A computer-aided simulation of hydraulic tailings disposal

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A COMPUTER-AIDED SIMULATION OF HYDRAULIC TAILINGS DISPOSAL

by

Adrian Michael Durrant, B.Sc.

A Doctoral Thesis
Submitted in partial fulfilment of the requirements
for the award of

Doctor of Philosophy

of the Loughborough University of Technology
November 1988

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"We live by patterns. The individuality of a loved face resides in its broken symmetry - the two halves not quite alike. Patterns tell us where we are.

Man in ten thousand years has superimposed his own patterns and rhythms on the world, and ours are often more complex than those that would persist without us. But millennia before that began, the growth and diversity and ubiquitous spread of living beings vastly elaborated the patterns of preanimate earth. The world we are transforming was already transformed by life. There's more syncopation for the eye and mind in a square mile of Alpine meadow or Sumatran rain forest than in all of Mars and Jupiter with our moon thrown in.

Put matter into space and the ways it can pack, or bend, or bulge, or flow, or break, or splash are stringently and inescapably controlled by the facts of geometry and of energy. The patterns of nature are built from a very few themes. Economies prevail. The world so abundant is at the same time parsimonious. Things make patterns, insofar as they do so at all, because they cannot do otherwise."

H.F. Judson
'The Search for Solutions'
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ABSTRACT

Computer-aided tools appropriate to architecture, engineering and construction have been summarised, including digital terrain modelling (DTM), computer-aided design and draughting (CADD) and database management systems (DBMS). DTM and CADD techniques have been applied to simulating the hydraulic filling of tailings, or mine waste, dams. A relational DBMS was used to structure and manage filling and terrain data relevant to hydraulic tailings disposal at the Wheal Jane mine in Cornwall.

Similarities in both pattern and geometry exist between the processes of hydraulic tailings disposal observed at the Wheal Jane tailings dam and that of natural fluvial geomorphology. The shape of tailings beaches and alluvial fans is characterised by radial-profile concavity and cross-fan convexity. A simulation model called Tailfan was developed to represent the sub-aerial flow and deposition of hydraulic tailings from one or more locations around the storage area. Tailings stream channel alignments were modelled using empirically derived equations, based on the terrain slope, the inertia of flow and the degree of stream branching. Deposition was assumed to occur as lateral streamwashing adjacent to the channel alignment, dependent upon the prevailing terrain slope and the tailings' slope profile. Tailfan accounts for the simulated disposal of hydraulic tailings around hills and re-entrant valley systems, as found at numerous tailings dam sites.

Tailfan's ability to represent the spatial and time dependent processes of hydraulic tailings disposal was examined, initially within the controlled environment of a flat storage basin, or digital 'pool', and subsequently on the filling records and terrestrial survey data relating to Wheal Jane. The parameters investigated included the tailings flow and deposition criteria, the simulated hydraulic filling pattern and the terrain data distribution and density. CADD modelling facilities were used to quantitatively analyse the volumetric distribution of the simulated tailings deposits.

Tailfan has been provisionally calibrated for the Wheal Jane project. Its long term validity will require further data samples to be collected and tested. Recommendations have been made to assist in extending both the Tailfan simulation model and the relational database model.
DECLARATION

No portion of the research referred to in this thesis has been submitted in support of an application for another degree or qualification at this or any other university or other institution of learning.
ACKNOWLEDGEMENTS

My thanks to Mr Roger Mayo and Dr John Strodachs, my research supervisors, for their guidance and friendship over the period of my research.

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I would like to pay tribute to all members of staff of the Department of Civil Engineering, Loughborough University of Technology (L.U.T), as well as those individuals and organisations listed below, for their freely given advice and assistance.

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A.Mills, Mill superintendent, Wheal Jane Mine, Baldhu, Cornwall.
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WLPU Consultants, U.K.

Many thanks to Dr. John Allen and Lee Finniear, both of the Department of Civil Engineering, L.U.T., for proof reading this thesis.

Finally, I wish to acknowledge the support of my family and friends.
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CHAPTER 1

INTRODUCTION
CHAPTER 1

INTRODUCTION

1.0 BACKGROUND

The shape of the terrain is of interest to both the geomorphologist and the engineer. Coates (1976) referred to the contact between geomorphology and engineering as environmental geomorphology. Environmental geomorphology is the practical use of geomorphology for the solution of problems where man wishes to transform landforms or to use and change surface processes. One example is the hydraulic disposal of tailings, or mine waste, within overland storage basins, which has been addressed in this thesis.

According to Coates, the goal of geomorphic environmental studies is to minimise topographic distortions and to understand the interrelated processes necessary in the restoration, or maintenance, of the natural balance. Reference is made directly to the activities of man that modify the land-water ecosystem, which he has broadly grouped into four classes. These are: water resources, such as irrigation; living resources, which includes agriculture; non-renewable resources, such as mineral exploitation; and service engineering including dams and roads. Coates envisaged the need for the 'geomorphic engineer', who possessed the combined talents of the geomorphological and engineering disciplines. His function would be to maintain the maximum integrity and balance of the total land-water ecosystem as it relates to landforms, surface materials, and processes.

The global aim of this research work was to appraise the availability and requirements of computer-aided tools applicable to terrain-based architectural, engineering and construction (AEC) projects. Such tools include digital terrain modelling (DTM), computer-aided design and draughting (CADD) and database management systems (DBMS), which have been applied to simulating the hydraulic disposal of mine tailings.

The architectural, engineering and construction industry has been predominantly concerned with the use of interactive computer graphics techniques to manipulate and present project data, generally in the form of working drawings. The need to manipulate large amounts of geometric and non-geometric information is characteristic of most AEC projects.
Computer-aided tools offer a mechanism to rapidly interact with large amounts of digital data. This data, regardless of discipline, only becomes of practical use once it has been appropriately structured and managed. Martin (1976) envisaged the Database Management System (DBMS) as a methodology by which to administer data and its transactions within an organisation, as opposed to traditional, fragmented file based philosophies. Management effectiveness was quoted as being related to the quality of the organisation's data sources, and the versatility with which they could be used. Data represents a major investment to organisations, in some cases even more so than the systems used to assimilate it. A DBMS approach potentially offers an increase in data handling efficiency to computer assisted organisations. The digital representation of terrain and its attributes, in addition to the use of computational draughting and analysis tools to interrogate, enhance and amend associated geometric and non-geometric data, can benefit from the structured and managed environment offered by a Database Management System.

A relational DBMS, supporting DTM and CADD software tools, was used to structure and manage all terrain and filling data relevant to hydraulic tailings disposal at the Wheal Jane tin mine in Cornwall. The development and testing of a computer-aided simulation environment applicable to hydraulic tailings disposal is presented in this thesis.

1.1 THE COMPUTER-AIDED SIMULATION OF HYDRAULIC TAILINGS DISPOSAL

A tailings dam is a unique structure, in that it is usually built from the same material that it is designed to impound. Finely processed mine waste is mixed into a slurry and hydraulically transported to an overland storage site. Discharge of material takes place from discrete locations around the dam perimeter. The material flows away from the point of discharge and is deposited. The rate of filling and structural development of the dam is thus controlled by the operation of the discharge points. Tailings dams are under continual construction throughout the period of their service lives, being typically 25 years and more. Tragic failures of tailings structures in recent years have focused attention on their safe design and management.

The need to control the tailings dam pond size and location, as well as the freeboard between the pond surface and the dam wall, necessitates that appropriate filling patterns be specified by the engineering consultant responsible for the technical management of the tailings structure. In reality, any localised encroachment of the pond will be dealt with by the
mine operators, who will start up and close down the appropriate valves, or move the appropriate discharge points, based upon their individual experience. This is, however, a short term solution; a long term mis-management of filling could result in the inefficient usage of the available storage area, or even structural instability. The efficient use of the available storage area is of major importance to the overall mining operation, and therefore longer term waste disposal management approaches need to be adopted.

WLPU Consultants is a firm of consulting engineers specialising in the design and management of tailings dams. WLPU make use of an in-house software package called 'DUMPS' to derive hydraulic filling schedules. Due to certain limitations within DUMPS, the emphasis of the research was directed at alternative methods of modelling hydraulic tailings disposal within overland storage basins. WLPU's technical services have been commissioned by Rio Tinto Zinc at the Wheal Jane tin mine, near Baldhu, Cornwall. For practical and logistical reasons, the Wheal Jane tailings dam was chosen to act as the research site, and two terrestrial surveys of the Wheal Jane tailings dam were subsequently carried out by the author in April and July of 1986.

The computer simulation of hydraulic tailings disposal dictates a reversal of normal terrain modelling procedures. In this instance, the quantity of material available for disposal is known, but the resulting terrain surface is not. The prediction of terrain evolution via sedimentation processes requires an interaction with both spatial and time dependent information, and is therefore a dynamic process. A comparison has been made between the landform processes of hydraulic tailings disposal and that of fluvial geomorphology. This included a brief laboratory investigation, which was conducted in the civil engineering laboratory at Loughborough University of Technology (LUT).

Cambridge Interactive Systems (CIS), of Harston, near Cambridge, are the authors of a Geographical Information System (GIS) aimed at large scale engineering data applications such as mapping and utilities handling. Their Medusa GIS was used by the writer to structure, manage and interact with all terrain and filling data relevant to hydraulic disposal at Wheal Jane between April and July 1986. Subsequent work carried out by the writer at CIS concentrated on developing, refining and testing the computer-aided simulation environment.

A relational data model was implemented using Medusa GIS, that described in the same database both the spatial and time dependent processes associated with hydraulic filling. Terrain topography was represented as a topological DTM within the GIS, which provided a
basis for dynamic terrain-based simulation. An empirical simulation model called TaiIfan was developed, that simulated the flow and deposition of hydraulic tailings over the terrain topology. Data capture and the creation of a computer-aided environment for hydraulic tailings disposal is discussed in chapter 6.

Initial model testing used the controlled environment of a digital 'pool', and subsequently the filling records and terrestrial survey data relating to Wheal Jane. Medusa 3D modelling facilities were used to quantitatively analyse the volumetric distribution of the simulated tailings deposits. The testing of the computer-aided environment for hydraulic tailings disposal is discussed in chapter 7.

Conclusions, and recommendations for further enhancements to the existing simulation and relational database models, have been made in chapter 8.
CHAPTER 2

DIGITAL TERRAIN MODELLING
CHAPTER 2

DIGITAL TERRAIN MODELLING

2.0 INTRODUCTION

The terrain provides the foundation for the majority of man-made structures. Once its topography has been satisfactorily represented in digital form, other mathematically defined objects may be superimposed onto it for the purposes of computer-aided visualisation and property interrogation.

A digital terrain model has been defined by Ayeni (1976a) as "a numerical and mathematical representation of a terrain by making use of adequate elevation and planimetric measurements, compatible in number and distribution with that terrain, so that one dimension of any other point of known other dimensions can be automatically interpolated with required or specified accuracy for any given application". Research was conducted in the late 1950's by Miller and LaFlamme (1958), within the Department of Civil Engineering at the Massachusetts Institute of Technology, into "new approaches to highway engineering through the application of photogrammetry, automation instrumentation and electronic computers". The result was one of the first digital terrain modelling (DTM) packages. This chapter covers some of the characteristics of digital terrain modelling (DTM) techniques.

2.1 TERRAIN CLASSIFICATION

Strodachs (1978) stated that two methodologies exist by which to define terrain. The first is descriptive, where the terrain's topographic and attribute characteristics are qualitatively defined. An example is the descriptive landsystem approach adopted by Beckett and Webster (1969), which divides terrain into the hierarchical elements of province, terrain pattern, unit and component. A terrain may thus be subjectively described according to its locality, topography, soil type and vegetation.

The second method of terrain classification is by parametric definition, whereby its characteristics are quantifiably defined. Chorley (1972) suggested that 'surface roughness' parameters be used to objectively describe the terrain. Ayeni (1976b) identified and reviewed a number of such 'surface roughness' parameters, which include gradient, curvature, surface...
area and bump frequency to name but a few.

Traditionally digital terrain modelling packages have quantitatively defined terrain in terms of Euclidean geometry, that is, in X, Y and Z spatial coordinates. The idealistic concept that the universe could be described in terms of perfect forms and the dynamics of Newton has been sufficient for mathematicians. Mandelbrot (1983) has questioned this traditional approach, and has introduced the concept of fractal geometry.

Sorensen (1984) suggested the example of a perfectly flat sheet of aluminium to demonstrate the concept of fractal geometry. It is a two-dimensional surface until it is wrinkled, then, in the topological sense, it fills three dimensions. In the fractal sense it has two-plus-some-fraction dimensions, directly dependent upon how wrinkly it is.

Roy et al (1987) have quoted terrain dimensions between fractal dimension D=2.6 for irregular and D=2.2 for flatter, smoother terrain zones. The actual dimension of a surface may be derived from the dimensions of its contours, with contours having a dimension one less than the surface itself. Roy believed that the fractal dimension of a natural terrain was a function of the landform processes and sediments involved. Examples listed were the rough, higher dimensions of the glacial terrains and the smooth, lower dimension of the fluvial landscapes. Although similarity exists for a whole terrain area, spatial variations in D may occur within the DTM. Similar changes also occur in the fractional dimensions of contours with altitude. Variations in processes and/or geological structures may be responsible for these dimension changes. The above rationale was applied to terrain sampling by Roy, who stated that the optimum density should be a function of terrain complexity. In this instance, hill-tops will be represented by fewer points than the valley floors, which is by no means a new revelation to users of existing DTM techniques.

To date, fractal techniques have only been used for generating realistic visualisations of artificial terrains, as opposed to quantitative, real-life applications. It is therefore the Euclidean approach to digital terrain modelling that is further discussed in this chapter.

2.2 DATA CAPTURE FOR DTM

The collection of three-dimensional coordinates and associated information is the first stage in the terrain modelling process. Nakamura (1968) suggested the following four criteria are important for the efficient use of DTM data:
(1). Data should be collected in an efficient manner.
(2). The DTM should be formed by as small a number of points as possible.
(3). The data points should approximate the terrain topography with sufficient accuracy.
(4). The computation of point elevation should not demand too much time.

Nakamura's criteria can be globally summarised as data collection, processing and computational performance. Computational performance is influenced by the data collection and processing methods adopted, and, additionally, by the data storage technique used. Three main methods of data capture for digital terrain modelling have been listed below, which may be selected according to the size of the area of interest and the required data accuracy.

2.2.1 Terrestrial Surveying

Petrie (1987a) quoted terrestrial surveying as limited to small area applications, returning a very high DTM accuracy. Traditional terrestrial surveying methods of grid levelling and stadia tacheometry have been gradually replaced by electronic surveying instruments. These instruments measure angles and distances electronically, which may then be reduced by an integrated microprocessor, and possibly stored in a memory unit, either internally, or in an external solid state data recorder. The instruments may be of integrated design, where the electronic theodolite and the electronic distance measuring (EDM) system form a single integrated unit such as the Zeiss Elta 40, or of modular designs where they are separate and can be operated independently, such as the Wild T1000 with distomat DI 5.

The more recent, laser based, systems allow a variety of methods to be adopted for remote, terrestrial surveying applications. Such instruments offer prospects for data capture in areas of limited access, an example being the measurement of tailings beaches as discussed in chapter 6. In this instance, a Zeiss Elta 40 and a Geotronics IMS 1000 laser surveying instrument were used to survey the Wheal Jane tailings dam, located in Clemows Valley, near Baldhu, Cornwall. Both instruments incorporate an RS232 serial port, which enabled electronic measurement data to be transmitted to a Husky Hunter data recorder.
Kennie (1987) has compiled a review of the dedicated memory systems as well as the more recent, flexible, hand-held data recorders. These units can be either dedicated surveying data recorders, such as the Wild GRE 3, or general hand-held data logging devices, for example the Husky Hunter. Kennie stated that a systematic approach to terrestrial data capture generally ensures optimum project productivity; that is, geometric data and associative information is picked up according to a systematic procedure using a predetermined feature coding system. The use of radio communication between the surveyor and chainman can assist in this objective. In areas of high topographic relief, such as changes in slope or breaks in the terrain surface, greater terrain detail needs to be collected in order that an accurate digital representation of the prevailing terrain is achieved.

2.2.2 Photogrammetry

According to Petrie (1987a) photogrammetric techniques offer the greatest flexibility in data collection for terrain modelling. They are applicable to large area projects, especially in rough terrain, returning a range of DTM accuracies dependent upon user requirement.

A stereo-plotting, or photogrammetric, instrument recreates a three-dimensional stereo model of the terrain from pairs of photographs. The photogrammetrist then derives terrain measurements from this stereo-model through a digitiser or digitiser/height encoding device. Lillesand and Kiefer (1979), in a comprehensive book on remote sensing and image interpretation, have covered the use of aerial photographs for terrain evaluation. Various terrain topographies, including aeolian deposits, glacial and fluvial landforms, are described in terms of their characteristic sizes and shapes. In addition to basic height data, further terrain information may be derived from aerial photo interpretation, such as drainage pattern and texture, vegetation and land use.

The accuracy of photogrammetrically derived data is dependent upon the relationship of the distance between successive photographs and the flying height. Petrie (1987a) has presented a detailed summary of photogrammetric techniques for DTM purposes. Sampling may be of a systematic grid-based nature, random, a combined grid/random approach or in stringed contours of data. The sampling type adopted is often dependent on the kind of instrument available. Automated or semi-automated devices, for example, generally imply a regular grid-based sampling approach, and are therefore biased towards a gridded DTM.
Progressive sampling can be carried out either automatically or semi-automatically, in areas of high slope and relief. This will have the effect of increasing the local data density, in order to optimise the relationship between specified accuracy, sampling density and terrain characteristics.

2.2.3 Digitising

The accuracy of digitised data from maps is dependent upon the accuracy of the original source. Petrie (1987b) stated that the accuracy of digitised elevation data is much lower than that achieved using terrestrial survey or photogrammetric instruments. However, it may nonetheless be acceptable to a considerable number of users concerned with the modelling of large areas of the terrain.

Many national mapping agencies hold vast archives of topographic maps, some going back as far as 200 years. In Great Britain, it is the Ordnance Survey (O.S.) which is responsible for the collation of topographic information. Map scales are typically in the range 1:1250 to 1:10000, with generally very sparse height information.

The digitising of contour lines from maps can be undertaken using manual digitising methods or, more recently, semi-automated line-following and fully automated raster scanning devices, as are discussed by Petrie.

2.3 DTM CLASSIFICATION

Two classes of digital terrain modelling technique exist, those of surface and solid modelling.

2.3.1 Surface terrain models

The majority of DTM's may be classed as surface models, where the terrain is represented as a digital surface of theoretically 'zero' thickness. The surface may be defined by a continuous three-dimensional mathematical equation or a set of polygons, or points and faces, that conjointly imply the terrain surface. Examples of surface modellers include Eclipse, GDS-Sites, Hasp, Intergraph TIN, MOSS and ProSURVEYOR.

Traditional surface modellers derived volumes using sectioning techniques, such as the
end area method. Others use a datum plane as a reference from which to calculate a series of finite volumes, and hence the accumulative volume.

2.3.2 Solid terrain models

A second class of modeller exists, the solid model, whereby the terrain is given both shape and substance. This is a more recent development, an example being the Medusa Terrain Modeller, as investigated by the author (Durrant, 1986a). Random points residing on the terrain surface are triangulated by the Delauney algorithm (McCullagh, 1983), the terrain representation being defined as a set of interconnected points, polygon edges and planes. At the boundary of the triangulated mesh, vertical planes are dropped down to a predefined datum plane, such that conjointly all boundary planes mathematically define a discrete volume in space. The enclosed volume is thus explicitly defined within the data structure of the mathematical model.

The terrain represented by the solid model is no different from a surface modeller, that is, it is merely a function of the algorithm used to define the data set interconnectivity. The terrain representation is stored topologically, the geometry being explicitly defined in the model. The implications of explicitly defined geometry become apparent when efficiently structuring, storing, retrieving and interactively modifying terrain data during simulation applications, an example of which is discussed in chapters 6 and 7 of this thesis.

A major difference between surface and solid modelling techniques exists in the methodology by which mathematical manipulations are carried out on the terrain. Examples include the use of boolean theory to add, subtract or intersect solid design models, such as dams and highways, with the terrain. Solid models do, however, suffer from a large storage and processing overhead. Boolean operations have been used to merge the survey of the Wheal Jane tailings storage area, the digitised dam embankment model and the lake, or pond, onto the digitised terrain model of Clemows Valley, as shown in Figure 2.3.1. A further discussion on surface and solid modelling techniques appears in chapter 3.

2.4 DTM Environment

The environments in which terrain and associated data is stored, managed and manipulated varies according to the computer hardware and software programming philosophy adopted. The more traditional DTM packages, written in the 1960's and 1970's
Figure 2.3.1  Boolean assembly of solid models representative of the Wheal Jane tailings dam project, Cornwall
were of a file based, batch processing type. The use of interactive graphics to manipulate terrain related information was a product of the availability of low cost computer-aided design and draughting (CADD) systems in the 1980's. A more recent type of DTM environment exists, referred to as a Database Management System (DBMS). Engineering DBMSs evolved in the mid-1980's, to structure and manage data associated with engineering applications.

2.4.1 File based DTM

File based terrain modelling systems store terrain information as a series of separate files. These files are accessed and modified mainly through batch processing. Examples of file based terrain modellers include Modelling Systems (MOSS), as described by Craine (1987), and the Surface Approximation and Contour Mapping (SACM) package, as discussed by the author (Durrant and Legge, 1982).

2.4.2 CADD based DTM

Interactive environments take advantage of computer graphics to facilitate the manipulation of terrain related information, with all data being stored within the graphics database. Such environments are usually referred to as computer-aided design and draughting (CADD) systems. Examples of CADD based terrain modellers include GDS-Sites as described by McGarry (1986), Intergraph, and ProSURVEYOR as discussed by Strodachs (1987).

In addition to terrain modelling facilities, comprehensive computer modelling and draughting facilities are generally available, for the purposes of engineering design and the production of working drawings. CADD systems appropriate to architecture, engineering and construction are discussed in greater detail in chapter 3.

2.4.3 DBMS based DTM

Database Management System (DBMS) environments are used to efficiently structure and manage terrain related information. An example includes the Medusa Geographical Information System (GIS), as discussed by Bundock (1987). The terrain information resides in a structured database and is accessed by the user through a controller program, or server. This has the advantages of multi-user access, data security and 'crash' recovery. It is usual that full CADD functionality is provided to act as the user/data interface, as well as a query
language with which the user can interrogate the database contents according to specified conditions.

The Medusa GIS manages all information, including terrain and attribute data, within the same relational database environment. Terrain geometry is topologically defined as described in 2.3.2, and is stored using a spatially referenced indexing system. Data duplication, such as the common boundary between two adjacent polygon facets, is omitted. The above features allow topological routing and condition based spatial interrogations to be interactively carried out on large amounts of terrain related information. Any subsequent updates to the terrain model and its topology can be made dynamically, or 'on the fly'. The use of the Medusa GIS for simulating the hydraulic disposal of tailings, or mine-waste, is covered in chapters 6 and 7.

2.5 **DTM TYPES**

A DTM may be considered as a digital representation of terrain, derived from a set of data points which reside on its surface. The data may either be grid based, including square, rectangular, hexagonal and triangular, in stringed form, or of an irregular distribution in terms of orientation and spot height value.

Stefanovic et al (1976) identified three reasons for adopting differing choices of data distributions. These include the DTM application, the nature of the terrain, and operational factors such as equipment, sampling time and computer processing.

2.5.1 **Grid based terrain models**

This is the simplest form of data distribution, being easily implemented in data capture instruments such as photogrammetric systems. Sampling patterns include square, rectangular, hexagonal and triangular grids of data points. Petrie (1987a) has discussed progressive sampling for gridded data sets using photogrammetric methods. Essentially a coarse distribution of original points is enhanced locally according to the terrain relief and slope. Progressive sampling is used because a regular data point distribution is not related to the characteristics of the terrain, that is too few points reside in areas of high relief and too many exist in relatively flat areas. Thus the progressive sampling technique addresses the aspects of specified accuracy, sampling density and terrain characteristics. Petrie cited the Height Interpolation by Finite Elements (HIFI) and the Stuttgart Contour Program (SCOP) as
examples of DTM packages using grid based terrain data.

Where data capture has taken place via terrestrial surveying, random point to matrix interpolation can be used to convert the measured data to a specified regular grid distribution. According to Strodachs (1978), pointwise, global or patchwise interpolating procedures may be used. The pointwise technique involves the calculation of the gridded spot height values from the neighbouring random measured heights, normally based on a nearest neighbour search. Global methods fit a single function, such as a high order polynomial, to the random measured points, and hence the corresponding gridded values are determined. The patchwise approach is a combination of the first two, where separate mathematical functions are fitted to equal sized data patches within the random measured data set.

Gridded data can be rapidly processed by computer during analysis, such as is discussed by Griffin (1984). In some applications, for example, data point inter-connectivity may be sufficiently implied by row and column number alone, as opposed to a more rigorous and explicit topological definition.

2.5.2 Triangulated Irregular Networks

The Triangulated Irregular Network (TIN) approach has been adopted by a number of more recent terrain modelling packages, examples being Eclipse, GDS-Sites, Hasp, Intergraph TIN, MOSS and ProSURVEYOR. All randomly measured data points are represented in the final surface, since they form the vertices of the triangles that collectively define the terrain model.

The random data points are interconnected, either manually or automatically, to form a triangular mesh. The author (Durrant, 1984a) produced a simple random surface modeller, that required the manual generation of the triangular mesh, for modelling rainfall data. McCullagh (1983) stated that an automated approach should attempt to create a unique set of triangles that are as equilateral as possible and with minimum side lengths. There are two main algorithms that are used which comply to these requirements, the Delauney and radial sweep algorithms, which have been summarised by McCullagh.

Whereas gridded, or ordered, data sets are unable to show terrain irregularities without an overall increase in data density, randomly located height data allows more freedom in data collection, such that sampling may be adapted to the characteristics of the terrain.
Furthermore, stringed sets of random data points allow existing topographic features such as cliff edges, and man-made structures, including road cuttings and embankments, to be included in the final TIN model.

2.6 DTM Accuracy

Error may be of three types. Random errors, a result of observational or measurement imprecision, are small and equally likely to be positive or negative. Systematic errors are introduced by procedures or systems, and are predictable but not easily corrected. They are small, but with a bias in the positive or negative direction. Gross errors are a result of human mistakes or exceptional conditions, are generally large, and thus easily identifiable.

Shearer (1987) has stated that accuracy is relative, rather than absolute, to the control used to assess its magnitude. The 'true' case is the terrain itself, and therefore the reference is usually another DTM measured to a much higher degree of specification. A qualitative analysis of the derived DTM contours against those of the reference form a preliminary basis of assessment. A comparison of interpolated spot height values, against those derived from the higher order control, provides a quantitative method of accuracy determination. Shearer has summarised DTM accuracy as a function of the method of data acquisition used, the density and distribution of the input data and the modelling process itself.

Grist and Stot! (1976) have addressed errors associated with earthwork volumes derived from DTM's. Earthwork volume errors may occur at three stages in their calculation. These include the survey, modelling and design phases. An overall error of 5 to 10 percent of the total volume is quoted as acceptable for earthwork volume calculation. Grist and Stott have also presented the results of a study known as the Wensleydale experiment. Earthwork volume errors are listed for differing data densities and modelling methods. Errors were found to behave consistently, decreasing in magnitude with increase in data density. Increasing the modelling complexity, however, gave relatively small improvements over simpler methods, with all modelling methods producing very similar volume estimates when used with the highest data density.

Siyam (1981) also investigated the accuracy of earthwork volumes derived from DTM's. Siyam stated that, in highway engineering, earthworks can account for 20 to 30 percent of...
the total project cost. Therefore highway designers consider earthwork quantities to be the major criterion in differentiating between alternative alignments. Siyam concluded from theoretical and experimental studies that a decrease in elevation accuracy may be compensated by an increase in data density. Additionally, the influence of both the elevation accuracy and data density on derived volumes decreases with increase in distance between highway cross-sections. Furthermore, the distance used between each of the highway cross-sections was found to have the largest influence on the accuracy of volume computation.

2.7 DTM APPLICATIONS

The uses of a DTM are multi-fold. For the purposes of this study, four main areas have been identified. These are by no means the only benefits to be derived from a DTM.

2.7.1 Contouring

Historically, terrain topography has been assessed by contouring the area of interest. The contouring algorithm adopted is dependent upon the modelling method used. Petrie (1987c) has produced a comprehensive summary of contouring techniques. For gridded data, linear interpolation across each of the grid cells is the simplest form of contouring but this can, however, cause ambiguities in the derived contours. Therefore more mathematically intensive approaches, involving polynomial fitting functions, are used which sub-divide each of the grid cells into component units prior to contour threading.

According to Petrie (1987c), triangulated data sets, unlike their gridded counterparts, lend themselves to linear interpolation methods because the potential ambiguities regarding interpreted contour direction are either not present or can be resolved. Usually interpolation commences at the boundary triangles, with the entry and exit points of each being located, the search process then moving progressively inwards.

Contour smoothing is also possible for both data types by fitting spline functions. However, although such contours may visually be more acceptable, it must not be forgotten that they are nonetheless derived from the same data. Additionally, smoothing may cause contour crossing to occur, which is obviously inconsistent with real terrain.
2.7.2 Visualisation

The use of computer graphics to determine the visual impact of a terrain data set is widespread in landscape planning and estate development. For example, the visual impact analysis of electricity transmission lines on the prevailing landscape has been covered by Turnbull and McLaren (1987). The three-dimensional visualisation of landforms is further enhanced when colour shading techniques are used, to display non-geometric terrain attributes such as vegetation.

Flight simulation using terrain models is discussed by Rowley (1986). In military applications, it is not only the terrain shape which is of interest but also the spatial location of ground installations relative to the flight path. For real-time applications, such as flight simulation, efficient terrain information handling and graphics display techniques are necessary to support the speed at which the user's viewing point is updated.

Colour shading techniques have become an integral part of many terrain modelling systems. Plate 2.7.1 shows an unsmoothed colour shaded model of Clemows Valley, generated using the Medusa colour shading facilities. Clemows Valley is the site of the Wheal Jane tailings dam, a smoothed colour shaded model of which is shown in Plate 2.7.2. Plate 2.7.2 is a visualisation of the composite solid model referred to in 2.3.2.

2.7.3 Design

The derivation of quantities in terms of lengths, areas and volumes is probably one of the major uses of DTM. For example, the determination of strip ratios in open-cast mining is one such area, which has been investigated by the author (Durrant and Legge, 1982).

Other geometric relationships such as local slopes, aspects and vector normals can also be derived from a DTM. These quantitative characteristics derived from the model can assist in, for example, the hydrological analysis of rainwater run-off within a catchment boundary, or in the colour shading of the terrain itself for visualisation purposes as mentioned in 2.7.2.

The creation of new features, for example a highway, based upon information derived from a DTM can be attributed to design. In such cases, it is the optimum spatial alignments of the design structure with the prevailing terrain that is of importance. This includes both the quantitative relationship between the design and the terrain, such as the cut and fill.
Plate 2.7.1 Unsmoothed colour shaded model of Clemows Valley, Cornwall (Medusa colour shader)

Plate 2.7.2 Smoothed colour shaded model of Clemows valley and the Wheal Jane tailings dam (Medusa colour shader)
volumes, together with environmental implications, which include the visual impact, of the composite model. Additional modelling tools may be needed to define the shape of the design itself, in addition to supporting procedures to mathematically manipulate the design in conjunction with terrain model.

Heil (1979) proposed the use of a DTM as the basis for hydrological and geomorphological analysis. Heil used a triangular network to achieve a continuous terrain representation, which included stream beds, ridge lines and drainage divides. He concluded that a TIN DTM can provide a useful analysis tool for terrain specialists, such as hydrologists and geomorphologists.

2.7.4 Simulation

Digital Terrain Models can offer much in terms of simulating earth surface processes, such as sedimentation and hydrology. For such applications both the terrain geometry and its attributes need to be efficiently structured and managed. In addition, updates may need to be rapidly implemented to the terrain representation, in accordance with the nature and effect of the phenomena being simulated.

Simulation applications of DTM's require the use of data sets complementary to the nature and geometric scale of the application, in terms of both data distribution and density. A relational Database Management System has been used by the author to structure, manage and interact with terrain data sets for the purposes of simulating the overland flow and deposition of mine tailings. The development and testing of the computer-aided simulation of hydraulic tailings disposal is discussed in chapters 6 and 7.

2.8 DTM SELECTION

A concise, yet comprehensive, checklist covering the desirable features in DTM selection has been provided by McLaren (1987). As with conventional CADD, the selection process should only take place after a thorough specification has been drafted that is specific to the user's application environment. This section looks at some important features which should be considered prior to the selection of a DTM package.
2.8.1 Data checking, reduction and editing facility

A mechanism that enforces some form of preliminary checking is desirable to locate blatant errors in the raw input data. It is also possible that a data reduction procedure is available to translate the raw measurements into a form compatible with the DTM package.

Interactive editing facilities to add, modify or delete points and lines may be provided. In the case of a CADD based terrain modeller, such facilities would generally be made available through the two-dimensional draughting functionality. Modifications may include changes to the model itself, for example the point elevations or triangulated edge relationships, which should automatically update the DTM data set, to ensure data integrity. Furthermore, some systems may allow the editing of the resultant contours, invoking the necessary changes to both the terrain model and the data set.

2.8.2 Model constraints

Accommodation is made within some DTM packages for the inclusion of modelling constraints. These are usually referred to as break lines, form lines or structure lines. Such constraints may be necessary to honour existing terrain characteristics in the digital model, without the need for increasing the data density. These characteristics may include the edge of a quarry or outcrop or some other form of terrain discontinuity, in addition to other topographical features such as river beds. In some cases, boundary inclusion is also possible, whereby a localised area of the data set is isolated, such as in the case of a lake perimeter.

Where points or strings of data, related to non-geometric terrain attributes, form an object of reference, for example a tree or hedge, a feature point or line may be specified. Feature points and lines are not represented in the resultant terrain model, that is, they are not treated as model constraints.

2.8.3 Model transfer

The sharing of terrain data amongst multi-disciplinary users may create problems as are discussed in chapter 4. A relevant example of multi-disciplinary use could include a consulting engineer using a terrain model for determining bills of quantities for excavations at the tender stage of a large civil engineering project. Furthermore, the terrain model could be updated throughout the project and used by the consultant, quantity surveyor and contractor.
to calculate and verify interim payments and monitor work progress.

Data exchange formats of direct relevance to DTM include the Ordnance Survey Transfer Format (OSTF), the National Transfer Format (NTF), MOSS GENIO and Autocad DXF. Some of these standards only support an exchange of graphical elements. Therefore a three-dimensional mathematical model, such as a DTM, will not be maintained once it has been transferred. Terrain data exchange will become more widespread, once the Ordnance Survey has implemented its plan to provide adequate height data for the whole of Great Britain.

The potential purchaser of a DTM system should include his organisation’s data transfer requirements in the DTM purchase specification. This would involve an analysis of existing standards used by collaborating organisations and national bodies, as well as an investigation into future trends. The military, with their widespread use of DTMs in flight and tactical simulation, will most likely play a major role in determining these future trends in terrain data exchange.

2.9 SUMMARY

A fractal approach to digital terrain modelling, as covered at the beginning of this chapter, offers new prospects. The applications of these theories have generally been applied to the more qualitative, visual analysis of terrain. It is most likely that fractal geometry will play a major role in visual impact analysis, such as in project planning and in environmental studies. In contrast, however, engineering uses of terrain models require that a quantitative approach be adopted in terms of discrete lengths, areas and volumes. It is the Euclidean concept of quantifiable three-dimensional space that is more easily understood and implemented. Therefore it is most likely that this approach will continue to be used in quantitative DTM applications.

The integration of DTM and computer graphics techniques has been a by-product of the intensive development of computer-aided design and draughting (CADD) systems. Computer graphics has provided a powerful man/data interface through which to visualise and interact with terrain related information. The selection, implementation and management of CADD tools in AEC is discussed in the next chapter.
DTM applications have traditionally involved the batch processing of fragmented data files. However, advances in both computer hardware and data processing philosophies have more recently enabled large integrated terrain databases to be interactively interrogated and modified. One such methodology involves the use of Database Management Systems, which are discussed in chapter 4.

Digital terrain modelling techniques lend themselves to a multitude of applications, from engineering to natural earth sciences. The choice of data capture and modelling approach adopted will vary according to the terrain characteristics, the nature and scale of the application and the accuracy required. This thesis addresses one such application, that of the overland disposal of tailings, or mine waste. Tailings dams are discussed in chapter 5.

A DBMS based DTM with fully integrated CADD functionality has been used by the author as a dynamic platform for simulating hydraulic tailings disposal, as is discussed in chapters 6 and 7.
CHAPTER 3

COMPUTER-AIDED DESIGN AND DRAUGHTING
CHAPTER 3

COMPUTER-AIDED DESIGN AND DRAUGHTING

3.0 INTRODUCTION

The evolution of interactive computer graphics in the 1960's was highlighted by Sutherland's (1963) pioneering work in the United States. However it was the early 1980's before the arrival of appropriate hardware to support such graphics software for practical everyday use. Relatively low-cost, high resolution computer graphics workstations have meant that the engineering professions can now interact with their data through a visual medium.

The hardware associated with a computer graphics system consists of a computer, an interactive display, input tools and hard-copy devices. The computer stores the data from which pictures are constructed, generates the information needed to drive the display and monitors the input tools. The interactive display is used to present the data in visual form. The device may be of storage tube, raster scan or vector refresh type. Bez (1984) believed the last to be most suitable for the display of high quality engineering drawings and animation applications. Input tools are used to control the method by which information is to be structured and displayed, and include keyboards, joysticks, mice and digitising tablets. Hard-copy devices include plotters and printers, which are used to derive a permanent record of the visual display and associated information.

Hubbold (1984) recognised business and commerce, medicine, cartography, architecture and engineering as immediate beneficiaries of computer graphics technology. Furthermore he identified data reduction, ease of interpretation, communication and ease of updating as the principle advantages that computer graphics had to offer.

Skok (1983) identified synthesis, including engineering design, analysis and optimisation, and the preparation of engineering drawings as areas applicable to computer graphics deployment within manufacturing processes. The use of interactive computer graphics within manufacturing industry is generally referred to as computer-aided design/ computer-aided manufacture (CAD/CAM).
For the purposes of unambiguity, a more apt abbreviation for the use of computer-aided design in architecture, engineering and construction (AEC) is adopted in this text. When design, analysis and optimisation, in addition to draughting facilities, are provided for AEC applications, then computer-aided design and draughting, or CADD, is referred to. Guidelines for the selection, implementation and on-going management of CADD are set out in this chapter.

Some of the views expressed in the following sections of this chapter are as a direct result of a three month in-house CADD study carried out by the author (Durrant, 1984c). At that time, a CADD system, installed within a firm of consulting civil engineers, had been up and running for eighteen months. In addition, several architectural practices, consulting engineers, government agencies and vendors were visited in an attempt to correlate a basis on which a CADD package was selected, implemented and managed within AEC work-cycles.

3.1 THE SELECTION OF CADD

CADD has represented a major adjustment to the working practices within AEC. Mitchie (1984) recognised that it would be the subsidiary tools of the information technology (I.T.) era, such as drawing interchange, videodisc and telefiche storage, that would instigate the greatest change. Mitchie believed the construction industry to be a particular beneficiary. This was due to the nature of the industry itself, where product and services suppliers were geographically fragmented and involved multi-organisational design and production teams. This therefore created a problem of communication and information dissemination, one which could be drastically reduced by the judicious use of I.T. tools.

The first move towards purchasing an in-house CADD system is usually the compilation of a rigorous specification, based on an in-depth study of the firm's actual needs and forecasted work areas. It is possible that such an approach might delay the purchasing of the system, until either an appropriate vendor and product have been located or until finances so permit. It may even be decided that the services of a CADD bureau best suit the needs of the organisation, as has been suggested by Pipes (1984), or even no CADD involvement whatsoever.

Brits (1984) stated the following aspects as being important in designing a CADD system from a vendor's point of view. These points are also applicable to potential purchasers of CADD products:
Other more obvious factors affecting both the vendor and the potential client are those of cost, supplier's past and present trading record and capability for on-going system enhancement. In addition, Port (1984) recognised software origin as having a profound effect upon the selection of a CADD system. For example, a package that originated from a mechanically based industry would be more suited to mechanically orientated activities, as regards database design and application area.

3.1.1 Database design

A CADD database must be geared towards the efficient handling of vast amounts of geometric and non-geometric data. To illustrate this need, Brits (1984) quoted an average A0 engineering drawing as containing anything between 8,000 and 20,000 graphical objects. In the simplest case, a drawn line might necessitate the storage of at least 3 pieces of information.

Brits (1984) identified display hardware as having a marked influence on the format of databases. He believed that a number of systems suffered from a hang-over effect as a result of the display technology available at the time when the databases were designed. Furthermore he believed that more recent display technology offered less constraints on the database philosophy adopted, thereby allowing the designer to develop more flexible systems. Therefore the underlying database design of a CADD system was usually a function of its date of origin, which should be taken into consideration during the selection process.

A more comprehensive coverage of database requirements, with emphasis on Database Management Systems (DBMS) is presented in chapter 4.

3.1.2 Programming language and CADD software quality

Although the feature of programming language does not initially affect the decision of a potential purchaser of a CADD system, it can have a long term influence on both system
performance and user customisation. It is important therefore to appreciate the relative merits of
the programming language used, as some languages are more applicable to graphical
applications than others. Pascal, for example, has been closely linked with graphical
applications due to its modular structure and data sorting attributes, whereas Fortran is
associated with numerical analysis. Some CADD systems incorporate an internal, or macro,
programming language for user customisation, such as Symbol in Pafec Dogs and BaCIS in
Medusa.

Computer-aided design and draughting involves both the numerical analysis and graphical
display of data, and whereas Fortran may be more applicable to its analysis in modelling and
calculations, Pascal may best suite the manipulation of its graphical 'views' in draughting.
Therefore a purchaser should appreciate that these differences exist when considering long term
in-house customisation of the CADD system. This necessitates a closer inspection of the work
areas of the organisation, whether they lay mainly in draughting procedures, applications, or
both.

The actual quality and suitability of the CADD software is of appreciable importance. The
graphical facilities available for the generation of line drawings, including point, line and arc
definition and text insertion, are a few of the primary features required of the CADD software
used for two-dimensional draughting. Also included is the manipulation, editing and shading
of components or part components on a CADD drawing. In addition, more complex, modelling
transformation and viewing algorithms are necessary to support a three-dimensional capability.

The suitability of the software to user requirements can be assessed through a benchmark
test. The potential purchaser provides the vendor with a typical working drawing, which the
vendor then reassembles on the CADD system. The approach, drawing times and finished
product should be appraised, which reflects the efficiency and capability of the graphics
software facilities, database design, computer hardware and human interface.

3.1.3 Computer hardware

The speed of evolution of computer hardware has left not only the potential purchaser but
also the CADD supplier in a predicament as to which hardware to adopt. This predicament has
grown as available hardware facilities offer increasingly more powerful processors,
addressing greater amounts of storage and higher resolution graphic displays. Suppliers have
had to carefully gauge trends and adapt software for compatible operation, in keeping with
market demands.

Knights (1984), in a paper covering the effect of trends in hardware upon CADD, believed that as hardware became more powerful and cost effective, distinctions between mainframe, mini and micro-computer based CADD systems were harder to define. Apart from the obvious processing and storage differences, the effect of actual system capability and user response times, and the necessary configuration to adopt, became more difficult to predict.

Three configuration types were identified. Firstly, the multi-user mainframe and mini-computer processors, generally 32 bit, addressing a number of workstations and peripheral devices. Secondly, the dedicated, or standalone, workstations, servicing a single graphics terminal, which could be configured to share resources through networks such as the Local Area Network (LAN). Finally, there were the desktop personal computers of 8 and 16 bit capability. At the time of writing, personal computers with 80386 processors could address up to 32 bit accuracy.

The first CADD systems to evolve were mainly of the multi-user configuration type. Examples include early versions of Pafec Dogs and Medusa on Prime, McDonnell Douglas Information System's General Design System (GDS) on DEC Vax mini-computers. Holton (1984) recognised some serious disadvantages associated with this type. These included processor cost, workstation degradation due to overloading, terminal limitations and total system failure when the central processor 'crashed'.

In the mid-1980's, vendors customised their CADD software to run on independent, or dedicated, processing devices, such as Pafec Dogs to Apollo and Medusa to the Sun and Vax workstations. Such devices did not suffer from slow response times, could be purchased at a lower start-up price, and yet could be extended and configured according to the user's needs. Due to their inherent advantages, CADD systems based upon dedicated workstations have become increasingly popular.

Examples of the third type of CADD hardware platform include the IBM PC and PS/2 computers and their clones, including the Compaq and Olivetti 386 machines, supporting packages such as AutoCAD and ProCAD.
3.1.4 Human interface

The methodology and tools available for the input, manipulation and editing processes associated with both two-dimensional draughting and three-dimensional modelling have an important place in the everyday CADD workcycle. Two well used CADD related words 'user friendly' and 'productivity', immediately come to mind, referring to the graphical software philosophy and supporting hardware design of a CADD package.

Brits (1984) attempted to define the phrase 'user friendly' as applied to CADD, in human terms.

"If you work in a manual draughting environment, as opposed to CADD, you make a conscious decision to draw something; if you stop and reflect on what actually happens, you will notice that the thought and action are carried out at virtually the same time. There is nothing in between that you have to think about or do; reaching for a rubber, pencil, compass, is a reflex and not a conscious action.

If you make a conscious decision to draw something, and that thought has to be mentally converted into a different set of instructions before you can realise the end result on the CADD screen, the system is not really 'easy to use'. The more complex that set of instructions, the less 'user friendly' the system is. The more the set of instructions differ from the original thought or intention, the more 'difficult' it is to use. This does not mean that you could not become accustomed to these 'sets of instructions' but normal continuity and flow are lost. First comes the thought, then the translation, and then the action. In a manual draughting environment, your mind may also be several steps ahead of the actual line that you are constructing, on a CADD system which is not 'user friendly', this becomes difficult if not impossible. Speed is lost, therefore productivity drops."

Brits has effectively linked 'user friendliness' with system 'productivity', and although the human interface plays a prominent role, it is not the sole contributor to 'productivity'. Other factors are discussed later in the chapter.

Typical input devices supported by a range of suppliers include keyboard, tablet, or
digitiser, mice and screen menus, or icons. The author (Durrant, 1984), found that it was the latter, that is mouse and screen menu input, that best complemented Brits definition of 'user friendliness'. This in turn reduced the learning cycle in operative training. The operative generally did not concern himself with the inner workings of the system, but was more influenced by the effectiveness and approach of the in-built man/machine interface. Pafec Dogs, CIS Medusa and ProCAD all support screen icons.

3.1.5 Application area

The Engineering News Record (ENR), published in the United States, has covered success stories of American firms that had acquired CADD tools and were actively employing them in numerous areas within their practices (ENR 3 December 1981).

Not all of the firms which had implemented CADD in the true sense, that is with some interactive graphics capability, had found that productivity was increased in all areas of design and draughting. An example was given (ENR 12 July 1984) where one firm of precast concrete component manufacturers, who due to the nature of their work, had abandoned their graphics workstations and moved back to alphanumeric terminals. It was found that, since their product range lay within a small band of similar items, only a 15 percent increase in productivity was gained over manual draughting methods. This example underlines the fact that CADD, with design and draughting capability, is not necessarily suited to all projects, or indeed parts within a project.

Potential CADD purchasers should closely examine the nature of their work, categorising it into the various application areas, and determining the relative weighting of each within their overall workload. It might then become apparent that only vendors with expertise in specific application areas, such as finite elements and building design, would need to be approached in the selection process.

3.1.6 Other factors in the selection process

Other important factors relevant to the selection of a CADD system includes the start-up, and on-going overhead costs of running a system, and the integrity of the supplier organisation. With reference to the supplier's organisation, Port (1984) cited length of trading, size, number of installed sites, forecasted expansion, turnover, area of market concentration, industry and discipline of origin and client support and training, as but a few important issues
to consider when assessing the integrity of a potential system supplier.

In summary, a well researched and defined specification is required before approaching a suitable vendor. The viability of CADD sites is often doomed from the outset due to the absence of stringent requirements from the client, or simply because market pressures have forced hasty decisions.

3.2 THE IMPLEMENTATION OF CADD

The author (Durrant, 1984c) identified that it was a popular misconception amongst potential AEC purchasers that the transition between manual and CADD working methods was a short term process. However like any major change in working procedures CADD has to be gradually implemented and well managed for any real gain to be achieved.

3.2.1 CADD committee

The author observed a common approach in the management of systems within organisations. This usually took the form of a CADD committee, which was chaired by a partner/director who held overall authority for the CADD operation. Responsible to him was a systems manager, who was in charge of the routine running and training affairs of the site. The systems manager co-ordinated with the users-by-proxy, or the project leaders, who themselves were responsible for the delegation of work to CADD among engineers and draughting staff.

It was found that although these users-by-proxy need not have a 'hands on' familiarity with the CADD package, they should nonetheless possess a basic appreciation of the facilities available, and the inherent advantages and disadvantages of using CADD in specific work areas. For example, the draughting process might be highly applicable to producing the general arrangement drawing of a foundation and column base layout, but not so for a one-off hydraulic channel design.

The CADD committee was usually selected about two months prior to installation of the system. The committee would meet to decide on matters ranging from training to the definition of the in-house CADD symbol 'library', and to establish areas suitable for CADD usage, including productivity benchmarks and the costing of hourly rates.
3.2.2 The human factor

Port (1984) stated that, since CADD systems are generally introduced on the premise of increased productivity, possible fears of job loss among draughting staff should be alleviated by management. Port also recognised that the area of work that CADD excelled in, that is, the routine manipulation of predefined components in the draughting process, was one of monotony, which could result in fewer personnel trained and willing to take up this career.

Although sparse literature exists covering the human factor of CADD implementation, it should nonetheless be appreciated that this factor is possibly one of the most important in determining the overall success of a user site.

3.2.3 Ergonomics

Hill (1984) set out comprehensive factors for consideration when planning the positioning of a CADD system within the office environment. The workstation and operating environment are all too easily overlooked in favour of more obvious productivity gains. However Hill maintained that the "comfort and well being of the individual must be assured in order to reap the long term economic and other benefits" of CADD. Hill recognised workstation considerations as including the siting of the equipment and the operator's working posture. Environmental features covered lighting, room temperature, humidity and noise levels. In addition, Port (1984) recognised requirements specific to the CADD hardware, such as power supplies, operating temperature, humidity, absence of static electricity, cable runs, layout of and access to equipment and fire/smoke detection as other parameters necessary for the successful implementation of a CADD system. All the above mentioned ergonomic factors should be considered by the CADD committee well in advance of installation.

3.2.4 Training

Horn (1984) quoted some CADD suppliers as claiming that a one week familiarisation period was sufficient for users to become competent in the use of their product. He stated, however, that "the result which usually accompanies this was a draughtsperson who after one week understands about 30 to 40 percent of the systems capabilities and who can achieve a system capability knowledge of about 60 to 70 percent after 4 to 6 months. After this point, the learning curve tapered off sharply. The individual person would develop their CADD draughting skills in the area in which their work normally lies. In these specialised areas, the
person may justly claim to have increased their productivity but, when encountering those functions not normally used, their productivity could in fact be less than their previous manual methods”.

Horn suggested an approach whereby he made two distinctions in the CADD training policy to be adopted by an organisation, that of system manager and system operator training. He envisaged system manager training as encompassing the day to day running of the CADD site and database administration, or more specifically:

- Consumables control and purchasing
- Work scheduling
- Drawing indexing
- Back up procedures
- Basic fault analysis
- Software evaluation

In addition, the systems manager would have attended a systems operator training course covering drawing production, including:

- System introduction
- Basic draughting
- Intermediate draughting
- Patterns
- Labelling
- Hatching
- Dimensioning
- Translation
- Layering
- Advanced draughting
- Colour features

Horn’s study concluded that supplier’s claims of training times can be vastly underestimated, geared towards a commercial sales pitch of a system that was seemingly ‘user friendly’ and hence easily implementable.

Less obvious to the potential client was the fact that his staff would require on-going
training, most probably held in-house and organised by the systems manager, to cater for periodic software updates from the supplier.

3.3 **THE MANAGEMENT OF CADD**

Once a CADD system is up and running, the management problems begin. Mismanaged sites can soon become the black sheep of the organisation in the eyes of the partners/directors, and the bane of the operators. It is therefore imperative that a CADD site be efficiently run, in accordance with policies and objectives laid down by the CADD committee.

3.3.1 **Operational methodology**

The author (Durrant, 1984c) found that large organisations, in an attempt to reduce the pay-back period of their respective CADD sites, sometimes resorted, in extreme cases, to introducing a three 8 hour shift per day system. In the main, these organisations were concerned with conducting multi-disciplinary work in-house.

From further enquiries, it was also found that such CADD operation generally suffered from communication problems, in addition to the more obvious human consideration. For example, an operator would come on shift at 12.00 p.m., only to find that the progress of work was impeded by technical queries which could only be satisfactorily answered by a member of staff who was off-shift. Such occurrences totally undermined the potential of the CADD site.

Some organisations ran 12 hour shifts, which were more compatible with the flow of work, while others ran a flexible time system where an operator was limited to one or two hours of CADD time per day. Most systems managers insisted on a schedule of work being completed by the operators prior to commencing a session on the CADD system.

Not only did a rota based system cause further management problems, but if implemented incorrectly it could reduce productivity, such as in the example given above. The day-to-day work within, say, a consulting civil engineering environment, involves a high degree of interaction between project leaders, engineers and draughting personnel, one factor that needs to be taken into account when deciding on a methodology for system usage.

Other routine duties of the system manager included the control of revisions to
on-going project drawings, the compilation of a register of completed working drawings and the archiving of inactive job drawing files. In addition, (s)he was responsible for system security, including the allocation of user codes and authority levels to prevent data base corruption, and for frequent back-up procedures to guard against potentially huge data losses caused by system 'crashes'.

3.3.2 Productivity benchmarks

The derivation of a means by which to judge the effectiveness of a CADD system within a working environment has caused a high degree of misunderstanding among CADD managers. The absence of a global benchmark can result in suppliers and CADD managers alike tailoring figures to suit their own individual purposes.

The CADCAM International magazine has devoted some of its coverage to the area of productivity and the establishment of productivity benchmarks in articles such as 'Cadcam turns Cost to Profit' (Thornton-Bryar, 1984) and 'Splashing out on Cadcam' (Billsdon, 1984). With reference to the former article, an overall productivity gain by CAD/CAM tools of 2.1 was cited, derived from an analysis of the actual time spent by draughting personnel on drawingboard activities. The latter article was concerned with productivity ratios as determined from drawings consisting of families of parts, for which a productivity gain of 5 was quoted. Furthermore, this article reported on the less tangible benefits of CADCAM such as reduced lead times, better designs, increased management control and improved market image. In conclusion, Billsdon stated that "a completely watertight cost justification based on direct benefits alone is seldom possible".

Bold (1984) developed the simple definition of productivity as shown below:

\[
\text{Productivity} = \frac{\text{Output}}{\text{Input}}
\]

From a preliminary assessment of typical architectural drawings, Bold arrived at an average productivity gain of 2.35. This figure was achieved using hourly rates alone. However, Bold further expanded the above to:

\[
\text{Productivity} = \frac{\text{Total results achieved}}{\text{Total resources consumed}}
\]
where the total result achieved was the actual completion of the project, and the total resources used referred to the time and cost of all resources applied to that project. Therefore, in effect, the numerator must include additional weighting factors accounting for the more intangible aspects of CADCAM, such as those suggested by Billsdon.

3.3.3 System customisation and upgrading

CADD system customisation may include the purchase of application software from the original vendor or a third party software house. Alternatively system enhancement may take place in-house.

It is at this stage that the existence and power of an internal programming language as mentioned in 3.1.2 becomes important. This enables the user to access most, if not all, of the available graphics algorithms within the package, as well as providing processing capability for file manipulation and mathematical calculations. The user can therefore tailor his system to his own unique requirements, by setting up a series of much used commands as a single executable statement.

Additionally, as a CADD site becomes more established, it may become necessary to increase the hardware capability, by acquiring further disc storage and by increasing processing power. The sheer volume of graphical information, and its non-graphical attributes, which need to be accessed and processed at speed, will necessitate this move.

It is in the upgrading process that standalone workstation systems offer their greatest advantage. The acquisition of a single or a number of standalone workstations can be undertaken without adverse side-effects on the rest of the network, and at a constant incremental cost. Multi-user systems, however, suffer system degradation with the connection of more terminals, until a point is reached where a further central processor is required, at obvious great expense.

3.4 CADD MODELLING

This section is concerned with the three-dimensional definition of shapes other than natural terrain. Three main types of modelling methods are discussed, namely wireframe, surface and solid techniques.
According to Pratt (1984), much work was undertaken within the aerospace and automobile industries in the United States throughout the 1960's, into ways of mathematically defining complicated surfaces such as aircraft fuselages and car bodies. Alternative methods of modelling object shape are those of wireframe and solid modelling. The wireframe technique was the least complex of the three methods, defining structural shape by a series of lines and edges in space. Solid modelling was developed in the 1970's, primarily for Computer-Aided Manufacturing (CAM) applications.

Strodachs and Durrant (1986) identified some desirable features of three-dimensional modelling systems applicable to the needs of civil engineers. CAD/CAM suppliers historically addressed the lucrative manufacturing market, which forged the mathematical philosophy adopted for defining real world shapes. Shape definition was therefore confined to those commonly occurring shapes of manufactured products, with obvious tolerance differences to those appropriate to AEC. For example, the necessity to accurately define a car cylinder head for the generation of punched tapes in automated milling control required a different mathematical approach to that appropriate to defining a facia panel of a building.

3.4.1 Wireframe modelling

This is the simplest and least CPU intensive method of defining real world objects in three-dimensional space. Spatial points define the boundary of the object, by interconnectivity of lines and edges.

Pratt (1983), globally referred to wireframe techniques as edge representation models, of which he recognised three inherent characteristics, which included:

1. Conceptual simplicity.
2. It was a natural extension of draughting technology.
3. It did not necessarily delineate a single, unique object.

Pratt (1984) recognised some wireframe modellers as merely offering what was termed a '2.5 D representation' of object shape. These systems allowed depth information to be allocated to lines in a 2D drawing, and as such were very complementary to the draughting process and therefore easy to use. However, edge information of structural shape was not sufficient to facilitate automatic computation of object properties such as area and volume. An example of a wireframe modeller is the Dogs 3D package from Pafec.
For such modellers, it is not possible to infer the nature of the surfaces from the nature of the edge data stored. Pratt (1984) cited an example of an object face that had five co-planar edges. The system might reasonably guess that the face lies in a plane. However, should the edges not have been co-planar, then the system could not make an automatic choice of geometry for the face which they enclosed. This usually inferred that the user had to attach faces to his model, which could be a tedious process. In addition, the user must ensure that enough faces have been attached to give his object a complete boundary dividing its interior from its exterior. The advantage of defined faces was that hidden line removal could be carried out to assist in the visualisation of more complex models. Once the viewing position had been defined, the computer could interrogate the model to determine which faces were visible and which were not.

Pratt (1984) believed that it was the inherent characteristics of wireframe models that render them unsuitable for the definition of more complex objects. This included the need for manual face definition to ensure boundary integrity, and the absence of topological features, such as the relationship between faces, edges and vertices, in the final stored model.

In conclusion, wireframe modellers are deemed unsuitable for the generation of computer models used for quantitative design purposes, due to the absence of model information that is required for property interrogation.

3.4.2 Surface modelling

Surface models mathematically define a plane of negligible thickness in space. They offer a more rigorous modelling technique than the wireframe types. Surface modelling in the context of digital terrain modelling has been discussed in chapter 2.

Surface techniques include sculptured modellers. Pratt (1981) defined a sculptured surface model as a series of patches joined together with the requisite mathematical continuity to give a smooth surface. Patched techniques were introduced in the early 1960's, to represent more complex surfaces such as aircraft fuselages and car bodies; finite element (FE) techniques evolved out of the requirement to analyse the structural performance of these complex shapes. An example of a sculptured surface modeller is the Design Using Computer Technology (DUCT) package, available from Deltacam Limited, Cambridge. DUCT was originally written for the solution of mechanically based surface definition problems, on a batch processing basis. Surfaces are constructed by a series of transitional two-dimensional cross-sections.
which are aligned by three dimensional spline curves (Fraser, 1985). The user defines the positions of the patch corners and the location of the spline curves as a set of data points. Curves and patches are fitted to spline and corner points, thereby generating a complete mathematical representation of the surface. The concept of structural alignment through cubic splines is applicable to modelling mechanical components, but not to the majority of AEC related shapes.

A model representative of hydraulic tailings disposal has been defined using DUCT, and is shown in Figure 3.4.1. Two radial fans representative of coalescing, or adjacent, tailings deposits have been defined and located with their focal points at the crest of a dam embankment. However there exists no model interaction, or explicit geometric relationship, between the tailings fan deposits and the terrain surface.

3.4.3 Solid modelling

In a solid modelling system, the computer contains not representations of drawings of an object, but representation of the object itself. Pratt (1984) sub-divided modellers of this type into three classes. Firstly, the systems which are based on volumetric decomposition, whereby the object is modelled as an array of occupied and unoccupied cells. These are referred to as cellular or spatial occupancy systems. Secondly, the systems where complex objects are modelled from relatively simple volumetric building blocks or primitive volumes.

If these primitive volumes retain their explicit representation in the data structure that defines the final model, then such systems are referred to as constructive solid geometrical (CSG) modellers. Lastly there are the systems that model the complete outer boundary of the object as a series of free form surfaces, called boundary representation (B-rep) modellers.

According to Pratt (1984), the concept of cellular models is one of simplicity. A finite volume of space entirely containing the object to be modelled is assumed to be divided into a large number of discrete cuboidal cells. The modelling system records whether each cell in a three-dimensional matrix data structure is occupied or unoccupied by material. Object boundaries are defined by finer meshes, with storage requirement being proportional to the degree of shape resolution required. Cellular modellers excel in terms of simplicity, however they suffer from either very poor resolution or large storage requirements.
Figure 3.4.1 Surface model of coalescing tailings fans (DUCT)
Pratt (1982) quotes the TIPS-I system, authored at Hokkaido University in Japan, as being an example of a cellular based modeller of practical use. The TIPS-I system operates with a coarse mesh, whose constituent cells are divided into three types as opposed to only two; those cells that are either completely full or empty, and those partially containing material. The latter are defined in greater detail. For property computation, including volume, mass and moments of inertia, the boundary cells are further subdivided into a regular array of sub-cells.

Constructive solid geometrical (CSG) modellers are created by an assembly of representations of simple volumetric primitives, which typically include cuboids, circular cylinders, cones, spheres and toruses. Boolean or set theory can then be invoked to provide set unions, differences or intersections. A record of the sequence of model creation is stored in a bottom-up binary tree data structure.

The primitives themselves are represented in terms of half-spaces, where any surface which apportions three-dimensional space into two disjoint regions defines two half-spaces. For example $x^2 + y^2 + z^2 < 1$ is the half-space inside the sphere $x^2 + y^2 + z^2 = 1$, the other half-space being $x^2 + y^2 + z^2 > 1$. This enables the definition of discrete, rigorously defined volumes within an infinitely large space or universe.

The advantages of CSG modellers include conceptual simplicity, robustness, small primary storage requirements, guaranteed model integrity and ease of representation of parameterised-part families. The latter has important implications in engineering applications, where the dimensions of commonly occurring primitives, or even combinations of such primitives, can be expressed as variables.

Disadvantages of CSG modellers include computationally expensive local model updates and visualisation procedures, and difficulty in provision for non-geometrical information associated with model surfaces. The former factor has serious implications on the interactivity of such modellers. During a design cycle, a design must be updated and redrawn many times, and therefore must be facilitated with ease and efficiency. For model visualisation the edge details are required. These are not explicitly available in a CSG data structure, which only contains geometry in the form of boundary surfaces of primitive volumes. They must therefore be computed by considering surface/surface intersections. This is likewise for relevant vertex and face information. In summary, the model enhancement process is computationally slow. An example of a CSG modeller is Boxer, developed at Leeds.
Boundary representation (B-rep) modellers record all elements that make up an object boundary, namely faces, edges and vertices, as well as the topological information which describes how these elements are linked together. The data structure of a boundary representation modeller is incrementally built up in tandem with model creation. Due to the fact that explicit edge details are present in the data structure, a wireframe picture of the model may be rapidly generated at any stage within the modelling cycle.

Boolean or set operations are generally provided with B-rep modelling systems. These tend to be computationally expensive since surface/surface intersections must be computed, with the new implied edges and vertices inserted into the data structure, along with other updated information. Subsequently a range of object construction methods are usually included to avoid the lengthy waiting periods associated with boolean operations. Sweeping is one such constructional method, where a closed two dimensional profile may be defined and subjected to a linear or rotational sweep to generate a volume. Another method of boundary model manipulation is referred to as local operations. These operations can be employed to allow slight modification of the topological or geometrical aspects of the data structure, in a more efficient manner than their boolean alternative. For example, a vertical plane face may be tilted by updating the local geometry of adjoining edges and faces, although the topology, or connectivity relationships, remains unaltered.

Some boundary representation modellers employ techniques in which curved surfaces are represented as assemblies of planar facets. This has the advantage of simpler computations for surface/surface intersections and hidden-line and surface calculations. Modellers supporting faceting techniques include Medusa 3D from Cambridge Interactive Systems, as described by Newell (1982), and Euclid from Matra-Datavision. The use of Medusa 3D for civil engineering applications has been reviewed by Mayo et al (1986).

Boundary representation modellers offer the advantage of a wider range of computationally efficient model creation techniques than their constructive solid geometry counterparts. Salient non-geometric information can be easily inserted into the data structure, and geometric information can be efficiently accessed for the purposes of visualisation and analysis. Associated disadvantages include a much larger storage requirement than CSG modellers. Model integrity cannot be guaranteed, since B-rep modellers are less robust than CSG systems due to the ill-conditioning of complex geometric relationships and the
numerical rounding errors associated with large and complex data structures. Difficulty is experienced in providing a facility for modelling families of parts, since consistency between parts must be maintained in the complex data structure. Therefore families of parts must be defined using a high-level macro approach in conjunction with a macro processor which constructs the corresponding evaluated data structure.

Figure 3.5.1 shows a Medusa 3D B-rep model of the Muntimpa tailings dam project in Zambia. The composite model was assembled as a family of parts using the assembly modeller facility within Medusa 3D. Boolean operations were then used to merge the dam embankment, the five tailings fan deposits and the pond onto the solid terrain model. The geometry of the final model is explicitly defined in the data structure of the model file. However, as was the case with the DUCT sculptured surface model shown in Figure 3.4.1, the tailings fans were manually located without prior interaction with the prevailing terrain geometry. The relevance of this factor to a computer-aided simulation of hydraulic tailings disposal is demonstrated in chapter 6, where terrain obstacles in the path of discharge will cause errors to occur when non-interactive modelling techniques are adopted.

3.4.4 Selection of a CADD modelling system

Johnson (1987a) provided a comprehensive report on 29 commercially available solid modelling packages, and has included a checklist of desirable features to assist in the selection of such a system.

As has already been discussed, digital representation of structural shape can be achieved by wireframe, surface or solid modelling techniques. However, the digital modelling of a terrain related project will generally include the merging of 'uniform', mathematically continuous shapes, such as buildings, onto a more 'random', discontinuous terrain model. The mathematical modelling theory used to represent the building will therefore not necessarily be applicable to creating the terrain model. Furthermore a geometrical interrogation of their individual and conjoint properties may also be required.

Wireframe modellers have been considered unsuitable for such applications, due to their inflexibility, low level of shape resolution and lack of property interrogation. This is likewise for sculptured surface modellers such as DUCT, which are constrained to modelling mathematically continuous profiles. Cellular and constructive solid geometrical modellers are not applicable to the definition of more complex shapes, although they offer
Figure 3.5.1 Solid model of Muntimpa tailings dam, Zambian Copperbelt (Medusa 3D)
the advantage of simplicity. Boundary representation modellers offer the necessary flexibility and efficiency in the modelling process. However they suffer from large model storage requirements. The Medusa 3D system, an example of the latter, has been used to analyse the volumetric distribution of simulated tailings deposits, and further discussion is available in chapter 7.

3.5 SUMMARY

As discussed in this chapter, the selection of a CADD system should involve the compilation of a rigorous specification prior to tender. The organisation's major work areas must be reflected in this specification, an example of which may appear in the benchmark. The implementation stage should involve all personnel concerned. Consideration should be given to the siting of the hardware as well as to the working environment. Training policies must be decided upon well in advance of purchase. The management of a CADD site should include the delegation of duties to suitably qualified personnel. Productivity should be measured as a function of the overall benefits derived by the organisation, as opposed to the more immediate advantages. The above points are of paramount importance to the long term success of the CADD site.

Recent developments in low-cost Personal Computers (PCs) have meant that extensive computer processing power is now within the reach of many professionals. CADD software, in keeping with this trend, has become more modular, transportable and user applications driven, in contrast to the 'black box' systems of yesteryear. CADD tools can now, more than ever, be employed to model, analyse and enhance engineering data and its spatial and semantic relationships, and subsequently present it in the form of working drawings. CADD offers a mechanism for interacting with, and generating, large amounts of engineering data. However, it is crucial that this digital data is efficiently structured and managed if maximum benefits are to be realised. A discussion on data management approaches is the subject of the next chapter.
CHAPTER 4

DATABASE MANAGEMENT SYSTEMS
4.0 INTRODUCTION

Wegner (1984) stated that "the computer revolution will fundamentally amplify man's ability to manage knowledge, just as the industrial revolution fundamentally amplified man's ability to manage physical phenomena". According to Wegner, it became apparent from examining the level of information propagated in 'soft', or digital form, that compatible and well organised data structures were required, if all this accrued data was to be disseminated in an intelligible knowledge based form, for the overall advancement of society.

In his paper, Wegner has adopted the concept of 'reusability' as a theme for identifying the need for carefully structuring reusable, or common, components in order to streamline all work cycles. He has defined 'reusability' as "a general engineering principle whose importance derives from the desire to avoid duplication and to capture commonality in undertaking classes of inherently similar tasks". This concept is extremely apt in engineering design cycles where common principles and elements are applied to conceptual ideas in order to reach a final solution. All the factors mentioned in this paragraph are of direct relevance to the use of Database Management Systems (DBMS) to structure and manage large data volumes.

The handling of large data volumes is an everyday part of modern engineering practice. The Information Technology era has meant that drawings, calculations and reference data are all being transformed into a digital format. Smith et al (1980) studied the conceptual design of data structures and observed that Database Management Systems (DBMS) have evolved from file based systems to serve two critical needs; the support of more inter-related data, and the sharing of data among many diverse applications. Sidle (1980) investigated the shortcomings of commercially available DBMS being applied to engineering applications. The move by engineering organisations towards more centralised databases; has meant, in some cases, inappropriate "off the shelf" systems being implemented, with a poor end result.

Staley et al (1986) have identified that the requirements of an engineering Database Management System are fundamentally different from those of a business system. Historically,
business data processes are characterised by a small number of different record types and a large number of instances of each type, examples being payroll and invoicing transactions. Most of these databases tend to exhibit large, but very business dependent, database structures. Business databases were primarily concerned with record keeping, and therefore involved the modelling of relatively simple relationships between data types, which were relatively stable over time. However this feature is changing with the evolution of Management Information Systems (MIS) to handle modelling applications relevant to marketing and the stock market.

Engineering databases are, however, characterised by many data types, each having a large number of instances, causing difficulties for both the database designer and administrator. This includes all CADD generated data, as discussed in the previous chapter. Unlike commercial DBMS, artificial intelligence (AI) databases generally support a large number of data types, but tend to suffer from performance problems, and hence can only practically support relatively few instances. In addition, CADD databases must support complex relationships between data items. The application of database technology to both AI and CADD will be discussed later in this chapter. It is the objective of this chapter to identify the requirements of Database Management Systems applicable to architectural, engineering and construction (AEC) work-cycles.

4.1 DATABASE MANAGEMENT SYSTEMS (DBMS)

4.1.1 Definition

Eastman (1981) defined a 'database' as "an organisation of data, too vast to be held in the main memory of a computer at any one time, and upon which effective operation requires some form of structuring". 'Database' usually refers to a particular collection of data, whereas 'Database Management System' (DBMS) relates to the system level program that supports the maintenance of a database.

According to Melkanoff (1987), a DBMS is a program designed to provide decision makers with the information they require to make decisions, and consists of the following four parts.

(1). A database (DB) and a data definition language (DDL).
(2). A query language (QL).
(3). A data manipulation language (DML).
(4). A system.
Melkanoff defined a database as "a linguistic, static, organised description of a universe". A linguistic description is in context to a natural or a computer language, where information is basically constructed from two types of sentences. The first are specific declarative sentences, such as "Fred is 45 years old", and general declarative sentences, for example "no worker can be greater than 65 years old". The word 'static' refers to the description of the database provided by declarative sentences, not to the characteristics of the data held in it.

A data definition language (DDL) allows the user to define the organisational structure of the database, analogous to the declarations of variables in a programming language. An efficiently structured database is a well organised set of data that actually represents intelligible and useful information, as discussed by Wegner (1984). The primitive unit of information is the data entity or field. Fields are defined according to the data type they hold, and may include reals, integers or character strings. Collections of fields are called records, the format of which is referred to as a record type.

The multitude of record types and structures define a complex data structure, which is referred to as the database schema. This schema is sometimes represented explicitly and stored on a separate file called a data dictionary file (DDF), so that it is accessible by the different database support facilities discussed in 4.1.2.

For data to provide information, it must be organised so that one record can refer to several others. For example, to determine the connectivity of a valve to two or more lengths of pipe, the data must be physically stored so that for a specific valve record its connecting pipe records can be identified. Likewise several records may refer to a single common one, where, for example, a group of pipes are of the same material type. These are referred to as one-to-many and many-to-one relationships, both of which may exist in the description of a certain user application. Database Management Systems use one of four methods to structure their data; either hierarchical, network, relational or object orientated, all of which are described in 4.2.

An access method is provided by all database systems, to guarantee optimal retrieval of records, using a unique key. In addition, most DBMS's support access via non-key fields, where, for example, it may be required to access all instances of a particular pipe size or material for the bill of materials.

The query language provides the user with access to the information stored in the database. It consists of sentences which are imperative rather than declarative, an typical example being
"report all pipes where diameter is greater than 150 millimetres". The Structured Query Language (SQL) has been adopted as an industry standard, being implemented within systems such as Oracle, dBase II and Ingress. However SQL cannot handle recursive data structures, such as would be required to compute the bill of material example given above.

According to Melkanoff, the static nature of the database prevents it from maintaining a valid representation of the universe whose properties change due to its dynamic nature. A data manipulation language (DML) is therefore provided to enable the user to carry out updates, and includes mechanisms to add, modify and delete information held in the database. In Melkanoff's description of a DBMS, the system refers to the computer hardware and software which responds to the DDL, QL and the DML, and takes the appropriate actions. In addition to the DBMS facilities mentioned by Melkanoff, further features are usually offered to assist in the development and administration of the database. These are referred to as support facilities or utilities.

4.1.2 Support facilities

Support facilities are provided within a DBMS to assist in the administration of the database. Due to the large investment made in the contents of a database, it is important that some form of backup and recovery mechanism is provided to protect against a system 'crash'. Data access control and security can be achieved by incorporating read/write priorities for each of the record types, to avoid data corruption by unauthorised users.

According to Martin (1976), it is desirable to isolate the application programs not only from changes in file hardware and increasing file size, but also from additions to the data that are stored, such as new fields and relationships. DBMS software must take into account the fact that a database is continually evolving and may also include new applications. New record types may have to be added, or the database structure amended so as to improve its efficiency and permit new types of database enquiries.

Data structures may be converted by unloading the existing database as is described by the DDF, and implementing an amended DDF. Therefore database tuning can be carried out without affecting the data itself.

In addition, multi-user access is usually made available, generally implemented through a server, or controller program, which allocates read and write locks preventing conflicts
between multiple users.

Furthermore, report generators are an important facility of any DBMS in terms of data presentation. They allow the user to create hard-copy reports based on the database records, according to specific tables, fields or conditions.

4.2 TYPES OF DBMS

In the formative years of data processing, each file contained a single record type. More advanced files allowed the user to designate one or more of the data items as the key used for sequencing the file and for locating the records.

DBMS's can support multiple record types within a single physical file. A range of access methods, for example, B-trees, ISAM indices and sequential, have been utilised to provide faster access to individual records. An in-depth coverage of accessing methods is provided by Martin (1976).

Hierarchical and network files are terms used to describe structures classed as tree and plex (a series of trees) structures. According to Martin (1976), the majority of the original databases were of this type. However there is a simpler and more elegant approach. The principle of 'great engineering is simple engineering' is Martin's theme as he foresees database systems becoming cumbersome, inflexible and problematic as new data and applications are added by the users. Hierarchical and network DBMS types suffer from complexity, in terms of how the data itself is visualised by the user. In order to add conceptual simplicity and clarity, and hence avoid the subsequent entanglement of the data structure, a third type of DBMS is used, which is based on the 'relation'. There is also a fourth kind of DBMS, the object orientated type, which is based on groups of interacting objects.

4.2.1 Hierarchical and network DBMS

A hierarchical DBMS is an assembly of data, that is composed of a hierarchy of sub-assemblies called nodes. The top level of the hierarchy has only one node, called the root. Excluding the root, every node has another node related to it at a higher level, which is called the parent, and no node can have more than one parent. In contrast, each node can have one or more elements related to it at a lower level, referred to as children.
The term hierarchical file refers to a file with a tree-structure relationship between the records. This tree-shaped structure usually implies that there is simple mapping from parent to child and that the inverse mapping of many-to-one is complex. An example of this is the corporate personnel structure where each project is run by one manager, who individually directs the work of several employees. In this instance, each manager is responsible for only one project, and each employee to only one manager.

'Tree' or 'hierarchical' structures cannot describe the relationship where a child has more than one parent. In the example given above, this would occur if it was corporate policy to allow a manager to be involved in several projects, or for an employee to be responsible to two or more managers. In such cases a network, or plex structure, approach is adopted, which caters for a one-to-many/many-to-one relationship by allowing bi-directional access. A hierarchical structuring mechanism therefore requires the copying of shared records, whereas a network does not.

4.2.2 Relational DBMS

Relational DBMSs are based on the rules laid down by Codd (1970). The relational model allows a logical, not a physical, view of data. It provides simplicity and hence clarity in data structure. Users are permitted to make database enquiries and obtain views of the data in the form of tables.

The relational database is composed of relations that consist of a set of data values called components. Relations are usually described in tabular format, in which columns hold components for a particular attribute, and rows correspond to record instances and are called tuples.

Normalisation is the term used to describe the step-by-step process used for replacing relationships between data with relationships given in a two-dimensional tabular form. Normalised data structures have gained in popularity over other data structures due to their ease of use, flexibility, ease of implementation, data independence, clarity, and redundancy elimination to name but a few advantages.

Westlake (1987) identified some important types of data that would need to be managed within an engineering database, along with their performance requirements. These included simultaneous equations for finite element analysis, the rapid graphics display of engineering
drawings and the efficient interrogation of large-scale mapping and utility information. Westlake has introduced his 'continuum' database, which is an extension to the classical relational model. In addition to its logical view, data is constructed in a physical tabular form and accessed directly by application programs. The result is an increase in transaction and enquiry performance, in keeping with the engineering requirements mentioned above. Since the extensions are only relevant to technical, engineering and spatial disciplines, the relational model is kept intact as a sub-set of the continuum model.

A Geographical Information System (GIS), built around a relational DBMS, was used in this research to structure, manage and interact with data relevant to the hydraulic disposal of mine tailings. The implications of the relational data model to this particular engineering application are further discussed in chapter 6.

4.2.3 Object orientated DBMS

According to Sernadas et al (1987), object orientated DBMS's have evolved to cater for the behavioural descriptions of data within a database universe. Sernadas assumed objects to be time evolving entities as opposed to inert data units. Whereas data types, common to traditional DBMS systems, are useful for describing the attribute domains, object types are needed to describe the entities themselves, and their behaviour.

They have developed the basic concepts and tools for the specification of object types as a more appropriate alternative to the traditional data types. The object approach to database specification requires that a full description of the society of interacting objects is given. This includes both their structure and behaviour.

Object orientated DBMS's are useful for representing linkages in kinematic applications. Take for example the relationships in a bicycle. Pedals are attached to the bicycle assembly by virtue of bearings, which allow circular movement. The pedals are themselves connected to a sprocket, which in turn is linked to a rear wheel sprocket by a chain. By turning the pedals, the sprocket revolves, driving the chain and hence the rear wheel. The whole bicycle assembly or society of objects are thus driven forward. The front wheel, although not directly driven, is also revolved by virtue of its explicit linkage within the bicycle assembly.

Examples of object orientated DBMS include PROBE and TIGRIS. PROBE was developed by Dayal et al (1987) to satisfy the information processing requirements of
geographical information systems, solid modelling and computer-aided engineering. The TIGRIS system has been developed by the Intergraph Corporation as a platform for a range of their software products.

4.3 DATABASE DESIGN FOR AEC

In addressing the design of an application database, it is important that a clear appreciation of the relevant data and its subsequent transactions is achieved prior to any preliminary work. Smith et al (1980) delineate database design into three phases. The first phase, the 'view design', is the identification and design of interfaces for the different end-user groups. A view should present data in a structure which is most effective for the user, and must provide tailored update facilities for the user to manipulate the database. Secondly, the 'conceptual design', which integrates all the concepts which are necessary to support the various application views. Data should appear in a structure that explicitly defines how concepts are related to one another, without containing any implementation detail, yet should be locally modifiable. The third phase, that of 'physical design' involves the mapping of the conceptual model onto physical computing devices. Here performance considerations must be analysed and shown to be compatible with the application requirements.

According to Martin (1976), there often exists a fourth phase, that of the terminal view. This is the view of the data obtained by a non-data processing trained user. It is important that this view is as close as possible to the view that is inherent to the user's job. This feature is similar in concept to the 'user friendliness' of CADD systems described in chapter 3.

Rock-Evans (1987), in a book on computer systems development, has provided general examples to enable a comprehensive data analysis of an organisation's data to be carried out from first principles. Bundock (1988) has produced a comprehensive set of training notes covering database design. The course included both the logical and physical design of a database, with an emphasis being placed on the relational type of DBMS.

4.3.1 Characteristics of engineering data

According to Benayoune et al (1986), an engineering database must be capable of handling complex objects, whether they be descriptions of civil engineering or architectural objects, which may involve the linking together of vast amounts of data through complex relationships. The handling of data with different structures, whether it be structural, pictorial or
alphanumeric information, is common-place in engineering design. Each of these objects may be an assembly of a multitude of units, or sub-objects, which may be common, and hence need only be described once in the database. Each of the components of the assembly have attributes which must be easily described. In addition, the dynamic nature of engineering data transactions must be accounted for, such as structural changes during the design stage in a multi-disciplinary project.

4.3.2 Design methodology

Benayoune et al (1986) quoted the following features as necessary prerequisites of an engineering database:

(1). A comprehensive data model for handling complex objects in a natural way, that is, implying the use of concepts which are familiar to the designer involved in the actual design of items of equipment or parts of the overall process.

(2). Modularity, where different portions of the database system should be capable of being designed and modified separately without affecting the rest of the user community.

(3). Supporting software tools, to assist in carrying out some of the database design, due to the complexity of engineering data structures.

(4). Ease of use by non-database experts is important if the methodology is to be adhered to without involving redundant data or data relations, thus allowing them to concentrate on the design of their databases.

(5). Independence of hardware, software and DBMS constraints.

4.3.3 Engineering data models

Benayoune et al describe an engineering data model as a set of well defined concepts used to represent the static and dynamic properties of data and to support the desired transactions. The most important tools in database design are the data model and its corresponding data definition and manipulation languages.
An engineering data model should have natural primitives, which are familiar to the designer. These primitives are grouped into two categories. The first are structural primitives, which are used to represent the structural information of a project, and alphanumeric primitives which consist mainly of attributes of the entities modelled in terms of the structural primitives.

The engineering data model should be expressive enough to describe the application without resorting to complex combinations of its primitives, and flexible so as to cater for both dynamic and static data structures. The primitives themselves should be precisely defined so as to avoid ambiguity.

4.3.4 Multi-disciplinary and multi-user design databases

So far, specific DBMS application areas have been discussed. The flexible data structures of a DBMS approach can allow for the modelling of dynamic, or transient, data sets. However it is in the management of large scale multi-disciplinary projects that a DBMS approach can offer its greatest dividends.

The simplest case is the single-user environment, where only one person is allowed to work on the database at any one time. However most AEC projects are of such magnitude and under such time constraints that parallel development by multiple users may be of the utmost importance. In order to support multiple users, the system must manage the multiple requests for data, resolving conflicts that occur between simultaneous read and write operations and when one user updates information that is being used in decisions by others.

According to Eastman (1981), the standard method for controlling concurrent use is a system of locks, whereby only one user may have read-write access to a data item at any one time. Another means of separating concurrent users is by spatial isolation. Communication between concurrent users is important. A design database should support attached messages, that are associated with particular data items, backing up direct 'mail' facilities.

Volkman (1984), in his approach to discipline integration from an architect's viewpoint, has cited that "it has been conservatively estimated by project management sources in the U.S.A that formal communication on any building project accounts for as much as 25 to 30 percent of the total design and management cost". He was in fact referring to traditional ways of managing projects, through the transfer of manually produced drawings, reports and documentation. Volkman has suggested a 'dedicated multi-discipline approach'. The most
significant difference about this approach is that all disciplines fall under one common management umbrella, as do the computing facilities. He does, however, recognise that initially there exists some real management problems to surmount in the setting up of lines of communication and procedure between the member organisations. The idea of a multi-disciplinary design database becomes attractive when attempting to reduce the project design and management cost percentages quoted by Volkman.

Johnson (1987b) identified the problems associated with supporting an environment distributed over a heterogeneous mix of computers and DBMS's, as may well be the case in a multi-disciplinary project. Lack of standardisation is apparent both in hardware devices as well as vendor software philosophies. For example, a problem area may be the logical and physical translation of data description and manipulation statements associated with a common central data model and the appropriate DBMS's within the distributed system.

4.4 DBMS FOR AEC APPLICATIONS

Today's vendors of software tools are increasingly utilising DBMS techniques for data management within their applications. Real-life projects involve a progressive increase in data, which must be judiciously managed if the user organisation is to benefit in the long-term. The application of DBMS technology to architecture, engineering and construction (AEC) related projects offers a wide range of prospects, some of which are discussed in this section.

4.4.1 DBMS and Geographical Information Systems

The nature of cartographic information, such as mapping and utility related data, is ideally suited to a DBMS approach. Guptill (1987) has studied the desired DBMS characteristics for geographic information. Systems for geographic applications must offer the facilities of a conventional DBMS and, in addition, provide special facilities for handling spatially related data. These include independent handling of feature, attribute, topology and coordinate data, as well as supporting alternative geometric representations. Once spatial phenomena has been accurately and appropriately structured for a given model, the user will generally require to extract, manipulate and display the corresponding data, possibly based on combinations of its geometry, topology and attributes, in a manner relevant to a specific application. Thus efficient access to the spatial data becomes a major requirement for a spatial DBMS, and therefore the design of the spatial indexing method becomes of paramount importance.
Aronson (1987) sees tabular, hierarchical, network, relational and object orientated models as possible models for the management of thematic data. Tabular models lack data integrity, since each table is independent and therefore identical data to be used in two different tables must be present in both. As a result data integrity, storage efficiency and flexibility can be impaired. Hierarchical models have not gained noticeable acceptance for use in GIS, mainly because they are orientated towards stable data sets, where primary relationships among the data change infrequently, or not at all, since the data relationships are built into the logical view of the database. Network types suffer the same drawback as their hierarchical alternatives. Furthermore both network and hierarchical structures have a procedural query language, which requires user knowledge of the actual storage scheme used by the DBMS.

Relational database models are the most widely accepted for managing geographic data, examples being ARC/Info and WILD SYSTEM 9. This is due to the inherent flexibility, storage efficiency and non-procedural nature.

The basic unit of the object-orientated DBMS is the object, which is a collection of data elements and operations that together are considered as a single entity. This is a relatively new development, an example being TIGRIS from the Intergraph Corporation. This approach has the attraction that query is natural, with features being bundled together as required.

Some GIS platforms may accommodate network tracing over large two and three-dimensional topological data structures. Two-dimensional applications include traffic routing problems, as described by Moreland et al (1987), and the determination of water-main distribution disturbances in the event of valve shut-off during maintenance. A three-dimensional search technique for simulating the overland flow and deposition of hydraulic tailings is discussed in chapters 6 and 7.

4.4.2 DBMS and Digital Terrain Modelling

As discussed in chapter 2, digital terrain models (DTMs) are derived from some form of connectivity between measured data points that reside on a terrain surface, and are essentially three-dimensional structures in Euclidean space.

Terrain is a continuous topographical structure, and therefore in digital form is most naturally represented by a continuous, topological data structure. This data structure should ideally be spatially indexed so that its physical locality in the computer store is a function of its
actual spatial locality in our 'universe'. The terrain information in the area of immediate user interest will need to be interactively accessed, displayed and amended, especially if it is to be used for modelling time-based phenomena. Furthermore all data should be efficiently managed to guarantee its integrity and avoid redundancy, corruption and loss. The relational DBMS of the Medusa GIS allows a 'natural' terrain model representation to be implemented within a managed environment, as is further discussed in chapters 6 and 7.

The boundary representation solid model approach of the original Medusa Terrain Modeller has a topological terrain definition, as discussed in chapter 2. However, it does not offer the desired level of user interaction, for access to, and modification of, the terrain topology itself.

An example of a DBMS approach to terrain modelling is described by Kavouras and Masry (1987). The DBMS is used to allow the handling of complex spatial data and their relationships, to model complex geological structures for resource exploration planning in mining applications. Point, line, surface and solid representations of geo-objects, which may be highly irregular, fragmented and non-homogeneous, is possible. Furthermore the data model permits efficient spatial and attribute queries, including Boolean operations and queries on object topology.

The preliminary results of the Loughborough Benchmark Challenge, as discussed by Finniear (1987), show a movement amongst some DTM vendors towards using DBMS for managing terrain related data, the majority of which have favoured the relational model approach.

4.4.3 DBMS and Computer-Aided Design and Draughting

Staley and Anderson (1986) offer a specification for a CADD database. A CADD database system should be capable of supporting multiple application programs and the iterative nature of the design process. The database schema should be such as to allow modification dynamically, or 'on the fly', without requiring recompilation of the schema itself or reloading of the database. Furthermore it should be capable of supporting both concurrent and multiple users whilst maintaining the integrity and security of the data.

The most often cited problem with currently available DBMSs is the lack of a capability to modify and extend the database conceptual schemas 'on the fly', to accommodate the differing representational requirements of CADD software tools. Staley and Anderson envisaged
possible opportunities for CADD database design in semantic data models and the use of Artificial Intelligence (AI) techniques for knowledge representation.

Ketabachi (1987) presented an in-depth checklist of data management requirements for CADD, providing a cross-reference matrix between them and existing DBMS capabilities. He concluded that conventional DBMSs did not meet all the data management requirements of CADD. They tended to support set-orientated applications, as opposed to the more object-orientated nature of CADD applications.

Richens (1984) identified four possible levels of CADD data integration. The first included a non-integrated collection of data processing tools, including word processors, draughting systems, spreadsheets and database enquiry and report generators. Each entity would have its own method of storage and output. Level 2 would involve some form of interconnection between the above mentioned tools. An example would be a draughting facility which would allow some scheduling of the components held in its database. At this level of integration, information is still kept in multiple independent forms. The example quoted for this level was Applied Research of Cambridge’s, now McDonnell-Douglas Information Systems (MDIS) Reinforced Concrete Detailing System (RCDS), which handled the production of reinforced concrete drawings, and included bar bending schedules which were automatically generated from the drawing text.

The third level was concerned with the sharing of information between users, similar in concept to the central database commented on by Staley and Anderson (1986). Here Richens (1984) used an example of the structural engineer wishing to edit the same drawing as the architect. At Level 3, integration can be achieved by each party dis-integrating their data. Thereby each had its own drawing which could be amended. In addition to each party being able to see his own drawing at any one time, each had the other’s drawing as a background to his own, in its last stable state. Richens saw the latter point as important; much design work is ‘doodling’, and hence design colleagues must not act upon it until an interim solution has been reached. Richens believed that the attainment of this level would enable multi-disciplinary users to derive greater benefits from CADD.

The fourth level of integration quoted was a total design database. This would include a single total design database which would store each fact, or packet of information, once, from which all documentation producers could derive their input. According to Richens, this level had never been achieved, one problem being that because a design has no single state,
alternatives are being evaluated all the time, and therefore 'doodling' must be accommodated without locking out other users of the information. Another problem cited by Richens was that no one had been able to design a database capable of representing all facets of a design. This is in addition to the problems discussed by Johnson (1987b), relating to the non-standardisation of DBMS hardware and software tools.

Richens quoted the most common AEC database approach as being the 'parts', or object, model, a technique used by MDIS's Building Design System (BDS), t² Solution's Rucaps and BDP Computing Service's Acropolis packages. Structural form is represented by predefined components located and orientated in space. In general, each component was modelled as a three-dimensional solid. Richens believed, however, that if all that was required were working drawings, then this would be a laborious method of producing them. He also believed that elements such as masonry and concrete are difficult to fragment into objects. He stated "costings and detailing tend to focus on the junctions between things rather than the objects themselves". This was due to the fact that parts often do not adequately describe the spaces they enclose, and spatial handling tools, such as the merging, subtraction and union of objects, were not of an adequate level of sophistication.

These problems reiterate the need for spatial integrity to be maintained in the actual data model itself. Without it, the models are invalidated and hence would not produce an accurate account of geometric properties derived from them. Furthermore the need for a spatially orientated query language with flexible data display capability, unlike SQL, becomes apparent in the design stage of large AEC projects.

4.4.4 DBMS for simulation

The concept of rapid interaction with vast volumes of spatially related data, together with the ability to update the data structure 'on the fly', infers great application to dynamic engineering problems. Such areas of DBMS application may include heat flow transfer processes in piped fluids, the interactive design of three-dimensional plant or terrain related applications.

It is the last of these examples that is of direct relevance to this thesis. Interaction with a topological terrain structure and its associated attributes offer great potential to real-time dynamic flow and sedimentation simulation. Einstein believed the fourth dimension to be time, which in our perception of worldly events may be true. Consider the change from one
geometric state to another in terms of simulated terrain evolution. An interrogation of the prevailing terrain geometry and associated attributes, in addition to environmental conditions, would dictate the next transient state of the terrain model. If we were to view the terrain at small time increments, we might not observe the transience of its geometry. However increase the time-slice and the change in geometric state becomes apparent.

It is a logical requirement that, when a user is working on a certain spatial locality of the terrain, he will be mainly interested in the terrain information residing adjacent to that locality, be it structural or attribute data. However this requirement must not be confused with data segmentation, which is common practice amongst existing terrain modelling systems. In order to simulate overland flow and sedimentation, of, say mine waste, in real-time, terrain information within the direct area of interest should be held in local memory, to speed up the data interaction processes. The local memory will need to be rapidly updated as the material flow and deposition progresses across the terrain, a situation not unlike the requirements of flight simulation mentioned in chapter 2. In the case of data segmentation, it could be theoretically possible for material to end up flowing along a terrain data parcel boundary, or even over the edge of a mismatched set of adjacent data sets! Therefore spatially referenced, continuous databases are a requirement of real-time terrain based simulation.

Benefit of a DBMS approach to simulation may be applicable to applications such as terrain evolution as described by Griffin (1984), the RESSILT reservoir sedimentation model written at Hydraulics Research (1985) and avalanche prediction as discussed by Toppe (1986). Each prespecified time-slice and transient state of the terrain data set could be managed, with a representation of any specified interim database state being reported on by the DBMS.

Examples of the existing use of DBMS in terrain related simulation, include a hydrological application as discussed by Silfer et al (1987). Silfer et al described a package called TINFLOW, based around a Geographical Information System, that utilises a Triangulated Integrated Network (TIN) data structure together with a deterministic, finite difference approach, to model rainfall run-off processes via overland flow and interflow within discrete watersheds. Attributes such as soil and vegetation type are stored directly in the data structure, whilst geometrical attributes such as facet slope, area and aspect are derived from the topological model.

Moreland et al (1987) used a relational DBMS based TIN model to provide the basis for traffic simulation. Both physical delays, such as slope, and temporal constraints, including
traffic congestion, have been included. Network analysis techniques are used to model real-life traffic conditions, with the view to optimising traffic routing around hazards such as road accidents and maintenance work.

The application of a Relational Database Management System for simulating the hydraulic disposal of mine tailings is discussed in chapters 6 and 7.

4.4.5 DBMS and Expert Systems

Lafue et al (1982) have examined the converging issues related to DBMS and Expert Systems (ES's), with particular emphasis on the implied benefits to CADD.

ES's make high level decisions on relatively small amounts of data, whereas DBMS's manage large amounts of data but do not make any high level decisions. However ES's and DBMS's face similar problems, since ES's must manage more and more data, and DBMS's must take more active control of data semantics and manage the database evolution accordingly. This has applicability in areas where multiple experts may be working simultaneously on the same project, where the facets of data knowledge representation and data manipulation control are of importance.

DBMS's use relatively simple and uniform representations both for the data structure and for integrity rules about data, in order to make the storage, access and manipulation of data more efficient. A uniform representation for integrity rules enhances the explicitness of rules and makes their checking easier. ES's incorporate rules about the generation and validation of particular classes of objects, and their goal is to maintain these rules. However data protection rules, in addition to these integrity rules, play an important role in maintaining design related databases. These protection rules specify what applications can do to the data. Therefore together DBMS's and ES's will become the coordinators of multiple users and diverse applications.

Hartzband et al (1985) believe it is descriptive capabilities of the data model that are a shortfall with current DBMS's for engineering applications. They see a need for enhanced data models, and introduce the concept of a 'knowledge base management system' (KBMS). The approach of knowledge base management can be twofold. Firstly the extraction of meaning from data, and secondly the enhancement or modification of data models to provide for intelligent database processing.
Rasdorf et al (1985) see the KBMS as proposed by Hartzband as being a 'generative database', one which automatically generates new engineering design data according to design constraints stored in the knowledge base. A database is seen as a repository for specific values of data items and attributes of database entities that represents knowledge as pure data. The knowledge base, however, contains data for heuristic processes, that is, relationships and interactions among the individual data item values, represented as rules.

Rasdorf proposed an extended relational DBMS. The database provides the structure for a general representation of the design data, while the knowledge base provides the structure for the generalised algorithmic processes, in the form of constraints, inherent in engineering design. The ES acts as the control mechanism for processing, invoking and generating the constraints in the knowledge base, and for supervising the knowledge base-database interaction.

An example of a KBMS, as proposed by Hartzband, could be for terrain evolution, whereby any current representation of the terrain could be exposed to rules, embedded by an expert in geomorphology, in order to derive its past state, and likewise its subsequent states. In this example, the generative rules of the ES would be checked with the integrity and protection rules of the DBMS before any update or restructuring of the data model would be carried out.

Morse (1987) discussed the interfacing of an existing expert system shell known as EXSYS to a DBMS based Geographical Information System (GIS). The objective was to enable rapid decisions to be made concerning the management of forestry. Spatial site characteristics held by the GIS are automatically passed to the expert system, where the data is analysed using the rule base created by the forestry experts. According to Morse, favourable results have been achieved, with suggestions having been made to extend the prototype to other management applications.

4.5 SUMMARY

The need for managing vast amounts of digital data is a by-product of the Information Technology era. Database Management Systems (DBMS) have traditionally addressed this area with a high level of success in business related areas. However DBMS's applicable to business activities do not adequately support the requirements of architecture, engineering and construction (AEC). This is due to the inherently different characteristics and transactions associated with business and AEC data.
The need for a clear idea as to the nature and use of the data is of paramount importance in database design, if the optimum use of information is to be achieved. The prerequisites of an engineering database as described by Benayoune et al (1986), and as listed in 4.3.2, provide useful selection guidelines for the engineering user of DBMSs.

The DBMS approach has been shown to be applicable to a wide range of AEC work-cycles, examples being mapping, utility information handling, terrain modelling, CADD database management for multi-disciplinary projects and simulation. It is most probable, however, that the optimum benefits of DBMSs will only be achieved through a totally integrated database, as proposed in 4.4.3.

Geographical Information Systems (GISs) have evolved from the need to support large, spatially related databases. By necessity these products have been developed around Database Management Systems. One such product, the Medusa GIS, has been used by the author to simulate hydraulic tailings disposal within overland storage areas. Tailings dams are discussed in the next chapter.
CHAPTER 5

THE DESIGN AND MANAGEMENT OF TAILINGS DAMS
CHAPTER 5

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5.0 INTRODUCTION

Thomas (1979) defined tailings dams as "dams built from mine wastes, and are a special category of hydraulic-fill embankment. They are unique in that the dam is built to dispose of the wastes, that is, it is composed of the particular waste of a particular mine, and there is no choice of materials. In most cases, the processing involves grinding and the addition of water and chemicals in the ore treatment plant and a large proportion of the waste is in the form of a slurry."

Colton (1984) stated that trends in the mineral industry over the past few decades have led mining engineers to attempt to satisfy the growing demand for minerals of decreasing grades. This has resulted in the increasing development and extraction of large low grade deposits. The majority of the material mined is reduced to a fine sand or silt from which the small proportion of valuable mineral is extracted, leaving the rest as tailings. Social restrictions have limited the disposal of this waste material to methods which cause minimal environmental impact. Usually the material is impounded within some sort of depository where the effects of environmental pollution are controllable. Colton has estimated that the world production of tailings is in the order of 1,500 million tonnes per year, occupying an area which increases annually by some 45 square kilometres.

Several disastrous failures of tailings dams have occurred, induced by factors such as material liquefaction due to earthquake vibration, and flooding. Greeman et al (1985) have reported on the tragedy which occurred near the Italian mountain villages of Stava and Tesero, on the 19th of July, 1985. Over 200 lives were lost when a wave of slurry surged down the Tirolean valley, after the dual tailings structure had been breached. The controversy that followed highlighted once more the lack of safety measures associated with the design and technical management of tailings dams.

The International Commission on Large Dams (ICOLD) originally deemed such structures unworthy of mention in their prestigious 'World Register of Dams', first published in 1964. Since that time, the register has been amended to include tailings dams.
An innovative and popular method of mine waste disposal involves the cycloning of slurry material. The solids in the tailings are 'split' to predetermined ratios under centrifugal force. The coarser fraction is directly used for embankment construction, with the finer fraction being deposited into the storage area. Such ideas applied to the disposal process have in themselves made an impact upon the financial viability of mineral extraction.

5.1 THE DESIGN OF TAILINGS DAMS

In the United Kingdom, tailings dams come under the Mines & Quarries (Tips) Act of 1969. Prompted by the failure of a coal tip at Aberfan, Wales, in 1966, the National Coal Board (NCB), currently British Coal, implemented two publications, which were subsequently reviewed by the Act of 1969. The first comprised mandatory codes and rules, specifying standards for the siting, design, construction and maintenance of spoil tips, with reference to the relevant statutory requirements. The second was in the form of a technical handbook, entitled 'Spoil Heaps and Lagoons', which laid down the engineering principles associated with waste tips and dams.

5.1.1 Siting of tailings dams

As with the siting of their more conventional water retaining counterparts, tailings dam location should be the result of a comprehensive site investigation. Parameters to be analysed include geological, soil and hydrological factors relevant to the proposed site.

Geological factors include sub-surface strata integrity and seismic record analysis. Guidelines laid down by the NCB (1970) for soils investigation involve in-situ permeability tests and laboratory work, including particle size distribution, specific gravity, plasticity characteristics, moisture content, density, shear strength, permeability and consolidation characteristics.

Hydrological studies include catchment boundary definition, rainfall record and storm routing analysis. The actual size of the catchment area plays a vital role in the site selection process, it being desirable to keep this as small as possible.

The more obvious considerations in terms of dam location include the storage characteristics of the site, the distance from the mine crushing plant, land costs and environmental factors.
5.1.2 Types of tailings dams

Thomas (1979) has identified two basic techniques which may be used in the construction of tailings dams. Firstly, where borrow material is used to build the impounding embankment, and secondly where the tailings themselves are used to construct the dam.

The more conventional, former practice, is adopted when the tailings contain only a small proportion of sand sizes, the remainder falling within the silt range, or when the desired crest height of the dam is relatively low, for example, 10 metres. The second technique, which generally constitutes the most economic alternative to tailings disposal, is suitable for tailings containing 30 to 40 per cent sand sizes. Furthermore, with this method, capital outlay on dam construction is spread over the life of the venture, a factor which could determine the financial viability of the overall operation.

For each of the two basic techniques, Thomas (1979) has recognised three types of tailings dam. These relate to the direction in which the dam crest moves during the raising process, namely upstream, downstream and remaining stationary above the original centreline. With all three types, a starter dam is initially constructed. This provides a pond area for the process water, which may be polluted, as well as maintaining a sufficient freeboard to prevent overtopping.

The upstream type of tailings dam is shown in Figure 5.1.1 (a). The starter dam is located at the downstream toe of the resulting embankment, with the tailings transportation pipeline running along the crest. Spigots, or delivery valves, are provided at set intervals, from which flexible pipes are run upstream and normal to the crest.

The tailings discharge through the spigot lines is controlled, it being usual to run a bank of emitters at any one time. The process of wall building from actual tailings material commences once the surface of the deposited fill reaches the crest of the starter dam. A small dyke is then dozed up, over which spigot lines are laid.

As discharged tailings flow upstream and away from the emitters, deposition by sedimentation processes takes place, leading to a gently sloping beach with a coarse to fine distribution of sand and silt as the slurry moves towards the pond. Therefore a decrease in the density, strength and permeability of the settled solids occurs with increasing distance from the spigots. As the tailings level reaches that of the crest of the dyke, progressive dyke
and pipeline raising is implemented.

An efficient, and economic, method of tailings separation is obtained by the use of cyclones, where the slurry is split into a coarse and fine fraction, where the underflow, or coarse sand fraction, is discharged directly upstream of the dyke, and the overflow, or fines, are deposited well clear of the sand zone.

Figure 5.1.1 (b) shows the downstream type of tailings dam, where the starter dam is situated at the eventual upstream toe of the embankment. Cycloned sand material is deposited on the downstream face of the starter dam, hence initiating progressive wall building. It is a frequent practice with downstream tailings dams to compact the sand to increase its strength, and provide under-drains to lower the prevalent phreatic surface. In addition, it may be necessary to mechanically transport the sand material to the downstream region of the embankment during wall building.

The centreline type of construction is essentially a variation on the downstream tailings dam, and is shown in Figure 5.1.1 (c). With this type, the planimetric location of the dam crest remains unchanged with progressive wall building, with the upstream boundary of the sand/silt zone assuming a vertical orientation.

With all the above mentioned types, a spillway, or decant, facility must be incorporated into the final structure. This must be capable of handling process water and natural inflow, so as to maintain a sufficient freeboard between pond surface and embankment.

In addition, the process water, once dissociated from the tailings material, must be ponded in an area large enough to permit clarification before being allowed to discharge from the dam. The type of outflow facility is dependent upon the existing topography and the magnitude of the maximum inflow hydrograph. Where the catchment area more or less coincides with that of the storage facility, a decant tower may be utilised in the pond area, connected to a culvert that conducts water under and downstream from the dam embankment. In areas of favourable topography, use can be made of more conventional open channel spillway structures.
Figure 5.1.1  Upstream (a), downstream (b) and centreline (c) forms of tailings dam construction
5.1.3 Structural characteristics of tailings dams

The integrity of any structure is a function of the material from which it is constructed. Burke (1972) has described tailings resulting from a concentrating process, as "consisting of uniform, sand-sized grains with a minimal span of grain sizes. In addition, the usual hydraulic transportation and deposition processes generally leave the placed or deposited tailings in a loose, saturated mass. Such a material is quite susceptible to liquefaction under dynamic stress conditions such as may be generated during an earthquake, or by continued local mine blasting".

A typical particle size analysis for the Wheal Jane tailings dam, situated near Baldhu in Cornwall, is shown in Figure 5.1.2. According to Burke (1972), the actual strength of deposited tailings is also dependent upon the method of deposition and the prevalent weather conditions. For example, the mechanical emplacement of hydraulic fill by plant would result in a higher degree of compaction, with its resultant effect of increase in characteristic strength. Tailings situated in dry zones increase in density, and hence strength, as water evaporates from the saturated mass. Conversely, however, some tailings structures are required to retain and store storm runoff or process water. In such instances, the deposit may be permanently saturated, thus presenting the worst possible conditions as regards liquefaction. Furthermore, the rate and location of tailings discharge may largely effect the character of the deposited material.

5.2 The management of tailings dams

Colton (1984) has identified three main differences between considerations for the design of tailings dams and those for the more conventional water retaining structures. Firstly, the bulk of the stored material is in a semi liquid-semi solid state, dependent upon material size, age and the location of the water table. Additionally, when subjected to seismic shock, saturated tailings tend to liquify into a fluid of high unit weight in an attempt to achieve a closer state of packing. Secondly, the larger part of the retaining wall is usually constructed of coarse tailings, and thirdly, unlike their conventional counterparts, tailings dams are constructed over the life of the mining operation, by mine operators who often provide minimal technical monitoring or control.
Figure 5.1.2  Typical grain size analyses of Wheal Jane mine tailings  
(courtesy of WLPU Consultants)
5.2.1 Hydraulic filling patterns

Tailings dams are continuing to grow in size, with greater implied consequences of failure, as operators endeavour to mine minerals of lower ore-bearing content. Some tailings dams are up to 5 kilometres in length and 300 metres in height. The scheduling and monitoring of filling patterns are necessary to ensure stability, whilst optimising the storage capacity to height ratio for the site.

The hydraulic filling pattern will affect the pond size and location, which in turn will determine the level of the phreatic surface through the embankment. In order to maintain stability it is usual for the consultant responsible to specify a minimum pond/embankment distance and freeboard. In the case of the Wheal Jane site, these figures are 5 metres and 1 metre respectively.

The actual day-to-day filling is carried out by mine operators. These personnel rely upon their experience to ensure that the minimum clearances specified by the consultant are adhered to. Delivery valves will be switched on or off so as to alleviate any localised pond/embankment infringements.

Blight and Bentel (1983) have studied hydraulic mine-waste characteristics, primarily of gold tailings, in Southern Africa. In their study on particle size gradation on hydraulic-fill beaches, they observed that sorting occurred both horizontally and vertically, depending upon the filling patterns adopted. This feature had significant effects upon the overall stability of the tailings structures, with coarser material near the embankment implying a lower phreatic surface and hence greater stability.

5.2.2 Water Balance

It is important that the water stored within the tailings dam structure is effectively managed, in order that structural integrity and pollution control are maintained. The controlled dewatering of a pond may be achieved with the deployment of either spillway, decant tower, floating barge pump or syphoning systems.

Watermeyer et al (1978) have stated that moisture tests undertaken on fine slimes indicate that as much as 70 percent of trapped water within the beach zone is permanently held in the slime voids by capillary forces. This is in addition to that portion of the process water,
discharged with the super-saturated overflow fines, which finds its way directly into the pond as excess runoff water. The majority of the outstanding water held in the beach zone is dissipated by evaporation, with a very small percentage eventually finding its way into the pond through seepage.

The inflow of water into the tailings structure also includes catchment runoff and direct precipitation. Water outflow from the structure occurs as 'free' water, released through a spillway or decant facility, seepage water and evaporation. Swaisgood and Toland (1972) cited that, taken over a long time period, there is no increase or decrease in the total amount of water within a tailings structure. They conclude that a water balance exists, where the total inflow volume equals the total outflow volume. Swaisgood and Toland have also recognised that very little can be done to control the inflow of water due to precipitation. A narrow range of regulation is possible for tailings process water. Surface runoff, however, may be indirectly controlled by site selection. The effective catchment area is regulated such that no inflow from surface runoff is associated with paddock type tailings dams, with the greatest volume of runoff inflow being related to cross-valley type structures.

5.2.3 On-going construction

The NCB (1970) has recognised the following disturbing forces as contributing to the overall loss of stability of existing tailings embankments:

(1). Additional loading on the top of a slope by either vehicles or seepage.
(2). Steeping of the slope due to local mining operations or surface erosion by uncontrolled drainage.
(3). Removal of support at the toe of the slope by uncontrolled excavation.
(4). An increase in water level and hence pore pressure within a dam or its foundations.
(5). Disturbance of the dam or its foundations from vibrations due to blasting, mining subsidence, localised slipping in adjacent dams, and, more obviously, earthquakes.
(6). Piping, encouraged by the formation of cracks within the dam or its foundations.
(7). Softening or swelling of the surface material, or of that at the toe.
(8). Rapid drawdown of water within the pond, wet deposits or slope, causing adverse changes in the seepage forces within the slope.
(9). Burning of spoil material resulting in local collapse and an adverse change in stress distribution within the spoil mass. This factor is applicable to dams or lagoons used for the storage of coal discard.

The need for monitoring and remedial work to existing waste storage sites in the United Kingdom became apparent after the Aberfan disaster in 1966. Since that time, the large scale use of overland dumping has receded in the UK, mainly due to land costs and environmental factors. Other avenues of waste disposal have been explored, such as underground disposal and dumping at sea, which have also received similar adverse reactions from environmentalists. However, the practice of large scale overland dumping is still adopted in countries such as Australia, Canada, South Africa and Zambia.

The analysis of tailings dam structures is undertaken with reference to the theories of soil mechanics, mainly to prevent instability due to rotational and surface slips. Rotational slips, such as that which initiated the failure at Stava, are characteristic of materials whose shear strength comprises both cohesive and frictional components. Surface slipping is a form of instability characteristic of tips built of dry cohesionless material which is deposited at the same angle as that of the natural angle of repose of the spoil.

Thomas (1979) recommended that, for minor tailings dams, the usual methods of slip-circle analysis be applied, with a pseudo-static increment of loading included to account for possible earthquake activity. For larger structures, Thomas identifies liquefaction as a feature which should receive careful consideration. An overall factor of safety of 1.5 for normal conditions is stated, dropping to around 1.2 for well-known and mild site conditions.

Seepage considerations may be accounted for with the use of flow nets, in conjunction with finite element or finite difference analysis, such as discussed by Colton (1984). The control of seepage, and hence pore pressure, may be achieved with the use of drains, which may be of a toe, blanket, strip, chimney or finger variety, depending upon the site conditions and the availability of suitable materials. The provision of a protective filter layer is also necessary to prevent the migration of embankment fines into the large voids of the drains, which might otherwise cause clogging.

The judicious management of pond size, and location away from the embankment, results in a longer seepage path, and hence a reduction in the phreatic level within the embankment. Therefore, pore pressure is reduced with a resultant increase in material strength.
5.3 **Previous Investigations into Hydraulic Tailings Disposal**

The industrial sponsor of this research work was WLPU Consultants, a firm of consulting civil engineers. WLPU have been responsible for the design and on-going management of numerous tailings dams world-wide. They have developed an in-house software package called 'DUMPS', to assist in the scheduling of filling patterns (WLPU, 1978a). A qualitative comparison between DUMPS and the system developed by the author is presented in chapter 6.

Carrier et al (1983) investigated the storage capacity, embankment stability and seepage characteristics of tailings dams. They have quoted compressibility and permeability of deposited material as the physical properties which affect the design evaluation. A finite-difference analysis program was developed based on non-linear finite strain consolidation theory, in order to evaluate one-dimensional consolidation. Their results indicated that the height of the beach sediment during stagnant consolidation is dependent only on the dry weight of the solids placed in the disposal area and is essentially independent of the filling rate.

Jeyapalan et al (1983) conducted laboratory flume tests to investigate the flow failure mechanisms of slurried mine wastes. Their studies indicated that the behaviour of liquefied slurry is in keeping with a Bingham plastic fluid, and that cohesionless soil deposits were vulnerable to earthquake induced failure. Jeyapalan et al observed that analysis via a computer simulation model, based on a Bingham plastic fluid, predicted turbulent flow for phosphate tailings, whilst other materials would remain in a laminar state of flow. Jeyapalan et al concluded that the probability of flow failure is directly related to the type of construction method used, with the upstream method being quoted as the weakest alternative. Such failures give rise to flow regimes similar to the more conventional sediment flows, which extend large distances away from the breach location, as was apparent at Aberfan and Stava.

Blight and Bentel (1983) examined the gradients of hydraulic-fill beaches. They observed that progressive flattening occurs with distance away from the point of discharge. Slope figures of around 5 degrees at discharge location as opposed to only 1 degree at the pond were quoted. In addition, a laboratory investigation into the sub-aqueous deposition of mine tailings revealed cross-sectional profile slopes of up to 30 degrees (WLPU, 1978b). The above figures are similar to those observed on naturally occurring fluvial landforms, comparisons with which have been made in chapter 6.
5.4 THE WHEAL JANE TAILINGS DAM PROJECT

In 1967, WLPU Consultants were approached to assist in the preparation of a disposal scheme for the waste product from the proposed mine at Wheal Jane. Production at the Wheal Jane mine commenced in 1970, with the waste product being deposited behind a cross-valley type dam, of upstream construction, located in the Clemows Valley, near Baldhu, Cornwall.

The original depository was operated by Consolidated Gold Fields from inception until closure of the mine in 1978. In 1979, the mine was reopened by Carnon Consolidated Tin Mines Limited (CCTM), a subsidiary of Rio Tinto Zinc (RTZ), and the production of tin recommenced in May 1980. At the current operating rates, the 8 million tonnes of storage capacity of the tailings dam is expected to last the mine until the end of the century, as is shown in Figure 5.4.1.

The Wheal Jane underground mine workings produce spoil, which is transported on an escalator to a nearby mill. The spoil is then finely ground, mixed with water and chemicals into a slurried solution, and processed. The non-ore bearing product is separated into a coarse and fine fraction by a primary hydro-cyclone situated in the mill.

The coarse hydraulic material is delivered by pipeline to the main embankment, on which are located 26 take-off valves. The valves are controlled by the mine operators, being switched on and off according to the scheduled filling pattern. The valves feed secondary cycloning devices which 'split' the tailings under centrifugal forces. The coarser, more stable material is discharged directly from a nozzle, or underflow. The underflow is attached to the cyclone body, which is positioned on the embankment itself, to allow for wall building. The finer material is fed through a flexible tube, or overflow, which is positioned on or above the beach. This material flows away from the point of discharge and either deposits on the sub-aerial sections of the beach or finds its way into the pond. The delivery pipeline, a take-off valve and a cyclone are shown located on the main embankment at Wheal Jane in Plate 5.4.1.

The finer product of primary cycloning typically falls within the silt size range, and is unsuitable for wall building due to its inherently low strength characteristics. This material is transported from the mill along open channels and is discharged directly into the storage area, as shown in Plate 5.4.2.
NOTES:
1. FUTURE EMBANKMENT CREST ELEVATION IS BASED ON MAINTAINING A FREEBOARD OF 2m
2. FUTURE RESERVOIR LEVEL IS BASED ON CLEMO'S VALLEY DEPTH/CAPACITY RELATIONSHIP
3. FUTURE TOTAL AMOUNT OF TAILINGS STORED IS BASED ON A THROUGHPUT OF 150,000 t/yr.

Figure 5.4.1 Storage requirements of the Wheal Jane tailings dam up to 1998
(courtesy of WLPU Consultants)
Plate 5.4  Valve assembly on tailings delivery pipeline in foreground, with cycloning in background

Plate 5.5 2 Open channel disposal of tailings, showing production mill in background
A lake, or pond, is formed by process water and natural precipitation within the cross-valley catchment area. Its surface level is controlled by a series of weir boards which are located on a decant structure. The operators can alter the pond level by adjusting the boards. Excess water flows over the weir crest and is routed away and downstream of the dam along an open culvert.

Data relating to the Wheal Jane tailings dam project has been used in this thesis. The author carried out two terrestrial surveys of the dam, during April and July of 1986. Between these dates, interim cyclone filling records were collated by the mine operators. All these data have been inserted into a Relational Database Management System, which is discussed in chapters 6 and 7.

5.5 SUMMARY

The processes associated with hydraulic-fill tailings structures have become an area of interest, following the worldwide boom in mineral resources extraction since the 1950's. Tailings dams are continuing to grow in size, as operators endeavour to mine minerals of lower ore-bearing content.

Legislation covering the design and technical management of tailings dams does already exist in some mineral producing nations. In the United Kingdom, for example, tailings dams are covered by the Mines & Quarries (Tips) Act of 1969. The need for on-going technical management has been instigated by some of the most tragic tailings dam failures over the past 50 years. The stability of a tailings structure is a function of its location, construction method and the filling patterns adopted.

The typical service life of a tailings dam may be 25 years or more. Large spatial and time related databases are implied by the size and timescale of such projects. One of the major problems associated with managing tailings dam construction is therefore the handling and analysis of vast amounts of project information. Such data may include computer drawings, periodic site surveys, mill production figures, filling records, service schedules, beach, rainfall, pond and phreatic levels, to name but a few examples.

The design and management of tailings dams using integrated computational aids such as Geographical Information Systems (GIS's) offer a means by which to efficiently structure and manage all project information. Furthermore the spatial effects of alternative filling schedules
can be rapidly assessed, as compared to the time consuming and laborious manual calculation methods. The development of a computer-aided simulation of hydraulic tailings disposal is discussed in the next chapter.
CHAPTER 6

DEVELOPMENT OF A COMPUTER-AIDED SIMULATION OF HYDRAULIC TAILINGS DISPOSAL
CHAPTER 6

DEVELOPMENT OF A COMPUTER-AIDED SIMULATION OF HYDRAULIC TAILINGS DISPOSAL

6.0 INTRODUCTION

The need to interact with terrain related information is common to many computer simulation areas within engineering and the natural earth sciences. The hydraulic filling of tailings dams covered in this thesis is one application relating to sedimentation processes that embraces both disciplines.

A number of different tailings dam sites were considered for the research case study. Due to the relative ease of access and the availability of filling records, the on-going Wheal Jane tailings dam was chosen as the research site. The Wheal Jane tailings dam project has been briefly described in chapter 5. Two terrestrial surveys of the storage area were carried out, the first in April 1986, and the second in July of the same year. Between the two surveys, the mine operators compiled site and filling logs, giving site details and dates with times of individual cyclone operation.

The computer model development work discussed in this chapter was carried out at Cambridge Interactive Systems (CIS) in Harston. CIS are the vendors of the Medusa range of engineering software products. Their pre-release Geographical Information System (GIS) has been used to support and manage all hydraulic filling and terrain data associated with the Wheal Jane project. The GIS is built around the Medusa Database (MDB), a relational Database Management System as described by Edwards (1986). The GIS has integrated functionality applicable to large scale mapping and utility handling, as has been discussed by Bundock (1987). Due to the pre-release status of the Medusa GIS software, and the absence of compatible computer hardware at Loughborough University, the GIS based model development work and the subsequent simulation runs were carried out by the writer at Cambridge Interactive Systems.

A relational data model, representative of hydraulic filling at Wheal Jane, has been implemented within the standard GIS. Data relating to the Wheal Jane project has been inserted into the corresponding database structure. This environment is referred to as a relational Database Management System (RDBMS) for simulating hydraulic tailings disposal.
A simulation model called Tailfan was developed, that interacted with the database records, to predict the sub-aerial flow and deposition of hydraulic tailings. Preliminary testing of the Tailfan model was carried out in the confines of digital 'pools' as well as on the Wheal Jane project data.

6.1 **COMPARISONS BETWEEN HYDRAULIC TAILINGS DISPOSAL AND FLUVIAL LANDFORM PROCESSES**

This section compares the transportation and deposition of hydraulic tailings to the patterns and geometry of natural landform processes. The comparative time-scale of tailings disposal is, however, generally much shorter than that of the natural geomorphological cycle associated with landform evolution. The objective of this study of natural earth processes was to achieve a better understanding of how terrain structures evolve. This knowledge would provide the basis for developing a computer model to simulate the hydraulic disposal of tailings.

6.1.1 **The Fluvial system**

Fluvial geomorphology describes some of the processes associated with landform evolution. Schumm (1977) has divided the fluvial system into three distinct zones. Zone 1 is the drainage basin, where erosion takes place. Zone 2 includes rivers and valleys, in which the eroded material is transported. Zone 3 are the plains, or piedmonts, where the material is finally deposited.

Schumm considered valley filling as being dependent upon the nature of the controlling factor. A change in base level, which reduces the gradient in the lower end of the valley, has been classified as a 'downstream control'. A 'downstream control' will initiate a progressive backfilling of the valley. If, however, there is an increase in the amount of sediment available for deposition, an 'upstream control' is said to be present. This will result in progressive downfilling, with coarser material being transported further down the valley. Schumm's zoning system is illustrated in Figure 6.1.1(a).

6.1.2 **Alluvial fans**

Alluvial fans are characteristic of Schumm's zones 1, 2 and 3, and have been intensively studied and documented. Bull (1968) has described a typical alluvial fan as having "both concave and convex curvature; the radial profiles are concave, and the cross-fan profiles are
convex". Bull's description of an alluvial fan provides a definition of the characteristic geometry of these landform structures. A block diagram illustrating radial concavity and cross-fan convexity is shown in Figure 6.1.1(b).

Blissenbach (1954) conducted field investigations based on the evolution of alluvial landform structures in the United States. He observed that stages of degradation, or erosion, are normally apparent by the existence of deep and narrow streams. Due to the progressive decrease in gradient along the fan profile, these channels frequently become silted up, causing overflowing and the formation of new tributaries. Blissenbach also considered the effects of varying the base level of alluvial fans. An aggrading, or rising, base level was reflected in an accelerated deposition on the alluvial fan. A degrading base level resulted in erosion on the fan body. The effect of climatic changes on fan growth was also studied, with precipitation having the most profound effect on alluvial fan development. An increase in precipitation resulted in the dissection of the fan body and gentler gradients. A decrease in precipitation was responsible for a period of aggradation and the development of steeper gradients.

Hooke (1968) carried out both laboratory and field investigations into alluvial fan evolution. His studies suggested that a steady-state exists among coalescing, or adjacent, fans in the same environment when fans are increasing in thickness at the same rate. With uniform deposition there was a tendency for a fan in a closed basin to reach and maintain a steady-state, or constant, area. Hooke's observations suggested that the steady-state slope of an alluvial fan was determined by the debris size, the depositional process and the water discharge, and varied directly with grain size, with coarser materials adopting steeper slopes. Larger discharges generally had higher flow velocities and higher bed shear stresses and thus attained lower slopes than fans built with lower discharges. Furthermore, an increase in discharge on a particular fan generally resulted in the regrading of the fan to a lower slope.

Semi-arid alluvial fans are a particular useful analogue for studies of tailings deposition, because of the lack of vegetation, the highly concentrated flows and the significant transmission losses associated with both phenomena.

Blight and Bentel (1983), in a study of tailings dams, examined the gradients of hydraulic-fill beaches. They observed that progressive flattening occurred with distance away from the point of discharge. They quoted slope figures of 5 degrees at the discharge location, as opposed to only 1 degree in the vicinity of the pond. Measured profiles were found to be
Figure 6.1.1(a) Schumm's zoning system

Figure 6.1.1(b) Block diagram of alluvial landform, exhibiting radial concavity and cross-fan convexity
consistent for individual beaches, being a function of material characteristics, filling technique and climatic conditions. Thomson (1983) stated that the average slopes of tailings beaches are dependent upon the percentage of coarse particles within the tailings, and not the total particle size distribution of the material. A high discharge rate will carry material further away from the discharge location, causing a flatter slope. In addition, more uniformly graded tailings will tend to form flatter slopes. The above observations by Blight and Bentel and by Thomson on the geometric characteristics of tailings beaches correlate with the observations made by Bull, Blissenbach and Hooke for alluvial fans.

6.1.3 The mathematical modelling of alluvial landform patterns and geometry

Troeh (1965) recognised that various landforms have characteristic shapes. He has attempted to fit three-dimensional mathematical equations to landform geometry. His equations may be used to describe both the radial-profile concavity and cross-fan convexity of alluvial fans, and can be solved for a specific fan by making a few measurements along radial lines constructed on contour maps.

Alluvial fans are taken as an example of land forms "which have a regular, non-random, surface configuration", the concave-convex curvature of which is describable by Troeh's paraboloid of revolution equation, given below:

$$Z = P + SR + LR^2$$

where

- $Z$ is the elevation at any point
- $P$ is the elevation at the centre of the fan described by the equation
- $S$ is the slope of the surface at the centre
- $L$ is half the rate of change of slope with radial distance from the fan centre
- $R$ is the radial distance from the fan centre

Troeh stated that "all parts of the surface of the cone are at or near a position of equilibrium, or steady state, controlled by the point of origin of the cone, the stream, and the supply of sediment. If the surface of the cone is appreciably lower in one downslope direction than in the other downslope directions, the stream will eventually shift its channel to the low area and deposit more sediment there. Thus there is a tendency towards similarity in various directions radiating from the uppermost portion of the alluvial cone."
Troeh suggested that paraboloids of revolution may be used to describe a wide variety of land forms, which may be very different to those adopted by alluvial fans. The shapes of such structures can be mathematically modelled by changing the algebraic signs of the slope gradient and of the coefficient L in his equation, or by shifting to a different radial distance. Paraboloids of revolution have been used as control shapes in the quantitative analysis of a tailings fan simulation model, which is discussed in chapter 7.

Troeh made a further important observation. He stated that the use of a single equation to describe two coalescing fans will imply a smooth junction between them. This could lead to relatively large deviations from the true elevations, and therefore inaccuracies in shape definition. Hence Troeh concluded that two or more coalescing fans should be treated separately, if scale permits. The relevance of Troeh's work to this thesis becomes apparent in chapter 7, where an investigation has been carried out into the simulation of both single and coalescing tailings fan morphology.

Murata (1966) carried out a theoretical study of alluvial fans in Japan. Murata was concerned with the ideal structure of alluvial fans, before they undergo tectonic and climatic deformations. A typical fan is described as having concentric contour lines radiating from the mouth of a valley. However, some fans had their apex, or focal point, some distance into a mountain system. In these cases, the concentric contours were limited to the upper portion of the fan. Contour distortions occurred at the sides of the valley/plain boundary, giving rise to lateral cones. The lateral cones themselves had their own concentric arcs, the apex of which was located at the valley/plain interface.

Murata's observations have similar implications when modelling tailings flow and deposition down a valley floor, or around a local re-entrant corner on a tailings beach. These topographic features have the effect of 'diffracting' the contours of the deposited material. Tailings simulation models which do not interact with the prevailing terrain geometry will not take the appropriate increase in stream channel distance into account. The result will be an inaccuracy in the shape, and therefore the derived volume of deposit. This factor is demonstrated in 6.7, where a comparison has been made between the author's simulation model and the DUMPS system.

Price (1974) has described a decision-tree analysis program, called Alfan, used to simulate alluvial fan growth over grid based data sets. Simulated stream channels, transporting the eroded, waterborne alluvial sediments, are assumed to flow between the grid nodes, advancing
from one adjacent node to the next. The internodal movement of the stream channels is based upon the empirically derived equations for terrain slope and stream inertia. Price assumed that the 'probability' of movement due to slope was 0.25 when the internodal slope was zero, and 1 when the slope was equal to 1.000, or 45 degrees. The 'probability' of movement due to inertia was 1.5 when the internodal deflection was zero, and zero when the deflection was 90 degrees to the left or right. Stream channels were assumed to flow only in a downslope direction. Price's equations therefore take the form:

\[ P_{\text{slope}} = 0.25 + 0.75s \]
\[ P_{\text{inertia}} = 1.5(1 - [\partial_b/90]) \]

and

\[ P_{\text{flow}} = P_{\text{slope}} + P_{\text{inertia}} \]

where

- \( P_{\text{slope}} \) is the 'probability' of flow due to slope
- \( s \) is the internodal terrain slope
- \( P_{\text{inertia}} \) is the 'probability' of flow due to inertia (based on flow direction only)
- \( \partial_b \) is the change in internodal direction (0 or 90 degrees)
- \( P_{\text{flow}} \) is the total probability of internodal flow

Alfan assumed that stream channels would follow paths of least flow resistance across the terrain according to the local components of slope and inertia, or momentum of flow. In the event of the flow moving into a localised depression in the terrain surface, the searching algorithm is able to back-track along its previous route and branch at the first available opportunity. Price's computer implementation of his algorithm only allowed for a single stream branch to occur. The time-based interaction of adjacent stream branches, and that of multiple alluvial fan growth, was not accounted for in the Alfan model.

Price (1974) validated his Alfan simulation algorithm qualitatively by visually comparing cross-sections and contour plots of simulated alluvial fans with observations made in the field. He did not undertake any quantitative analysis of the simulated redistribution of alluvial sediments. Furthermore, the effects of slope and inertia dependency, and that of multiple stream branching, on simulated alluvial fan morphology, were not examined.
Rachocki (1981) has described a random-walk model for the mathematical generation of alluvial streams, based upon random number generation. His algorithm simulates the patterns associated with alluvial stream channels, and, unlike Price's algorithm, takes account of their multi-braided characteristics.

Sub-aerial tailings deposition is completed once the transported material arrives at the pond perimeter. Sub-aqueous deposition is characterised by a steepening up of the deposition slope profile, as has been observed within tailings ponds, by Blight and Bentel (1983) and under laboratory conditions (WLPU, 1978b). A grid-based computer simulation model for delta formation has been suggested by Bonham-Carter and Sutherland (1968), which may have application to the sub-aqueous deposition of tailings. Due to the lack of relevant data for the Wheal Jane study, sub-aqueous deposition of tailings has not been further pursued in this thesis.

6.1.4 Laboratory investigation into hydraulic tailings disposal

A laboratory investigation was conducted into the hydraulic disposal of tailings from single and multiple discharge locations. The objective of this study was to visually assess the processes of tailings fan growth in order to derive an appropriate computer simulation model. The processes along the boundaries of adjacent tailings fan interaction were of particular interest.

The test apparatus consisted of a header tank which fed material at a controlled rate into a filling basin of 600 by 400 millimetres. An opening was situated in the downstream wall of the filling basin to permit the outflow of water.

Coal tailings from a local mine was used for the tests, due to the unavailability of a suitable amount of Wheal Jane tailings. The material was agitated into suspension within the header tank by a motorised stirrer. Three discharge pipes were spaced equidistantly along the length of the header tank. Throttle clips were located on the discharge pipes to enable differing flow rates to be achieved.

Initial tests to study tailings stream patterns were carried out with the filling basin in a horizontal attitude. Observations were made for increasing flows from single and multiple discharge locations. This was repeated with the filling basin set at an approximate slope of 2 degrees.
Problems were encountered for tailings deposition on the perspex surface. The surface finish was such as to cause surface tension to have a major effect, with the discharged material acting as a slurried mass. Surface roughening was achieved by mixing a finely sieved sand with a gloss paint, and applying the mixture to the filling surface. The tests were then repeated, with the surface tension problem overcome.

For the single discharge case, a radially issuing tailings fan occurred, as seen in Plate 6.1.1(a). For multiple hydraulic filling, the adjacent fans gave rise to a single material 'front' advancing towards the downstream end of the basin, as shown in Plate 6.1.1(b). Furthermore, as can been seen from Plates 6.1.1(a) and 6.1.1(b), tailings fan growth appeared to display a more random geometric characteristic than that defined by a mathematically ideal paraboloid of revolution as described by Troeh (1965). It is suggested that this randomness may best be simulated by using a randomly distributed data set, as further investigated in 6.7.

Due to the small-scale dimensional effects discussed by Thomson (1983), all laboratory observations were purely qualitative.

6.1.5 Requirements of a simulation model for hydraulic tailings disposal

Harbaugh et al (1970) identified the representation of time and space as the basis of any earth process related simulation model. They have addressed simulation applications ranging from sedimentation to hydrology, and have provided guidelines to assist the engineer and natural earth scientist in developing a computer simulation model relevant to these physical phenomena. Harbaugh et al stated that the continuous transition of time can be conveniently approximated by a sequence of increments or steps. It is important to establish the duration of each increment relative to the phenomena and the computer resource available, in order to effectively approximate the passage of time. The representation of space is of prime importance in any terrain based simulation model. Spatial continuity, the representation of complex spatial relationships, the inclusion of non-geometric attributes and the ability to derive discrete material quantities have been identified as the major requirements of any spatial representation system employed for simulation purposes. Harbaugh et al used a gridded framework to model both quantitative and qualitative terrain attributes, by assigning data to its relevant location in a three-dimensional matrix. The data values in the computer store are then updated according to stimuli provided by the phenomena being simulated.
Plates 6.1.1  Single point discharge of hydraulic tailings showing radial infilling (a) and multiple point discharge of hydraulic tailings showing advancing tailings front (b) - laboratory study
Figure 6.1.2 Comparison between hydraulic tailings disposal and Schumm's zoning system.
The patterns and geometry observed within tailings dam basins exhibit similar characteristics in pattern and geometry to natural landform processes, as discussed in 6.1.1. Schumm's (1977) zoning system was therefore adopted as a basis for comparison due to its similarity to the processes which occur within tailings impounding areas. In the latter case, however, it is Man's intervention that defines the boundaries of the system and sets the controls.

The location of dam embankments defines the boundaries of the storage area, setting the constraints of the subsequent transportation and deposition of tailings within the basin. In addition, within the confines of tailings structures, Schumm's Zone 1 is much more closely defined than that of the fluvial system. The characteristics, amount, time and location at which material is available for transportation is determined by the filling patterns adopted by the mine operators. The base level may be likened to the tailings pond height, which again is governed by the decant boards set by the operators. The above comparison between hydraulic tailings disposal and Schumm's zoning system is illustrated in Figure 6.1.2.

It was therefore envisaged that a computer simulation model for hydraulic tailings disposal would need to interact with both spatial and time dependent data. Additionally, the hydraulic filling patterns generally adopted on site would necessitate the concurrent simulation of tailings from numerous discharge points located around the storage basin perimeter. The life-span of a typical tailings dam project is 25 years or more. Large geometric and time dependent data volumes are implied by the size and length of such projects, and hence data management will impose its own requirement on a suitable simulation platform. The specification of the Medusa Geographical Information System (GIS) fulfilled the above requirements of a simulation model for hydraulic tailings disposal. The Medusa GIS was described as a structured and managed computer-aided environment, allowing user interaction with a large, spatially ordered and continuous database. The Medusa GIS is further described in the following section.

6.2 THE MEDUSA GEOGRAPHICAL INFORMATION SYSTEM

The Medusa GIS was primarily developed to support large scale mapping and utility applications. It is based around the Medusa Database (MDB), a relational Database Management System (RDBMS). The GIS was developed by Cambridge Interactive Systems (CIS) of Harston, near Cambridge, on DEC Vax computer hardware. MDB supports engineering data queries by optimising data retrieval. It provides an engineering applications
development environment, including multi-user transaction processing, full recovery facilities and engineering data type support.

6.2.1 The Medusa GIS data model

The underlying data model representing the cartographic entities of the GIS is shown in Figure 6.2.1. The SOLID entity represents a volume in space that is bounded by a set of surfaces. A many-to-many relationship exists between solids and surfaces, as a single surface may also be common to more than one solid, an example being the interface between overburden and an underlying coal seam.

The SURFACE entity represents a single continuous surface that is formed by a set of planar, polygonal facets, each polygon of which may be shared by multiple surfaces. A many-to-many relationship exists between surfaces and polygons, an example being the modelling of borehole data as a series of surfaces.

POLYGON entities represent closed areas formed by a set of edges, or lines. Any number of lines may be used to form a closed polygon, for example, three in a triangular integrated network (TIN) and four in a rectangular grid based terrain model. Each line may form part of the boundary of more than one adjacent polygon. Hence a many-to-many relationship is said to exist between polygons and lines.

LINE entities represent any type of line segment, be it a straight line, a curve or a line string consisting of many vertices. As a line is defined by two or more vertices, each vertex of which may be shared by more than one line, a many-to-many relationship exists. Therefore from any vertex, adjacent vertices can be identified via their explicit line connectivity. A line, shared by adjacent polygons, will only appear once in the database, thereby ensuring that data duplication does not occur.

A VERTEX, or point, is the base component of the data model, that describes a unique location in X,Y,Z space. The vertex is the only entity to directly contain coordinate information, and each vertex and all lines referencing it are only stored once in the database. When modifying a vertex, all end points of lines referenced to it are duly amended to maintain data consistency.
Figure 6.2.1 Data model of Medusa GIS cartographic entities
The previous paragraphs describe the structural, or geometric, attributes represented by the Medusa GIS data model, to which non-geometric information may be assigned. This may consist of alphanumeric TEXT, such as a survey point number and description assigned to a vertex, or SYMBOLs, such as the graphical representation of a data entity. A GRAPHICAL SET entity relates to a set of graphical representations which by necessity need to be referenced as a single entity.

6.2.2 Medusa GIS facilities

MDB features include a data definition language to define, modify and delete tables, fields and indices. Multi-user transaction processing is available to enable concurrent access from a combination of applications or users, with full database integrity protection. Recovery facilities are provided to protect against system or database crashes.

Utilities to interactively query the database structure are available. A data manipulation language has been incorporated to interactively insert, retrieve, modify and delete database records. An interface is provided to the Medusa 2D draughting system to enable database access and modification via on-screen data manipulation. Furthermore, a high level macro programming language called BaCIS2 (version 2.0) was available, to allow flexible application development.

The GIS query language (QL) is a modified sub-set of the structured query language (SQL). QL was developed to cater for three main features relevant to large scale engineering applications. Firstly, it allowed more flexible data displays than SQL. This was relevant to both graphical and alpha-numeric views of the database universe. Secondly, it facilitated spatial predicates, enabling spatially related data manipulations to be carried out. Finally, QL enabled sets of data to be selected and manipulated according to user specified criteria.

6.2.3 Medusa GIS sheet administration

The need for an efficient drawing administration system becomes an important issue in managing large or long term projects. This is even more so when a consulting practice is involved in a diversity of projects. This management requirement in context to computer-aided design and draughting (CADD) tools has already been discussed in chapter 3.
Most tailings dam projects involve the compilation of numerous graphical and non-graphical reports. These may be concerned with the location or routing of salient project attributes such as mechanical plant and tailings delivery networks; or merely to report on non-geometric data relationships. Some, if not most, of the information will be derived from the design stages, such as depth/capacity curves and scheduled filling patterns. Therefore all graphical representations of project data must be efficiently documented and managed. This should include data version control, multi-user access and transaction locking mechanisms.

The GIS concept is one of a vast, managed data repository. Information may be extracted according to user specified criteria, and displayed in a graphical format, or in the form of a report. All graphics output may subsequently be amended or enhanced by the standard Medusa 2D draughting tools. Sheet administration within GIS is controlled by the Medusa Database (MDB).

6.2.4 The spatial representation of terrain using Medusa GIS

The GIS data model represents terrain topography in the relational topological structure discussed in the previous section and illustrated in Figure 6.2.1.

A set of terrain data points is triangulated according to the Delauney algorithm. The individual entities of the tessellation, including vertices, edges and polygons are inserted into their relevant database tables. Data redundancy is omitted by ensuring that shared records appear only once in the database, an example being the edge, or line segment, defining the boundary between two adjacent polygons.

Geometric data is spatially referenced using an indexing mechanism that is a function of its location in X,Y space. The Medusa GIS achieves this by recursively sub-dividing the spatial universe of the database. At each iteration, a digit is added to the disk address, corresponding to the sector number in which the data entity is located. The process continues until all data has been allocated a unique primary key value. In this manner, the spatial/logical similarity of the geometric data is established. The process is referred to as a quadtree approach, because it effectively breaks down the user's 'universe' into quadrants.

However no data partitioning exists, since terrain is represented as a continuous topological structure within the database. Due to the efficiency of the retrieval technique mentioned above, data access times are not proportional to database size. Therefore interaction with large
continuous topological terrain networks is possible, without the implied degradation of response times. Additionally, all geometric and non-geometric project data are logically structured and managed within the same database.

Furthermore, the GIS makes use of a disk 'caching', or high speed, local memory, technique. Data that resides in the same disk block as the required record are automatically placed into cache. If another record is required that is already in cache then no further disk access will be necessary. This enables the efficient interrogation and amendment of spatially adjacent areas of the database. This feature has direct relevance to topological search applications, an example being the simulation of overland flow and deposition of hydraulic tailings.

6.3 DATA CAPTURE FOR THE WHEAL JANE TAILINGS DAM PROJECT

Two terrestrial surveys were carried out at the Wheal Jane tailings dam in April and July 1986. Their objective was to validate the comparisons between hydraulic tailings disposal and fluvial geomorphology discussed in the 6.1. Furthermore, these observations and measurements provided the basis on which to develop and quantitatively test a suitable simulation model for hydraulic tailings disposal.

6.3.1 The April 1986 survey

The initial site survey of the Wheal Jane tailings repository was carried out between the 13th and 18th of April 1986. A traverse of 6 control points was initially established around the perimeter of the dam. From these, a further 4 intermediary stations were included, so that all beach and feature information could be collected. Ground points on the cycloned beach area were measured using a Zeiss Elta 40 total station linked to a Husky Hunter electronic data recorder. All data were processed at the end of each day on a BBC micro-computer, and then stored on diskette.

Two permanent photographic stations were set up, to monitor both a cycloned and a leated beach. The cycloned beach study was initiated after a cyclone was started up on the third day of the survey, and photographs were taken at hourly intervals. Flag markers were located on the cycloned beach immediately in front of the expected path of tailings fan growth. Ball markers were periodically dropped into the hole scoured out by the cyclone overflow. A leated stream channel was already well established at the time of the survey, with deposition taking place in
the pond. A photographic station was set up behind the leat discharge location, and photographs were taken every 4 hours. In addition to the above, various material samples were taken for laboratory testing.

Access within tailings dam impounding areas becomes limited in areas of loosely consolidated deposits. It was therefore decided to use a Kern laser beam for the April survey, to identify beach points in such areas. The beam was shone on the surface of the beach, marking the desired ground point with a reflected spot. Two single second instruments, set up at discrete stations on the perimeter of the dam, were then focused onto the laser spot, and measurements taken using an angle intersection technique. The X, Y and Z point coordinates were derived by reducing the dual measurements.

6.3.2 Results of the April 1986 survey

In total, 551 survey measurements were made, which included feature information such as valve, leat and decant location. On return to Loughborough University, all processed data was transferred from the BBC to the University Computer Centre's Prime computer. The data was then modelled by the Medusa Terrain Modeller (MTM). A general arrangement drawing of the Wheal Jane site is shown in Figure 6.3.1. The Delauney triangulation of the April survey, showing the location of the survey stations, can be seen in Figure 6.3.2.

Due to the low power output of the laser, it was extremely difficult to locate the reflected spot, even during night-time observation. As a result, sparse survey information was gathered in the areas of limited access. These areas included beach sectors affected by cyclone overflow operation during the survey as well as the leated and slimed sectors of the retained material, as can be observed from the triangulated survey data in Figure 6.3.2.

Further information was digitised from mine plans supplied by the consultant. This included the original contours of Clemows Valley and of the main embankment at Wheal Jane. Both data files were modelled by the MTM. Boolean operations within Medusa 3D were then used to manipulate the valley, embankment and survey models, from which visualisations (refer to Plates 6.3.1 and 6.3.2), contours and volumes were derived. Plate 6.3.2 shows a series of invalid terrain depressions that was created by an unconstrained Delauney triangulation of the embankment data set. This resulted in the simulated flow of tailings over the downstream face of the dam, which is discussed in 6.7.3.
A total tailings deposit volume, including the dam embankment, of 1,750,000 cubic metres was calculated by the Medutil (Medusa utilities) properties program. WLPU Consultants confirmed that the above figure correlated with their filling records for Wheal Jane.

The flag and ball markers served as useful reference objects, facilitating a better appreciation of the processes associated with tailings beach evolution. The flow and deposition of tailings displayed radial infilling by progressive channel abandonment and re-routing, as can be observed from Plates 6.3.3 and 6.3.4. The cycloned beach was seemingly built up by a series of streamwashing and incision cycles, with time periods of 1 hour. The leated system exhibited progressive deltaic abandonment and stream re-routing as shown in Plates 6.3.5 and 6.3.6, over a time period of around 12 hours.

The sub-aerial beach profiles measured at Wheal Jane exhibited geometrical characteristics similar to those described by Blight and Bentel (1983) and Thomson (1983) for other tailings beaches, and Blissenbach (1954), Bull (1968) and Hooke (1968) for alluvial fans. Figure 6.3.3 shows median slope profiles measured along stream channels, for both leated and cycloned beaches at Wheal Jane. The leated beaches tend towards shallower slopes due to the fact that they are built up from finer material discharged at higher discharge rates than the cycloned sectors, as can be observed from Figure 6.3.3. The cycloned beach contours, typical of those for a fluvial landform, are shown in Figure 6.3.4.

In summary, the patterns and geometry associated with hydraulic tailings disposal, as observed and measured at Wheal Jane, closely correlated with the processes of fluvial geomorphology as discussed in 6.1.
Figure 6.3.1  General arrangement of the Wheal Jane tailings dam
(courtesy of WLPU Consultants)
Figure 6.3.2  Delauney triangulation of the April 1986 dam survey
Plate 6.3.1 Colour shaded view of Wheal Jane tailings dam showing April 1986 survey triangulation

Plate 6.3.2 Colour shaded view of Wheal Jane tailings dam, showing main embankment modelling errors due to unconstrained Delauney triangulation
Plate 6.3.3 *Cycloned* beach study, showing flag and ball markers and lateral stream washing.

Plate 6.3.4 *Cycloned* beach study, showing cyclone overflow (middle left) and flow of tailings and ball marker around re-entrant corner (bottom left).
Plate 6.4.5 Open channel disposal of tailings, exhibiting deltaic characteristics

Plate 6.4.6 Dried up channel showing recent stream branching
Figure 6.3.3  Deposition slope profiles as measured at Wheal Jane
Figure 6.3.4  Cycloned beach contours derived from the April 1986 survey
6.3.3 The July 1986 survey

A further site survey of the Wheal Jane tailings dam was carried out between the 19th and 25th of July 1986. The data collected from this survey formed the basis of calibrating the simulation model for hydraulic tailings disposal. The second site visit included a second cycloned beach survey, a full-scale beach modelling exercise and a pond survey. In addition, a trial was carried out on the deployment of an IMS1000 laser-based total station, for beach measurement in the areas of limited access. The IMS1000, supplied by Geotronics, had been successfully used by the steel industry in Sweden for measuring steelwork furnace linings whilst still at service temperatures.

The April traverse was checked and required the replacement of station No.5 (refer to Figure 6.3.1), which had become buried during interim wall building. A cyclone location was chosen for the beach modelling exercise, and 39 flag markers were sited accordingly and surveyed. A permanent photographic station was established above the beach area. An access ramp onto the beach area was positioned so that turbidity and flow readings could be taken during the modelling exercise. The survey of the pond area was conducted from the mine's boat. The Zeiss Elta 40 was set-up over the station near the decant, with the instrument's reflector being positioned in the boat.

6.3.4 Results of the July survey

In total, 671 survey points were collected. As in the April survey, the data files were adjusted on a BBC micro-computer and modelled on the University's Prime by the Medusa Terrain Modeller.

Preliminary trials of the IMS1000 laser instrument on the cycloned beach area at Wheal Jane proved successful over distances between 10 and 75 metres. Reflected readings were achieved over the above distances at shallow vertical angles, typically of 5 degrees and less. Problems were encountered when the IMS1000 was deployed near the slimed beach sector. The measurement display reading began to drift off the zero during the calibration sequence, and numerous attempts failed to re-calibrate the instrument. Time considerations dictated that no further experimental use of the IMS1000 could be carried out. On return to Loughborough, a dislodged focusing prism was found to be the cause of this fluctuation.
The concept of the IMS1000 is thought to offer great potential in the surveying of tailings beaches where difficulties of limited beach access are encountered. However, these areas can stretch to distances of over 1000 metres in the case of the larger tailings dams, whereas the range of the IMS1000 was limited to around 75 metres. The calibration sequence was too long and complex for practical purposes, and could possibly be bypassed by incorporating an electronic calibration 'chip'. Furthermore, the reading stability times were lengthy, which might be improved by including a 'hold' button to ensure that the laser was not in continual operation.

The full-scale beach modelling exercise was conducted on the western sector of the cycloned beach. The objective was to observe and measure short term tailings fan growth, without the small-scale dimensional effects of the laboratory investigation discussed in 6.1.4. A grid of flag reference markers was positioned and surveyed across the test area. A nearby cyclone overflow was relocated and activated. Unfortunately, during the preliminary course of the beach modelling exercise, localised beach erosion caused the tailings to be unexpectedly diverted into an adjacent dried up stream channel. This had the effect of invaliding any additional measurements. Due to the saturated state of alternative beach sites, and the survey time schedule, no further modelling work took place. However, the above did reflect the importance of including an erosion component in any short term tailings disposal simulation model.

Initial use of an echo sounder for the pond survey proved to be unsuccessful, due to the shallow depths and the loosely compacted nature of the pond floor. Hence a duralumin weight and line was used for a total of 60 depth measurements. The pond survey revealed maximum depths in the order of 2.0 metres, which were encountered near a previous floating decant location. Pond floor measurement, perpendicular to, and progressively away from, the sub-aerial beach sectors, enabled the sub-aqueous profiles for the cycloned, leated and slimed areas to be recorded. These readings revealed a rapid steepening of the sub-aqueous deposition profiles, the slopes of which were found to be greater for the cycloned sector, with shallower profiles being encountered near the slimed beach.

The beach contours derived from the July survey are shown in Figure 6.3.5. As was the case with the April survey, the July beach contours displayed shapes characteristic of fluvial landforms.
Figure 6.3.5  Cycloned beach contours derived from the July 1986 survey
6.4 DESIGN OF A DATA MODEL FOR HYDRAULIC TAILINGS DISPOSAL

The required characteristics of databases suitable for handling large engineering data volumes have been summarised in chapter 4. The underlying data model must logically describe the phenomena under consideration. Its structure should be such as to provide clarity and meaning to the data stored within the database repository. It should allow subsequent queries and modifications to be carried out without having to resort to complex data manipulation.

A conceptual data model for hydraulic tailings disposal, as applicable to the Wheal Jane project, is shown in Figure 6.4.1. Tailings are delivered to the overland storage area and are discharged on a time dependent basis from numerous discrete spatial locations around the dam perimeter. The hydraulic material subsequently flows away from the active discharge points, and deposits according to the prevailing beach topography. Hence the tailings beach evolves with time. The filling pattern adopted also affects the location of the pond perimeter.

It can be observed from Figure 6.4.1 that beach erosion, embankment building and sub-aqueous deposition have been omitted. The inclusion of these components in a more comprehensive data model for hydraulic tailings disposal has been recommended later in chapter 8.

The standard cartographic data model of the Medusa Geographical Information System (GIS) expressed terrain geometry in a relational topological data structure. A further data model was designed to represent the processes associated with the disposal of tailings via cycloning methods.

6.4.1 Tailings production

A data model representative of the tailings production process, as described in 5.4, is shown in Figure 6.4.2, and has been implemented within the relational Database Management System (RDBMS) alongside the standard GIS tables. Monthly tailings production figures were provided by the mine, with site records being collated for each consecutive day of the month. A one-to-many relationship is said to exist between tailings production and daily site records, as any one month will have many associated days. This relationship has been schematically represented in Figure 6.4.2.
Figure 6.4.1 Conceptual schema (data model) for hydraulic tailings disposal
On each day of the month, any one of the twenty-six delivery valves may be either opened or closed, at times logged by the operators. Once more, a one-to-many relationship is said to exist between the daily site table and the valve records. Furthermore, an individual valve may be switched on and off several times during any one day.

Each valve has a unique identifier which it shares with its related underflow and overflow. Valves, underflows and overflows may be related to separate spatial locations on the terrain. These locations will be altered by the operators during the course of on-going construction.

Each element of the data model is represented by a table consisting of several fields with corresponding records. Table 6.4.1 shows the database definition of the DAILYVALVE table. This provides a description of the associated data, the names of the data elements, verbal descriptions of their characteristics, and their logical and physical structure within the database.

It can be observed from Table 6.4.1 that the prime indexing keys for this particular table are the start date (startdate), the start time (startime) and the valve number (valvenum). This enables the database records to be scanned for any day of the month, between user specified filling dates. The operative valves for the current day are then automatically sorted, according to their start-up time and identity number.

The discharge tonnage for each operative valve was retrieved from the appropriate record, as were the current X, Y and Z coordinates of its related cyclone overflow. The simulation of hydraulic tailings disposal commenced once all the necessary test information for the current run had been defined.

In addition to providing a logical framework for the project data, it was necessary to calibrate the simulation model for the particular tailings dam project. This meant that the simulation model would need to be run on numerous occasions against project data held in the database. To facilitate this, two tables called TESTRECORDS and TESTFACTORS were defined. A test factor identifier, a test description and a filling period were assigned to fields within the TESTRECORDS table. The information held in this table was accessed by a unique test number. Each test number has a unique set of criteria, necessary for calibrating the simulation model. This information is held in the TESTFACTORS table, and is accessed by the test factor identifier. Data 'reuse' is possible, as a unique set of test factors can be used many times for differing terrains or filling patterns. Therefore a many-to-one relationship is said to
Figure 6.4.2 Data model for hydraulic tailings disposal at Wheal Jane

---

Table DAILYVALVE contains daily valve records

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>valvenum</td>
<td>Valve number</td>
<td>int</td>
</tr>
<tr>
<td>startdate</td>
<td>Start date</td>
<td>date</td>
</tr>
<tr>
<td>starttime</td>
<td>Start time</td>
<td>int</td>
</tr>
<tr>
<td>stopdate</td>
<td>Stop date</td>
<td>date</td>
</tr>
<tr>
<td>stoptime</td>
<td>Stop time</td>
<td>int</td>
</tr>
<tr>
<td>oflOnnes</td>
<td>Overflow tonnage</td>
<td>real</td>
</tr>
<tr>
<td>uft onnes</td>
<td>Underflow tonnage</td>
<td>real</td>
</tr>
<tr>
<td>valuvehours</td>
<td>Valve hours</td>
<td>real</td>
</tr>
</tbody>
</table>

Key: startdate, starttime, valvenum
Index: valvenum, startdate

Table 6.4.1 Data definition of the DAILYVALVE database table

118
exist between the TESTRECORDS and TESTFACTORS table.

A complete listing of all the tables within the relational DBMS for hydraulic tailings disposal, including those standard to Medusa GIS, is presented in Appendix A. In addition, a full database description of each of the individual Wheal Jane project data attribute tables has been given.

6.4.2 Hydraulic filling patterns

Tailings dam projects generally involve the discharge of tailings from multiple locations around the impounding basin. At Wheal Jane for example, up to 26 valves may be in operation around the main embankment at any one time. The monthly production figures, daily site and valve operation logs provided by the mine for the period mid-April to end of July 1986, were inserted into their relevant database tables.

Filling patterns were simulated by retrieving a list of active cyclones from the DAILYVALVE records, beginning on the user specified start date. The active cyclones were sorted into a time-based priority list according to their recorded start-up times. Filling commenced from that cyclone which appeared first in the list. The mechanism for simulated tailings flow and deposition is described in 6.6. If, during a discharge cycle, the volume deposited exceeded that actually discharged by the cyclone on that day, then that particular cyclone was removed from the active list. Filling continued for the current day until all cyclones had been removed from the active list. This sequence was repeated for each of the consecutive operational dates, until the specified finish date had been reached, whereupon the whole simulation process closed down.

In addition to the actual Wheal Jane filling records, synthesised filling patterns were inserted into the database. This allowed the simulated effects of adjacent, or coalescing, tailings fan growth to be investigated under clinical, controlled conditions.

6.5 WHEAL JANE PROJECT DATA INTERACTION USING MEDUSA GIS

The April and July Wheal Jane survey data sets were triangulated according to the Delauney algorithm, with all vertices, edges and polygons being inserted into the database. Graphical interaction with data held within a GIS database is conducted through a Medusa 2D sheet. That is, all geometry in an area of interest is extracted from the database and imaged in
its graphical representation on a two-dimensional sheet. This is referred to as the 'user's view', and may be likened to a 'window' into a continuous universe.

The Wheal Jane terrain models were accordingly extracted onto Medusa sheets. All necessary amendments to the models were subsequently carried out interactively on a workstation screen using Medusa 2D functionality. The screen cursor, for example, was used to locate and move graphical elements. Furthermore, spatial queries and amendments could also be used through typed QL statements. For example, to retrieve information salient to a vertex of known X and Y coordinates, the following command would be used:

```
REPORT VERTEX WHERE AT 14575.567 11780.453
```

The information relevant to this vertex could subsequently be UPDATED or DELETED as appropriate.

Edge lines and polygons could also be interactively interrogated, amended or deleted. GIS facilities were used to 'clean up' the Delauney triangulation across the pond at Wheal Jane, as can be seen in Plate 6.5.1(a).

As was the case with terrain geometry, project attributes could likewise be associated with graphical representations and then manipulated on the workstation screen. Graphical views representative of valves, cyclone underflows and cyclone overflows were defined as parametric symbols using Medusa 2D. These symbols were positioned on the Wheal Jane sheet in their surveyed locations along and near the main embankment. In the case of a cyclone overflow, its graphical representation, an 'arrow, gave not only its location, but also the initial direction of simulated tailings discharge.

The Medusa 2D draughting system allows all graphics to be assigned to layers between numbers 0 and 1023. The line elements representative of terrain topology were assigned to layer 1. The simulated stream channel alignments were allocated to layers 300 to 325 according to their individual valve numbers. The valves, cyclone underflows and cyclone overflows were assigned to layers 501, 503 and 505 respectively. The layering facility was used to switch on and off graphical detail. This alleviated any unnecessary screen cluttering caused by too many project attributes being displayed at any one time. This feature was particularly relevant to visualising adjacent stream channel patterns.
In addition, different colours were assigned to the project attributes. This enabled the user to make a rapid distinction between attributes whilst viewing the sheet at large scales. Furthermore, each stream channel alignment was allocated a colour, such that differentiation could be easily made in the event of adjacent channel growth.

Valve, cyclone underflow and overflow records were selected from the database using appropriate QL statements, and held in local memory. The user could then associate each of the selected records with its corresponding graphical representation on the sheet.

The following example shows a typical QL statement to select all cyclone overflows (cycloneof) related to valves with identity numbers (valvenum) less than or equal to 26:

\[
\text{SELECT CYCLONEOF WHERE VALVENUM LE 26}
\]

The following statement prompted the user to probe the appropriate cyclone overflow using the screen cursor:

\[
\text{ASSOCIATE CYCLONEOF TO FIGURE}
\]

It was possible to associate tables to figures using non-graphical input. In the above case, for example, instead of using the cursor, the typed coordinates of the relevant figure locations could be given.

Once a database record has been associated with a figure, that record may be interrogated, moved, rotated and deleted directly through its graphical representation on the screen. Spatially referenced project attributes, such as valves, underflows and overflows, could therefore be interrogated and modified interactively, their new state being automatically updated in the database.

It can be seen from Plate 6.5.1(b) that valve number 4, and its related components, have been highlighted in red. Valve number 4 has been highlighted because it has satisfied certain user specified conditions. It could be, for example, that it has exceeded a certain number of accumulative operating hours, and will therefore require immediate inspection and servicing. This feature further serves to demonstrate the effectiveness of having a graphical interface to an efficiently managed project database.
Plates 6.5.1 April survey triangulation, showing graphical representation of project attributes, including valves, cyclone underflows, cyclone overflows, leats and decant (a), and zoom view of eastern embankment, showing highlighted attributes of valve No.4 (b)
6.6 THE TAILFAN SIMULATION MODEL OF HYDRAULIC TAILINGS DISPOSAL

A simulation model for the hydraulic flow and deposition of tailings was developed using the BaCIS2 programming language supported by Medusa GIS. The model, called Tailfan, was based on the author's investigations into previous work on tailings disposal and fluvial geomorphology, as summarised in 6.1, as well as the observations made at Wheal Jane, as discussed in 6.3.

6.6.1 The Tailfan stream flow criteria

The Tailfan flow criteria are based on an extension of the Alfan algorithm proposed by Price (1974) for simulating alluvial fan deposits (refer to 6.1). Price's model used the following empirically derived equations to simulate the flow of stream channels over a regular grid network, according to the prevailing slope and inertia, as has been described in 6.1.3:

\[ P_{\text{slope}} = 0.25 + 0.75s \]  
(1)

\[ P_{\text{inertia}} = 1.5(1 - [\theta_b / 90]) \]  
(2)

and

\[ P_{\text{flow}} = P_{\text{slope}} + P_{\text{inertia}} \]  
(3)

Equations (1) and (2) have been individually plotted in Figures 6.6.1(a) and (b). Figures 6.6.1(a) and (b) have been superimposed on Figure 6.6.1(c). As can be observed from 6.6.1(c), Price's inertia component remains dominant over cross-fall slopes of up to 39 degrees. This feature implies that stream flow will tend to a straight-line path regardless of cross-fall slopes of less than 39 degrees, even in the instance of low stream velocity/energy states. Tailings beaches, however, with geometric similarity to alluvial fans, generally tend to average slopes of 5 degrees and less. Their cross-fall convexity shape characteristic is formed by radial infilling, which itself implies the progressive divergence and branching of the sediment carrying stream, as opposed to the single major straight-line stream alignment modelled by Price's algorithm.

The Wheal Jane survey data, in contrast to Price's regular grid, was of a semi-random distribution. A semi-random data distribution enabled a more accurate representation of the meandering characteristic of tailings stream channels patterns to be simulated. The simulated internodal stream deflections could be of varying magnitudes within the range of -180 to +180 degrees, as opposed to being constrained to just four possible directions on a regular grid.
(a) $P_{\text{slope}} = 0.25 + 0.75\text{slope}$

(b) $P_{\text{inertia}} = 1.5(1 - [\text{bearing} / 90])$

(c) $P_{\text{slope}}$ and $P_{\text{inertia}}$

Figure 6.6.1 Alfæn stream channel alignment equations
(a) \( P_{\text{slope}} = \sin(\text{slope}) \)

(b) \( P_{\text{direction}} = \cos(\theta_{\text{direction}}) \)

(c) \( P_{\text{inertia}} = \sin(\text{slope}) \cdot \cos(\theta_{\text{direction}}) \)

\( \text{for} \ \frac{\text{slope}}{\text{inertia}} = 5 \text{ degrees} \)

Figure 6.6.2 Tailfan stream channel alignment equations
For a zero stream channel deflection, that is, movement in the same direction, the direction 'probability' was assumed to be 1.0; zero for movement at right angles, and -1.0 for flow in opposition to the original direction. A cosine function over the range -180 degrees to +180 degrees was used to model the continuity of stream deflection, or change in direction, as given by equation (4), and as plotted in Figure 6.6.2(a):

\[ P_{\text{direction}} = \text{COSINE}(\partial_{\text{direction}}) \]  

where 
\[ \partial_{\text{direction}} \] is the change in stream channel direction (degrees)

The slope 'probability' was assumed to tend towards 1.0 for a sheer drop-off, and to zero for a horizontal plane; likewise a 'probability' of -1.0 was returned for flow up a cliff face. An equal distribution of probabilities of flow due to slope was assumed over the range of -90 to +90 degrees. A continuous sine function was therefore used to model the slope component, as given by equation (5) and as plotted in Figure 6.6.2(b).

\[ P_{\text{slope}} = \text{SINE}(\text{slope}) \]  

where 
\[ \text{slope} \] is the stream channel bed slope (degrees)

In addition to the change in channel direction suggested by Price, the inertia component of flow was assumed to be also dependent upon the incoming stream energy. The stream energy was considered to be a function of the incoming stream channel slope and was modelled as in (5). The resulting stream inertia component therefore took the form:

\[ P_{\text{inertia}}(n) = [P_{\text{slope}}(n)] [P_{\text{direction}}(n+1)] \]  

The product of the stream energy and the change in channel direction would ensure that the 'balance' and continuity of the empirical simulation equations were maintained over the whole range of terrain slopes, and changes in slopes, encountered. This is demonstrated in Figure 6.6.2 (c), where the effect of the inertia component has been plotted for an average terrain slope of 5 degrees. Equations (5) and (6) are in contrast to those postulated by Price, which model a dominance towards straight-line flow, even when low stream energy states and possible alternative cross-flow slope increases of up to 39 degrees are present!
The total empirical 'probability' of stream channel flow between adjacent nodes was assumed to be the summation of the prevailing 'energy' states of the slope (potential energy) and inertia (kinetic energy) components, thus:

\[ P_{\text{flow}(n+1)} = P_{\text{slope}(n+1)} + P_{\text{inertia}(n)} \]  

(7)

In order that the individual and varied effects of the slope and inertia components could be examined, linear weighting factors were imposed on both equations. The expanded stream alignment equation was thus:

\[ P_{\text{flow}(n+1)} = f_{\text{slope}} [P_{\text{slope}(n+1)}] + f_{\text{inertia}} [P_{\text{inertia}(n)}] \]  

(8)

where

- \( P_{\text{flow}(n+1)} \) is the total empirical 'probability' of flow from the current node (n) to an adjacent node (n+1)
- \( f_{\text{slope}} \) is the slope weighting factor (between 0 and 1)
- \( f_{\text{inertia}} \) is the inertia weighting factor (between 0 and 1)

The above equation ensures a 'balance' between slope and inertia simulation criteria, where dominancy is dependent upon the prevailing conditions at the current node. For example, if the incoming slope is greater than all the outgoing slopes, then the inertia component will be dominant. However should the incoming slope be less than all the outgoing slopes, then the slope component will be dominant.

In addition to the single branch allowed by the Alfan algorithm (Price, 1974), it was assumed that stream flow may also split at a node when the empirical components of slope and inertia were such that no single unique solution could be found. This will occur in low slope, low energy areas such as in close proximity to the tailings pond. A multi-branching facility was therefore incorporated to enable multiple stream splitting to be simulated. The user controlled the degree of stream branching by specifying a 'probability' of branching [\( P_{\text{b}} \)] between 0 and 1. A factor of 0 disabled secondary branching, whilst a factor of 1 allowed maximum stream re-routing to take place at the current node. All nodes satisfying the branching criteria were inserted into a list. Once the major stream channel had been terminated by a downstream control, the list was re-sorted so that branching commenced from the last listed node on the major alignment and moved back towards the discharge location. In this way, a distributed stream channel network could be simulated which initiated progressive backfilling of the
Stopping criteria were established, based upon the current state of the slope and inertia components. An individual stream channel would be terminated if the maximum accumulated 'probability' was less than or equal to zero. Furthermore, stream channel movement was assumed to only take place in a downslope direction. Therefore termination would also occur if the slope component in the proposed direction of flow was less than zero.

6.6.2 The Tailfan tailings deposition criteria

Material deposition was assumed to take place according to the prevailing terrain and material slopes. This criterion is explained by considering the discharge of tailings down a steep slope, such as a valley system. The siting of a discharge point high up in the valley will cause initial deposition of the hydraulic material to occur further downstream due to the relatively high terrain slopes. A progressive backfilling of the valley will take place, commencing from the downstream control of the slope reduction at the valley/plain interface, as discussed in 6.1.1. This implies that the effective discharge point, or focus of the tailings fan deposit, will initially be downslope of the actual discharge location. However, should the filling and environmental conditions remain unchanged, the effective deposition point will gradually migrate back towards the actual discharge location.

Tailings deposition was assumed to occur as lateral streamwashing adjacent to the stream channel alignment. This essentially implied tailings deposition over the entire surface of each of the adjacent triangular polygons. The depositional state of tailings was simulated by using a material slope profile, measured in-situ along dried up tailings stream channels. The geometry of the slope profile was held in an attribute table called GEO$LOOKUP. Work carried out by other investigators (refer to 6.1.2) has indicated that these beach slope profiles are a function of the material characteristics, the filling pattern and climatic changes. Under uniform conditions, tailings beaches, like alluvial fans, tend towards static equilibrium shapes.

Without accounting for the effective focus of tailings deposition, large deposit volumes will be calculated when the discharge points are located at high points on the terrain. Deposition was therefore considered to be dependent upon the equilibrium profile of the tailings material and the prevailing terrain slope. The equilibrium profile itself is a function of the particle sizes present. That is, the coarser/heavier the particle size, the greater the equilibrium slope, and hence the greater the slope that it will come to rest on. In summary, material will not be
deposited on terrain slopes which exceed the material's equilibrium profile at the accumulated channel distance away from the effective deposition point.

The simulation cycle began at the discharge location, with the next node being determined according to the prevailing criteria of slope, direction and stream re-routing. The slope of the material profile is calculated for the effective accumulated stream channel distance. Deposition occurred if the material slope was greater than that of the prevailing terrain. If this criterion was satisfied, the corresponding height drop from the effective deposition point was calculated, and hence a thickness of deposit was derived. Polygons adjacent to the current node were accessed via their explicit geometric relationships within the database. Their accumulated surface area, and hence local volume of deposit, was calculated. The current node was duly updated in the database.

The stream flow and deposition process was then repeated for the next node along the simulated stream channel alignment. A rolling tally was kept of the accumulated deposit volume for each active discharge point. The disposal cycle would then either move on to the next active discharge point, the following day, or close down, according to the specified filling pattern held in the database.

Due to the lack of appropriate short term information, the Tailfan model does not account for the erosion, or reworking, of tailings deposits, as would be initiated by changes in the filling or environmental conditions. However, it is recommended in chapter 8, based on the results of quantitative tests, that an erosion component should be included in a short term or real-time simulation model of hydraulic tailings disposal.

The pond was assumed to be a major downstream control, with its surface level being held in a field within the DAILY SITE table. On arrival at the pond perimeter, the transported tailings material will undergo sub-aqueous deposition. In reality, the pond acts as a partially absorbing barrier to the incoming flow, reducing its energy and hence causing the steepening of the sub-aqueous slope profile discussed in 6.1.3. However, due to the lack of appropriate data, sub-aqueous deposition was considered outside the scope of this work, and therefore the pond was assumed to be a totally absorbing barrier to flow. This effectively curtailed simulated tailings flow into the pond area, the consequences of which are discussed in chapter 7.

A flow chart description of the existing Tailfan model is presented in Appendix B.
6.7 PRELIMINARY TESTING OF THE TAILFAN SIMULATION MODEL

6.7.1 The 'Pool' tests

The initial testing of Tailfan was carried out on synthesised terrain data sets. It was decided that once the performance of the simulation model had been assessed within the confines of controlled filling basins, more appropriate tests could be carried out on the larger Wheal Jane data set. A BaCIS2 procedure was written to generate terrain data sets of specified distributions and densities. Each data set defined a horizontal plane, or digital 'pool', 100 metres long by 75 metres wide. The 'pool' coordinates were offset in X and Y so as to reside in spatially discrete areas of the database. These data sets were then triangulated and loaded into the database as individual terrain models. Each 'pool' model was extracted from the database and allocated to a unique Medusa 2D drawing sheet.

The performance of Price's Alfan equations and those proposed by the author were examined within the confines of a square grid 'pool'. A single disposal point was set up, and 1000 cubic metres of tailings was discharged into the 'pool' area. Figure 6.7.1(a) clearly shows the effects of the direction dominancy of Price's stream alignment criteria, which has resulted in the simulated flow and deposition of the tailings along discrete paths across the 'pool'. This figure also shows the effects of the bias in symmetry towards the left of the direction of discharge, caused by a Delauney triangulation of the square grid data set. The Tailfan stream alignment criteria, by comparison, resulted in the radial infilling of the 'pool' area directly in front of the discharge point. Figure 6.7.1(b) shows a simulated deposit which is, in contrast to Figure 6.7.1(a), more characteristic of a tailings fan structure as discussed in 6.1. This shape was a result of stream channel alignment criteria with slope and inertia weighting factors of 1.0, (i.e. \( f_{slope} = 1; f_{inertia} = 1 \)) and a branching 'probability' \([P_b]\) of 1.

A preliminary investigation was also carried out into the sensitivity of the slope, inertia and stream re-routing components. Tailfan was run within a 'pool' of semi-random data points, for a discharge volume of 1000 cubic metres. Slope dependency \((f_{slope} = 1; f_{inertia} = 0)\), without stream branching \((P_b = 0)\), was responsible for the simulation of meandering stream channels, in close proximity to the discharge point. This resulted in a localised tailings deposit around the discharge point, as seen in Figure 6.7.2(a). Conversely, inertia dependency \((f_{slope} = 0; f_{inertia} = 1)\) without stream branching \((P_b = 0)\) caused a straightening up, and outwards movement of the simulated stream channels. It can be observed from Figure 6.7.2(c)
Figure 6.7.1  Isometric views of Alfan (a) and Tailfan (b) simulated tailings deposits
Figure 6.7.2 Contour plots of Tailfan simulated tailings deposits, with and without stream branching (Pb=1 and 0)
that inertia dependency caused a rapidly diverging tailings deposit to develop. This shape can be likened to that resulting from a bucket of the same material being splashed over a flat surface. Unbiased, or 'balanced', stream alignment criteria ($f_{\text{slope}}=1; f_{\text{inertia}}=1$) produced a compromise between the tailings deposit shapes shown in Figures 6.7.2(a) and (c). It can be observed from Figure 6.7.2(e) that a radial deposit resulted from these criteria.

The stream branching component [$P_b$] allowed secondary channel routing for all three stream alignment cases, which resulted in the infilling of the 'pool' area around the discharge location. The radial infilling resulting from a branching 'probability' of 1 ($P_b=1$) is shown for each case in Figures 6.7.2(b), (d) and (f) respectively.

The quantitative analysis of further simulated 'pool' deposits is discussed in chapter 7.

6.7.2 The DUMPS comparison

DUMPS is a suite of computer programs used by WLPU Consultants to derive hydraulic filling schedules. It is based on the matrix array, or regular grid, modelling technique, where all existing and updated tailings levels are assigned to grid nodes. Beach profiles are defined as radially swept templates, of conic cross-section, derived from in-situ surveys. The package has been found to model straight-line deposition of tailings within reasonable bounds of accuracy. However modelling inaccuracies have arisen in situations where terrain structures such as hills and re-entrant river valleys are present in the path of discharge.

The suite originally relied on a straight-line deposition profile being fitted onto the existing terrain. Its radial-profile concavity was derived from in-situ beach measurements, whilst the cross-fall was taken to be a linear function of the material's shear strength. More recently, the package has been updated to define tailings fan geometry as a paraboloid of revolution, the radial profile of which is the same as in the former approach.

The volume of deposit is specified by the user, and the program iteratively calculates the corresponding height increase at the discharge location and at all nodes influenced by the material template. Output is in the form of a print-out of the re-computed terrain matrix and a contour plot of the updated tailings surface.

A qualitative comparison was carried out between DUMPS and the Tailfan simulation.
model. This included deposition on a flat plane, deposition in-line with a hill, discharge down a valley and deposition around the re-entrant corner of an embankment. The objective was to observe how both systems accounted for natural terrain and man-made obstacles, as are generally experienced within tailings storage basins. Each terrain data set for the comparison comprised of 150 points, being orientated on a square grid for DUMPS and of a semi-random distribution for Tailfan.

The resultant DUMPS and Tailfan contours of a single 1000 cubic metres deposit over a flat plane are shown in Figures 6.7.3(a) and (b) respectively. It can be seen that there is little difference between the models, both displaying the radial shape characteristics of a swept paraboloid of revolution representative of classic alluvial fan shape. Figures 6.7.3(c) and (d) show the contours of a total deposit of 1000 cubic metres, having been discharged from three discrete locations onto the flat plane. It can be observed that the DUMPS and Tailfan contours exhibit differing characteristics. The former implies a smooth juncture between the adjacent fans, whilst the latter displays the effects of stream channel interaction along the coalescing fan boundaries. This phenomenon has been quantitatively examined in chapter 7.

For 2000 cubic metres of deposit, it can be seen from Figures 6.7.4(a) and (b) that DUMPS has not accounted for the hill located in front of the discharge point. The DUMPS contours show no disturbance, whereas those generated using Tailfan do reflect the interaction with the prevailing terrain obstacle.

This is likewise for 1500 cubic metres of deposit along a valley floor. The DUMPS contours in Figure 6.7.4(c) show no shift in focal point, as observed by Murata (refer to 6.1.3) for alluvial fans, around the valley head, as is displayed by the Tailfan result in Figure 6.7.4(d). This characteristic is similar in concept to the diffraction of waves through restricted openings.

The re-entrant case, as seen in Figure 6.7.4(e), clearly shows the DUMPS modelling errors which will result when existing terrain obstacles, or man-made structures, are located directly in the path of tailings discharge. In contrast, with reference to Figure 6.7.4(f), the Tailfan model has accounted for the in-line obstacle, simulating flow around the embankment and onto the 'pool' floor behind it.

The colour shaded Tailfan models of the hill and valley cases are shown on Plates 6.7.1(a) and (b).
Figure 6.7.3  Contour plots of DUMPS and Tailfan tailings deposits for single and multiple discharge over a horizontal plane.
Figure 6.7.4  Contour plots of DUMPS and Tailfan tailings deposits for discharge around a hill, down and valley and around a re-entrant corner.
Plates 6.7.1 Colour shaded view of simulated single point tailings discharge around a hill (a), and down a valley (b)
Quantitative modelling errors associated with hydraulic tailings disposal may arise as a result of the lack of terrain data interaction that is associated with the DUMPS package. These errors will become more apparent when modelling tailings disposal on 'virgin' site data, where natural or man-made terrain obstacles are predominant. Furthermore, the DUMPS model does not account for the time based interaction of adjacent discharge operations within discrete spatial areas of tailings dam catchments, as is the case at Wheal Jane. This lack of time-based interaction may adversely effect simulated beach geometry for certain adjacent filling patterns.

The Medusa GIS environment facilitates user/data interaction by supporting integrated software tools, such as a graphics interface, a spatial query language and a high level programming language. These facilities allow user access to a structured, spatially referenced and continuous database. All data within the repository is managed by the DBMS support facilities described in 6.2. The long term database interaction and management requirements of hydraulic tailings disposal become a major issue when considering the nature, size and time-scale of these terrain related projects.

In summary, the DUMPS philosophy towards computer-aided hydraulic tailings disposal is conceptually different to that of the relational DBMS. The former fragments project data across many separate files, as opposed to the single, managed project database of the latter. The latter environment enables dynamic interaction with, and modification of, all data held within the single project database, and as such provides a sound basis for simulation program development.

6.7.3 The Wheal Jane tests

Suitable commenting was included within Tailfan to enable the author to monitor the progress of each Wheal Jane simulation run. Table 6.7.3 presents the format of a report scrolled on the alpha-numeric monitoring screen during a typical session. The comment 'Material to pond @ 54.100 (mAOD)' informed the author that the simulated stream channels had reached the downstream control, that is, the pond perimeter. In reality, material would then flow into the pond and be deposited sub-aqueously. In this instance, if it was the objective of the consulting engineer to achieve rapid beach building, then the relevant valve should either be switched off, or the cyclone overflow moved to a position where a new stream channel can develop.
<table>
<thead>
<tr>
<th>Wheal_Jane</th>
<th>Medusa GIS</th>
<th>Multi_cyclone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depositing</td>
<td></td>
</tr>
<tr>
<td>Current operating site date:</td>
<td>23 April 1986</td>
<td></td>
</tr>
<tr>
<td>Number of cyclones still active:</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Cyclone overflow No. 1 @:</td>
<td>55.432 (mAOD)</td>
<td></td>
</tr>
<tr>
<td>Volume so far deposited from overflow No. 1 for current day:</td>
<td>22.25 (m3)</td>
<td></td>
</tr>
<tr>
<td>for discharge height increment of:</td>
<td>0.050 (m)</td>
<td></td>
</tr>
<tr>
<td>Total overflow volume to be deposited for day:</td>
<td>35.64 (m3)</td>
<td></td>
</tr>
<tr>
<td>Material to pond @:</td>
<td>54.100 (mAOD)</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.7.3 Alpha-numeric screen report details of a typical Tailfan simulation run

Figure 6.7.5 Graphics screen view of Wheal Jane during a typical Tailfan simulation run
Preliminary simulation runs on the Wheal Jane site data predicted tailings flow over the downstream face of the main embankment, as shown in Figure 6.7.5. This simulated embankment overtopping was a consequence of an unconstrained Delauney triangulation of the Wheal Jane data set. The absence of model constraints had allowed invalid terrain depressions to be created by a set of mismatched polygons on the downstream face of the embankment. This observation served to demonstrate the need for a data constraint capability to be included in the terrain modelling algorithm, if the model was to be used for flow simulation purposes. Interactive modifications were subsequently carried out on the model to correct the triangulation errors.

6.8 SUMMARY

This chapter has described the processes involved in developing a computer-aided environment suitable for simulating the hydraulic filling of tailings dams. A comparison has been made between the patterns and geometry of natural fluvial geomorphology and those observed at Wheal Jane. Geometric and non-geometric data relating to the Wheal Jane project has been collected.

A Geographical Information System (GIS) was used to structure, manage and interact with data relevant to hydraulic tailings disposal. A relational data model was implemented that described the Wheal Jane project attributes within a single database.

A simulation model, called Tailfan, has been described, that interacts with the database records to simulate the sub-aerial flow and deposition of hydraulic tailings. Preliminary qualitative testing of this model was carried out in the confines of a digital 'pool' as well as on the Wheal Jane site data.

The overall factor governing the operation of a tailings dam is the quantity of waste produced by the mining operation. Yields of ore bearing material from extracted mine spoil at Wheal Jane are generally low, typically in the order of 5 per cent or less. A desired increase in the production of ore will therefore imply a large increase in the volume of tailings to be stored. Hence a rapid means of assessing the competency of the existing tailings dam structure to accommodate this material is necessary.

To facilitate the practical implementation of the Tailfan simulation model, a rigorous, quantitative based analysis methodology was required. This would enable Tailfan to be rapidly
calibrated for a particular project, and then used to assess the longer term effects of alternative hydraulic filling patterns. The volumetric variation of a simulated deposit from a control shape was adopted as the basis for assessing the performance of the Tailfan simulation model. The results of these tests are discussed in the next chapter.
CHAPTER 7

TESTING OF THE COMPUTER-AIDED SIMULATION OF HYDRAULIC TAILINGS DISPOSAL
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TESTING OF THE COMPUTER-AIDED SIMULATION OF
HYDRAULIC TAILINGS DISPOSAL

7.0 INTRODUCTION

The performance of the Tailfan simulation model was quantitatively examined within the confines of horizontal 'pools'. Parameters tested include the sensitivity of the stream flow and tailings deposition criteria, the simulated hydraulic filling pattern and the terrain data distribution and density. The results of these tests provided the basis for testing and calibrating the simulation model for the Wheal Jane project.

The pre-release version of the Medusa Geographical Information System (GIS) was used by the author to structure, manage and interact with project data relevant to hydraulic tailings disposal at the Wheal Jane mine. The Medusa GIS was built around a relational Database Management System (DBMS), and was developed on DEC Vax computers by Cambridge Interactive Systems (CIS) of Harston. Compatible hardware was unavailable at Loughborough University and therefore all simulation runs were carried out at CIS, initially on a Vax 11/750, and during the later stages on a Vax 8550 computer.

A procedure was written that allowed multiple consecutive tests to be run against the database contents. This allowed sequential tests to be set up and left to run during the night and over the weekends. Data files containing the final X, Y and Z coordinates of the simulated tailings deposits were transferred via magnetic tape to the Prime 750 at Loughborough University. The original Medusa Terrain Modeller, the Medusa 3D boolean facilities and the Medusa utility programs, available on the Prime at Loughborough, were then used to quantitatively analyse the volumetric distribution of the simulated deposits.

During the model testing period of 18 months, the relational DBMS unerringly managed all database queries and updates, ensuring that no data loss or corruption occurred.
7.1 METHODOLOGY

7.1.1 Methodology for investigating the sensitivity of the simulation model parameters

Tailfan's ability to simulate the spatial and time dependent processes of hydraulic tailings disposal was quantitatively examined. This included a study of the sensitivity of the tailings flow and deposition criteria, the filling pattern and the terrain representation. The parameters investigated were broadly categorised into into the three groups, (a) to (c), shown below:

(a). Tailfan stream flow and tailings deposition criteria
(b). Simulated hydraulic filling pattern
(c). Terrain data distribution and density

The sensitivity of the parameter groups (a) to (c) was investigated within the confines of horizontal 'pools'. This eliminated any adverse effects which may have been associated with real, developed terrains, such as the fluvial landform characteristic exhibited by the Wheal Jane cycloned beach models.

The Wheal Jane terrain data was of a semi-random distribution, and therefore the majority of 'pool' tests involving both single and multiple point discharge were carried out on semi-random data distributions. For the latter case, three equidistantly spaced discharge points were used to examine the effects of coalescing, or adjacent, tailings fan interaction.

The sensitivity of Tailfan's slope and inertia variables were studied, by setting the weighting factors for slope \([f_{\text{slope}}]\) and inertia \([f_{\text{inertia}}]\) in turn to zero. The stream re-routing variable was examined for slope dependent \((f_{\text{slope}}=1; f_{\text{inertia}}=0)\), inertia dependent \((f_{\text{slope}}=0; f_{\text{inertia}}=1)\) and unbiased \((f_{\text{slope}}=1; f_{\text{inertia}}=1)\) channel alignment criteria, by progressively increasing the branching 'probability' \([P_b]\) from zero to 1.

Tailfan's ability to allow for changes in material slope profile was studied. This was relevant to the simulated deposition of tailings of differing material slope characteristics. Three profiles were specified, of average slopes 0.005 (0.3°), 0.010 (0.6°) and 0.015 (0.9°), with maximum slopes 0.009 (0.5°), 0.012 (0.7°) and 0.017 (1.0°) respectively. These comprised the upper, median and lower bounds of the cycloned stream channel measurements recorded during the Wheal Jane surveys.
The effect of varying the simulated hydraulic filling pattern was examined. This parameter was tested in the 'pools' by adjusting both the discharge iteration height and volume increment, in steps of 10, 50, 100 and 250 millimetres and 10, 50, 100, 500 and 1000 cubic metres respectively. Both variables were progressively incremented until a total control volume of 1000 cubic metres had been deposited. These filling increments represented the time steps within the computer simulation model. The effect of the filling pattern parameter was tested on the Wheal Jane data by summarising the 3 month filling logs into daily, weekly, monthly, 60 day, 80 day and quarterly records. The total number of hours that each valve was active during these periods was entered into the database.

The semi-random Wheal Jane terrain data had an average point spacing of 10 metres. The majority of the controlled tests were therefore carried out on a semi-random 'pool' model with an average point spacing of 10 metres. Simulation tests were also carried out on the commonly used terrain data distributions, including square grid, equilateral, semi-random (stratified) and random data orientations. Further tests were conducted on semi-random data distributions with average point spacings of 5, 10 and 15 metres. The 'pool' test results, discussed in 7.2, provided the basis for testing parameter groups (a) and (b) on the Wheal Jane filling and terrain data. The Wheal Jane test results and the subsequent calibration of Tailfan is discussed in 7.3.

7.1.2 Methodology for carrying out the simulation model tests

Each 'pool' and Wheal Jane simulation test had a its own number. This related to a unique set of test factors in the database. The TESTRECORDS table held information associated with the management of all tests undertaken on the simulation model. This information included an alphanumeric description of the individual test, a test factors identifier, the required filling period and the test date. The prime keys for the TESTRECORDS table were the test number and the test factors identifier. It was possible to REPORT, SELECT, UPDATE or DELETE a record, or series of records, according to its unique test number, a common test factors identifier or a combination of both. The date on which an individual test was carried out was automatically written to the relevant field in the TESTRECORDS table.

The test factor identifier related to the TESTFACTORS table which held information such as the slope, momentum and stream branching factors as well as the material type identifier. The appropriate test factors were retrieved from the database, together with the relevant material slope profile and filling records.
Prior to commencing a simulation test, the relevant sheet was called up on the screen. The discharge points were selected and associated with their corresponding figure on the sheet. The model testing sequence itself was controlled by a BaCIS2 procedure. The user was prompted to insert all relevant test details, such as sheet name and sequential test numbers. All terrain model vertices on the current sheet were reset to a reference datum of 1.0 metre. The relevant test factors were retrieved from the TESTFACTORS table. Simulated tailings flow and deposition commenced for all active discharge points, as has previously been described in 6.6. As the flow alignment tracked across the terrain topology, its path was highlighted on the current Medusa 2D drawing sheet. Thus the patterns of simulated stream channel morphology could be observed. On completion of the specified filling pattern, the updated vertex information was extracted from the relevant area of the database into an X, Y and Z coordinate file.

7.1.3 Methodology for quantitative analysis of the simulated tailings deposits

The simulated deposits were quantitatively analysed against their appropriate controls using Medusa CADD solid modelling software. The X, Y and Z coordinates representative of the final simulated tailings deposits were extracted from the appropriate area of the database at the end of each simulation sequence. The Medusa 3D assembly modeller allowed individual deposit and control models to be defined and assembled on a Medusa 3D sheet, so that boolean operations could be used for their volumetric analysis.

The total volumetric difference in distribution of material between the simulated deposit model (A) and the control model (B) was determined by using the following boolean statement:

\[\text{MAKE} \ (A \ - \ B)\]

Although the total volume of each model was the same, the spatial distribution of their volumes differed. This volumetric difference was derived from the resulting difference model, using the Medusa utilities (medutil) properties program (prop). The volume figure was subsequently checked by reversing the Boolean operation command, thus:

\[\text{MAKE} \ (B \ - \ A)\]

The existence of co-incident faces between the control and deposit models caused mathematical description errors to be flagged by Medusa 3D. Co-incident faces were usually
eliminated by lifting the control model by 1 millimetre at a time and remodelling until a successful and valid difference model was obtained. This had the effect of mathematically validating the difference model, without adversely effecting its volume.

An arbitrary control volume of 1000 cubic metres of deposit was used for all 'pool' tests. Preliminary runs confirmed that this figure would be suitable in magnitude to enable both a qualitative and quantitative analysis of the simulated fan morphology to be carried out. A paraboloid of revolution, similar to that used by the DUMPS package discussed in 6.7.2, was used as the control model for all single point discharge tests. The profiles of each of the three material slopes examined were swept through a 360 degree arc using the volume of revolution facility within Medusa 3D. The focus of each fan was positioned at the discharge point, with its apex being incremently lifted until the model enclosed the control volume of 1000 cubic metres.

Each Medusa 3D sheet allowed a chord tolerance to be specified that defined the required model accuracy. The chord tolerance defined the greatest allowable distance, in sheet units, between an actual curve and its mathematical representation as a series of linear planes in the model. A further parameter was specified which sub-divided each chord into sub-sections. The Medusa command CHOTOL 1.0/1 was the default value for curve or arc definition. This implied that the maximum chord offset in the final model would be 1.0 sheet unit, with the latter value of 1 indicating no further chord sub-division.

Brief tests were conducted to examine the effect of chord tolerancing on the volume of the paraboloid control model. Initially the default chord tolerance of 1.0/1 was used to define the 1000 cubic metres control volume, which was then replaced by 0.1/5, where the Medusa 3D sheet coordinates were in metres. For identical material slope profiles, set at the same focal height, a volumetric difference of 16 cubic metres was returned. Therefore a 50 fold increase in model definition had resulted in a volumetric difference of just 16 cubic metres for the total control volume of 1000 cubic metres. The CPU time and model storage requirement had dramatically increased for the latter chord tolerance, the resultant paraboloid model using up 400 blocks of storage on the Prime, as opposed to only 8 blocks for the former. The 'pool' testing process would involve the analyses of numerous simulated deposits, and therefore the default value of 1.0/1 was used for defining the control models.

The control model for multiple point discharge was created by booleaning together three adjacent paraboloids, as described above, with their apices being equally adjusted until the accumulated volume was 1000 cubic metres. This model was similar to that used by DUMPS
to represent coalescing tailings fans.

The graphical results of a boolean subtraction MAKE (A - B) of the control model (B) from a simulated single point deposit model (A) is shown to the left in Figure 7.1.1(a). The shaded areas indicate the locations where the simulated deposits are above the surface of the control model. The calculated volume difference between the two models was checked, by reversing the boolean command to MAKE (B - A), as shown to the right in Figure 7.1.1(a). The above was repeated for a multiple discharge point deposit, as shown to the left and right in Figure 7.1.1(b). The figure on the left exhibits deposits in excess of the control model along the common boundaries of the adjacent fans. Whereas the multi-paraboloid control model implied a smooth junction between the coalescing fans, simulated tailings stream interaction had caused additional deposition in these areas. This geometric discrepancy had been observed by Troeh (1965) on coalescing alluvial fan structures, as discussed in 6.1, and has been further examined by the author in 7.2.

Initial boolean analyses of the Wheal Jane models produced mathematical errors. The Medusa 3D error message 'WARNING - Problems resolving faces of model' was consistently flagged at the end of each modelling session. The method adopted for the 'pool' test analyses of progressively lifting the control model did not resolve the problem. After consultation with the Medusa 3D Support Group at CIS, Harston, the error was traced to the modelling limitation of the software version (Revision 5.0) on the Prime at Loughborough. The precision of the Medusa 3D model definition, prior to version 7.0, was limited to six significant figures. However, each extracted Wheal Jane data set was defined to the nearest millimetre in the range of 14,500 to 15,250, 11,000 to 11,750 and 50 to 60 metres in X, Y and Z coordinates respectively. Therefore the above mentioned error was due to the manipulation of ill-defined volume models recreated from overly large coordinates. The problem was subsequently resolved by writing a BaCIS2 procedure to adjust each of Wheal Jane data sets towards the 0,0,0 datum.

Between April and July 1986, cycloning took place on both the eastern and western beach sectors of the Wheal Jane tailings dam. This hydraulic filling pattern was adopted with the intention of moving the encroaching pond perimeter away from the dam embankment in these areas. This filling pattern was reflected in the graphical results of the boolean subtraction MAKE (B - A) between the April (A) and the July (B) survey models, as shown in Figure 7.1.2.
Figure 7.1.1  Graphical results of boolean subtraction between simulated tailings deposits (A) and paraboloid control models (B)
Figure 7.1.2  Graphical results of boolean subtraction of April survey model (A) from July survey model (B)
A total interim sub-aerial tailings deposit of 6,927 cubic metres was returned, distributed over a beach area of 40,374 square metres. This represented an average sub-aerial deposit thickness of approximately 175 millimetres. Further deposits totalling 7,660 cubic metres were calculated for the area beyond the April survey pond perimeter. This was assumed to represent sub-aqueous tailings deposits. The filling period for the Wheal Jane tests was taken to be 17 April to 21 July 1986. The 6,927 cubic metres of sub-aerial deposit was distributed amongst the active valves according to their recorded number of operating hours between the aforementioned dates. An average in-situ beach density of 1.6 tonnes per cubic metre was assumed, in order to convert individual valve times into discharge tonnages. Due to the lack of appropriate information, no adjustment was made for head loss between the valves along the length of the delivery pipeline.

The April cycloned beach model acted as the base surface for the Wheal Jane tests. A boolean addition $MAKE(A + B)$ was carried out on the April and July models. The result acted as the control model, against which the simulated Wheal Jane deposits were analysed.

The results of analyses of the 'pool' and Wheal Jane simulation tests, and the subsequent calibration of Tailfan for the Wheal Jane project, are presented in the following two sections of this thesis. For purposes of both clarity and consistency these have been reported as a percentage in volumetric difference from the control volumes. The control volumes for the 'pool' and for Wheal Jane were 1000 and 6,927 cubic metres respectively. Therefore a reported figure of 10 percent, for example, refers to either 100 or 692.7 cubic metres in actual volumetric difference.
7.2 THE 'POOL' TESTS

7.2.1 Tailfan stream flow and tailings deposition criteria

Figure 7.2.1.1(a) shows the results of boolean analyses of single point discharge deposits using the parabolic control model discussed in 7.1.2. Discharge height and volume increments of 50 millimetres and 1000 cubic metres respectively were used in all of the above cases. The simulated distribution of tailings deposits was highly susceptible to the degree of stream branching specified. A progressive increase in the 'probability' of stream branching produced volumetric distributions of deposited material closer to that described by the paraboloid control. The range of simulated stream flow results returned for single point discharge with and without branching (i.e. Pb=1-0) were, in ascending order of magnitude; slope dependency (i.e.f_slope=1; f_inertia=0) (7-33%), unbiased (i.e. f_slope=1; f_inertia=1) (8-30%) and inertia dependency (i.e.f_slope=0; f_inertia=1.0) (16-43%).

The results of the material slope profile tests are shown in Figure 7.2.1.1(b). Tailfan returned consistent deposition results for the three material slope profiles specified, the simulated single point discharge deposits all being spatially distributed within 8% of their relevant paraboloid control models.

The results of the differing Tailfan stream flow criteria on the simulation of coalescing tailing fans are shown in Figure 7.2.1.2(a). The results of analysis using the multi-paraboloid control produced no correlation with the equivalent single point discharge results. A close correlation was achieved when the multiple point discharge deposits were reanalysed using a highest order simulated deposit model as the control. Figure 7.2.1.2(b) shows the results of the multiple point discharge deposits analysed against the simulated deposit derived from slope dependent stream alignment criteria (f_slope=1; f_inertia=0) with a branching 'probability' of 1, at a discharge height increment of 10 millimetres, over a semi-random 'pool' with an average point spacing of 5 metres. This highest order simulated deposit model, unlike the multi-paraboloid control, reflected the effects of stream channel interaction at the boundaries of coalescing tailings fans as observed by Troeh (1965) for alluvial fan structures.

The range of simulated stream flow results returned for multiple point discharge with and
Figure 7.2.1.1 (a) **Influence of stream branching - single point discharge** ('Pool' test)

Figure 7.2.1.1(b) **Influence of deposition profile - single point discharge** ('Pool' test)
Figure 7.2.1.2(a) Influence of stream branching - multiple point discharge: multi-paraboloid control ('Pool' test)

Figure 7.2.1.2(b) Influence of stream branching - multiple point discharge: simulated control ('Pool' test)
without branching were; slope dependency (4-17%), unbiased (5-21%) and inertia dependency (16-31%).

7.2.2 Simulated hydraulic filling patterns

The effects of differing filling patterns were investigated using slope dependent alignment criteria \((f_{slope}=1; f_{inertia}=0)\) with a branching 'probability' of 1 \((P_b=1)\). Figure 7.2.2.1(a) shows the results of iteratively lifting both the single and multiple discharge points in increments of 10, 50, 100 and 250 millimetres. An increase in the discharge increment height resulted in an increase in the volumetric difference between the simulated deposits and their relevant controls. The best results for both single and multiple point discharges were achieved for discharge height increments of 10 millimetres. The single point results fell within the range 5 to 22\% in percentage volumetric difference from the paraboloid control, with the multiple point cases being clearly more sensitive to the discharge height increment, ranging between 4 and 49\% from the highest order simulated control model.

Figure 7.2.2.1(b) shows the results of varying both single and multiple discharge volume increments by 10, 50, 100, 500 and 1000 and 10, 50, 100 and 333 cubic metres respectively, at discharge height increments of 10 millimetres, for the total deposit volume of 1000 cubic metres. The boolean analysis results varied from between 5 and 47\% and 4 and 9\% for the single and multiple cases respectively. The results showed that the single point discharge deposits were more sensitive to small volume increments than were the multiple cases. Filling threshold values of 5\% and 4\% were found to exist for single and multiple point discharges respectively, for volume increments in excess of 50 cubic metres.

7.2.3 Terrain data distribution and density

In addition to the semi-random 'pool' tests, Tailfan was also run on square grid, equilateral and random terrain data distributions for slope dependent stream alignment criteria with a branching 'probability' of 1 \((P_b=1)\), with discharge height and volume increments of 10 millimetres and 1000 cubic metres respectively. The results of these tests, including those for the semi-random terrain, are shown in Figure 7.2.3.1(a). The trend exhibited by the semi-random 'pool' results was repeated for the other three terrain data distributions, whereby an increase in the 'probability' of stream branching resulted in a decrease in the percentage volumetric difference from the paraboloid control. The best results achieved were;
Figure 7.2.2.1 (a) **Influence of discharge height increment - single point discharge**
('Pool' test)

Figure 7.2.2.1 (b) **Influence of discharge volume increment - single point discharge**
('Pool' test)
equilateral (4%), semi-random (5%), random (5%) and square grid (8%).

Tailfan returned consistent deposition results for the three material slope profiles tested, for single point discharge, as shown in Figure 7.2.3.1(b). The range of results for each data distribution were; equilateral (4-7%), semi-random (5% no range), random (5-7%) and square grid (7-8%).

Figure 7.2.3.1(c) shows the results of differing single point discharge height increments over the four terrain data distributions. The range of results for each data distribution were; equilateral (4-23%), semi-random (5-22%), random (5-24%) and square grid (8-24%).

The analysis results of differing single point discharge height increments over semi-random terrains of average point spacings 5, 10 and 15 metres are shown in Figure 7.2.3.2(a). The previously observed trend, whereby an increase in the discharge height increment resulted in an increase in the volumetric difference, was maintained over the three data densities. Likewise the best results over the three data densities were achieved for discharge height increments of 10 millimetres. Figure 7.2.3.2(b) shows the results of varying the discharge volume increment over the three data densities. The common trend was repeated for each of the three densities, whereby volume increments in excess of 50 cubic metres resulted in a minimum filling threshold value. The threshold values were; 5 metre point spacing (3%), 10 metre spacing (4%) and 15 metre spacing (6%).

The above data density tests were carried out for multiple point discharge. The results are shown in Figures 7.2.3.3(a) and (b). With reference to these figures, it can be seen that the common trends were again reproduced for each the three data densities. The minimum threshold values achieved for multiple point discharge with increments of 10 millimetres were; 5 metre point spacing (3%), 10 metre spacing (4%) and 15 metre spacing (6%).

7.2.4 Summary of the 'Pool' test results

The simulated hydraulic filling pattern had the major influence on both single and multiple, coalescing, fan deposits. Single point discharge deposits were adversely affected by low discharge volume increments, whereas the multiple cases were more sensitive to the discharge height increment used. Both single and multiple discharge cases produced minimum filling threshold values for discharge volume increments in excess of 50 cubic metres.
Figure 7.2.3.1 (a) Influence of terrain data distribution on stream branching - single point discharge ("Pool" test)

Figure 7.2.3.1 (b) Influence of terrain data distribution on the deposition profile - single point discharge ("Pool" test)

Figure 7.2.3.1 (c) Influence of terrain data distribution on the discharge height increment - single point discharge ("Pool" test)
Figure 7.2.3.2 (a) Influence of terrain data density on discharge height increment - single point discharge ('Pool' test)

Figure 7.2.3.2 (b) Influence of terrain data density on discharge volume increment - single point discharge ('Pool' test)
Figure 7.2.3.3 (a) Influence of terrain data density on discharge height increment - multiple point discharge ('Pool' test)

Figure 7.2.3.3 (b) Influence of terrain data density on discharge volume increment - multiple point discharge ('Pool' test)
Single and multiple point deposits were highly susceptible to degree of stream branching specified, returning maximum and minimum volumetric differences for branching 'probability' values of zero and 1 respectively. The best 'pool' results were achieved for slope dependent Tailfan flow criteria with stream branching 'probabilities' of 1 \( (f_{\text{slope}}=1; f_{\text{inertia}}=0; P_b=1) \). In addition, the range of material slope profiles tested was adequately accommodated by the computer simulation model.

Tailfan produced consistent trends over the four terrain data distributions and the three data densities tested. The volumetric distribution of simulated deposits was found not to be adversely affected by either terrain data distribution or density.

7.3 THE WHEAL JANE TESTS

7.3.1 Simulated hydraulic filling patterns

The 'pool' test results revealed that the performance of the computer simulation model was most affected by the filling pattern used, and therefore the preliminary Wheal Jane tests concentrated on this particular parameter.

The filling threshold of 50 cubic metres was exceeded for the majority of active valves for summarised time periods in excess of 30 days. The sensitivity of the discharge height increment was therefore examined for the monthly summarised Wheal Jane filling records, initially using unbiased alignment criteria with included stream branching \( (f_{\text{slope}}=1; f_{\text{inertia}}=1; P_b=1) \). Figure 7.3.1.1(a) shows the results of discharge height increments of 10, 25, 50, 75, 100, 125, 150, 175, 200 and 250 millimetres. The best result of 12.6 percent was achieved for the monthly summarised filling records for cyclone height increments of 50 millimetres. It was concluded that a discharge height increment of 50 millimetres represented the optimum value for simulating beach infilling on the real, developed, fluvial terrain of Wheal Jane. This figure was a compromise between too large a value so as not to be able to attain the shape defined by the material slope profile, and too small a figure so as to become liable to the short term effects of erosion. An erosion component, causing the short term reworking of simulated deposits, has not been included within the existing Tailfan model.

The effects of differing filling patterns were further investigated for a discharge height increment of 50 millimetres, over a wide band of Tailfan stream alignment criteria, to examine
the effects of the daily, weekly, monthly, bi-monthly, 80 days and quarterly summarised filling records. This included unbiased \((f_{\text{slope}}=1; f_{\text{inertia}}=1)\), slope \((f_{\text{slope}}=1; f_{\text{inertia}}=0)\) and inertia \((f_{\text{slope}}=0; f_{\text{inertia}}=1)\) dependent alignment criteria with and without stream branching \((P_b=1 \text{ or } 0)\).

The alternative simulated filling patterns returned results which exhibited a cyclic characteristic, the period of which appeared to be in the order of 90 days, or 3 months. The cyclic characteristic is clearly exhibited in Figure 7.3.1.1(b). A minimum volumetric difference from the actual in-situ deposit of just 10.3 percent was achieved for the monthly summarised filling logs, with the maximum figure of 61 percent being returned for the daily filling logs. The non-uniform shape characteristic of the latter deposit is demonstrated by its contours shown in Figure 7.3.1.2. The localised beach depressions resulting from the small, daily discharge volumes were caused by the absence of a simulated erosion component to initiate beach reworking and thus the infilling of these areas.

7.3.2 Tailfan stream flow and tailings deposition criteria

The Tailfan simulation model was run against the monthly filling records for the range of stream alignment criteria and material slope profiles, with a discharge height increment of 50 millimetres, for the monthly summarised filling records. With reference to Figure 7.3.2.1(a), it can be observed that stream alignment criteria with branching 'probabilities' both zero and 1 returned the closest volumetric approximations to the actual beach deposit. A best overall result of 10.3 percent was returned for slope dependent alignment criteria with a stream branching probability of 1 \((f_{\text{slope}}=1; f_{\text{inertia}}=0; P_b=1)\). The contours of this simulated deposit are shown in Figure 7.3.2.2. This figure displays a similar smooth, fluvial landform shape to that exhibited by both the April and July beach contours.

The effects of the upper, median and lower cycloned beach profiles were investigated using the best fit criteria \((f_{\text{slope}}=1; f_{\text{inertia}}=0; P_b=1)\), for a discharge height increment of 50 millimetres over the 6 summarised filling periods. It can be observed from Figure 7.3.2.1(b) that the upper and lower material slope profiles followed a similar trend in percentage volumetric difference, reducing from a maximum of 63% to around 30%. By contrast, the results for the median profile exhibited the cyclic characteristic previously demonstrated, returning the best result of 10.3% for the monthly summarised filling periods.
7.3.1.1 (a) **Influence of discharge height increment** (Wheal Jane)

7.3.1.1 (b) **Influence of filling period, as summarised from mine records** (Wheal Jane)
Figure 7.3.1.2 Contours of simulated Wheal Jane deposit for daily filling records, exhibiting non-uniform shape characteristic and localised beach depressions.
7.3.2.1 (a) **Influence of stream branching** (Wheal Jane)

7.3.2.1(b) **Influence of deposition profile** (Wheal Jane)
Figure 7.3.2.2  Contours of simulated Wheal Jane deposit for monthly filling records, exhibiting a smooth, fluvial landform shape characteristic.
7.3.3 Guidelines for data capture and calibration of the Tailfan simulation model

The Tailfan simulation model was calibrated for the Wheal Jane cycloned beach, to within 10.3% in volumetric difference from the July control. This figure was achieved for slope dependent stream alignment criteria with a branching 'probability' of 1 \( (f_{\text{slope}}=1; f_{\text{inertia}}=0; P_b=1) \), using the median material slope profile, at a discharge height increment of 50 millimetres for the monthly summarised filling logs.

The large computer processing overhead became very apparent during the Wheal Jane simulation runs. The best fit Tailfan criteria, for example, took 340 minutes to run on a dedicated DEC Vax 8550, as shown in Figure 7.3.3.1. The computer processing time has obvious implications for the practical deployment of the computer-aided simulation tool within the design office environment. Brief guidelines have therefore been provided to assist the user in both data capture and calibration of the Tailfan model, for its subsequent use in the determination of hydraulic filling schedules.

The processing time taken for each simulation run was directly proportional to the stream branching 'probability', and inversely proportional to the discharge increment height and the summarised filling time period used. Simulated tailings disposal using slope and direction dependent stream alignment criteria took approximately 5 hours at a discharge height increment of 50 millimetres, and nearly 15 hours at a increment of 10 millimetres!

The Wheal Jane data distribution was of the semi-random type. The 'pool' tests showed that equilateral and semi-random terrain data distributions produced the most accurate representations of simulated tailings deposits, down to data densities with an average point spacing of 15 metres. Semi-random data distributions, due to their inherent flexibility in orientation, can easily accommodate the inclusion of man-made structures such as tailings dam embankments. By comparison, data sets with a regular data distribution constrain shape definition according to the grid interval used. Therefore they may not be appropriate for modelling the existing topographical relief of a 'virgin' disposal site, as would be required at the start of the project, or additional structural geometry such as the dam embankment.

The Wheal Jane terrain data had an average point spacing of 10 metres. The clinical 'pool' tests revealed that Tailfan's simulation accuracy was not directly proportional to data density. Shape definition of simulated coalescing tailings fans was maintained down to an average
Figure 7.3.3.1 Computer processing time (dedicated Vax 8550) taken for Tailfan computer simulation runs.
point spacing of 15 metres to within 6%. It was therefore assumed that the Wheal Jane survey density of an average point spacing of 10 metres, with the exception of the sparse data areas affected by cycloning during the April survey, is sufficient for simulation purposes.

The calibration of the Tailfan simulation model for the Wheal Jane project will require long term filling and terrain information. It is recommended that monthly summaries of valve operating times compiled over a 12 month period be used on semi-random (stratified) data distributions with average point spacings of between 5 and 10 metres. Filling data should include other relevant information, such as any head loss characteristics that may be associated with the delivery pipeline and blocked discharge assemblies. The location of the discharge points with time should also be recorded so that their spatial alteration can be accounted for accordingly in the computer simulation. Beach surveys carried out on a quarterly basis over the 12 month period will enable a further examination of the cyclic filling phenomena.

7.3.4 Sources of error

The overall validity of Tailfan is dependent upon its ability to simulate the time and spatial dependent processes associated with hydraulic tailings disposal. The accuracy of its subsequent calibration for the Wheal Jane project (i.e. \( f_{\text{slope}} = 1; f_{\text{inertia}} = 0; P_b = 1 \)) was proportional to the accuracy and availability of appropriate filling and terrain data samples.

Tailfan was found to be most sensitive to the simulated filling pattern used, returning volumetric distributions that varied from the controls by 4 to 49% within the 'pools', and by 10.3 to 63% for the Wheal Jane tests. The simulated filling pattern was altered by changing the discharge height increment and the volume discharged per deposition cycle.

Incomplete Wheal Jane filling records led to errors in the individual valve operating times. Many of the daily filling logs received from the mine had either the delivery valve start-up or shut-down times missing. In the case of incomplete valve records, a full 7.5 hour shift was assumed. Valve number 1 on the eastern embankment, for example, had a database accumulated active total of 295 hours, obtained by the 7.5 hour shift assumption, compared to a positive recorded figure of just 115 hours, supplied by the mine operators. Likewise valve number 14 on the main embankment had a database summary of 113 hours as opposed to a positively logged 30.5 hours. Head loss along the delivery pipeline, blocked cyclone overflow delivery pipes and local adjustment to the discharge positions will affect both the rate and location of simulated tailings disposal. Head loss tests should therefore be carried out to
determine the effect on the individual valve discharge rates. Likewise blocked delivery feeds should be reported in the filling logs. The results of the in-situ head loss tests, and the recording of blocked feeds or any change in their positions, can then be accounted for in the computer simulation model.

Beach survey inaccuracies would have introduced errors in the April and July data sets, which in turn would have caused corresponding inaccuracies in both the beach surface shape and the derived volume of the interim sub-aerial tailings deposit. The calculated 6,927 cubic metres of deposit was distributed over a beach area of 40,374 square metres. Therefore a 1 millimetre error in height would correspond to approximately 40.3 cubic metres or 0.6% in percentage volumetric difference.

Consolidation will also affect the volume of the hydraulically emplaced tailings material. WLPU Consultants calculated a total average beach consolidation of 12.5 millimetres, for a 175 millimetres thick deposit over a 30 metre depth of tailings, during the three month period. This figure equated to approximately 500 cubic metres over the 40,374 square metre deposit area, or just over 7 percent of the total interim deposit volume.

In summary, the lack of definitive filling information was accredited as the major source of error. However, within the scope of this research study, the Tailfan simulation model proved to perform consistently on both the 'pool' and the Wheal Jane data sets. The simulation model returned a best result of 10.3 percent in volumetric difference from that measured at Wheal Jane between April and July 1986. Although the current version of Tailfan can be customised with relative ease, such modifications should only be carried out in conjunction with the collection and testing of further filling and terrain data samples. Future improvements in data capture for the simulation model may be achieved by setting down clear and concise filling and beach data logging guidelines, as discussed in 7.3.3.

7.4 SUMMARY

The relational data model represented the time based events associated with hydraulic tailings disposal with sufficient accuracy to allow its simulation to be carried out. Correct time dependent filling data transactions were carried out between the database and the Tailfan BaCIS2 procedures over the period of the 'pool' and Wheal Jane tests.
The 'pool' environments allowed controlled tests to be carried out on the empirical stream alignment criteria of slope, inertia and stream branching, with differing material slope profiles and simulated hydraulic filling patterns over varying terrain distributions and densities.

Simulated tailings stream channel alignment criteria were highly sensitive to the branching 'probability' used. Large percentage volumetric differences were achieved for inertia dependent stream alignment criteria without secondary branching ($f_{\text{slope}}=0; f_{\text{inertia}}=1; P_b=0$). Inertia dependent criteria without secondary stream branching had been previously used by Price (1974) to simulate alluvial fan deposits, as discussed in chapter 6. Price confirmed his algorithm by qualitatively assessing both cross-sections and contour plots of his simulated deposits, without investigating their volumetric distribution. The 'pool' test results indicated that a wide range of volumetric distributions may exist for simulated deposits derived from empirical alignment criteria based upon terrain slope and stream inertia. It is therefore a recommendation that flow and sedimentation type simulation models be quantitatively assessed and calibrated, as has been reported on in this thesis. This has particular relevance to the hydraulic filling of tailings dams, where the storage capacity is of primary importance.

Simulated cycloned beach geometry for a single discharge case exhibited a radially infilled fan shape for slope, and slope and direction dependency with multiple stream branching. However, for the multiple discharge cases, all simulation models displayed geometric characteristics different from that of the idealistic multi-paraboloid control. A forwardly progressive 'front' was observed. This geometric feature had also been observed under laboratory conditions. It is suggested that this phenomena is due to stream channel reinforcement along the boundaries of adjacent tailings fans.

The best volumetric approximation to a single paraboloid control model was achieved for single point discharge with slope dependent alignment criteria with included stream branching ($f_{\text{slope}}=1; f_{\text{inertia}}=0; P_b=1$). The simulated geometries of single and multiple point discharge deposits were consistently maintained over semi-random, equilateral, random and square grid data distributions, down to the lowest data density tested with an average point spacing of 15 metres. The volumetric redistribution of simulated tailings deposits was more sensitive to the stream alignment criteria and filling patterns adopted than the terrain data distribution and density used. Alternative filling patterns were simulated by changing both the discharge height increment and the volume discharged per cycle.
The filling pattern used had the major effect on the distribution of simulated 'pool' deposits. As discussed in 6.6, the Tailfan model was purely depositional, and therefore the combination of both variables simulated time steps within the deposition cycle. In reality, an erosion parameter would initiate reworking of deposited material and thus break up the equilibrium shape defined by the static material slope profile. It will therefore be necessary to include an erosion component in a short term or real-time simulation model of hydraulic tailings disposal.

The simulated filling pattern parameter was investigated during initial tests on the Wheal Jane data, as it had been shown to have had the major effect on the simulated 'pool' deposits. The results of these tests confirmed that an erosion component should be included in a short term simulation model. Tests carried out over the 6 summarised filling periods returned volumetric differences which exhibited a cyclic characteristic, the period of which appeared to be in the order of 90 days, or 3 months. This phenomenon proved important when selecting the optimum time at which to collate both filling and terrain data for the purposes of model calibration. The results indicate that the Tailfan simulation model can be run to predict quarterly tailings beach surfaces from monthly compiled filling schedules. Due to the lack of longer term terrain and filling data, further investigation of the cyclic phenomena was outside the scope of this research. It is a recommendation, therefore, that more work be carried out in this area, once the appropriate longer term data is available.

The Tailfan alignment criteria were tested over a monthly filling cycle. The Tailfan simulation model was calibrated to within 10.3 percent in volumetric difference from the July beach control. This figure was achieved for slope dependent stream alignment criteria with a branching 'probability' of 1 ($f_{\text{slope}}=1; f_{\text{inertia}}=0; P_b=1$), using a material slope profile with a maximum slope of 0.012 (0.7°), at a discharge height increment of 50 millimetres for monthly summarised filling logs.

Tailings dam projects typically involve both large time-scales and land areas. Guidelines have therefore been provided in 7.3.3 to assist in filling and terrain data capture for the calibration of a computer simulation model of hydraulic tailings disposal. These guidelines are necessary to ensure that excess project data is not unnecessarily generated.

The effect of differing terrain distributions and densities was not studied for the Wheal Jane project. A polygon sub-division algorithm, discussed in 8.2.1, could be implemented within Tailfan to dynamically enhance the local terrain data density and the terrain model topology as
required.

Over a model testing period of 18 months, the relational DBMS logged a total of 500 million database requests, with an overall first attempt data access efficiency of 98 percent. The latter figure referred to the level of direct data retrieval from local memory, or cache, as opposed to disk access. No data loss occurred during this period.

Recommendations have been made in chapter 8 for enhancing both the Tailfan simulation model and the relational data model. The testing of additional terrain and filling data samples will enable the long term validity of Tailfan to be confirmed.
CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK
8.0 INTRODUCTION

As a result of the development and testing of the computer-aided simulation of hydraulic tailings disposal presented in this thesis, the following conclusions and recommendations can be made.

8.1 CONCLUSIONS

The Medusa Geographical Information System (GIS) has been used to successfully structure, manage and interact with filling and terrain information relevant to hydraulic tailings disposal at the Wheal Jane mine. The Medusa GIS is built around a relational DBMS, and was primarily developed for mapping and utilities applications. The GIS supports integrated software tools, including a graphics interface, a database query language and an application programming language. Terrain topography was represented as a relational, spatially referenced and continuous topological model within the database. This representation provides a well structured spatial platform on which to simulate hydraulic tailings disposal.

Similarities in both pattern and geometry exist between the processes of hydraulic tailings disposal observed at the Wheal Jane tailings dam and that of natural fluvial geomorphology. The shape of tailings beaches and alluvial fans is characterised by radial-profile concavity and cross-fan convexity. The Tailfan simulation model was developed, using the Medusa GIS application programming language, to represent the spatial and time dependent processes of hydraulic tailings disposal. Tailfan's empirically derived equations, based on terrain slope, inertia of flow and stream branching, can account for the simulated sub-aerial disposal of hydraulic tailings around hills and re-entrant valley systems, as found at numerous tailings dam sites.

The material storage implications of varying sites and filling patterns are of prime importance in any computer-aided simulation approach to the scheduling of hydraulic tailings disposal. CADD solid modelling techniques, used in conjunction with boolean operations, provide useful volumetric analysis tools with which to quantitatively validate and calibrate the
simulation model.

The results of simulation tests carried out within the confines of horizontal 'pools' revealed that Tailfan was most sensitive to the hydraulic filling pattern adopted and the degree of stream branching specified, and least sensitive to the terrain data distribution and density used. Tailfan performed consistently over square grid, equilateral, semi-random (stratified) and random data distributions, and for semi-random data orientations with average point spacings of 5, 10 and 15 metres.

The Tailfan simulation model was tested and provisionally calibrated for the cycloned beach at Wheal Jane. A best result of 10.3 percent in volumetric difference from a terrestrial survey control was achieved for slope dependent stream alignment criteria with a channel branching 'probability' of 1.0, using a material profile with a maximum slope of 0.012 (0.7°) for discharge height increments of 50 millimetres. The simulation model exhibited a cyclic characteristic over the 3 month filling period studied. This cyclic result indicates that the aforementioned criteria can be used to simulate quarterly tailings beach surfaces from monthly compiled filling schedules.

The testing and quantitative analysis of the computer-aided simulation model has been discussed in chapter 7.

8.2 RECOMMENDATIONS FOR FURTHER WORK

8.2.1 Recommended extensions to the Tailfan simulation model and the relational database model

The lack of definitive filling data was identified as the major contributing factor to the sources of error. More filling and terrain data samples will be required for the long term calibration of the simulation model. Tests should include an investigation into the time dependent cyclic phenomena discussed in 8.1.

Interactive enhancements to the terrain model will become necessary in areas of sparse data. The inclusion of a procedure within Tailfan to dynamically increase the local data density, by inserting additional vertices, lines and polygons into the terrain model, can be accommodated by using the existing GIS facilities. It must be ensured that any changes to the terrain topology are followed by model integrity and data duplication checking routines.
The Tailfan simulation model tested was purely depositional, that is, no allowance was made for the reworking of simulated tailings deposit by beach erosion due to increases in discharge rates or climatic variations. Furthermore, the current version of Tailfan does not include sub-aqueous tailings deposition. Both erosion and sub-aqueous deposition can be included in the Tailfan simulation algorithm without modifying the existing relational data model.

The relational data model can be extended to accommodate the longer term interrelated processes of hydraulic tailings disposal. These extensions should address both geotechnical parameters, including seepage and consolidation, and hydrological parameters, such as climatic conditions and the water balance. Long term effects on the terrain data, such as consolidation, will require that time based events are recorded and monitored. The time dimension can be included by inserting an appropriate field into the vertex table of the standard GIS data model. An additional table can be inserted to record the evolution of a series of different surface types and their attributes. Such surfaces may refer to beach, embankment or seepage levels at prespecified time intervals during a tailings disposal project.

8.2.2 Benefits of an extended computer-aided simulation of hydraulic tailings disposal

Interactive, computer-aided tools, such as discussed in this thesis, offer great potential to terrain based simulation applications such as the overland disposal of hydraulic tailings. Additional benefits of a computer-aided approach to hydraulic tailings disposal exist in site planning and restoration, project design, data management and tailings recovery.

The use of interactive computer graphics in site planning and restoration has increased in tandem with environmental pressures. This is especially applicable to the location of tailings dam structures in developed countries. High population densities dictate that land-take be kept to a minimum, whilst the visual impact of the design becomes increasingly important. In some tailings disposal contracts it is legally binding that the area be aesthetically restored on project completion by capping and grassing. It is in such cases that computer graphics will have an important role to play, in generating colour shaded visualisations to assist in both feasibility studies and long term planning proposals.

The Medusa Geographical Information System (GIS) provides a flexible and powerful environment in which to develop and validate simulation models to assist in the design process. Its ability to allow multi-procedural access to the database records will enable other interrelated
phenomena to be modelled. This can include beach erosion and sub-aqueous deposition, as well as the geotechnical and hydrological parameters discussed in 8.2.1. The time based interaction of these parameters with the structural evolution of the tailings dam can thus be represented, to provide a more comprehensive basis for assessing the overall structural stability using finite element analysis techniques. The hydraulic filling patterns can be adjusted iteratively until the optimum filling/stability criteria have been satisfied.

Data management is an important issue for the majority of tailings disposal projects. Large amounts of filling and terrain information are collected over a typical project life of 25 years. A Database Management System (DBMS), such as that provided by the Medusa GIS, enables all project data to be efficiently structured and managed. DBMS facilities include database priority levels and transaction locking mechanisms, to prevent unauthorised database access or corruption. Database recovery techniques are also provided to eliminate costly data loss caused by hardware or software 'crashes'. Furthermore, a report generator allows project information to be listed according to user specified tables, fields, conditions and format. This can include the automatic compilation of filling schedules from optimised Tailfan simulation runs, valve servicing details, and periodic beach level reports.

Tailings reprocessing is becoming a more widespread practice, in an attempt to extract further minerals from older repositories. In such instances, prior knowledge of the actual filling history adopted during tailings disposal will be required. A DBMS can be used to assist in the compilation of the history of hydraulic filling during each project, which can at a later date be used in the planning for optimum ore recovery.
APPENDIX A

Wheal Jane database attribute tables
A.1 Summary of Wheal Jane database, including standard Medusa GIS tables
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<tr>
<td>testrecords</td>
<td>Channel alignment records</td>
</tr>
<tr>
<td>text</td>
<td>Geometrical text data</td>
</tr>
<tr>
<td>text_rules</td>
<td>Text positioning rule data</td>
</tr>
<tr>
<td>user</td>
<td>User information</td>
</tr>
<tr>
<td>user_access</td>
<td>User access information</td>
</tr>
<tr>
<td>valve</td>
<td>Valve</td>
</tr>
<tr>
<td>vertex</td>
<td>Geometrical Vertex data</td>
</tr>
<tr>
<td>view</td>
<td>Database view data</td>
</tr>
<tr>
<td>viewfield</td>
<td>Database table and view associations</td>
</tr>
</tbody>
</table>
A.2 Listing of Wheal Jane project attributes tables
The following tables are specific to the testing of a relational database management system for tailings dams:

### Table TAILS PROD

<table>
<thead>
<tr>
<th>Field</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>month</td>
<td>int</td>
<td>Month beginning</td>
</tr>
<tr>
<td>totaltonnes</td>
<td>int</td>
<td>Total tails tonnes</td>
</tr>
<tr>
<td>cychours</td>
<td>int</td>
<td>Cyclone hours</td>
</tr>
<tr>
<td>millhours</td>
<td>rea</td>
<td>Mill hours</td>
</tr>
<tr>
<td>runpercent</td>
<td>rea</td>
<td>% running</td>
</tr>
<tr>
<td>leattonnes</td>
<td>int</td>
<td>Leated tonnes</td>
</tr>
<tr>
<td>beachtonnes</td>
<td>int</td>
<td>Beach tonnes</td>
</tr>
<tr>
<td>wallsand</td>
<td>int</td>
<td>Wall sand</td>
</tr>
</tbody>
</table>

**Key:** month

### Table DAILYSITE

<table>
<thead>
<tr>
<th>Field</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>sitedate</td>
<td>int</td>
<td>Date</td>
</tr>
<tr>
<td>head</td>
<td>rea</td>
<td>Head (mm)</td>
</tr>
<tr>
<td>addweirboard</td>
<td>int</td>
<td>Number weirboards added</td>
</tr>
<tr>
<td>reslevel</td>
<td>rea</td>
<td>Reservoir level (m AOD)</td>
</tr>
<tr>
<td>beachwdtok</td>
<td>int</td>
<td>Beach ≥ 5 m wide?</td>
</tr>
<tr>
<td>beachlevok</td>
<td>int</td>
<td>Beach top ≥ 0.75 m above pond</td>
</tr>
<tr>
<td>cycok</td>
<td>int</td>
<td>Hydrocyclones OK?</td>
</tr>
<tr>
<td>pipeleak</td>
<td>int</td>
<td>Leaks along pipeline?</td>
</tr>
<tr>
<td>cyccrunhours</td>
<td>rea</td>
<td>Cyclone running hours</td>
</tr>
<tr>
<td>leatsused</td>
<td>chr</td>
<td>Leats in use</td>
</tr>
</tbody>
</table>

**Key:** sitedate

---

184
-- Table DAILYVALVE contains daily valve records
--
Table dailyvalve Channel 5  -- Daily valve records
Field valvenum 1 int  -- Valve number
Field startdate 1 int  -- Type int 1
Field starttime 1 int  -- Start date
Field stopdate 1 int  -- Stop date
Field stoptime 1 int  -- Stop time
Field oftonnes 1 real  -- Overflow tonnage
Field uftonnes 1 real  -- Underflow tonnage
Field valvehours 1 real  -- Valve hours

-- Key
startdate starttime valvenum

-- Index
valvenum startdate

--

-- Table VALVE contains valve data
--
Table valve Channel 5  -- Valve
Field valvenum 1 int  -- Valve number
Field figure$id 3 int  -- Figure identifier

-- Key
valvenum

--

-- Table CYCLONEUF contains cyclone underflow data
--
Table cycloneuf Channel 5  -- Cyclone underflow
Field valvenum 1 int  -- Valve number
Field figure$id 3 int  -- Figure identifier

-- Key
valvenum

--

-- Table CYCLONEOF contains cyclone overflow data
--
Table cycloneof Channel 5  -- Cyclone overflow
Field valvenum 1 int  -- Valve number
Field figure$id 3 int  -- Figure identifier

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<table>
<thead>
<tr>
<th>Field</th>
<th>cycbearing</th>
<th>1</th>
<th>int</th>
<th>-- Name figure_id</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-- Cyclone bearing (deg)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-- Type int 1</td>
</tr>
<tr>
<td>Key</td>
<td>valvenum</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

Table TESTRECORDS contains data relevant to the testing of the RDBMS

<table>
<thead>
<tr>
<th>Table</th>
<th>testrecords</th>
<th>Channel 5</th>
<th>-- Channel alignment records</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>testno</td>
<td>1</td>
<td>int</td>
</tr>
<tr>
<td>Field</td>
<td>testdate</td>
<td>1</td>
<td>int</td>
</tr>
<tr>
<td>Field</td>
<td>testfactid</td>
<td>1</td>
<td>int</td>
</tr>
<tr>
<td>Field</td>
<td>project</td>
<td>20</td>
<td>chr</td>
</tr>
<tr>
<td>Field</td>
<td>description</td>
<td>40</td>
<td>chr</td>
</tr>
<tr>
<td>Field</td>
<td>modelname</td>
<td>40</td>
<td>chr</td>
</tr>
<tr>
<td>Field</td>
<td>startdate</td>
<td>1</td>
<td>int</td>
</tr>
<tr>
<td>Field</td>
<td>stopdate</td>
<td>1</td>
<td>int</td>
</tr>
</tbody>
</table>

Key      | testno testfactid  |

---

Table TESTFACTORS contains criteria for simulating stream channel alignment and tailings deposition

<table>
<thead>
<tr>
<th>Table</th>
<th>testfactors</th>
<th>Channel 5</th>
<th>-- Channel alignment test factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>testfactid</td>
<td>1</td>
<td>int</td>
</tr>
<tr>
<td>Field</td>
<td>profileid</td>
<td>1</td>
<td>int</td>
</tr>
<tr>
<td>Field</td>
<td>geometrywt</td>
<td>1</td>
<td>rea</td>
</tr>
<tr>
<td>Field</td>
<td>energywt</td>
<td>1</td>
<td>rea</td>
</tr>
<tr>
<td>Field</td>
<td>braidwt</td>
<td>1</td>
<td>rea</td>
</tr>
<tr>
<td>Field</td>
<td>beachdensity</td>
<td>1</td>
<td>rea</td>
</tr>
<tr>
<td>Field</td>
<td>deltatime</td>
<td>1</td>
<td>int</td>
</tr>
<tr>
<td>Field</td>
<td>heightinc</td>
<td>1</td>
<td>rea</td>
</tr>
</tbody>
</table>

Key      | testfactid  |

---

Table GEO$LOOKUP contains depositional slope geometry
for various material types

<table>
<thead>
<tr>
<th>Table</th>
<th>geo$lookup</th>
<th>Channel 5</th>
<th>-- Profile geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>mat$type</td>
<td>int</td>
<td>-- Material type identifier</td>
</tr>
<tr>
<td>Field</td>
<td>esdist</td>
<td>rea</td>
<td>-- Slope distance to start node</td>
</tr>
<tr>
<td>Field</td>
<td>delta$h</td>
<td>rea</td>
<td>-- Height drop (m)</td>
</tr>
<tr>
<td>Field</td>
<td>mat$char</td>
<td>rea</td>
<td>-- Material characteristic</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>Key</th>
<th>mat$type esdist</th>
</tr>
</thead>
</table>

---

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APPENDIX B

Flow chart description of the Tailfan simulation model
B.1 Flow chart description of procedure for controlling the Tailfan simulation runs
B.2 Flow chart description of procedure for simulating the concurrent filling from one or more discharge points.
Simulate tailings flow and deposition

Locate adjacent vertices

Calc internodal probabilities

Set up probability list for vertex n

Determine next vertex (n+1)

Set up stream branching list for vertex n

Stream channel termination?

Yes

No

Terrain slope (n+1) > Material slope?

No

Calc height of local deposit

Calc volume of local deposit

\[ \sum V_{\text{deposited}} > \sum V_{\text{discharged}}? \]

No

Update last vertex (n)

Display stream channel

Report interim filling details

RETURN

RETURN

\[ \sum V_{\text{deposited}} = \sum V_{\text{discharged}}? \]

Yes

Stream branching list empty?

Amend branching list for vertex n

Yes

No

Go to last vertex in branching list

B.3 Flow chart description of procedure for simulating hydraulic tailings flow and deposition
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REFERENCES


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