Effect of Soil Type on the Dynamic Impedance of Two Rigid Surface Strip Foundations Resting on a Saturated Porous Layer under Simultaneous Excitation

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ABSTRACT

This paper determines the dynamic impedance of two rigid surface strip foundations resting on a saturated porous layer composed of different soil types and subjected to simultaneous vertical, horizontal, and rocking harmonic motions. The problem is modeled in the frequency domain using the direct boundary element method with full-space fundamental solutions, whereby discretization is confined to the horizontal ground surface and the interface between the saturated layer and the underlying rigid bedrock. First, Biot's poroelastic theory and the governing boundary integral equations are briefly introduced. The resulting formulation is then discretized and implemented step by step in a computational code based on the boundary element method. The numerical procedure is validated by comparing the calculated response of a single strip foundation with results available in the literature. Subsequently, the geometric properties of the model, including the thickness of the saturated layer and the spacing between the two foundations, are held constant to isolate the influence of soil type. The real and imaginary components of the dynamic impedance are determined over a range of dimensionless frequencies for four materials: red clay, coarse-grained sand, sandstone, and soft sediments. Two foundation–soil interface conditions are examined: smooth (frictionless) contact and perfectly bonded (welded) contact. In addition, the normalized pore water pressure at the center of the foundation is evaluated as a function of dimensionless frequency under perfectly bonded contact conditions. The results reveal that soil type strongly affects both the dynamic impedance coefficients and the pore water pressure developed beneath the foundations. In general, fine-grained soils exhibit higher pore pressures and more pronounced resonance peaks. For soft sediments, the maximum pore water pressure occurs within the dimensionless frequency range of 2–3. Under smooth contact conditions, red clay exhibits a peak dynamic stiffness of approximately 23 at a dimensionless frequency of 2.1. Under perfectly bonded contact conditions, the dynamic stiffness of soft sediments at a dimensionless frequency of 2.2 is approximately 500% higher than that of sandstone. These findings underscore the need for thorough subsurface investigations and reliable identification of site-specific soil properties when evaluating dynamic soil–structure interaction.

KEYWORDS

Dynamic Impedance, Soil Type, Saturated Porous Layer, Frequency-Domain Boundary Element Method, Pore Water Pressure.

1. Introduction

Dynamic soil–structure interaction is a fundamental issue in geotechnical engineering, particularly under vibrations induced by machinery, moving trains, and other dynamic sources. Dynamic impedance functions, which describe the relationship between applied forces and foundation displacements, play an essential role in evaluating the vibration response of foundations. Although numerous studies have modeled soil as an elastic or viscoelastic medium, the coupled behavior of solid and fluid phases in saturated porous soils requires more comprehensive consideration. Biot[1, 2] established the theoretical framework for wave propagation in saturated porous media by accounting for solid–fluid interactions and energy dissipation. Subsequently, various analytical and semi-analytical approaches were developed to

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investigate the dynamic response of foundations resting on saturated soils[3-5]. Numerical techniques, particularly the finite element and boundary element methods, have also been extensively employed to evaluate foundation impedance and pore water pressure under different loading and boundary conditions[6-8]. Despite these developments, most previous investigations have focused on isolated foundations or simplified loading conditions, while the influence of soil type on the coupled dynamic response of multiple foundations remains insufficiently explored. Therefore, extending previous studies[9, 10], the present research investigates the effects of soil type on the dynamic impedance of two rigid surface strip foundations resting on a saturated poroelastic layer under simultaneous vertical, horizontal, and rocking harmonic excitations. A developed computational code, DAS-BEM, based on the direct frequency-domain boundary element method with full-space fundamental solutions, is employed. Boundary discretization is restricted to the ground surface beneath and around the foundations and the interface between the saturated layer and rigid bedrock. Four soil types, including red clay, coarse sand, sandstone, and soft sediments, are examined under constant geometric conditions. The real and imaginary impedance components are evaluated for smooth and perfectly bonded contact conditions over a range of dimensionless frequencies. Furthermore, pore water pressure at the foundation center is investigated. The results provide further insight into soil-type-dependent dynamic soil–structure interaction and demonstrate the applicability of the proposed numerical approach.

2. Methodology

As shown in Fig. 1, two massless rigid strip foundations resting on a homogeneous saturated poroelastic layer over rigid bedrock are subjected to simultaneous unit harmonic excitations in the vertical, horizontal, and rocking modes. The dynamic impedance coefficients are determined from the resulting force–displacement relationships. Four soil types with material properties based on Cheng[11] are considered, including red clay, coarse sand, sandstone, and soft sediments. To ensure numerical accuracy, boundary discretization follows the wave propagation criterion of Kuhlemeyer and Lysmer [50]. Accordingly, nodal spacings of 0.75 and 1 m are adopted around the foundations, while a finer spacing of 0.5 m is employed beneath them. The corresponding mesh configurations and boundary conditions are illustrated in Fig. 1.

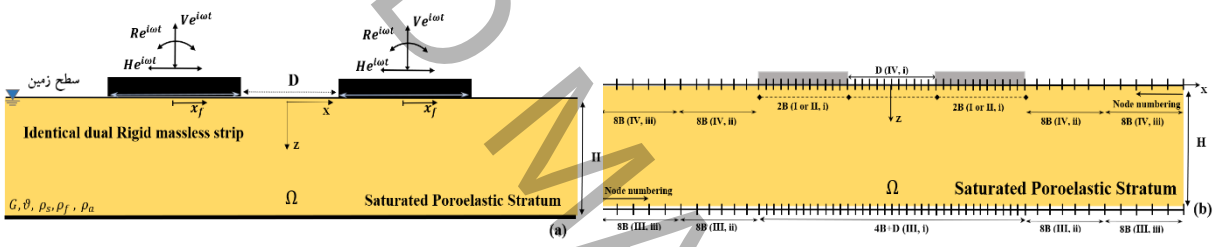

Fig 1. (a) Geometric model of two rigid, massless strip foundations resting on a saturated poroelastic layer, including the boundary conditions and different mesh configurations. (b) Boundary element discretization of the saturated layer overlying a rigid half-space.

3. Results and Discussion

The influence of soil type on the dynamic impedance of two rigid strip foundations resting on a saturated poroelastic layer is investigated under simultaneous vertical, horizontal, and rocking harmonic excitations for smooth and perfectly bonded contact conditions. Under smooth contact, red clay exhibits the highest frequency sensitivity and vertical damping, while sandstone shows the most stable response with lower energy dissipation. Coarse sand and soft sediments display intermediate behavior. Horizontal impedance peaks occur at dimensionless frequencies of approximately 0.8, 1.6, and 2.5, with the real and imaginary components of sandstone being about 50% and 40% lower than those of other soils at the dominant peak. Under rocking excitation, red clay exhibits the highest stiffness at low frequencies, whereas sandstone shows the greatest damping as frequency increases. Perfectly bonded contact intensifies the dynamic response and resonance peaks, particularly at dimensionless frequencies above 1.5. Vertical excitation produces the highest damping, especially in red clay and soft sediments, while rocking excitation exhibits the lowest. Under horizontal excitation, soil-type sensitivity decreases due to complete shear stress transfer. At dimensionless frequencies above 2, differences in rocking stiffness become negligible, emphasizing the importance of frequency-dependent damping. Overall, soil type and contact conditions significantly govern the dynamic response of coupled strip foundations.

Normalized pore water pressure beneath two rigid strip foundations is evaluated for different soil types under perfectly bonded contact conditions. The results indicate that soil type and excitation frequency significantly affect pore pressure and resonance behavior. Under vertical excitation, wave interactions amplify pore pressures, particularly at dimensionless

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frequencies above 1. Red clay and soft sediments exhibit higher pressures due to lower permeability and slower drainage. Under horizontal and rocking excitations, soft sediments produce the highest pressures at dimensionless frequencies of 2–3. Coarse sand also develops considerable pressures at higher frequencies despite its greater permeability. Overall, soil properties and excitation characteristics strongly influence pore pressure development in saturated poroelastic media.

4. Conclusions

In this study, the direct frequency-domain boundary element method was employed to investigate the dynamic impedance of two rigid strip foundations resting on a saturated poroelastic layer under simultaneous vertical, horizontal, and rocking harmonic excitations. The developed numerical algorithm was successfully validated against available solutions for a single foundation, demonstrating satisfactory accuracy. A parametric analysis was subsequently conducted to evaluate the influence of four soil types and foundation–soil contact conditions on the real and imaginary components of dynamic impedance and pore water pressure.

The results indicate that soil properties significantly influence dynamic stiffness, damping, and resonance characteristics, particularly under vertical excitation. At a dimensionless frequency of approximately 2, red clay and soft sediments exhibit greater energy dissipation, whereas sandstone demonstrates a more stable response with lower damping. Under horizontal excitation, soil type mainly affects resonance amplitudes, while the overall frequency-response patterns remain similar. For rocking motion, soil-type sensitivity is more pronounced at low frequencies and decreases with increasing frequency. Perfectly bonded contact generally produces greater dynamic stiffness and damping than smooth contact, accompanied by more pronounced resonance effects. Furthermore, pore water pressure exhibits greater frequency sensitivity in fine-grained soils, particularly red clay and soft sediments, whereas coarse sand and sandstone show relatively lower responses. These findings emphasize the importance of soil characterization and suggest that vertical and rocking excitations deserve particular attention in dynamic foundation design, while horizontal excitation has a comparatively smaller influence on pore pressure. Future research should address nonlinear and partially saturated soil behavior, foundation geometry and spacing, realistic loading conditions, and experimental validation to improve the practical applicability of the proposed approach.

5. References

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