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Dynamic Response of Machine Foundations Supported on Rigid Inclusions

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Abstract - This paper presents a numerical investigation on the behaviour of a machine foundation resting on rigid inclusions. The study aims to present a comparison on the performance of machine foundations resting on rigid inclusions with pile and shallow foundations. The analysis is carried out using PLAXIS 3D, a finite element software for geotechnical engineering applications, and based on a previous research carried by the author to investigate the behaviour of pile foundations under cyclic vibrations. The results show that the use of rigid inclusions can significantly improve the performance of machine foundations by reducing the vibration amplitudes and obtaining a more uniform response under a wide frequency spectrum of the imposed dynamic load. The study provides useful insights into the selection of an appropriate type for machine foundations and highlights the importance of considering different design options and parameters.

***Keywords*:** Rigid Inclusions - Dynamic Loads - Machine Foundations - Pile Foundations

1. Introduction

Design of equipment foundations is a crucial process in ensuring safe and efficient operation of the mounted machines. One of the main considerations during such design is the ground condition supporting these foundations. Soil conditions can greatly affect the dynamic behaviour of the foundation, which can lead to excessive vibrations affecting the performance and integrity of the mounted equipment.

Traditionally, piles and shallow foundations have been widely used as a means of supporting machine foundations. Pile foundations are more suitable for equipment imposing high vibrations resting on soft soil condition, while shallow foundations are ideal for compact soils. Hence, most of the past studies have focused on the dynamic behaviour of machines resting on shallow and piled foundations.

Two primary methods have been established for analysing the behaviour of shallow foundations under dynamic loading. The first method, proposed by Barkan in 1962 [1], is the linear elastic weightless spring approach, while the second method is the elastic half-space approach.

The elastic half-space approach, which is based on Ressiner's (1936) work [2], is now more commonly used comparing to the first method. Ressiner's solution addressed the problem of a flexible circular area vibrating uniformly and exerting pressure on the surface of an elastic half-space. Lysmer and Richart (1966) [3] used Ressiner's work to develop a mass-spring-dashpot system for analysing the behaviour of a rigid circular footing subjected to vertical vibrating load. Meanwhile, other researchers extended Lysmer and Richart's approach to horizontal, rocking, and torsional motions. Finally, Chae's research in 1969 [4] demonstrated that the elastic half-space solutions can be utilized for rectangular footings by converting them into an equivalent circle with the same area for vertical and horizontal oscillations, or same moment of inertia for rocking and torsional vibrations.

Due to the complexity of the Pile-Soil interaction problem, some analysis approaches were developed which ignore the contribution of soil and relate all stiffness to the pile or estimate the single pile stiffness based on field measurements. However, in 1974, Novak [5] introduced an approximate approach, which can simulate the dynamic interaction of single pile with the surrounding soil.

On the other hand, the dynamic Pile–Soil–Pile interaction was investigated by early studies such as Wolf and Von Arx (1978) [6], Nogami (1979) [7], Kaynia and Kausel(1982) [8], Sheta and Novak (1982) [9]. All these studies have shown that the dynamic impedance parameters of pile groups can exhibit strong oscillatory behaviour with the change of frequency, piles spacing and other parameters.

Dobry and Gazetas (1988) [10] introduced an approach for calculating the dynamic interaction factors between piles with simple equations deduced from the cylindrical waves propagation theory in an elastic media. The previous work of the author [11] [12] has shown that combining the two approaches of Novak (1974) and Dobry and Gazetas (1988) can yield sufficiently accurate results when compared with other manual approaches against Finite Element analysis results.

Rigid inclusion is a soil improvement technique utilized in geotechnical engineering to enhance the load-bearing capacity of weak soils. The method entails embedding non-reinforced concrete columns within the ground, which are separated from the structure foundation by a load transfer soil layer. This load transfer platform (LTP) performs a crucial role in distributing stresses between the concrete columns and the surrounding soils, resulting in a more economical system than conventional deep foundations.

In recent years, the use of rigid inclusions to support foundations under static loading conditions has gained popularity due to their effectiveness in reducing structure settlement. The French recommendations of the national research project ASIRI [13] "Améliorations de Sols par Inclusions Rigides," published in 2013, provide the foundation for designing such systems under static loads. However, there is a dearth of research on the dynamic behaviour of such systems under machine foundations and other foundation systems that impose dynamic loads on the underlying soil.

2. Research Background

The author of the present study has conducted previous research, Khalil and Hassan (2019 & 2020) [11] [12], on the dynamic behaviour of pile foundations, which has proven the effectiveness of the Finite Element approach in simulating the dynamic interaction between piles and soil. The validity of the numerical model was confirmed by comparing its results with those obtained from a laboratory model of a monopile offshore wind turbine constructed by Hetland (2015) [14].

The primary objective of the earlier research was to examine the dynamic behaviour of single piles and pile groups, as well as to assess the accuracy of theoretical analysis approaches recommended in existing Codes of Practice. The research findings have confirmed the conclusion of previous research, Wolf and Von Arx (1978) [6], Nogami (1979) [7], Kaynia and Kausel(1982) [8], Sheta and Novak (1982) [9], about the significant variation of the dynamic behaviour of pile foundations with respect to various factors, including the frequency of the forced motion, spacing between piles, and soil stiffness.

Furthermore, the research demonstrated that the methods employed in the Canadian Manual, which employs Novak (1974) [5] for Pile-Soil interaction and Dobry and Gazetas (1988) [10] for Pile-Soil-Pile interaction, are capable of producing the most precise results in comparison to the Finite Element approach. This implies that the recommended methods outlined in the Canadian Manual may prove to be valuable for practitioners working in this area.

3. Research Methodology

The current study adopts the same Finite Element analysis approach employed in the previously related research [11] [12]. The numerical model was built using the Finite Element software PLAXIS 3D, a widely used geotechnical software. Soil profile selected for analyses composed of loose to medium sand with increasing stiffness with depth (as shown in Table 1). The small strain shearing stiffness of the soil was estimated using Eq. (1), based on the approach proposed by Imai and Tonouchi (1982) [15]. Mohr-Coulomb model was employed to simulate soil behaviour in this study.

The maximum meshing size under the foundations can be defined by Kramer (1996) [16] empirically relating the maximum meshing size with the wavelength as can be seen in Eq. (2).

$$G_o = 15{,}560\ N_{60}^{0.68} \qquad \text{(kPa)} \tag{1}$$

$$\text{Maximum Meshing Size} = \left(\frac{1}{5}\ \text{to}\ \frac{1}{8}\right) V_{wave}/f \tag{2}$$

Where:

V_{wave} is the wave velocity

f is the dynamic motion frequency

Table 1: Soil Properties used in the Finite Element Model

Depth (m)		N-SPT	G_o (kPa)	E_o (kPa)	E_{inc} (kPa/m)	Rayleigh Damping		Φ (°)
Start	End					Damping Ratio	Defining Frequencies (Hz)	
0	5	4	42000	109000	14600	0.05	10 & 60	30
5	10	9	70000	182000	9800	0.05	10 & 60	32
10	15	13	89000	231000	8400	0.05	10 & 60	32
15	20	17	105000	273000	4200	0.05	10 & 60	33

Concrete elements of 10m length and 40cm diameter, with an elastic deformation modulus of 2.5 x 10^7 kPa and Poisson's Ratio of 0.2, were utilized as rigid inclusions and piles in this study. Rayleigh Damping values were determined for concrete material based on 1% damping ratio at 10Hz and 60Hz. Both the piles and rigid inclusions were modelled using Embedded Beam elements within PLAXIS 3D. These elements can simulate the behaviour of a volume pile using one-dimensional elements, thereby reducing computational resources and calculation time. The interface used to model interaction of these elements with surrounding soil is capable of replicating the skin friction and tip resistance of an actual pile.

The dynamic force is applied on a concrete foundation 60cm in thickness. For simulations involving Rigid Inclusions and Shallow foundations, the foundation was placed directly on the ground. However, in simulations involving Piled Foundations, the foundation was elevated by 5mm to replicate the subsidence of soft ground around the piles beneath the foundation. This was done to mitigate the transfer of dynamic forces by the foundation directly to the underlying soil. Furthermore, on an attempt to further limit the deformation of the concrete foundation, the elasticity modulus of the foundation has increased by 10^5 while maintaining the same Poisson's ratio and damping parameters as used with piles and rigid inclusions. Photo samples from inside the model for Rigid Inclusion simulation are presented below in Fig. 1.

The foundation is subjected to a uniform dynamic load of 5 kPa in both the horizontal and vertical directions, separately. The frequency of the harmonic motion is assigned using the Dynamic Load Multiplier option in PLAXIS. Furthermore, to prevent wave reflections within the model, the boundaries of the model were placed no less than 6m away from the edge of the foundation, and viscous boundaries were applied to the bottom and four side boundaries of the model.

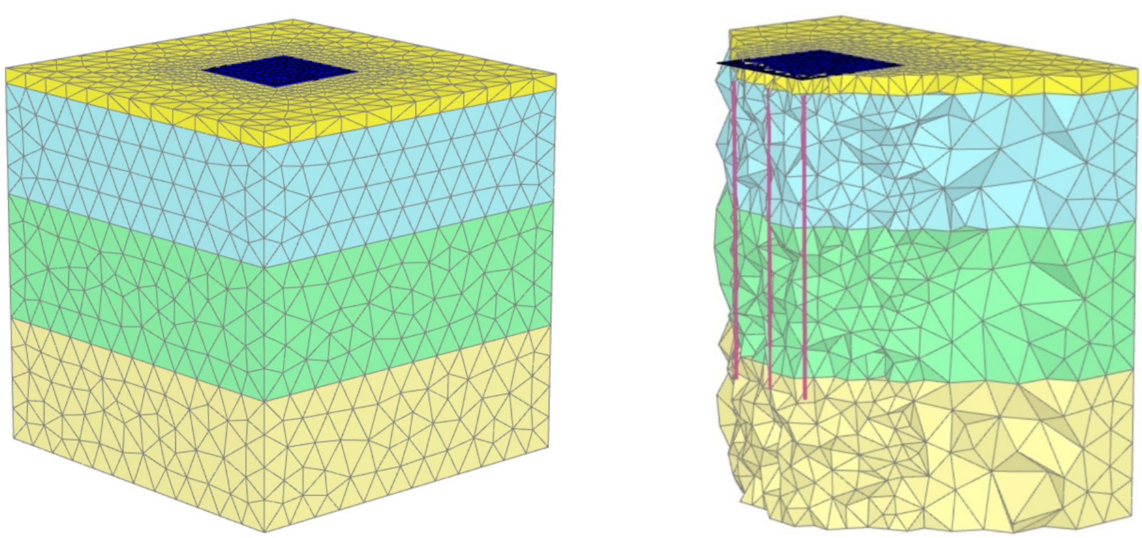


Fig. 1: Sample of Finite Element Simulation for Rigid Inclusions

4. Finite Element Modelling of Rigid Inclusions

The use of Embedded Beam Elements had been proved by the author to be capable of simulating the dynamic Pile-Pile interaction with sufficient accuracy (Khalil and Hassan, 2019) [11]. Nevertheless, as a first step of the present a verification model has been constructed to compare the dynamic behaviour of machine foundations resting on Rigid Inclusions when modelled using both Embedded Beam and Volume Elements.

Both models used 3 x 3 rigid inclusion arrangements with 1.8m spacing and 60cm LTP thickness, and were studied in the horizontal and vertical directions over a frequency spectrum ranging from 10 Hz to 60 Hz. The results of this study, illustrated in Fig. 2, show that both modelling approaches yield almost identical results for Rigid Inclusions. Therefore, adopting the Embedded Beam Elements to simulate the dynamic response of Rigid Inclusion is an effective method that can be practically implemented, resulting in significant time and resource savings.

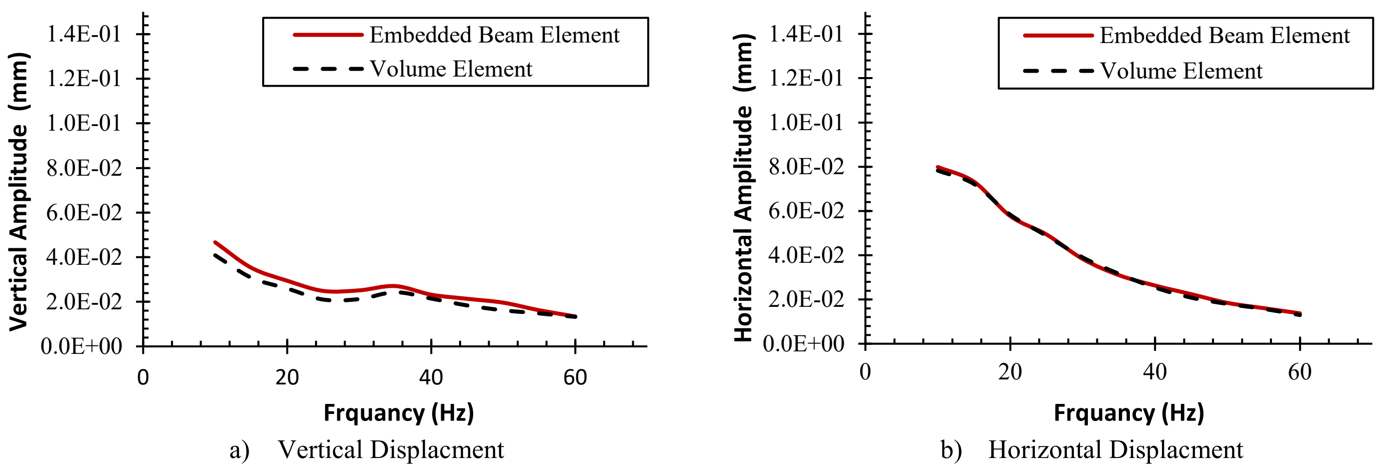


Fig. 2: Comparison of Rigid Inclusion Results Modelled Using Embedded Beam Elements and Volume Elements

5. Performance Comparison Between Rigid Inclusions and Other systems

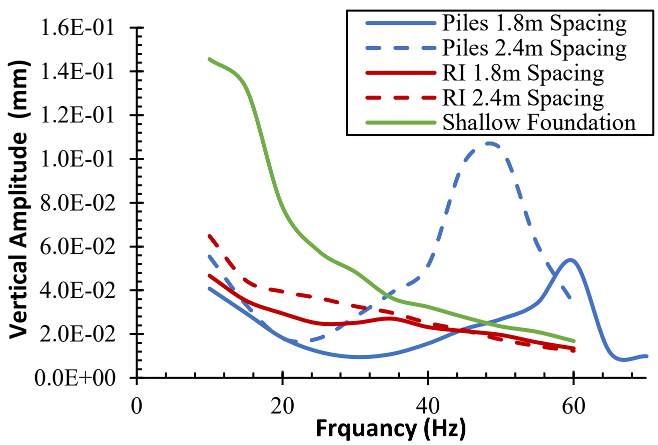
An investigation was conducted to compare the behaviour of machine foundations supported on Rigid Inclusion, Piles, and Shallow Foundation. The study examined a 3 x 3 arrangement of Rigid Inclusions and Piles, with spacing of 1.8m and 2.4m for each system. The foundation was positioned directly on the ground for Rigid Inclusions and Shallow Foundation. However, in the case of Piled systems, the foundation was raised by 5mm to prevent the transfer of dynamic loads directly to the ground. Additionally, the analysis of Rigid Inclusions involved the use of a 60cm LTP layer.

PLAXIS 3D can produce Time-Displacement curves as a direct result of dynamic motion analysis. Nevertheless, the system's stiffness and damping can still be calculated using Eq. (3) and (4), which can be derived directly from the general equation of motion. These two equations rely on parameters such as the amplitude of the applied force (f_o), the resulting displacement (x_o), the frequency of the forced motion (ω), and the phase difference between the applied force and the resulting displacement (φ).

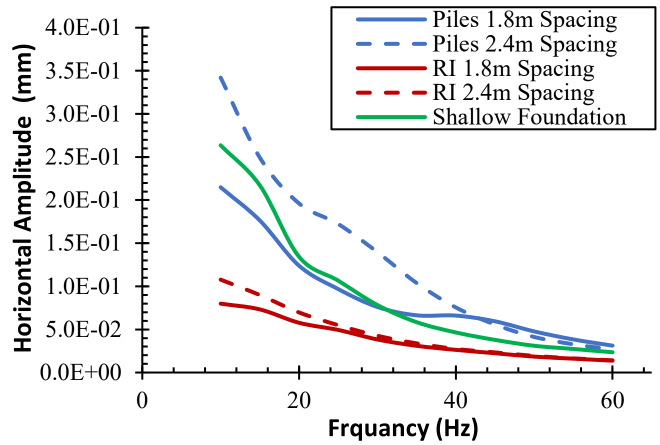
$$k = \frac{f_o}{x_o}\cos(\varphi) + m\omega^2 \qquad (3)$$

$$c = \frac{f_o}{x_o\omega}\sin(\varphi) \qquad (4)$$

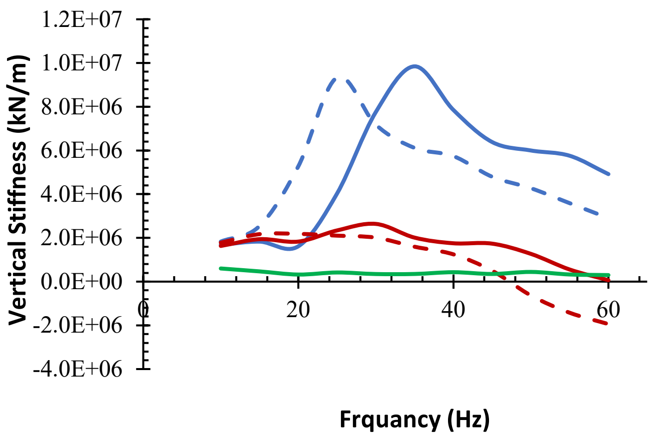
The results of these analyses are illustrated in the charts presented in Fig. 3 where the displacement amplitudes, equivalent stiffness and damping of the three foundation systems are displayed both in the vertical and lateral directions.



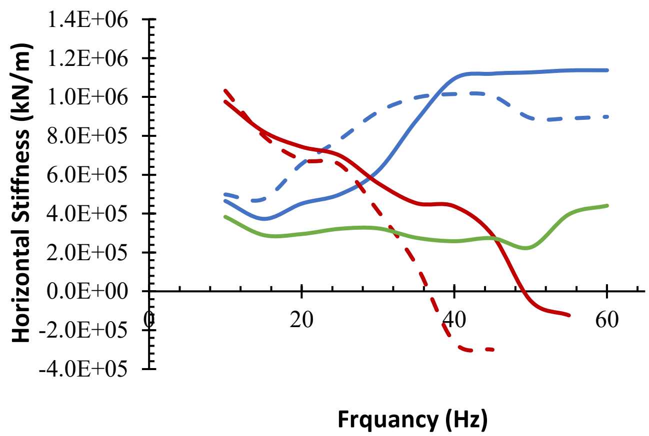
a) Vertical Amplitudes



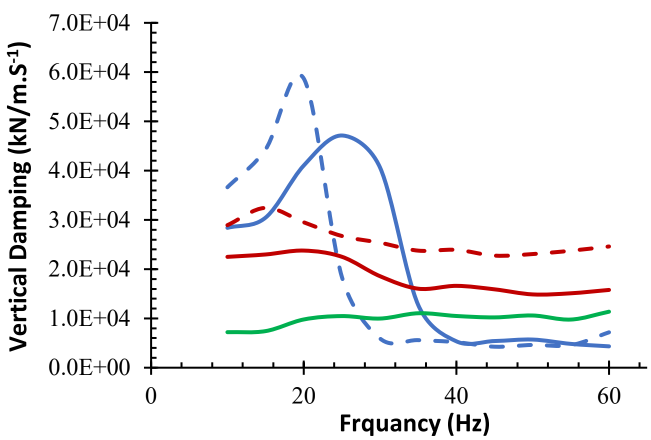
d) Horizontal Amplitudes



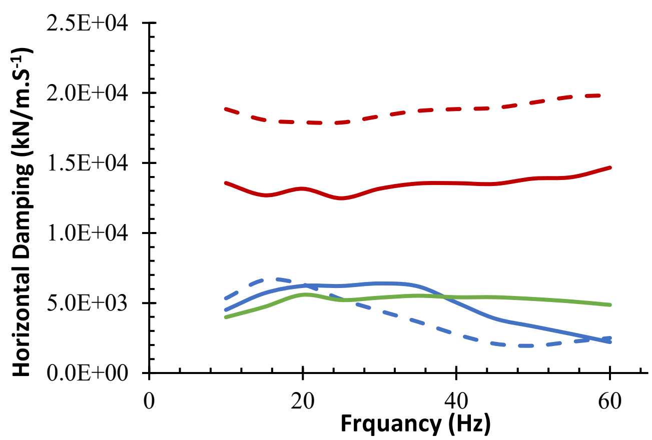
b) Vertical Stifness



e) Horizontal Stifness



c) Vertical Damping



f) Horizontal Damping

Fig. 3: Comparison of Rigid Inclusion Piled Foundation and Shallow Foundation Under Horizontal and Vertical Dynamic Excitation

When subjected to vertical excitation, Pile Foundations display a strong frequency-dependent behaviour, characterized by a reduction in displacement amplitude followed by a significant rapid increase till reaching a peak value at 50Hz and 60Hz, for the 2.4m and 1.8m pile spacing, respectively, before experiencing a sudden drop again. At this peak frequency, the displacement amplitude of Pile foundations can be 4 to 6 times greater than that of rigid inclusions. This pronounced frequency-dependent oscillation can also be observed in the equivalent stiffness and damping curves. Furthermore, it is evident from these curves that the foundation's response demonstrates considerable variation contingent on the inter-pile spacing.

Meanwhile, under vertical vibrations the Shallow Foundation system displays a notable amplification of amplitudes at low frequencies, likely attributed to its comparatively lower stiffness and correspondingly lower natural frequency. These lower equivalent impedance parameters of the shallow foundation can be readily discerned in the equivalent stiffness and damping curves of the system, as opposed to those of the other two systems. At a frequency of 10 Hz, for example, the displacement magnitude of the Shallow Foundation system is found to be two to three times greater than that of the two Rigid Inclusion systems subjected to the same frequency.

The Rigid Inclusion system exhibits a relatively consistent displacement response compared to pile and shallow foundation systems. In terms of vertical excitation amplitudes, it does not exhibit pronounced peaks or elevated values at lower frequencies, as seen in the other two systems. Instead, the Rigid Inclusion system shows a gradual decline in displacement magnitude as frequency increases, resulting in a smoother response.

When subjected to lateral vibrations, both pile and shallow foundations exhibit higher displacement amplitudes compared to rigid inclusions at low frequencies. For example, at 10 Hz, the displacements of piled and shallow foundations are in the order of two to three times those observed with rigid inclusions.

The equivalent stiffness curves for rigid inclusions shows some negative values at high amplitudes. Negative stiffness values and group efficiency higher than unity for piled foundation under dynamic load are reported in previous research by Kaynia and Kausel (1982) [8], Sheta and Novak (1982) [9] and Khalil and Hassan (2019) [11]. This can happen due to the interference of the generated waves from the dynamic motion with piles movement. In the case of rigid inclusions, the foundation is in direct contact with the ground (on contrast to piled foundations models). Therefore, the negative stiffness values observed in rigid inclusions can also be attributed to the vibrating soil mass in contact with the foundation. However, this mass is ignored in Eq. 3, used to calculate the stiffness of the equivalent Mass-Dashpot system, potentially resulting in a lower equivalent stiffness value.

The consistent behaviour of machine foundations supported by rigid inclusions is critical to ensure the stable performance of mounted machines across different operational frequencies. The low motion amplitudes observed at low frequencies, in contrast to shallow and pile foundations, ensure a smooth machine start-up as the rotating parts accelerate to reach the desired operating speed. Additionally, the lack of high response oscillation in rigid inclusions when changing the excitation frequency guarantees a smooth machine behaviour, comparing to piles, when increasing or decreasing the machine speed.

To illustrate, the outcomes of the present analyses conducted on Piles and Rigid Inclusions are overlaid on the chart established by Ritchart (1962) [17] for evaluating the maximum allowable vibration amplitudes across a broad frequency spectrum to prevent damage of the machinery foundation system and ensure the safety of the operating personnel. Fig. 4 shows that the response of Piles is highly oscillatory and can result in vibration impacts ranging from being "Noticeable to persons" to exceeding the "Limits of machines and machine foundations". On the other hand, the rigid inclusion exhibits a relatively stable response, hardly exceeding the "Severe to persons" limit and never reaching the machine limit. It should be noted that with a well-designed rigid inclusion system, better outcomes can be yielded than those depicted in Fig. 4.

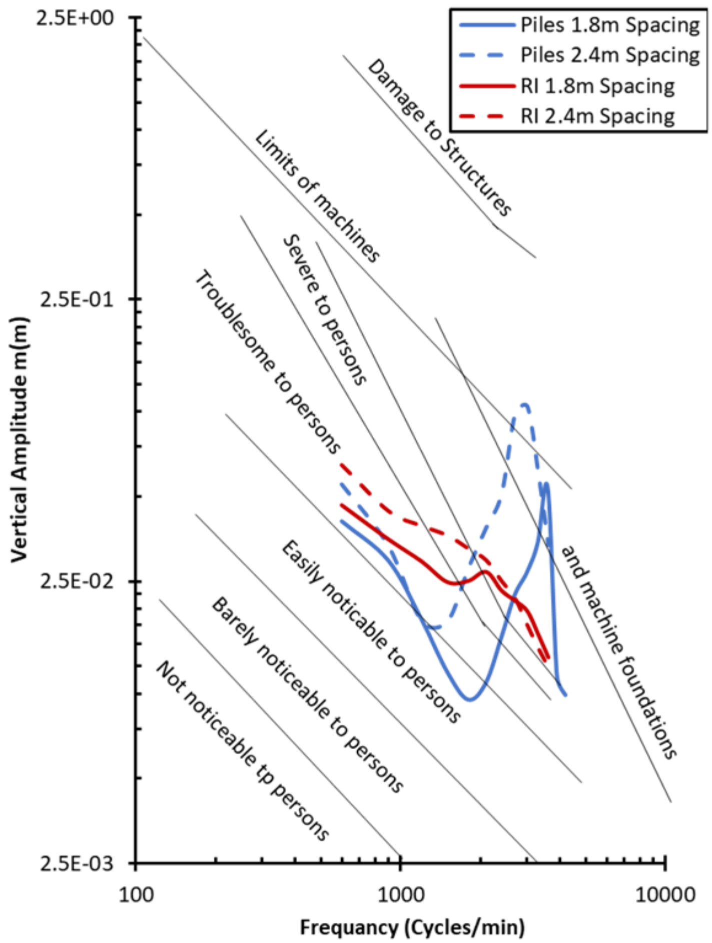


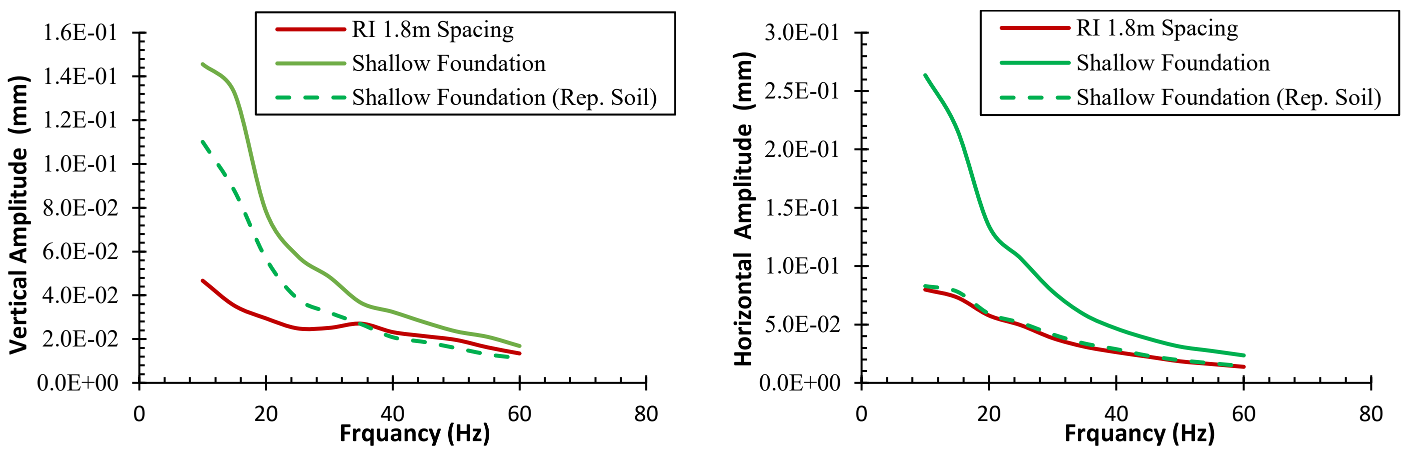
Fig. 4: Vertical Amplitudes of Rigid Inclusion and Piled Foundations Superimposed on Vibration Limits Defined by Ritchart (1962)

6. Impact of Replacement Soil on the Foundation's Dynamic Response

As part of rigid inclusion design, a load transfer platform (LTP) is installed on top of the inclusions to distribute the imposed load between soil and rigid inclusions. In the present study, a 60cm LTP layer is added on top of the rigid inclusions. Hence, additional calculations are conducted to examine the effects of using a replacement soil of the same depth under the shallow foundation system. Results of this analyses is illustrated in Fig. 5.

Studying the results presented in the figure indicates that the LTP layer installed on top of the rigid inclusions is the primary factor responsible for the dynamic response of the rigid inclusion system to lateral vibrations, since the response of the shallow foundation system is similar to that of the rigid inclusion system when the same layer is added as replacement soil beneath the foundation.

In the vertical direction, however, it was observed that while the addition of the replacement soil has improved the dynamic response of the shallow foundation system, it continues to exhibit high dynamic displacement at low frequencies. At a frequency of 10 Hz, the response of the shallow foundation system with the replacement soil is still approximately three times higher than that of the rigid inclusion system.



a) Vertical Amplitudes b) Horizontal Amplitudes

Fig. 5: Comparison of Rigid Inclusions with Shallow Foundations with and without Replacement Soil

7. Conclusions

In summary, this study investigates the behaviour of machine foundations supported by rigid inclusions, piles, and shallow foundations. The results of the analyses conducted reveal that rigid inclusions exhibit a more stable response and lower dynamic displacement compared to the other two systems. These findings suggest that rigid inclusions hold promise as a superior solution for mitigating vibration impact on both machinery and personnel. Additionally, further research and experimentation could explore the feasibility of enhancing the design of rigid inclusions under machine foundations to further improve their efficiency. Overall, this study provides valuable insights for engineers and designers seeking to optimize the performance of machine foundation systems.

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