:

\[
\frac{1}{2} \rho C_D A_p S_F U^2 V_{ew} = \frac{1}{2} \rho c_f U^2 \tag{7.19}
\]

where \(V_{ew}\) is the water volume in the whole channel, \(D\) is the diameter of the rod, \(L\) is the channel length and \(c_f\) is the dimensionless friction coefficient.

The Chazy friction coefficient \(C\) can be expressed by \(C = \sqrt{\frac{2g}{c_f}}\) and \(C = 7.83 \log_{10} \frac{H}{k}\) (See TELEMAC-2D principle note), the equivalent roughness height \(k\), can be estimated by combining these two formulae. In the STC-4 case, the equivalent friction coefficient \(c_f\) is 0.94067 and the equivalent roughness height \(k\) is 0.12298 m.

Figures 7.11a and 7.11b show the quasi-2D model prediction results for case STC-4 and those obtained from 2D-LES with TELEMAC. The mean wall velocities used in the quasi-2D model are listed in Table 7.4. In these figures, "\(a\)" represents the predicted variables using \(\Gamma/\alpha p g H S_0 = 0\) and without considering the shear contribution to the eddy viscosity, "\(o\)" represents the predicted variables using \(\Gamma/\alpha p g H S_0 = 0\) and considering the shear contribution to the eddy viscosity, "\(\Delta\)" represents the predicted variables considering the shear contribution to the eddy viscosity and assuming \(\Gamma/\alpha p g H S_0 = 0.60\) in the main channel and \(\Gamma/\alpha p g H S_0 = 0.30\) on the floodplain, "\(\bullet\)" represents the predicted variables considering the shear contribution to the eddy viscosity and using the fitting values of \(\Gamma/\alpha p g H S_0\), "\(o\)"
represents the results of 2D-LES with TELEMAC, "*" represents the measured data and "—" represents the bed level.

Table 7.4 Calculated mean wall velocities in vegetated channel cases

<table>
<thead>
<tr>
<th>Case</th>
<th>STC-4</th>
<th>LC-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left wall</td>
<td>0.194</td>
<td>0.434</td>
</tr>
<tr>
<td>Right wall</td>
<td>0.139</td>
<td>0.171</td>
</tr>
</tbody>
</table>

Figures 7.11a and 7.11b show that the predicted velocity profile does not agree with the measured one when the value of $\Gamma/\alpha \rho g H_0$ is set to zero. This indicates that this value of zero is not justified since the secondary currents are significant to this emergent case. As reported by Rameshwaran and Shiono (2006), the sign of $\Gamma/\alpha \rho g H_0$ is positive across the section and the magnitude of $\Gamma/\alpha \rho g H_0$ is linear to the relative water depth in the compound channel with emergent vegetation over the whole floodplain. They also showed that that the magnitude of $\Gamma/\alpha \rho g H_0$ is larger in the emergent vegetation case than in the non-vegetated case. Using their values of $\Gamma/\alpha \rho g H_0$ at $Dr = 0.50$, which are $\Gamma/\alpha \rho g H_0 = 0.60$ in the main channel and $\Gamma/\alpha \rho g H_0 = 0.30$ on the floodplain, the predicted velocity profile does not agree with the measured one, either. The best fitting values of $\Gamma/\alpha \rho g H_0$ listed in Table 7.5 for case STC-4 are also different to those in the compound channel with emergent vegetation on the whole floodplain and this could be caused by the different secondary current structure. Using the fitting values of $\Gamma/\alpha \rho g H_0$, the predicted discharge is $3.5\%$ larger than the measured one. As bed shear stress is calculated using Equation 7.17, the bed shear stress varies in a similar way to velocity.

Unlike the quasi-2D model, 2D-LES with TELEMAC-2D cannot predict the two-dimensional flow structure in the narrow compound channel with emergent rods on the floodplain. This is due to the limit of imposing the proper boundary conditions on the walls, which has been explained above.
Table 7.5  Best fitting values of $\Gamma/\alpha p g H S_0$ in case STC-4

<table>
<thead>
<tr>
<th>Y(m)</th>
<th>0</th>
<th>0.06</th>
<th>0.12</th>
<th>0.156</th>
<th>0.168</th>
<th>0.26</th>
<th>0.306</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma/\alpha p g H S_0$</td>
<td>-0.3</td>
<td>-0.3</td>
<td>0.4</td>
<td>0.8</td>
<td>0.8</td>
<td>-0.3</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

### 7.4 Flow prediction for the compound channel with submerged vegetation

To further explore the predictive capability of the quasi-2D SKM model, one submerged rod case was further investigated in this section. To date, the quasi-2D model has not been applied to a submerged-rod case. In case LC-4, the floodplain is covered with submerged round rods. The water depth in the main channel is 0.310 m and the relative water depth is 0.52. The detailed flow conditions in case LC-4 are listed in Table 5.1.

As discussed in section 7.1.2, the drag force due to submerged vegetation is more complicated than that due to emergent vegetation. The interfacial shear force on the top surface of the submerged vegetation makes a significant contribution to the total apparent drag force. The key to using the quasi-2D model is to determine an appropriate apparent drag coefficient for the submerged vegetation.

The apparent drag coefficient ($C'_D$) can be determined by a force balance method. For a vegetated flow domain of length $L_v$, the apparent drag coefficient ($C'_D$) can be evaluated using the following force balance:

$$
\left(\bar{\tau}_{wl} H + \bar{\tau}_{wr} h\right)L_v + L_v \int_0^y \tau_b dy + \sum \frac{1}{2} \rho (C'_D A_F S_F) U_d^2 V_{ew} = \rho g V_{ew} S_0
$$

where $\bar{\tau}_{wl}$ is the mean wall shear stress on the left channel wall, $H$ is the water depth in the main channel, $\bar{\tau}_{wr}$ is the mean wall stress on the right channel wall, $h$ is the water depth on the floodplain, $L_v$ is the length of the vegetated domain, $B$ is the total width of the channel, $\tau_b$ is the local bed shear stress, $y$ is the lateral direction and $V_{ew}$ is the effective water volume in the computation domain which is the total water volume with the total vegetation volume in the computation domain subtracted.
The data concerning the mean wall shear stress $\tau_{wl}$ and $\tau_{wr}$ were obtained using a Preston tube on the sidewalls. Data of depth-averaged streamwise velocity $U_d$ were obtained by averaging the local velocity over the water depth and the local velocity was measured with the ADV. For simplification, the mean velocity on the floodplain was used to calculate the apparent drag coefficient ($C'_D$) because the rods are uniformly placed on the floodplain. Data concerning the local bed shear stress $\tau_b$ were acquired from Equation 7.17 and the data required by Equation 7.17 were obtained from the results of LES with TELEMAC.

Using the above force balance method, the apparent drag coefficient was calculated using the data on the velocity, wall shear stress and bed shear stress. In case LC-4, the apparent drag coefficient is 0.9081. According to Nepf (1999), the bulk drag coefficient ($C_D \times S_F$) is approximately 0.6 in case LC-4. The difference between the apparent drag coefficient and the bulk drag coefficient is 0.3081, which comes from the additional interface drag. The interface drag force is significant in this submerged case.

Figures 7.12a and 7.12b show the predicted and measured results using the quasi-2D model in case LC-4. In these two figures, "▲" represents the predicted variables using $\Gamma/\alpha_p g H S_0 = 0$ and without considering the shear contribution to the eddy viscosity, "Δ" represents the predicted variables using $\Gamma/\alpha_p g H S_0 = 0$ and considering the shear contribution to the eddy viscosity, "●" represents the predicted variables using best fitting values of $\Gamma/\alpha_p g H S_0$ and considering the shear contribution to the eddy viscosity, "○" represents the results of 2D-LES with TELEMAC, "*" represents the measured data and "—" represents the bed level. The measurement data were obtained from one cross-section 6.52 m downstream from the inlet.

From Figure 7.12a, when the shear contribution to the eddy viscosity is taken into account, the quasi-2D model gives a better prediction of the depth-averaged velocity in the compound channel with submerged rods on the floodplain. This confirms that the lateral shear is dominant under this flow condition. As listed in Table 7.6, the best fitting values of $\Gamma/\alpha_p g H S_0$ are larger near the left wall and the MC-FP junction.
region and this corresponds to the measured secondary current structures as shown in Figure 5.2 d. The LES results from TELEMAC-2D, as shown in Figure 7.12a, roughly agree with the measurement data, except for the data above the submerged rods.

Table 7.6 Best fitting values of $\Gamma/\alpha p g H S_0$ in LC-4 case

<table>
<thead>
<tr>
<th>Y(m)</th>
<th>0</th>
<th>0.4</th>
<th>0.49</th>
<th>0.55</th>
<th>0.915</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma/\alpha p g H S_0$</td>
<td>-0.6</td>
<td>-0.1</td>
<td>0.7</td>
<td>0.7</td>
<td>0</td>
</tr>
</tbody>
</table>

From Figure 7.12b, the peak Reynolds shear stress occurs near the MC-FP edge and the zero Reynolds shear stress occurs where the depth-averaged velocity peaks in the main channel. The Reynolds shear stress behaviour coincides well with that from the measurement data. The predicted Reynolds shear stress by quasi-2D using the best fitting values of $\Gamma/\alpha p g H S_0$ agrees well with the measurement data in the area $y > 0.20$ m. The predicted Reynolds shear stress by 2D-LES near the MC-FP junction is smaller than that based on the measurements.

7.5 Summary

The quasi-2D model is capable of predicting depth-averaged velocities, Reynolds stress and bed shear stresses in compound channels and it better predicts the two-dimensional flow structure in the compound channel than 2D-LES with TELEMAC-2D. The secondary current term $\Gamma/\alpha p g H S_0$ needs to be carefully selected in narrow channels and further work is needed to generalise the distribution of $\Gamma/\alpha p g H S_0$ across the section in compound open channels.

For a compound channel with one-line emergent vegetation on the floodplain, the total drag force can be introduced as a source term in the quasi-2D model by transferring it into the local bed friction force and the two dimensional flow structure was well predicted by this new method.

For a compound channel with submerged vegetation on the floodplain, the interface shear plays an important role in the total drag force in submerged vegetated flow. The total drag force consists of the drag force due to the projected area and the interface
shear force due to the top surface of the vegetation. By introducing a new concept of the apparent drag coefficient, the total drag force can be related to the depth-averaged velocity. Using this new approach, the quasi-2D model was successfully applied to predict the 2D flow structure in a compound channel with submerged vegetation on the floodplain. The apparent drag coefficient needs to be properly determined under different flow conditions in the future.

Figure 7.1 Illustration of the drag force and the interface shear force on a submerged circular rod.
Figure 7.2  Shear effects on the depth-averaged velocity prediction using different mean wall velocities for cases STC-1 – STC-3. (a) Case STC-1; (b) STC-2, (c) STC-3.
Shear effects on the bed shear stress prediction using different mean wall velocities for cases STC-1 ~ STC-3. (a) Case STC-1; (b) STC-2, (c) STC-3.

Figure 7.3
Figure 7.4 Effects of secondary flow on the depth-averaged velocity prediction using mean measured wall velocities for cases STC-1 ~ STC-3. (a) Case STC-1; (b) STC-2, (c) STC-3.
Figure 7.5  Effects of secondary flow on the bed shear stress prediction using mean measured wall velocities for cases STC-1 ~ STC-3. (a) Case STC-1; (b) STC-2, (c) STC-3.
Figure 7.6 Prediction results using the quasi-2D model and 2D-LES against the experimental data for STC-1 case. (a) Depth-averaged velocity; (b) Bed shear stress.

Figure 7.7 Lateral distributions of the predicted depth-averaged velocity using various secondary flow assumptions for LC-1 case.
Figure 7.8  Lateral distributions of the predicted depth-averaged velocity using various secondary flow assumptions for LC-2 case.

Figure 7.9  Lateral distributions of the predicted bed shear stress for cases LC-1 and LC-2.
Figure 7.10  Lateral distributions of the predicted Reynolds stress for non-vegetated cases. (a) Case LC-1; (b) Case LC-2.

Figure 7.11  Prediction results of the depth-averaged velocity and bed shear stress using the quasi-2D model and 2D-LES for STC-4 case. (a) Depth-averaged velocity; (b) Bed shear stress.
Figure 7.12 Prediction results of the depth-averaged velocity and Reynolds stress using the quasi-2D model and 2D-LES for STC-4 case. (a) Depth-averaged velocity; (b) Reynolds stress.
Chapter 8

Conclusions and Future Research Prospects

In this chapter, the important observations and new findings from this research are summarised. Section 8.1 presents the experimental observations of the compound channel flows with and without vegetation. Section 8.2 illustrates the numerical investigations of the unsteady flow characteristics from the Large Eddy Simulation with TELEMAC-2D. Section 8.3 gives the numerical studies of the 2D mean flow characteristics from the quasi-2D flow prediction. Section 8.4 recommends the future research prospects.

8.1 Experimental investigations

A Pitot tube and a Preston tube have been used to measure the mean velocity and the boundary shear stress in both a rectangular and a trapezoidal compound open channel. A non-intrusive, 3D, ADV technique has been used to measure the turbulence in a large, compound, open channel with and without vegetation on the floodplain. Based on these data, the following conclusions can be drawn.

8.1.1 Compound channel with non-vegetated floodplain

8.1.1.1 Small compound channel

(1) The inlet turbulence and the boundary roughness influence the flow development. The distance ratio \(X/R\) of the longitudinal distance from the inlet \(X\) to the hydraulic diameter \(R\) can be used to select the measurement section for a fully-developed flow in open channel experiments and the appropriate values of \(X/R\) were suggested.

(2) Narrow, rectangular, open-channel flow is characterised by the strong velocity-bulging towards the corners and the maximum velocity located below the free surface. Non-vegetated, compound, open-channel flow is characterized by the velocity-bulging near the MC-FP junction and the corners due to the momentum transfer via secondary currents and the velocity-bulging is stronger under larger relative water depth conditions, especially in the rectangular compound channel. The observed flow characteristics in this work are consistent with those in the literature.
(3) The lateral shear in the shear layer zone was found to play an important role in the momentum exchange in the shallow non-vegetated, compound, open channels. The shear layer width decreases as the relative water depth increases and the value of the shear layer width is larger in the rectangular compound channel than that in the trapezoidal compound channel. The dimensionless, depth-averaged, eddy viscosity peaks at the MC-FP junction and the peak value decreases as the relative water depth increases. The depth-averaged eddy viscosity due to the large eddies is much larger than that due to the small eddies under shallow water conditions.

(4) Using the mean wall shear stress as the boundary condition, the method of Shiono and Knight (1991) was modified to calculate the depth-averaged apparent shear stress from the data of the bed shear stress and water depth in the compound channel. The apparent shear stress peaks near the MC-FP junction and decreases as the relative water depth increases due to reduced shear strength. The peak value of the apparent shear stress is smaller in the trapezoidal, compound channel than that in the rectangular one under similar relative water-depth conditions.

(5) The secondary current \( - \rho \bar{uv} \) was calculated from the apparent shear stress and Reynolds shear stress. Based on the suggested secondary current pattern in the literature, a new expression for the lateral velocity over the water depth was proposed and the maximum lateral velocity \( V_{\text{max}} \) across the section was calculated. The calculated \( - \rho \bar{uv} \) and \( V_{\text{max}} \) profiles roughly agree with the measurements in the literature, but they are more complex near the MC-FP junction.

(6) In non-vegetated, compound-channel cases, the bed shear stresses are smaller than \( \rho g H S_0 \) in the main channel and larger on the floodplain and this is caused by the gradients of the Reynolds shear stress and secondary currents. The contributions of Reynolds stress and the secondary currents to the flow resistance were found to be significant near the MC-FP junction. The proper value of \( \partial H \left( - \rho \bar{uv} \right) / \partial y / \rho g H S_0 \) near the MC-FP junction is required in quasi-2D modelling.
8.1.1.2 Large compound channel

(1) Near the main channel bed, a pair of secondary currents caused strong velocity bulging in this region. The secondary currents are generated by the anisotropy of turbulence. The turbulent intensities and turbulent kinetic energy peak near the main channel bed due to the strong bed-generated turbulence. The eddy viscosity $\varepsilon_t$ increases from near the left wall towards the MC-FP junction. The magnitudes of the Reynolds stresses $\tau_{yx}$ and $\tau_{xz}$ decrease from near the main channel bed towards other areas and the magnitude of $\tau_{yx}$ is larger than that of $\tau_{xz}$. The magnitude of $\tau_{yx}$ is much smaller than those of $\tau_{yx}$ and $\tau_{xz}$, which indicates that the shear stress generated by the secondary currents can be neglected. Under relative water depths $Dr = 0.42$ and 0.50, the flow characteristics are similar.

(2) Under deep-water conditions, there are no strong large eddies as no obvious oscillations can be recognised in the velocity correlation curves. The peak frequency of the energy spectra $v'^2$ is smaller than that of $u'^2$ and larger than that of $w'^2$. The cross spectrum shows that the momentum-exchange is dominated by the motions of frequencies smaller than 1 Hz. The phase relation between $u'$ and $v'$ is zero indicating that the lateral shear near the MC-FP junction is produced by horizontal large eddies and the phase relation between $u'$ and $w'$ is $\pm \pi$, indicating that the vertical shear is produced by the bed-generated turbulence.

8.1.2 Compound channel with emergent vegetation on the floodplain

(1) In the compound open channel with one-line emergent rods along the floodplain, two shear layers were recognised in the main channel and on the floodplain separately. Two high-velocity zones were recognised in the main channel and on the floodplain separately. The ratio of the dimensionless eddy viscosity due to the large eddies to that due to the small eddies is larger in the main channel than on the floodplain. Under relative water depth $Dr \approx 0.5$, the channel discharge and bed shear stress are noticeably reduced and the shear layer width in the one-line rod case is twice that in the no rod case.
(2) In the one-line, emergent-rod case, the depth-averaged, apparent shear stress, Reynolds stress and the secondary current were properly calculated by distributing the drag force linearly in the affected area, and they peak near the MC-FP junction in the rod case and their peak values are larger than those in the no rod case. They behave with greater complexity near the MC-FP junction than those in the no rod case owing to the large eddies and wakes around the rods.

(3) In the compound open channel with emergent rods on the whole floodplain, a large, counter-clockwise, secondary current cell and a small, clockwise, secondary current cell were recognised in the main channel and near the MC-FP junction respectively. The small secondary cell causes the velocity bulging towards the sloped main channel wall. The secondary currents are generated by the anisotropy of turbulence in this emergent-rod case. The turbulent intensities and kinetic energy peak near the MC-FP junction and the peak values of $u'$, $v'$, $w'$ and k are 4.0 $U_*$, 2.3 $U_*$, 0.9 $U_*$ and 5.8 $U_*$ respectively.

(4) In the compound open channel with emergent rods on the whole floodplain, horizontal large eddies exist near the junction as the longitudinal velocity correlation curve drops slowly from one to zero and there are obvious oscillations along the time lag axis. The eddy size decreases from the junction to the main channel as the shear becomes weaker from the junction to the main channel. The phase relation between $u'$ and $v'$ is $\pm \pi$ indicating that the lateral shear near the rods is produced by wakes and the phase relation between $u'$ and $w'$ is zero indicating that the vertical shear is possibly produced by the wakes. This indicates that the turbulence around the rods is generated by the wakes.

8.1.3 Compound channel with submerged vegetation on the floodplain

(1) The velocity patterns in the compound channel with submerged rod on the floodplain were recognised and they changed greatly as the relative water depth increased from 0.4 to 0.5. This was caused by the secondary current patterns under different flow conditions. A large, clockwise, secondary current cell was recognised in the main channel, but a counter-clockwise secondary cell and a clockwise secondary cell seem to exist near the free surface under
relative water depths of 0.4 and 0.5 respectively. The secondary currents in the submerged channels became stronger as the relative water depth increased, and they were stronger than those in the no rod case under similar relative water depth conditions. In the submerged rod case, the anisotropy of turbulence was found to be the main generation mechanism and the shear stress term was found to be more important to the generation of secondary currents than in the no rod case under similar relative water depth conditions.

(2) The turbulent intensities of $u'$, $v'$, $w'$ and the turbulent kinetic energy $k$ peaked near the MC-FP junction due to the strongest shear, they varied in a similar manner under relative water depths 0.44 and 0.52; but their peak magnitudes became slightly smaller as the relative water depth increased.

(3) The depth-averaged Reynolds shear stresses $\overline{\tau_{yx}}$, $\overline{\tau_{zx}}$ and $\overline{\tau_{xz}}$ peaked near the MC-FP junction. The peak magnitude of $\overline{\tau_{yx}}$ was larger than that of $\overline{\tau_{zx}}$ indicating that the lateral transfer of the longitudinal momentum was stronger than the vertical transfer of the longitudinal momentum. The peak magnitude of $\overline{\tau_{xz}}$ was only slightly smaller than that of $\overline{\tau_{zx}}$ indicating that the shear stress generated by the secondary currents was also important in the submerged rod case. The Reynolds shear stresses became slightly smaller as the relative water depth increased from 0.4 to 0.5. These results indicate that the vertical exchange of the longitudinal momentum is also important in the submerged-vegetation case and this might be due to the three-dimensional wakes around the rods.

(4) The periodicity of the large eddies is obvious from the velocity correlation curves and the eddy size decreases from the junction to the side walls. The cross spectra show that the phase relation between $u'$ and $v'$ is $\pm \pi$ indicating that the lateral shear near the rods is produced by the wakes and the phase relation between $u'$ and $w'$ is zero indicating that the vertical shear is possibly produced by the wakes. This is similar to the emergent rod case and different to the no rod case.

(5) The large eddies moved and grew from the junction to the edge of the sloped main channel wall and then they decreased towards the left main channel wall as judged from the characteristics frequency profile across the cross section in
the submerged vegetation case. This was caused by the wakes around the submerged rods. The contributions of the large eddies to the depth-averaged Reynolds shear stress $\tau_{xy}$ were larger in the submerged rod case than in the no rod case.

8.2 Numerical investigations of the unsteady flow characteristics

(1) Mesh resolution, advection scheme and boundary conditions were all found to play an important role in the generation of large eddies. This work shows that fine mesh resolution, the SUPG scheme and slip boundary condition encourage the generation of large eddies.

(2) Significant spatial and temporal fluctuations of velocity, vorticity, free-surface and bed shear stress were found to be associated with the large eddies generated in the compound channels. The magnitude of the instantaneous flow parameter was larger than the mean value. In the small compound channel with one-line rods on the floodplain, under relative water depth $Dr = 0.52$, the temporal variation range of the velocity $U$ decrease from near the left wall to near the centre of the main channel, then increased near the rods and then decreased to the right floodplain. The variation trend corresponds to the shear strength influenced by the velocity gradient of $\partial U/\partial y$. In the large compound channel with submerged rods on the floodplain, the temporal variation range of $U$ increased from near the left wall to the edge of the sloped main channel wall, then increased rapidly to near the submerged rods, and then decreased towards the right wall. Compared with the one-line, emergent-rod case, the shear layer was depressed in the submerged-rod case.

(3) In the one-line, emergent-rod case, the flow moved from the main channel to the floodplain and from the floodplain to the main channel alternately. In the submerged-rod case, the flow inundation area was limited to around the rods, which is weaker than that in the one-line, emergent-rod case.

(4) The characteristics frequency of the large eddies were determined with the time series data for velocity $U$. In the no-rod case, the characteristics frequency of the large eddies was 0.27 Hz under relative water depth $Dr = 0.24$. In the one-line rod case, the characteristics frequency of the large eddies was 0.43 Hz under relative water depth $Dr = 0.52$. In the submerged-rod case,
the characteristics frequency of the large eddies was 0.36 Hz under relative water depth $Dr = 0.52$.

(5) The mean parameter was better predicted using the finer mesh resolution, non-slip boundary condition and SUPG scheme. In the shallow FCF case 020201, the mean velocity, bed shear stress and Reynolds shear stress were predicted reasonably compared with the experimental data. In the one-line, emergent-rod case, the mean velocity and bed shear stress were over-predicted in the centre parts of the main channel and the floodplain, but under-predicted near the MC-FP junction because of the imposed non-slip boundary condition. In the submerged-rod case, the mean velocity and the Reynolds shear stress were well predicted, except in the small regions near the submerged rods.

(6) LES with TELEMAC-2D can be used to predict the unsteady 2D flow characteristics in large channels.

8.3 Numerical studies of the mean flow prediction using the quasi-2D model

(1) Using the mean wall velocity as the boundary condition, the mean parameters such as velocity and bed shear stress, especially in the shear layer, were better predicted for the compound channel flow than when the traditional boundary condition of zero velocity on the wall was used. The mean wall velocity can be calculated using $y^+ = 30$.

(2) In the small compound channels without vegetation on the floodplain, using the assumption of $\left( \frac{\partial H(-\rho\bar{U}V)}{\partial y} \right)_d/\rho g HS_0 = 0$, the mean velocity and bed shear stress were well predicted under small relative water depths of 0.24 and 0.38, but they were not predicted satisfactorily in the shear layer and on the floodplain under a large relative water depth of 0.50. These results indicate that the effect of the secondary currents under the large relative water depth condition needs to be considered when using the quais-2D model because the secondary currents become stronger as the relative water depth increases.

(3) The mean flow parameters in the deep, narrow, compound channels can be well predicted by choosing the appropriate values of $\left( \frac{\partial H(-\rho\bar{U}V)}{\partial y} \right)_d/\rho g HS_0$. In the large, deep, compound channels without vegetation on the floodplain, under large relative water depths of 0.41 and
The best fitting values of \( \frac{\partial H(-\rho \overline{UV})}{\partial y} \rho g HS_0 \) differ from those from the FCF experimental data (see Rameshwaran & Shiono 2006) and this could be caused by the differences in the shape of the cross section and the bed roughness across the cross section.

(4) The drag force due to the vegetation can be introduced as a source term into the depth-averaged momentum equation; however, the treatment of the drag force is the key to accurate prediction using the quasi-2D model.

(5) In the one-line, emergent-rod case, the total drag force due to the rods was treated as equivalent to the local bed friction force and so an equivalent local bed roughness height was used as an input parameter in the quasi-2D model. The mean velocity and bed shear stress' in the one-line rod case were well predicted with this new method using the best-fitting values of \( \frac{\partial H(-\rho \overline{UV})}{\partial y} \rho g HS_0 \).

(6) In the submerged-rod case, a new concept of the apparent drag coefficient was introduced to treat the total drag force due to the submerged rods. The value of the apparent drag coefficient was determined by using the force balance method. The mean velocity and the Reynolds shear stress in the submerged-rod case were well predicted with this new method by choosing the best fitting values of \( \frac{\partial H(-\rho \overline{UV})}{\partial y} \rho g HS_0 \).

8.4 Future research prospects

The above are the main conclusions of this research, which leads to the better understanding of the flow mechanisms and 2D flow predictions in the straight compound channels with and without vegetation on the floodplain. The following shortcomings of this research and the future research prospects are listed below:

(1) The effects of the secondary currents and the shear-generated turbulence were found to have an important influence on the flow characteristics in compound channels. Further detailed studies under different flow conditions should be carried out to investigate and generalise these effects for the engineering applications.

(2) Turbulence measurements were not carried out in the one-line, emergent-rod case and further study is needed. To further study the effect of wakes on the
flow characteristics, the use of sophisticated non-intrusive technology is suggested in order to measure the turbulence in the vegetated compound channels.

(3) For LES, the capability of applying TELEMAC-3D to simulate the unsteady flow characteristics in compound channels needs further assessment.

(4) For the quasi-2D model, how to consider the wake effects and generalise the apparent drag coefficient in the submerged-rod case are topics requiring further study.
References


Sellin R. H. J. (1964) A laboratory investigation into the interaction between the flow in the channel of a river and that over its flood plain, La Houille Blanche, No. 7, pp. 793-801.


