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Reduced-scale ultrasonic modelling of Rayleigh wave transmission over seismic barriers

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Abstract
Several types of seismic barriers have been proposed in the past to protect buildings from traffic-induced ground vibrations, mainly from propagating Rayleigh surface waves. In many cases the developers are forced to use direct experimental measurements on real size seismic barriers at frequencies typical for traffic-induced ground vibrations, i.e. at 10-100 Hz. As an alternative and much less expensive approach, a reduced-scale experimental modelling using ultrasonic Rayleigh wave propagation over very small-scale replicas of real seismic barriers is considered in the present work. Rayleigh wave pulses with the central frequency of 1 MHz have been used, which corresponds to the value of scaling factor about 1:1000. Propagation over three types of seismic barriers was investigated: 1) arrays of periodic vertical holes, 2) combinations of periodically positioned trenches, including a single trench, and 3) statistically rough surfaces. The results of the measurements of transmission and reflection coefficients are presented.

1 Introduction

One of the ways of reduction of ground vibrations from railways or road traffic is to affect the propagation path from source to receiver by introducing seismic barriers. The advantage of interventions on the propagation path is that no modifications of the track or road are required. Several types of seismic barriers have been proposed in the past to protect buildings from traffic-induced ground vibrations, mainly from propagating Rayleigh surface waves. Among such barriers are trenches (both open and in-filled) [1-4], large concrete blocks embedded in the ground [5-7], rows of vertical piles [8, 9], periodic arrays of vertical holes [10], heavy masses placed on the ground surface [11, 12], etc.

Theoretical predictions of Rayleigh wave propagation through such barriers are extremely difficult. Analytical solutions are possible only for a limited number of cases, for example for very shallow trenches [13]. In the majority of situations though the only methods of theoretical prediction are numerical approaches, which require much of computer time. For that reason, in order to obtain a reliable prediction of the behaviour of seismic barriers in specific locations, a typical practical solution is to use direct experimental measurements on real size seismic barriers at frequencies typical for traffic-induced ground vibrations, i.e. at 10-100 Hz [7, 14, 15]. Such direct measurements are costly and time consuming.

In the present paper, an alternative and much less expensive approach to a full-scale experimental testing is proposed. This is reduced-scale experimental modelling using ultrasonic Rayleigh wave propagation over very small-scale replicas of real seismic barriers. Note that very similar problems are considered in ultrasonic non-destructive testing with regard to identification of parameters of cracks and other defects (see e.g. [16-19]). In the present work, we describe the methodology of the approach and the results of the experimental investigations of propagation of Rayleigh wave pulses with the central frequency of 1 MHz,
which corresponds to the scaling factor of about 1:1000, over three types of seismic barriers: 1) arrays of periodic vertical holes, 2) combinations of periodically positioned trenches, including a single trench, and 3) statistically rough surfaces.

All these small-scale replicas of real seismic barriers have been made on the surfaces of Aluminium rectangular blocks having the dimensions of 350x250x20 mm (each of these blocks can be considered as an elastic half space for Rayleigh waves at frequencies around 1 MHz). The results of the measurements of transmission and reflection coefficients of Rayleigh waves for different incident angles show that the most efficient suppression of transmitted waves can be achieved by periodic combinations of open trenches. This is followed by periodic arrays of vertical holes. The least efficient are statistically rough surfaces. Recommendations are being made regarding applications of the obtained results to real practical situations.

2 Manufacturing of experimental samples

The experimental samples have been made of 20 mm-thick aluminium plates having horizontal dimensions of 350 x 250 mm. Figure 1 shows a photograph of an aluminium rectangular plate with an array of vertical holes drilled on its surface.

![Figure 1: Photograph of an Aluminium rectangular plate with an array of vertical holes (on the left); the right-hand side of the plate is used for measurements of a reference signal transmission.](image)

In order to investigate ultrasonic Rayleigh wave propagation over seismic barriers, three types of very small-scale replicas of real seismic barriers have been considered: 1) arrays of periodic vertical holes, 2) combinations of periodically positioned trenches, including a single trench, and 3) statistically rough surfaces. A CNC (Computer Numerically Controlled) milling machine was used to produce arrays of vertical holes and trenches; and, a Sand Blasting Machine and a hammer point were used to produce rough surfaces. The central frequency of Rayleigh wave pulses used in the experiments was 1 MHz.

First, an array of vertical holes was produced as a reduced-scale model of the array of vertical holes drilled in the real ground and investigated in the work by Brule et al [10]. A scale factors have been calculated from the diameter, depth and lattice to wavelength ($\lambda =1.56$ m, according to the 50 Hz source used in [10]) ratios of the experimental mesh (5 m deep self-stable holes of diameter 0.32 m with centre-
to-centre spacing of 1.73 m), \( n_D = 0.2, n_h = 3.2, n_a = 1.11 \), respectively. A mesh of the reduced-scale model taking into account the scale factors calculated and the wavelength for a 1 MHz Rayleigh wave in aluminium, \( \lambda_R \) (Rayleigh wave velocity in aluminium, \( V_R = 2920 \text{ m/s} \)), was made in square lattice of three lines of ten vertical holes 0.6 mm in diameter, \( D \), 9.2 mm in depth, \( h \), (owing to the difficulty of drilling the holes with 0.6 mm in diameter, the depth \( h \) was chosen to be 5 mm instead of 9.2 mm) and 3.2 mm in lattice, \( a \), (for convenience, we will use the following shortened notation for this sample: D06h50a32; similar notations will be also used for other experimental samples).

To investigate the influence of holes' sizes and spacing of reduced-scale model on the results, different meshes with different sizes of holes and lattice were produced in different samples; mesh of square lattice of \( D = 0.6 \text{ mm}, h = 5 \text{ mm} \) and \( a = \lambda_R \), (D06h50a29); mesh of rectangular lattice of \( D = 0.6 \text{ mm}, h = 5 \text{ mm} \) and \((a,b) = (3.2, 9) \text{ mm} \), (D06h50a32b90); mesh of square lattice of \( D = 1.2 \text{ mm}, h = 9.2 \text{ mm} \) and \( a = 3.2 \text{ mm} \), (D12h92a32) and mesh of square lattice of \( D = 1.2 \text{ mm}, h = 9.2 \text{ mm} \) and \( a = \lambda_R \), (D12h92a29). Figure 2 shows photographs of arrays of vertical holes drilled in Aluminium rectangular plates.

![Figure 2](image)

Figure 2: Close up photographs of the arrays of vertical holes drilled on the surface of Aluminium rectangular plates: (a) D06h50a32; (b) D06h50a29; (c) D12h92a32; (d) D12h92a29 and (e) D06h50a32b90.

A single trench (1Th07w15) and three (3Th07a29w15) and six (6Th07a29w15) periodically positioned trenches with the same length (29.4 mm) were produced on the surface of Aluminium rectangular plates with a constant depth, \( h = \frac{\lambda_R}{4} = 0.7 \text{ mm} \), and width, \( w = \frac{\lambda_R}{2} = 1.5 \text{ mm} \). The separation, centre-to-centre, between two trenches was selected to be equal to Rayleigh wavelength in Aluminium at frequency of 1 MHz, \( a = \lambda_R = 2.9 \text{ mm} \). Figure 3 shows photographs of a single trench, and of three and six trenches.
Figure 3: Close up photographs of the combinations of periodically positioned trenches, and of a single trench, made on the surfaces of Aluminium rectangular blocks: (a) three trenches, 3Th07a29w15, (b) six trenches, 6Th07a29w15, and (c) a single trench, 1Th07w15.

Figure 4: Close up photographs of the statistically rough surfaces made on the surface of Aluminium rectangular blocks: (a) a rough surface produced by a Sand Blasting Machine, RS; (b) a rough surface produced by a hammer point, RH.
Finally, two samples of statistically rough surfaces were produced on the surfaces of similar blocks of Aluminium. The first one (RS) was produced by a Sand Blasting Machine and the second one (RH) - by hitting the block of Aluminium with a hammer point. Photographs of the rough surfaces produced using a Sand Blasting Machine and a hammer point are shown in Figure 4.

3 Experimental setup.

The laboratory arrangement used for measurements of transmission and reflection coefficients of propagating Rayleigh wave pulses with the central frequency of 1 MHz, which corresponds to the value of scaling factor of about 1:1000, over three types of seismic barriers is shown in Figure 5. Two Phoenix angle-beam piezoelectric ultrasonic transducers of 1 MHz, 20mm diameter crystal and L51xW27XH31 mm, were used to generate and receive ultrasonic Rayleigh waves on the surfaces of Aluminium rectangular blocks. A Sitescan150 testing system from Sonatest Ltd was used both to drive the transducer and to receive/display the ultrasonic signals. A Sonatest Data Management System version 3 (SDMS 3) was installed in the Laptop to interface and record the acquired data from Sitescan150 for further post processing.

Figure 6 represents a schematic of the experimental arrangement used for measuring the ultrasonic Rayleigh waves transmitted and reflected for different incident angles.

The separation between the transmitter and the receiver was $d = 5$ cm for arrays of vertical holes and trenches; and $d = 8.5$ and 12 cm for rough surfaces produced by a Hammer point and a Sand Blasting machine respectively.
The reduced-scale models of seismic barriers were produced in the middle of one half of the Aluminium rectangular plates. Another half was used for the measurements of the propagation of ultrasonic Rayleigh waves over smooth surface (in the absence of seismic barriers) for reference purposes. Measurements were performed in transmission mode. The transducer connected to the Transmitter of Sitescan150 generated an ultrasonic Rayleigh wave pulse on the surface of an Aluminium plate. Another transducer was connected to the Receiver of Sitescan150 and placed behind the seismic barriers, separated by distance $d$, and received the ultrasonic Rayleigh waves generated by the transducer (transmitter).

For measurements of Rayleigh wave transmission, different incident angles, $\theta_i$, of ultrasonic Rayleigh waves were used. As angles of reception, the following angles were used: $\theta_r = -60^\circ$, $-30^\circ$, $0^\circ$, $30^\circ$ and $60^\circ$. Due to the symmetry of the geometries of the seismic barriers, only angles of $\theta_i = 0^\circ$, $30^\circ$ and $60^\circ$ were considered for the incident waves. The positions and angles of the transducers (transmitter and receiver), are shown in Figure 6(a).

With regard to the reflection from the seismic barriers, $30^\circ$ and $60^\circ$ degrees of the incident angles have been chosen, and the receiver was placed as shown in Figure 6(b). For reference purposes, the two transducers, transmitter and receiver, were located at the same distance, $d$, between them in the other half of the Aluminium rectangular plate (in the absence of seismic barriers) for measuring the propagation of ultrasonic Rayleigh waves over smooth surface. The measurements were repeated several times for each configuration, and the results were averaged statistically.

4 Experimental results and discussion

4.1 Rayleigh wave interaction with arrays of vertical holes

The aim of this part of the investigation was to reproduce in a small scale the full-scale experimental measurements carried out in the work [10] on Rayleigh wave transmission through periodic arrays of vertical holes, also termed as 'seismic metamaterials' or 'seismic crystals'.
In the first step of the measurements, the transmitter and the receiver were placed in the normal position (0°). The measurements results for ultrasonic Rayleigh wave propagation over smooth surface and over an array of vertical holes, D06h50a32, as a reduced-scale model, at 1 MHz, of the full-scale experiments carried out in [10] are shown in Figures 7 and 8 respectively.

![Figure 7](image1.png)

Figure 7: The received signals of ultrasonic Rayleigh waves propagating over a smooth surface at θ_1 = 0 and θ_2 = 0: (a) the time-domain waveform, (b) the full-wave rectifier, (c) the expanded time-domain waveform, and (d) the corresponding frequency spectrum.

The amplitude reduction factor for the above-mentioned model array of vertical holes was introduced as the ratio of the maximum value of the Rayleigh wave signal transmitted over the array of vertical holes and the maximum value of the Rayleigh wave signal transmitted over a smooth surface. The reduction factor calculated from Figures 7 and 8 is about 0.73, which shows a moderate attenuation of the signal transmitted through this array of vertical holes. This attenuation of ultrasonic Rayleigh waves transmitted through this type of array of vertical holes is substantially smaller than in the case of full-scale measurements of paper [10], where the signal hardly reaches the second row of boreholes.

For oblique incidence, the transmitter was placed at the angles θ_i = 30° and 60°, while the receiver still was in the normal position. In what follows only the full-wave rectifier signal will be presented. The corresponding measurement results are shown in Figure 9.

The amplitude reduction factors calculated from Figures 7 and 9 are 0.22 and 0.07 for 30° and 60° respectively. These values are substantially lower than that obtained for the normal angle of the incident wave.
Figure 8: The received signals of ultrasonic Rayleigh wave propagating over the array of vertical holes, D06h50a32, as a reduced-scale model of the seismic array of boreholes experimentally investigated in [10]; $\theta_i = 0$ and $\theta_r = 0$: (a) the time-domain waveform, (b) the full-wave rectifier, (c) the expanded time-domain waveform, and (d) the corresponding frequency spectrum.

Figure 9: The full-wave rectifier signal of ultrasonic Rayleigh wave propagating over the array of vertical holes, D06h50a32; receiver at normal position, $\theta_r = 0$: (a) Transmitter at $\theta_i = 30^\circ$, (b) Transmitter at $\theta_i = 60^\circ$.

The next measurements were to measure the reflection coefficients from the same model array of vertical holes. In the case of Rayleigh wave reflections from the model array, two pairs of incidence and reflection
angles have been used, \((\theta_i = 30^\circ, \theta_r = 30^\circ)\); and \((\theta_i = 60^\circ, \theta_r = 60^\circ)\). The results are not shown here for shortness.

### 4.2 Rayleigh wave interaction with periodic combinations of open trenches

Single trenches, both open and in-filled, are used widely as seismic barriers against train- and traffic-induced ground vibrations [1-4]. Periodic combinations of trenches are not known to be used as seismic barriers, but they are used widely as reflective gratings in signal processing devices using different types of surface acoustic waves, including Rayleigh waves (see e.g. [13]). In what follows we describe the results of reduced-scale ultrasonic investigations of the behaviour of single trenches and of their periodic combinations as seismic barriers.

A single trench and combinations of three and six periodically positioned trenches were produced on the surfaces of Aluminium plates with the dimensions mentioned above. The transducers (transmitter and receiver) were initially located in the normal position and separated by the distance \(d = 5\) cm, as in the previous cases of arrays of vertical holes. The measurements results for ultrasonic Rayleigh wave propagation over a smooth surface and over a single trench are shown in Figure 10.

![Figure 10: Signals of ultrasonic Rayleigh waves, \(\theta_i = 0^\circ\) and \(\theta_r = 0^\circ\): (a) Full wave rectifier signal transmitted over a smooth surface, and (b) the corresponding frequency spectrum; (c) Full wave rectifier signal transmitted over a single trench, and (d) the corresponding frequency spectrum.](image)

It can be seen that the amplitude reduction factor for a single trench is 0.30. For oblique incidence and for the receiver being in normal position, the measurement results are shown in Figure 11. The amplitude reduction factors in these cases are 0.16 and 0.02 for \(\theta_i = 30^\circ\) and \(60^\circ\) respectively.
In the case of Rayleigh wave reflection, the results are shown in Figure 12. The reflection coefficients were 0.19 and 0.29 for angles of 30° and 60° respectively.

Measurements of Rayleigh wave transmission were repeated for the cases of three and six periodically positioned trenches when both transducers (transmitter and receiver) were located in the normal position. The results for Rayleigh wave transmission over a smooth surface and over three trenches, as well as over a smooth surface and over six trenches are shown in Figures 13 and 14 respectively.
Figure 13: Full wave rectifier signals of ultrasonic Rayleigh waves, $\theta_i$ and $\theta_r = 0^\circ$: (a) signal transmitted over a smooth surface, and (b) signal transmitted over three trenches.

Figure 14: Full wave rectifier signals of ultrasonic Rayleigh waves, $\theta_i$ and $\theta_r = 0^\circ$: (a) signal transmitted over a smooth surface, and (b) signal transmitted over six trenches.

The corresponding amplitude reductions factors are 0.1 and 0.04 - for three trenches and for six trenches respectively. A strong attenuation of the signals for these cases is apparent. These results demonstrate that the attenuation of Rayleigh waves propagating over periodic systems of trenches, if the period is equal to the Rayleigh wavelength, is much stronger than their attenuation in the case of arrays of vertical holes.

4.3 Rayleigh wave transmission over statistically rough surface areas

Statistically rough surface areas were the last configurations that were tested in this paper. The aim of this testing was to check the possibility of using them as seismic barriers. One should note in this connection that propagation of Rayleigh waves over statistically rough surfaces was investigated in the past both theoretically and experimentally, mainly with regard to applications in ultrasonic non-destructive testing and in signal processing devices using surface acoustic waves, where the effect of roughness is considered as one of the 'negative' factors reducing distances of Rayleigh wave propagation. This is in contrast with the present paper, where the effect of rough surfaces on damping ground vibrations is considered as 'positive' and desirable. It is well known (see e.g. [13] and references therein) that multiple scattering of Rayleigh waves by small random irregularities forming rough surfaces results in attenuation of Rayleigh
waves with distance of propagation that depends strongly on frequency of Rayleigh waves and on average vertical and horizontal sizes of small irregularities.

In the experiments described in this section, two experimental samples containing rough surface areas have been tested. The separation between the transmitter and the receiver was \( d = 8.5 \) cm - for a rough surface produced by a hammer point and \( d = 12 \) cm - for a rough surface produced by a Sand Blasting Machine, which took into account the difference in horizontal dimensions of these two rough surface areas produced on surfaces of the experimental samples.

The measurements results for ultrasonic Rayleigh wave propagation over a rough surface area produced by a hammer point and over a smooth surface, as well as over a rough surface area produced by a Sand Blasting Machine and over a smooth surface are shown in Figures 15 and 16.

![Figure 15](image1.png)

**Figure 15:** Full-wave rectifier signals of ultrasonic Rayleigh waves, \( \theta_i \) and \( \theta_r = 0^\circ \): (a) signal transmitted over a smooth surface, and (b) signal transmitted over a rough surface produced by a hammer point.

![Figure 16](image2.png)

**Figure 16:** Full-wave rectifier signals of ultrasonic Rayleigh waves, \( \theta_i \) and \( \theta_r = 0^\circ \): (a) signal transmitted over a smooth surface, and (b) signal transmitted over a rough surface produced by a sand blasting machine.

It follows from Figures 15 and 16 that the amplitude reduction factor is 0.73 for the case of rough surface produce by a hammer point. For the second case of 'smoother' rough surface produced by a Sand Blasting Machine, the amplitude reduction factor is only about 0.84, even though the horizontal dimensions of this
rough surface area are larger. This means that, as expected, this rough surface provides a smaller attenuation of Rayleigh waves than in the previous case. Note that the above-mentioned values of the amplitude reduction factor are in agreement with the estimated values of the total wave attenuation following from the theory of Rayleigh wave propagation over statistically rough surfaces (see e.g. [13]) for the distances of Rayleigh wave propagation (8.5 cm and 12 cm) used for these two experimental samples. It can be seen from the above measurements that, although statistically rough surfaces can be used as seismic barriers, their efficiency for typical parameters of roughness is relatively low.

5 Conclusions

It has been demonstrated in this paper that reduced-scale ultrasonic modelling of Rayleigh wave interaction with seismic barriers can be a useful tool for experimental investigations of the properties of different types of seismic barriers as mitigation measures against railway- and traffic-induced ground vibrations.

The advantage of reduced-scale ultrasonic modelling over full-scale experimental measurements is that it is compact (all experiments can be conducted on a laboratory table) and much less expensive (it is easy to manufacture numerous experimental samples modelling different configurations of seismic barriers).

The main disadvantage of reduced-scale ultrasonic modelling is that standard ultrasonic transducers used for generation and reception of Rayleigh waves are relatively narrow band devices designed for specific central frequencies, in contrast to real sources of railway- and traffic-induced ground vibrations that are broadband, typically between 10 and 100 Hz. Broadband sources of ground vibrations can be modelled using measurements with several pairs of ultrasonic transducers having different central frequencies. Another possible solution is using a single pair of ultrasonic transducers working in a non-resonant regime, i.e. when the frequencies of interest are much less than the resonant frequencies of piezoelectric plates in the transducers. In the latter case though the efficiency of generation and reception of Rayleigh waves is significantly reduced.

Considering the specific measurements on a number of Aluminium samples modelling the three types of seismic barriers with different geometrical parameters considered in this paper, it can be concluded that periodic combinations of open trenches provide the most efficient suppression of transmitted Rayleigh waves. This is followed by periodic arrays of vertical holes. And the least efficient are statistically rough surfaces.

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References


