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AN IBEM-FEM MODEL OF MULTIPLE SURFACE WALLS FOR GROUND VIBRATION ATTENUATION

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Abstract. *Surface walls have been presented as an effective strategy to attenuate ground vibration and protect vibration-sensitive facilities. This attenuation is based on properties of the walls as locally-resonant bodies, the attenuation effectiveness of which is maximized at their natural bending and compression frequencies. This paper presents a numerical analysis of the effectiveness of a series of surface walls in attenuating ground vibration and modifying wave propagation in the soil. The model uses a classical Finite Element Method (FEM) formulation to represent the surface walls, coupled with Indirect Boundary Element Method (IBEM) formulation to accurately represent the soil as an unbounded, wave-propagating medium. Seismic excitation is represented by Rayleigh waves propagating along the surface of the soil. The results show that the spacing between the walls and the number of walls significantly influence the attenuation of ground vibrations induced by Rayleigh waves.*

Keywords: *Soil-structure interaction, Ground vibration, Coupled methods, Vibration attenuation.*

1. INTRODUCTION

Ground vibration control has gained significant attention in recent years due to the increasing demand for protecting vibration-sensitive structures, such as laboratories, data centers, and high-precision manufacturing facilities. These vibrations, often generated by construction activities, rail transit systems, blasting or industrial machinery, can propagate through the soil and negatively impact the performance or integrity of nearby structures. Among the passive mitigation techniques available, the use of heavy surface bodies has shown promising results in attenuating wave energy and modifying the propagation characteristics of surface waves (Carneiro *et al.*, 2022; Wang *et al.*, 2024).

Numerous studies have focused on developing effective countermeasures for ground-borne vibrations. Schevenels *et al.* (2017) investigated the use of double wall barriers to reduce ground vibrations caused mainly by railway traffic. Using advanced numerical modeling (a 2.5D finite element methodology), the authors compare the effectiveness of jet-grout and concrete wall barriers in homogeneous soil by simulating the soil's response to point loads and passing trains. Pu and Shi (2020) presented a numerical investigation of surface wave attenuation—particularly Rayleigh waves—using periodic trench barriers filled with geofoam. A complex band structure approach with Bloch–Floquet conditions is employed to capture both propagating and evanescent wave modes in damped elastic media. A finite element model is developed and validated against existing results.

In particular, (Carneiro *et al.*, 2022) investigated the performance of surface walls in attenuating ground vibration generated by Rayleigh waves and by applied harmonic forces, and concluded that gabion and concrete walls can provide dramatic ground vibration attenuation in many cases. The performance of the walls is strongly tied to their vibration modes and natural frequencies. An additional phenomenon is involved, related to the conversion of Rayleigh (surface) waves into body (primary and secondary) waves, that are dissipated into the bulk of the soil. The study by Carneiro *et al.* (2022), however, is limited to the case of a single surface wall.

Gabion walls have become a widely adopted and environmentally friendly solution for retaining structures in civil engineering. These systems consist of stones confined within galvanized wire mesh baskets, which are connected using wire hooks and bends. Among their main advantages are their natural aesthetic, compatibility with landscape integration, and the ability to support vegetation growth. Additionally, this type of structure has potential applications in mitigating ground-borne vibrations. Carneiro *et al.* (2023) have shown that gabion walls can reduce ground motion caused by railway traffic by up to 99%, particularly near their natural frequencies. While wall height strongly influences attenuation performance, wall width has a comparatively minor effect.

This paper investigates the dynamic behavior of a series of surface gabion wall systems and their interaction with Rayleigh surface waves. The purpose of the study is to understand whether the inclusion of multiple walls improves the performance of these surface bodies in attenuating ground vibration. A coupled numerical framework is employed, combining the Finite Element Method (FEM) to model the structural components with the Indirect Boundary Element Method (IBEM) to represent the unbounded soil domain. The study focuses on evaluating the influence of the number of walls and their spacing on the overall ground attenuation performance, aiming to explore the potential of such systems as practical implementations for vibration mitigation.

1.1 Problem Statement

Consider a system of n infinitely long, linear-elastic walls with width L and height H, separated from each other by a distance a center-to-center, all fully bonded to the surface of a homogeneous, isotropic, linear-elastic half-space representing the soil (Fig. 1). The problem is formulated as a 2D plane strain problem in the x–z plane. The origin of the coordinate system is placed in the midpoint of the bottom of the leftmost wall. The system is subjected to time-harmonic plane Rayleigh wave excitation at frequency ω. Displacements of a point P of coordinates $x = d, z = 0$ are computed in the horizontal and vertical directions ($x-$ and $z-$directions, respectively). The problem consists in determining the effect of the walls in the magnitude of the vibration of P.

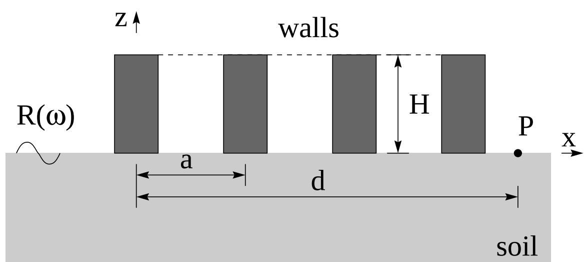


Figure 1: Model of a series of surface walls under the effect of Rayleigh wave excitation.

2. FORMULATION

To model the interaction between the surface walls and the underlying soil, this paper employs a coupled Indirect Boundary Element–Finite Element Method (IBEM-FEM) approach. The walls, considered a linear-elastic structure, are modeled using quadrilateral, four-noded finite elements, each with two degrees of freedom per node. The governing equation in the frequency domain for the finite element model is $\overline{\mathbf{K}}\mathbf{u} = \mathbf{f} - \mathbf{f}_\mathrm{s}$, where $\mathbf{u}$ and $\mathbf{f}$ denote the nodal displacements and forces acting on the wall–soil interface, and $\mathbf{f}_\mathrm{s}$ are the contact forces exerted by the soil. The dynamic stiffness matrix of the walls is given by $\overline{\mathbf{K}} = \mathbf{K} - \omega^2\mathbf{M}$, in which $\mathbf{K}$ and $\mathbf{M}$ are the global stiffness and mass matrices, respectively.

The soil domain is treated as a semi-infinite medium, for which a boundary element discretization is more suitable. Its interface with the walls is divided into constant boundary elements, each associated with horizontal and vertical displacements calculated via influence functions for a 2D elastic half-space (Rajapakse and Wang, 1991).

The interaction between walls and soil is enforced through continuity conditions $\mathbf{D}\mathbf{u} - \mathbf{u}_\mathrm{s} = \mathbf{0}$ and equilibrium conditions $\mathbf{f}_\mathrm{s} - \mathbf{A}\mathbf{t}_\mathrm{s} = \mathbf{0}$ at their interface, in which $\mathbf{u}_\mathrm{s}$ and $\mathbf{t}_\mathrm{s}$ are the displacements and tractions on the soil side, respectively, and matrices $\mathbf{A}$ and $\mathbf{D}$ map boundary element node quantities to the finite element nodes with which they are in contact. An expression for transformation matrices $\mathbf{A}$ and $\mathbf{D}$ is given by Carneiro *et al.* (2022). Substituting these conditions into the equation of motion of the walls–soil system resuts in $\overline{\mathbf{K}}\mathbf{u} + \mathbf{A}\mathbf{t}_\mathrm{s} = \mathbf{f}$.

In this problem, excitation is given by Rayleigh waves, so that $\mathbf{f} = \mathbf{0}$. The excitation from Rayleigh waves can be written as $\mathbf{u}_\mathrm{s} = \mathbf{u}_\mathrm{s}^\mathrm{i} + \mathbf{u}_\mathrm{s}^\mathrm{sc}$, in which $\mathbf{u}_\mathrm{s}^\mathrm{i}$ and $\mathbf{u}_\mathrm{s}^\mathrm{sc}$ are the incident and scattered wave fields, respectively. The scattered field is computed as $\mathbf{u}_\mathrm{s}^\mathrm{sc} = \mathbf{U}\mathbf{t}_\mathrm{s}$, in which $\mathbf{U}$ represents the influence matrix for the elastic half-space (Rajapakse and Wang, 1991). The continuity condition can be written for the Rayleigh wave excitation as $\mathbf{D}\mathbf{u} - \mathbf{U}\mathbf{t}_\mathrm{s} = \mathbf{u}_\mathrm{s}^\mathrm{i}$, from which comes the equation of motion for the walls-soil system:

$$\begin{bmatrix} \overline{\mathbf{K}} & \mathbf{A} \\ \mathbf{D} & -\mathbf{U} \end{bmatrix} \begin{Bmatrix} \mathbf{u} \\ \mathbf{t}_\mathrm{s} \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \mathbf{u}_\mathrm{s}^\mathrm{i} \end{Bmatrix}. \quad (1)$$

Solving this system yields both the wall displacements $\mathbf{u}$ and the tractions $\mathbf{t}_\mathrm{s}$, from which the scattered field $\mathbf{u}_\mathrm{s}^\mathrm{sc}$ and total soil response $\mathbf{u}_\mathrm{s}$ can be derived.

The formulation summarized in this is paper has been presented in detail by Carneiro *et al.* (2022).

3. NUMERICAL RESULTS

The results in this section consider a system of n identical walls on the soil surface. Each wall has height $H = 2$m, width $L = 1$m, Young's modulus of $E = 367$ MPa, Poisson's ratio $\nu = 0.2$, and mass density $\rho = 1700\mathrm{kg/m^3}$. The supporting soil has material properties $E = 361$MPa, $\nu = 0.485$, and $\rho = 1945\mathrm{kg/m^3}$.

The vibration attenuation performance of the system of walls is measured in terms of the insertion loss $\mathrm{IL}_{i\mathrm{R}} = 20\log_{10}(u_i^0/u_i)$, in which u_i^0 and u_i are the magnitude of soil motion in the $i-$direction ($i = x, z$) without and with the presence of the walls, respectively, such that $\mathrm{IL} > 0$ indicates that installing the walls on the soil results in vibration attenuation.

Figure 2 shows the vertical and horizontal insertion loss measured at a point P that is $x = 30$m from the first wall. This case considers various numbers of walls, all spaced $a = 3$m from each other. Although vibration attenuation is promoted in some cases, these results show that increasing the number of walls result in negative insertion loss for most of the frequency spectrum, indicating that including more walls has a negative effect in the vibration attenuation performance of the system. These results seem to contradict classical assumptions that including more walls (more mass) on the soil surface would improve vibration attenuation (Krylov, 2007).

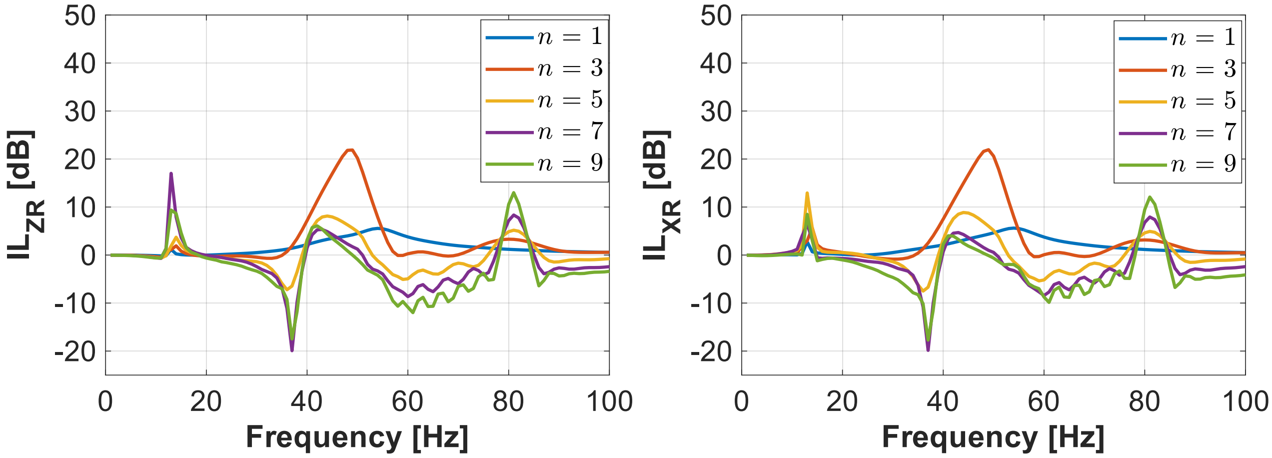
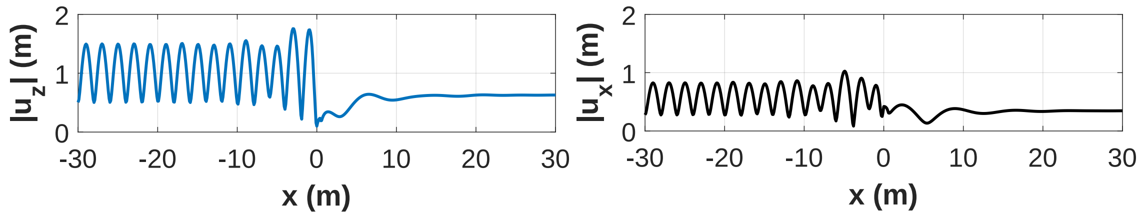


Figure 2: Insertion loss for the wall–soil system with n walls spaced by $a = 3$m at the measurement point $x = 30$m in the (a) vertical and (b) horizontal directions.

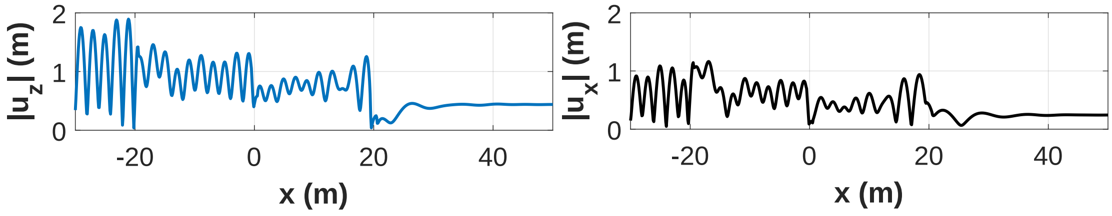
This apparent contradiction can be explained by analyzing the type of waves that each wall in the sequence is subject to. Because of the conversion of Rayleigh waves into body waves by the first (leftmost) wall, each subsequent wall is subject to a combination of surface and body waves, which makes the vibration attenuation performance of each wall unpredictable. However, because body waves are quickly attenuated in the bulk of the soil, when the walls are far enough apart the body waves scattered by each wall are dissipated, and each wall is subject only to surface waves.

Figures 3–5 are aimed at investigating how far apart each wall must be from each other in order for each wall to be subject to only surface waves. These results show the magnitude of the vertical and horizontal components of the total (incident + scattered) waves along the soil surface, for a given frequency of excitation. Pure Rayleigh waves in these results correspont to the case in which $|u_i|$ is invariant with x. Figure 3, which considers a wall installed at $x = 0$, shows that about 20m behind (right of) the wall, only Rayleigh waves remain. Figure 4 shows the case in which a second wall has been installed at $x = 20$m, and it shows that only Rayleigh waves remain 20m behind the second wall. Finally, Fig. 5 shows the case in which a third wall has been installed at $x = 40$m, and it shows that once again only Rayleigh waves remain 20m behind the third wall. This shows that installing the walls at $a = 20$m from each other causes each wall in the sytem to be subject to only Rayleigh waves.



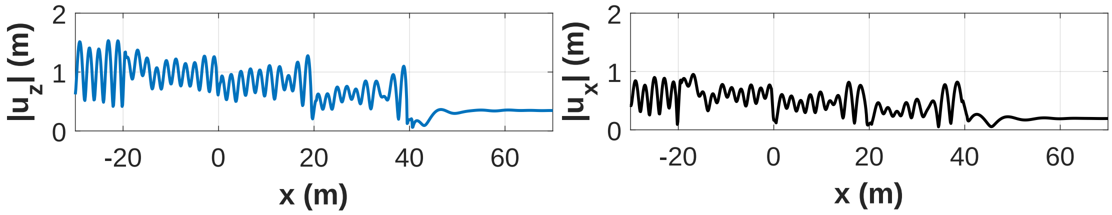
(a) (b)

Figure 3: Amplitude of the vertical and horizontal displacement of the surface of the soil for the system with $n = 1$ wall.



(a) (b)

Figure 4: Amplitude of the vertical and horizontal displacement of the surface of the soil for the system with $n = 2$ walls.



(a) (b)

Figure 5: Amplitude of the vertical and horizontal displacement of the surface of the soil for the system with $n = 3$ walls.

Figure 6 shows the vertical and horizontal insertion loss for systems with $n = 1 - 3$ walls that are $a = 20$m apart, with the measurement point located at $x = 60$m. These results show predominantly positive IL values across the entire frequency range analyzed, indicating effective attenuation of surface vibrations. However, including more walls does not result in improved attenuation performance for all frenquecies of excitation.

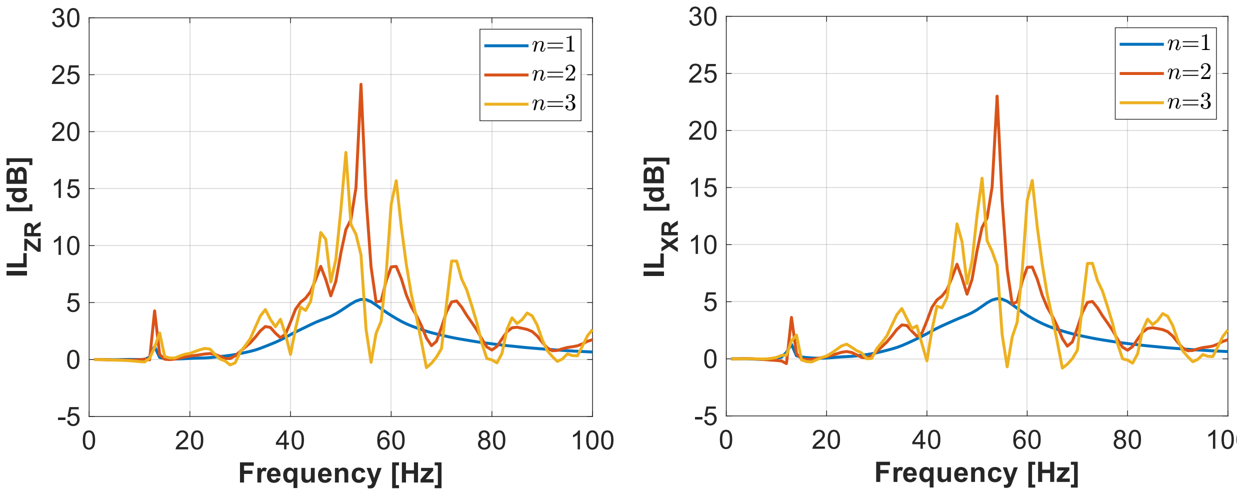


Figure 6: Insertion loss for the wall-soil system at the measurement point $x = 60\ m$ in the (a) vertical and (b) horizontal directions.

4. CONCLUDING REMARKS

This study explored the use of an array of surface walls for the attenuation of ground vibrations induced by Rayleigh waves. A coupled IBEM–FEM formulation was employed to accurately model the interaction between the elastic structures and the semi-infinite soil domain.

Numerical results showed that the attenuation performance of the wall system is strongly dependent on the spacing between walls. While closely spaced walls can lead to complex wave interactions and even vibration amplification in certain frequency bands, increasing the spacing enables each wall to interact predominantly with Rayleigh waves, resulting in more predictable and generally positive attenuation effects.

Although adding more walls does not guarantee improved performance across all frequencies, the results indicate that careful geometric configuration can enhance vibration mitigation.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Carneiro, D., Barros, P.L. and Labaki, J., 2022. "Ground vibration attenuation performance of surface walls". *Computers and Geotechnics*, Vol. 149, p. 104715.

Carneiro, D., de Almeida Barros, P.L., Marques, L.A. and Labaki, J., 2023. "Gabion walls: an effective solution to ground vibration generated by railway operations". In *Simpósio de Engenharia Ferroviária (6.: 2023: Campinas, SP)*.

Krylov, V.V., 2007. "Control of traffic-induced ground vibrations by placing heavy masses on the ground surface". *Journal of low frequency noise, vibration and active control*, Vol. 26, No. 4, pp. 311–321.

Pu, X. and Shi, Z., 2020. "Broadband surface wave attenuation in periodic trench barriers". *Journal of Sound and Vibration*, Vol. 468, p. 115130.

Rajapakse, R. and Wang, Y., 1991. "Elastodynamic Green's functions of orthotropic halfplane". *Journal of Engineering Mechanics*, Vol. 117, No. 3, pp. 588–604.

Schevenels, M., Lombaert, G. *et al.*, 2017. "Double wall barriers for the reduction of ground vibration transmission". *Soil Dynamics and Earthquake Engineering*, Vol. 97, pp. 1–13.

Wang, Y., Chen, X., Meng, F., Yi, L., Li, T., Xie, K. and Tang, L., 2024. "A novel vibration barrier for low-frequency surface waves in the ground". *Journal of Vibration and Control*, p. 10775463241248290.

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