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Simone dos Santos
Federal University of Piauí

Jenario Souza dos Reis Júnior
Federal University of Piauí

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INFLUENCE OF BURIED FOUNDATIONS ON THE GROUND VIBRATION ATTENUATION PERFORMANCE OF SURFACE WALLS

Jenario dos Santos Reis Junior
Simone dos Santos
Centro de Tecnologia; Federal University of Piauí (UFPI); Av. Universitária, s/n, Teresina PI
jenariojunior4@gmail.com; simone.santos@ufpi.edu.br

Josue Labaki
School of Mechanical Engineering; University of Campinas (Unicamp); 200 Mendeleyev St., Campinas SP
labaki@unicamp.br

Abstract. *This paper investigates the influence of buried foundations on the ground vibration attenuation performance of surface walls. Using a coupled IBEM-FEM model, we analyze the effects of a partially buried wall subjected to surface waves. The results show that embedding the wall alters its vibration attenuation performance by affecting its ability to scatter surface waves into bulk waves. These findings provide valuable insights for designing vibration mitigation solutions in environments where ground vibration is a concern.*

Keywords: *Ground vibration, vibration attenuation, gabion walls, coupled methods*

1. INTRODUCTION

Ground vibration caused by traffic, construction, and other external sources can severely impact the structural integrity of buildings and impair the proper function of some facilities installed in these buildings. In urban environments, where vibration-sensitive structures like hospitals, research laboratories, and residential buildings are common, the need for effective vibration mitigation methods is paramount. Among the various solutions studied, the installation of barriers, such as surface walls, has proven to be a viable approach to attenuating ground vibration (Carneiro *et al.*, 2022; Dijckmans *et al.*, 2015). Previous work has demonstrated that these walls can significantly reduce vibration levels at specific frequencies by interacting with the energy carried by surface waves, transforming a portion of this energy into body waves, and modifying the dynamic response of the surrounding soil.

In our earlier study presented at the International Symposium on Dynamic Problems of Mechanics (Diname 2023), we explored the effectiveness of gabion walls installed on the surface of the soil in mitigating vibration caused by time-harmonic external loads (Carneiro *et al.*, 2023). Gabion walls are structures made from wire mesh cages filled with materials such as rocks or concrete, extensively used for applications like erosion control or retaining walls (Fig. 1).

Figure 1. Our previous paper showed that gabion walls can provide effective ground vibration attenuation.

Using a coupled Indirect Boundary Element Method-Finite Element Method (IBEM-FEM) approach, we modeled the dynamic interaction between the wall, the soil, and a target structure located behind the wall. Our findings indicated that surface walls could significantly attenuate vibrations, particularly at specific excitation frequencies linked to the wall's vibration modes. The ability of the wall to convert surface waves into bulk waves further enhanced its effectiveness as a protective device for nearby structures.

However, several open questions remained regarding the influence of buried foundations on the vibration attenuation performance of these walls. During our interactions with attendees at Diname 2023, the topic of partially buried walls generated considerable interest. While our previous study focused solely on walls resting on the surface, practical applications often require walls to be embedded into the soil to increase their structural stability. Thus, the effect of a buried foundation on the dynamic behavior of the wall and its interaction with the surrounding soil presents an important area for investigation.

In this extended study, we aim to address these questions by examining how the inclusion of a buried foundation impacts the vibration attenuation performance of surface walls. Specifically, we investigate how the foundation modifies the wall's vibration modes and its ability to scatter incoming surface waves into bulk waves. The problem (Fig. 2) consists of a linear-elastic wall of height $H + h$ and witdh L, with Young's modulus E, Poisson ratio ν, and mass density ρ, a portion h of which is embedded in the soil, here modeled as a linear-elastic layer of thickness D with material properties E_s, ν_s, and ρ_s. By modeling the wall–foundation system using an IBEM-FEM scheme, we account for the soil's unbounded nature and radiation conditions, ensuring an accurate representation of wave propagation in the soil. The results, presented in terms of insertion loss, quantify the extent to which the buried foundation affects the wall's vibration attenuation capabilities compared to a surface wall alone.

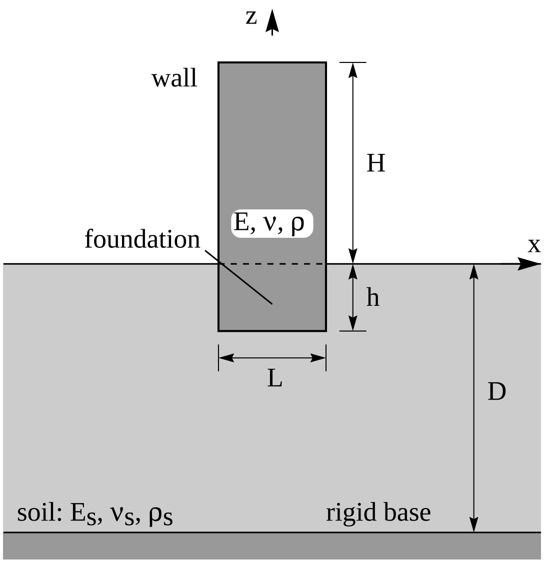

Figure 2. Model and dimensions of partially buried wall.

The significance of this study lies not only in the new insights it provides into the dynamic behavior of partially buried walls but also in its potential to inform the design of effective vibration mitigation solutions for large-scale projects. Engineers and architects can use these findings to optimize the design of walls in environments where ground vibration poses a significant challenge. Additionally, this work contributes to the growing body of knowledge on the use of coupled numerical methods to solve complex soil–structure interaction problems in vibration-sensitive contexts.

2. FORMULATION

In this section, we formulate the problem of ground vibration attenuation using partially buried walls under the framework of a coupled Indirect Boundary Element Method (IBEM) and Finite Element Method (FEM). This coupled method allows for the accurate representation of wave propagation in an unbounded soil medium and the dynamic interaction between the soil and the wall. The wall is modeled using classical finite elements, while the surrounding soil is modeled using boundary elements.

The wall and its foundation are modeled as linear-elastic bodies using a plane strain formulation, which is reasonable considering that the off-plane ($y-$direction) length of the wall is much larger than H and L. The domain is discretized using four-noded isoparametric quadrilateral finite elements (Fig. 3), with two degrees of freedom per node: displacements in the x and z directions. The stiffness matrix for each element is given by $\mathbf{k} = \int_{-1}^{1} \int_{-1}^{1} \mathbf{B}^T \mathbf{C} \mathbf{B} \, det(\mathbf{J}) \, d\xi d\eta$ and

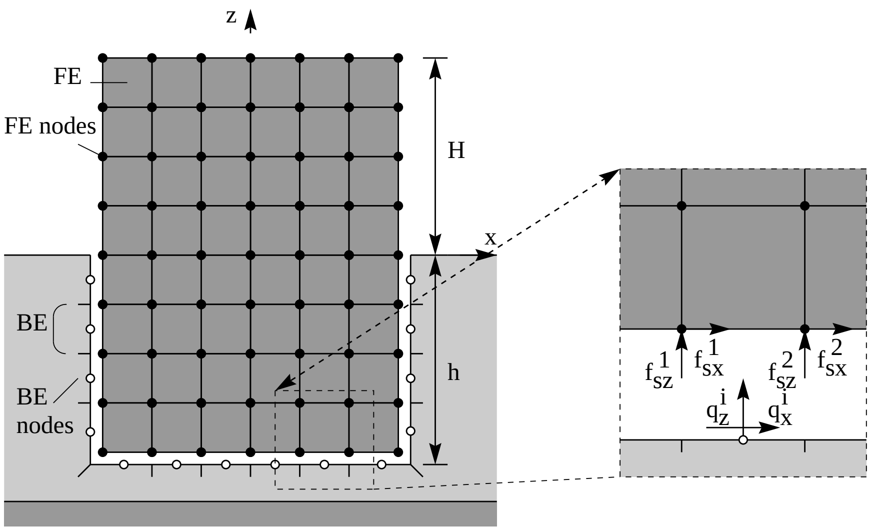

Figure 3. IBEM-FEM coupling scheme to model the partially buried wall.

$\mathbf{m} = \rho \int_{-1}^{1} \int_{-1}^{1} \mathbf{N}^T \mathbf{N}\, d\xi d\eta$, where $\mathbf{B}$ is the strain-displacement matrix, $\mathbf{C}$ is the constitutive matrix for a plane strain case, $\mathbf{N}$ is the shape function vector, and $\mathbf{J}$ is the Jacobian matrix for the transformation from natural (x, z) to parametric (ξ, η) coordinates. The global stiffness matrix for the structure is assembled from the individual element stiffness matrices using the classical finite element assembly procedure. The equation of motion for the wall is written as $\bar{\mathbf{K}} = \mathbf{K} - \omega^2 \mathbf{M}$, where $\mathbf{K}$ and $\mathbf{M}$ are the global stiffness and mass matrices, and ω is the frequency of excitation.

The surrounding soil is modeled as an unbounded, linear-elastic, homogeneous layer over rigid base using the Indirect Boundary Element Method (IBEM). The boundary between the soil and the structure is discretized into constant boundary elements (Fig. 3). The displacements and tractions along the soil boundary are related through fictitious tractions q applied to the boundary elements, expressed as $\mathbf{u}_b = \mathbf{U}\mathbf{q}$ and $\mathbf{t}_b = \mathbf{T}\mathbf{q}$, where $\mathbf{u}_b$ is the vector of displacements at the boundary, $\mathbf{t}_b$ is the vector of tractions at the boundary, and $\mathbf{U}$ and $\mathbf{T}$ are the displacement and traction influence matrices, respectively. These matrices are computed based on influence functions for an elastic soil layer, which are given by improper integrals in the Fourier transformed space. The horizontal ($x-$direction) and vertical ($z-$directoin) displacement components in the soil due to a unit load applied at a boundary element of the wall-soil interface are given by ((Siqueira *et al.*, 2021)):

$$u_x = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \left(\overline{\omega}_1 A e^{-\alpha_1 z} + \overline{\omega}_2 C e^{-\alpha_2 z} \right) e^{i\xi x} d\xi \text{ and} \tag{1}$$

$$u_z = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \left(A e^{-\alpha_1 z} + C e^{-\alpha_2 z} \right) e^{i\xi x} d\xi \tag{2}$$

where A, C, α_1, α_2, and $\overline{\omega}$ are functions derived from the soil properties, and ξ is the wavenumber in the Fourier space. These influence functions allow us to compute the displacements and stresses in the soil for any arbitrary set of loads applied at the boundary.

To ensure equilibrium and continuity at the soil-structure interface, the nodal displacements of the finite elements representing the structure are coupled with the boundary elements representing the soil. The interface condition between the soil and the structure can be written as $\mathbf{u}_b = \mathbf{D}\mathbf{u}_e$, where $\mathbf{u}_b$ is the vector of boundary displacements in the soil, $\mathbf{u}_e$ is the vector of nodal displacements in the wall, and $\mathbf{D}$ is a transformation matrix that relates the finite element displacements to the boundary element displacements (Siqueira *et al.*, 2021). The equilibrium condition at the interface is written as $\mathbf{f}_s = \mathbf{A}\mathbf{q}$, where $\mathbf{f}_s$ is the vector of nodal contact forces in the structure, $\mathbf{q}$ is the vector of fictitious tractions in the soil, and $\mathbf{A}$ is a transformation matrix that distributes the boundary tractions to the finite element nodes (Siqueira *et al.*, 2021). By combining the equilibrium and continuity conditions, the coupled system of equations for the soil-structure interaction is written as

$$\begin{bmatrix} \bar{\mathbf{K}} & \mathbf{A}^T \\ \mathbf{D} & -\mathbf{U} \end{bmatrix} \begin{bmatrix} \mathbf{u}_e \\ \mathbf{q} \end{bmatrix} = \begin{bmatrix} \mathbf{f}_e \\ 0 \end{bmatrix}, \tag{3}$$

where $\mathbf{f}_e$ is the vector of external nodal forces applied to the structure. A detailed derivation of this formulation, including the expression for matrices $\mathbf{A}$ and $\mathbf{D}$, is presented by Siqueira *et al.* (2021). Solving this system of equations yields the displacements in the structure and the tractions in the soil. From these quantities, we can also compute the insertion loss, which quantifies the reduction in ground vibration due to the installation of the wall. The effectiveness of the wall in attenuating ground vibration can be evaluated by calculating the insertion loss at various points of the soil surface. The insertion loss in decibels (dB) at a given point is defined as

$$\mathrm{IL} = 20\log_{10}\left(\frac{|u_{\mathrm{before}}|}{|u_{\mathrm{after}}|}\right) \tag{4}$$

where u_{before} is the displacement at the measurement point before the installation of the wall, and u_{after} is the displacement after the wall has been installed. Positive values of IL indicate vibration attenuation, while negative values indicate amplification.

3. NUMERICAL RESULTS

The results discussed in this section are based on a typical gabion wall system with the following material properties: the wall has height $H = 2$ m, width $L = 1$ m, Young's modulus of $E = 367\,\mathrm{MPa}$, Poisson's ratio of $\nu = 0.2$, and mass density of $\rho = 1,700\,\mathrm{kg/m^3}$. The soil layer is modeled with a Young's modulus of $E_s = 292\,\mathrm{MPa}$, Poisson's ratio $\nu_s = 0.2$, and density $\rho_s = 1,945\,\mathrm{kg/m^3}$. The results were computed at the insertion point ($x = z = 0$), the point in which the wall is installed (Fig. 2).

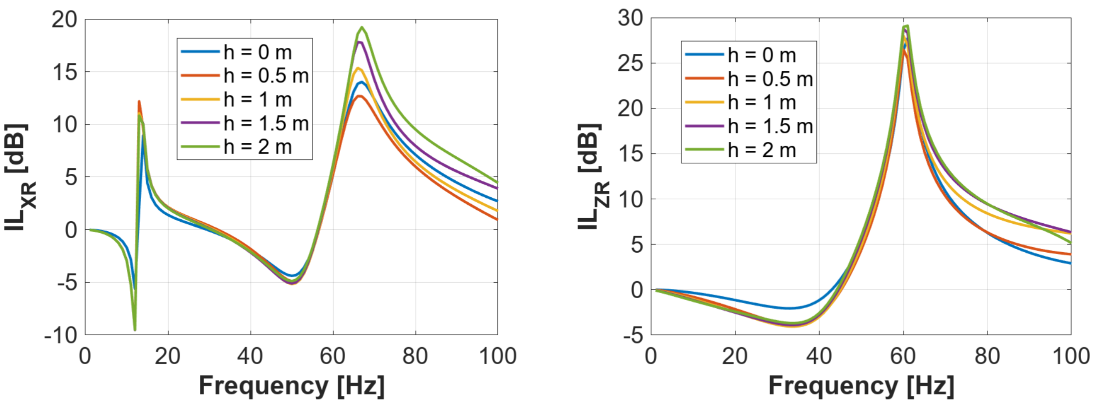

Figure 4. Insertion loss for the wall-soil system at the insertion point in the a) horizontal and b) vertical directions.

Figure 4 show the insertion loss of the partially buried wall at the insertion point across various frequencies of excitation. These results show both the case of horizontal and vertical displacements, considering various depths h for the buried portion of the wall. The blue curve, $h = 0$, correspond to the case in which the wall simply rests on the surface of the soil, with no buried portion. These results match the ones we presented in Diname 2023 in our analysis of the surface wall problem (Carneiro *et al.*, 2023). The peaks of insertion loss observed in these blue curves match the natural frequencies of the 2m-tall body of the wall. In the vertical case, the peak around 60 Hz in Fig. 4b match the first natural frequency of compression of the wall. In the horizontal case, the peak around 65 Hz in Fig. 4a match the first natural frequency of bending of the wall, while the peak around 10 Hz match the natural frequency of rigid body rocking motion of the wall around the $y-$axis. Figure 4 shows that an increase in the foundation depth h has negligible effect in the frequencies at which attenuation is maximum. This indicates that the peak insertion loss continue to match the natural frequencies of the exposed part of the wall (H), rather than the natural frequencies of the entire wall ($H + h$). The buried portion of the wall does have an effect in the attenuation performance of the wall, which is not necessarily positive. For the horizontal case, the inclusion of a foundation has negligible effect in the response of the system for lower frequencies. For frequencies at and above the first natural bending frequency of the wall, including a shallow foundation ($h = 0.5\,\mathrm{m}$) slightly reduces the attenuation performance of the wall. The inclusion of deeper foundations ($h \leq 1\,\mathrm{m}$), generally has a positive effect on the attenuation performance of the wall. For the vertical case, including any foundation generally improves or reduces the attenuation performance of the wall for frequencies above and below the natural compression frequency of the wall, respectively. In general, these results show that the buried portion of the wall affects the insertion loss without changing significantly the frequency at which insertion loss is maximum. This indicates that the main mechanism by which the buried part of the wall contributes to vibration attenuation is the scattering of surface waves into bulk waves by the buried part, rather than the vibration of the buried part at its natural frequencies. This is the opposite of the behavior of the exposed part of the wall.

4. CONCLUDING REMARKS

This paper explored the effect of a buried foundation on the vibration attenuation performance of gabion walls. Our results confirm that adding a buried portion to the wall alters the effectiveness of vibration attenuation of the system.

Including a buried portion to the wall promotes a marginal gain in vibration attenuation performance is some cases, but causes the opposite, indesired effect in others. These findings suggest that in partially buried walls, wave scattering by the foundation plays some role in attenuation, supplementing the attenuation provided by the natural vibration modes of the wall. This study highlights the importance of considering both horizontal and vertical vibrations when designing vibration mitigation solutions with embedded walls.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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