ISSN 1063-7710, Acoustical Physics, 2011, Vol. 57, No. 3, pp. 420–426. © Pleiades Publishing, Ltd., 2011.

ACOUSTIC SIGNAL PROCESSING AND COMPUTER SIMULATION

Seismic Waves and Seismic Barriers[1]

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Received October 10, 2010

Abstract—The basic idea of seismic barrier is to protect an area occupied by a building or a group of buildings from seismic waves. Depending on nature of seismic waves that are most probable in a specific region, different kinds of seismic barriers are suggested. For example, vertical barriers resembling a wall in a soil can protect from Rayleigh and bulk waves. The FEM simulation reveals that to be effective, such a barrier should be (i) composed of layers with contrast physical properties allowing "trapping" of the wave energy inside some of the layers, and (ii) depth of the barrier should be comparable or greater than the considered seismic wave length. Another type of seismic barrier represents a relatively thin surface layer that prevents some types of surface seismic waves from propagating. The ideas for these barriers are based on one Chadwick's result concerning non-propagation condition for Rayleigh waves in a clamped half-space, and Love's theorem that describes condition of non-existence for Love waves. The numerical simulations reveal that to be effective the length of the horizontal barriers should be comparable to the typical wavelength.

DOI: 10.1134/S1063771011030109

INTRODUCTION

Methods of Seismic Protection

Generally, current approaches for preventing failure of structures due to seismic activity can be divided into two groups: (i) approaches for creating seismically stable structures and joints; this group contains different methods ensuring either active or passive protection; and (ii) approaches for creating a kind of seismic barrier preventing seismic waves from transmitting wave energy into a protected region.

While the first group includes a lot of different engineering approaches and solutions, the second one contains very few studies; see Takahashi et al. (2001) and more recent works by Motamed et al. (2008), Kusakabe et al. (2008). The proposed research belongs to the second group.

Possible Types of Wave Barriers

The considered seismic barriers can be of two types: vertical, aimed to reflect, trap, and dissipate most of the seismic wave energy; and horizontal, based on Chadwick and Smith (1977) and Love (1911) theorems, and aimed to prevent certain types of seismic waves from propagation; see, Fig. 1a.

Yet another interesting approach is to create a "rough" surface of the half-space to force the propagating Rayleigh wave scatter by caves and swellings; see Fig. 1b, where part of a free surface with the sinusoidal roughness is pictured. In this respect, the rough surface apparently transforms the elastic half-space into viscoelastic one. To be effective, periodic imperfections should have magnitude and period comparable to the magnitude and wavelength of propagating Rayleigh wave (Sobczyk 1966, Maradudin & Mills 1976, Maradudin & Shen 1980).

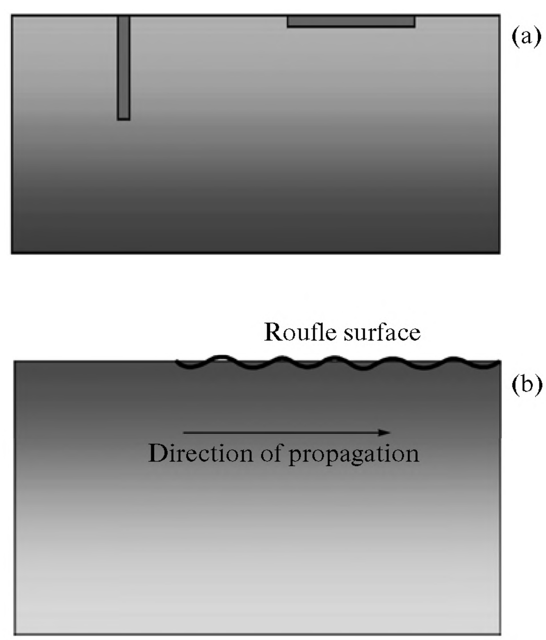

Fig. 1. (a) Vertical and horizontal seismic barriers. (b) Rough surface acting as seismic barrier against Rayleigh waves.

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In practice, such a rough surface can be achieved by a series of rather deep trenches oriented transversally to the most probable direction of the wave front. Some of obvious deficiencies of this method are: (i) its inability to persist the surface waves other than Rayleigh waves; (ii) protection from Rayleigh waves travelling only in directions that are almost orthogonal to orientation of the trenches; and (iii) high sensitivity to the frequency of travelling Rayleigh waves. These shortcomings made an idea of exploiting a rough surface as a kind of protective barrier, unrealizable.

Vertical Barriers

For bulk waves the most effective vertical barrier would be an empty trench, or a trench filled in with a lighter material than the ambient soil. For such a barrier most of the wave energy would be reflected, as is shown on Fig. 2a. However, propagating Rayleigh or Love wave will simply overflow an empty trench, as Fig. 2b shows. Thus, to be effective against the most dangerous types of seismic Rayleigh and Love waves, the vertical barrier should be of a more elaborate type. Possible structures of vertical barriers will be discussed later on.

Horizontal Barriers

Horizontal barriers can be constructed by modifying properties of the outer layer preventing the corresponding surface wave from propagation.

In practice, modifying physical properties of the outer layer can be achieved by reinforcing ground with piles or "soil nails"; see papers where reinforcing was studied for increasing bearing load of the soil (Blondeau 1989, De Buhan et al. 1989, Abu-Hejleh et al. 2002, Eiksund 2004, Herle 2006).

If distance between piles is sufficiently smaller than the wave length, then a reinforced region can be considered as macroscopically homogeneous and either transversely isotropic or orthotropic depending on arrangement of piles. Of course, homogenized physical properties of the reinforced medium depend upon material of piles, distance between them, and their arrangements.

For stochastically homogeneous arrangement of piles and the initially isotropic upper soil layer, the reinforced soil layer becomes transversely isotropic with the homogenized (effective) characteristics that can be evaluated by different methods:

Voigt homogenization yields the upper bound for effective characteristics (Bensoussan, Lions, Papanicolaou 1978):

$$\mathbf{C}_{\text{effective}} = (1-f)\mathbf{C}_{\text{soil}} + f\mathbf{C}_{\text{piles}}, \quad (1)$$

where $\mathbf{C}_*$ are the corresponding elasticity tensors and f is the average volume fraction of piles.

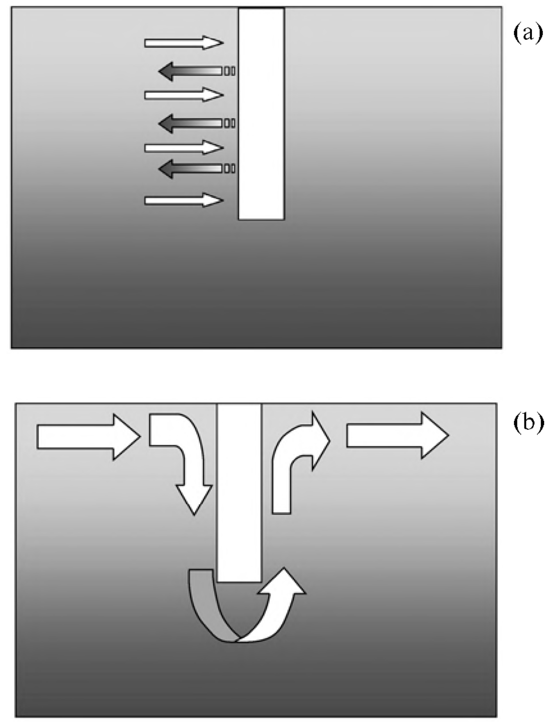

Fig. 2. (a) Full reflection of an incident bulk wave from an empty trench. (b) Flow of Rayleigh wave around an empty trench.

Reuss homogenization. This method is related to constructing the homogenized inverse tensors:

$$\mathbf{S}_{\text{effective}} = (1-f)\mathbf{S}_{\text{soil}} + f\mathbf{S}_{\text{piles}} \quad (2)$$

yields the lower bound, where $\mathbf{S}_*$ are the corresponding compliance tensors. In the case of pile reinforcement these two methods give too broad "fork" and thus, are not reliable.

Two-scale asymptotic expansion method. Much more accurate results give the two-scale asymptotic expansion method (Bensoussan, Lions, Papanicolaou 1978, Sanchez-Palencia 1983):

$$\mathbf{C}_{\text{effective}} = (1-f)\mathbf{C}_{\text{soil}} + f\mathbf{C}_{\text{piles}} + \mathbf{K}, \quad (3)$$

where $\mathbf{K}$ is the corrector that is defined by solving the special boundary value problem for a typical periodical cell. It is interesting to note that taking the corrector $\mathbf{K}$ in Eq. (3) as the null tensor we arrive at Voigt homogenization (1).

Methods for constructing the corrector within the two-scale asymptotic expansion methods are discussed by Michel, Moulinec, and Suquet (1999), Cecchi and Rizzi (2001).

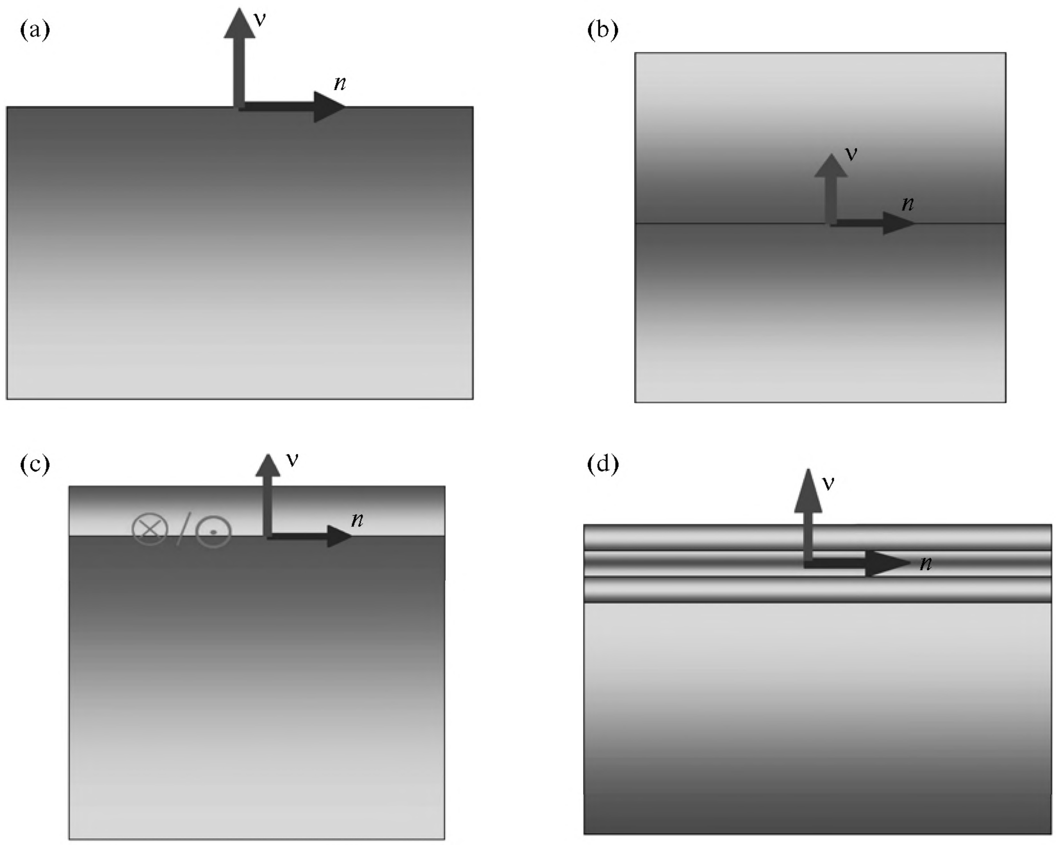

Fig. 3. (a) Rayleigh wave in a half-space. (b) Stoneley wave on the interface between two contacting half-spaces. (c) Love wave propagating on the interface. (d) Rayleigh-Lamb waves.

THE MAIN TYPES OF SURFACE ACOUSTIC WAVES

In this section we proceed to analyzes of the main types of seismic surface waves and conditions for their non-existence.

Rayleigh Waves

These waves discovered by Lord Rayleigh (Strutt 1885) propagate on a plane surface of a halfspace; see, Fig. 3a and exponentially attenuate with depth. These waves transmit the most seismic energy and lead to most severe damage in earthquakes.

One interesting problem associated with Rayleigh waves is a problem of "forbidden" directions of "forbidden" (necessary anisotropic) materials that does not transmit a Rayleigh wave along some directions. Forbidden materials and forbidden directions have been intensively searched both experimentally and numerically (Lim & Farnell 1968, 1969, Farnell 1970) until mid seventies when the theorem of existence for Rayleigh waves was rigorously proved (Barnett & Lothe 1973, 1974a,b, Lothe & Barnett 1976, Chadwick & Smith 1977, Chadwick & Jarvis 1979, Chadwick & Ting 1987). This theorem states that no materials possessing forbidden directions for Rayleigh waves can exist.

Despite proof of the theorem of existence, a small chance for existence of forbidden materials remained. This corresponded to the case of non-semisimple degeneracy of a special matrix associated with the first-order equation of motion; actually, this matrix is the Jacobian for the Hamiltonian formalism used for Rayleigh wave description. However, it was shown (Kuznetsov 2003) that even at the non-semisimple degeneracy a wave resembling the genuine Rayleigh wave can propagate. Thus, for waves propagating on a homogeneous half-space, no forbidden materials or directions can exist.

Stoneley Waves

These are waves were introduced by Stoneley (1924), and analyzed by (Sezawa & Kanai 1939, Cagniard 1939, Scholte 1947). Stoneley waves propagate on an interface between two contacting half-spaces, Fig. 3b.

In contrast to Rayleigh waves, Stoneley waves can propagate only if material constants of the contacting half-spaces satisfy special (very restrictive) conditions of existence. These conditions were studied by Chadwick & Borejko (1994), Sengupta & Nath (2001).

It should be noted that for the arbitrary anisotropy no *closed analytical* relations between material constants of the contacting half-spaces ensuring existence or non-existence of Stoneley waves have been found (2010).

Love and SH Waves

Love waves (Love, 1911) are horizontally polarized shear waves that propagate on the interface between an elastic layer contacting with elastic half-space; Fig. 3c. At the outer surface of the layer traction-free boundary conditions are generally considered.

In the case of both *isotropic* layer and half-space the conditions of existence derived by Love are:

$$c^S_{\text{layer}} < c^S_{\text{halfspace}}, \tag{4}$$

where c^S_* are the corresponding speeds of the transverse bulk waves. At violating condition (4) no Love wave can propagate. For the case of both anisotropic (monoclinic) layer and a half-space the condition of existence is also known (Kuznetsov 2006a).

SH waves resemble Love waves in polarization, but differ in absence of the contacting half-space. At the outer surfaces of the layered plate different boundary conditions can be formulated (Kuznetsov 2006b). In contrast to genuine Love waves, the SH waves exist at any combination of elastic properties of the contacting layers.

Besides Love and SH waves a combination of them can also be considered. This corresponds to a horizontally polarized wave propagating in a layered system consisting of multiple layers contacting with a half-space. Analysis of conditions of propagation for such a system can be done by applying either transfer matrix method (Thomson 1950, Haskell 1953), known also as the Thomson–Haskell method due to its originators; or the global matrix method mainly developed by Knopoff (1964).

At present (2010) no closed analytical conditions of existence for the combined Love and SH waves propagating in anisotropic multilayered systems are known; however, these conditions can be obtained numerically by applying transfer or global matrix methods; see (Kuznetsov 2006a,b; Djeran-Maigre & Kuznetsov 2008).

Different observations show that genuine Love and the combined Love-SH waves along with Rayleigh and Rayleigh–Lamb waves play the most important role in transforming seismic energy in earthquakes (e.g., Agnew 2002, Braitenberg & Zadro 2007). But, as we have seen, there is a relatively simple (at least from a theoretical point of view) method for stopping Love and the combined Love and SH waves by modifying the outer layer in such a way that conditions of existence (4) are violated.

Lamb and Rayleigh–Lamb Waves

Lamb waves (Lamb, 1917) are dispersive waves propagating in a homogeneous plate and (if a plate is isotropic) polarized in the saggital plane, similarly to polarization of the genuine Rayleigh waves; see also Victorov (1967). It is known (Lin & Keer 1992, Ting 1996) that Lamb waves can propagate at any anisotropy of the layer and at traction-free, clamped, or mixed boundary conditions imposed on the outer surfaces of the plate. The same result can be extrapolated to a layered plate containing multiple anisotropic homogeneous layers in a contact (Ting 2002). Thus, for Lamb waves no forbidden materials exist.

More interesting from seismological point of view are Rayleigh–Lamb waves; see Fig. 3d. These are dispersive waves propagating in a layered plate contacting with a (homogeneous) halfspace. Rayleigh–Lamb waves in isotropic media are polarized in the saggital plane defined by vectors **ν** (normal to a median plane) and **n** (direction of propagation), as Lamb and Rayleigh waves. Needless to say that Rayleigh–Lamb waves are much more difficult for theoretical studies than Rayleigh or Lamb waves.

SEISMIC BARRIERS

Herein, we present some results on numerical simulation of propagating seismic waves and their interaction with seismic barriers. The presented results were obtained by the explicit FE code implemented on a cluster and metacluster computers.

Vertical Barriers

Theoretical analysis and numerical simulations reveal that to effectively protect from Rayleigh and Rayleigh–Lamb waves a vertical barrier (Fig. 1) should satisfy several conditions: (i) the barrier should have a composite layered structure composed of vertical layers with contrast physical properties; (ii) depth of the barrier should be comparable to the wavelength of the most probable seismic wave; (iii) the protected zone should be completely surrounded by a barrier to avoid flowing of the seismic wave inside the protected zone.

Henceforth, all the numerical simulations are done with Abaqus/Explicit® CAE software.

Figure 4 demonstrates a movie frame related to numerical simulation of a propagating seismic Rayleigh wave interacting with a round-shaped vertical barrier; the latter completely surrounds the protected region. The ratio of the wavelength to depth of the barrier was taken ~ 0.8. This corresponded to the reference frequency about 7 Hz and the Rayleigh wavelength 20 m (speed of Rayleigh wave was set as 140 m/s; speed of the transverse bulk wave was

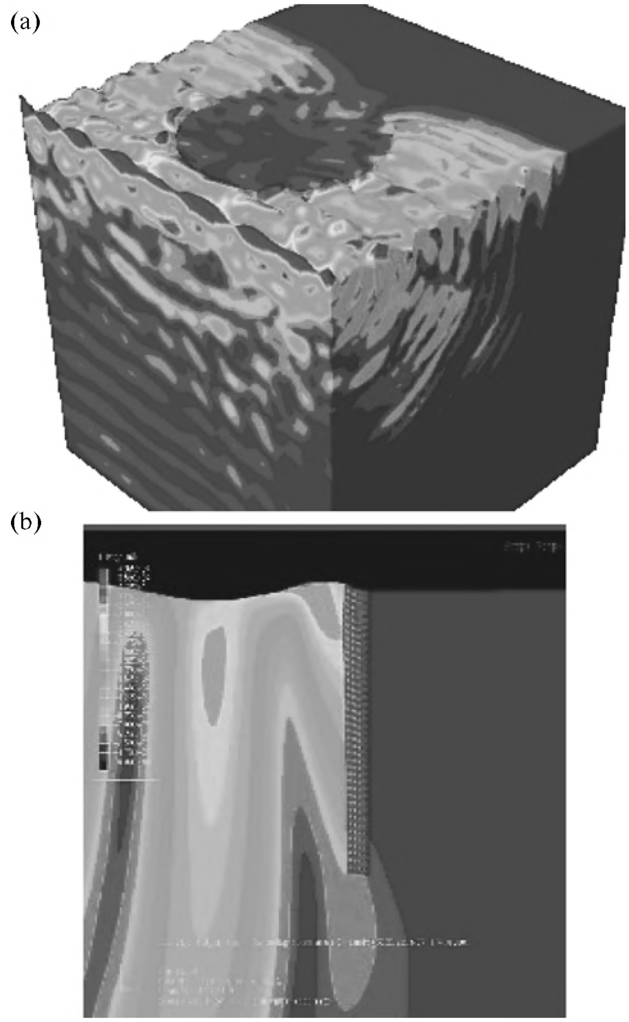

Fig. 4. Round-shaped composite vertical barrier protecting from Rayleigh waves: (a) 3D model; (b) cross-section.

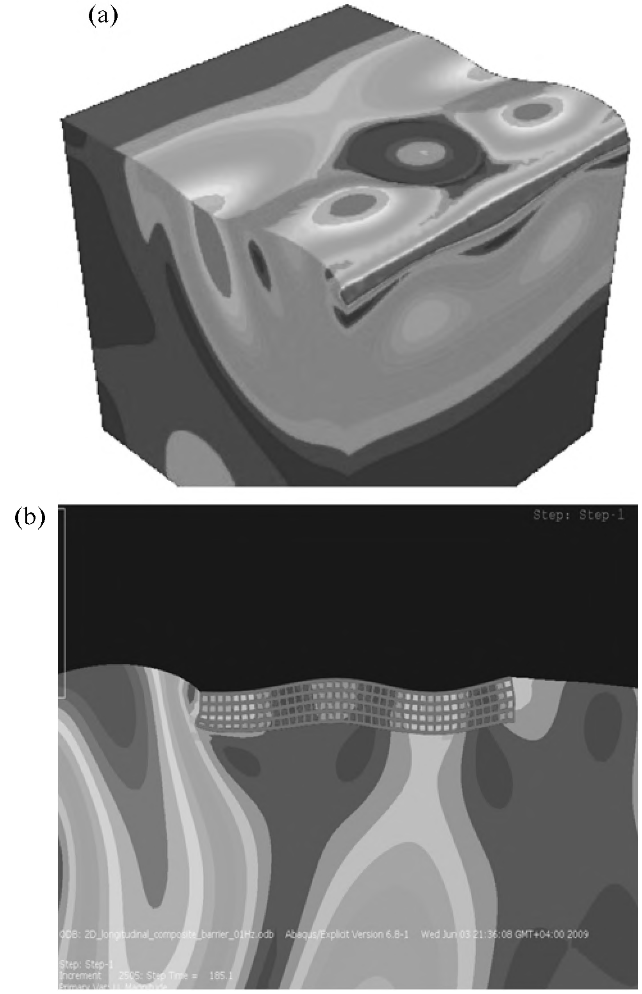

Fig. 5. 3D model of the horizontal round-shaped barrier interacting with a long Rayleigh wave: (a) 3D model; (b) cross-section near the barrier.

~180 m/s); diameter of the protected region was 120 m. Inside the protected region reduction of the magnitude of displacements was more than ten times comparing to the outside territory.

Transverse (Horizontal) Barriers

Our analyses revealed that similarly to vertical barriers, the transverse barriers should satisfy several conditions to effectively protect from seismic waves: (i) length (horizontal) of the barrier should be comparable to the wavelength; (ii) material of the barrier should have larger density than the ambient soil for Rayleigh waves; that is in agreement with Chadwick's theorem stating that at the clamped surface of a halfspace, no Rayleigh wave can propagate; (iii) material of the barrier should satisfy the opposite Love's propagating condition (4) for protecting from propagating seismic Love waves.

Figure 5 demonstrates a movie frame related to numerical simulation of a propagating seismic Rayleigh wave having a long wavelength and interacting with a round-shaped transverse (horizontal) barrier; the latter completely surrounds the protected region. The ratio of the wavelength to length of the barrier was taken one and a half. Inside the protected region reduction of the magnitude of displacements was about three times comparing to magnitude of displacements at the outside territory.

CONCLUDING REMARKS

Herein, a brief outline of future research directions related to creating more efficient seismic barriers is given. A practically important case, when seismic barriers appear to be indispensable, is discussed in the last subsection.

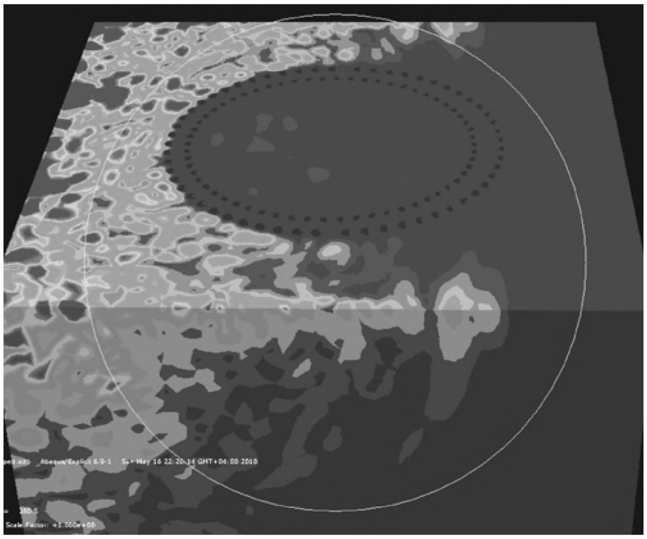

Fig. 6. A ring-shaped double pile field used to scatter seismic wave energy.

Setting up an Optimization Problem

To make search of the optimal geometric and physical properties of the protecting barriers more systematic, solution of the following optimizing problem can be suggested. Mathematically the optimization problem for minimizing magnitudes of deflections can be written as finding minimum of the following target function F:

$$\min_{\mathbf{C}_1,\,\rho_1,\,l_1,\,h_1} (F(\mathbf{C}_1;\,\rho_1;\,l_1;\,h_1) \equiv (\max_{\omega\in\Omega}\max_{x\in D}[s(\omega)m(x,\omega)])), \quad (5)$$

where $\mathbf{C}_1$, ρ_1, and h_1, l_1 are the elasticity tensor, density, depth, and length of the barrier (in the case of isotropic material, Lamé constants can be used instead of the elasticity tensor), ω is the angular frequency, Ω is a spectral set, $s(\omega)$ is the corresponding spectral density, D denotes the protected zone, and m is the magnitude of deflections in the protected zone. This problem resembles one that is usually solved at finding optimal parameters of shock absorbers (Den Hartog 1985, Balandin et al. 2000, 2008).

A Barrier Utilizing Concept of Scattering Seismic Wave Energy

That is another type of seismic barriers. From technological point of view, such a barrier can be even simpler and possibly cheaper to create than vertical or horizontal barriers. To demonstrate this concept, consider a ring-shaped pile field as shown on Fig. 6.

While interacting with seismic waves each pile acts as a scatter obstacle.

Arrangement, material, and profile of the piles can be obtained by an optimization procedure that is similar to one outlined in the previous subsection.

Where Seismic Barriers Can Be Most Efficient?

Simple observations reveal that different types of seismic barriers can be most efficient at soft soils especially subjected to liquefaction, when more traditional seismic protection measures can be inadequate. Indeed, by diminishing amplitude of seismic waves inside the protected zone, the considered barriers should improve stability of liquefied soils.

However, for such soils a more complicated analysis of traveling waves involving Biot's theory of poroelasticity can be needed; see Detournay E. & Cheng (1993). It should also be mentioned that according to the genuine Biot's theory all governing equations are linear, that ensures validity of the harmonic wave approach.

ACKNOWLEDGMENTS

The author thanks Russian Foundation for Fundamental Research (Grant 09-01-12063-ofi) for partial financial support.

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