

Comprehending the Performance Characteristics of Periodic Pile Barriers with Various Infilled Waste Materials

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ABSTRACT: Recent developments in industrial sectors have upgraded machines to enhance production and efficiency. This ultimately leads to heavy vibrations, which are quite detrimental to nearby structures. Therefore, it is essential to mitigate these generated waves using different passive techniques, such as periodic pile barriers. Moreover, in India, the output of waste materials produced every year is double as compared to the production. Hence, utilizing these waste materials into constructional activities will not only protect environmental and ecological damages but also conserve dwindling resources. Thus, this paper aims to utilize the industrial waste materials like fly ash, tyre chips and geofoam as infilled materials for periodic pile barriers, with an intention to isolate these vibrations due to rotating machines. The analysis has been performed using PLAXIS 3D to comprehend the screening efficiency of infilled pile barriers in both sand and clay. A model has been created, and an analysis has been performed to determine the optimal number of piles required for effective isolation. Ten piles with a center-to-center distance of 1 m, a diameter of 0.6 m, and a depth of 9 m have been modelled and kept at a distance of 10 m from the source for validation. Further, analysis has been extended to obtain amplitude reduction curves and time versus acceleration response of each material-infilled pile barrier in clay and sand. The study showcased that geofoam-filled piles have more screening efficiency in clay as compared to the other two materials. However, in sand, the efficacy of the infilled materials is not fulfilled, leading to mediocre performance. This appreciable performance of infilled materials in clay can be due to their better damping effect and impedance ratios.

KEYWORDS: Periodic Piles, Attenuation Zone, Amplitude Reduction Factor, Vibration Isolation and Screening Efficiency.

1. INTRODUCTION

Ground borne vibrations can be generated due to prevalent reasons like trains, constructional activities such as blasting, tunneling, excavation and heavy machines. These vibrations can cause enormous detrimental effects on human life, structures, and soil; therefore, research in recent decades has placed much emphasis on understanding mitigation strategies. High-frequency vibrations dissipate rapidly with distance, whereas low- and medium-frequency vibrations are more pronounced, as they take longer to decay. Hence, the most efficient method for isolating these vibrations is to construct wave barriers between the source and the protective area, incorporating both active and passive isolation. The former refers to mitigating vibrations at the source, whereas the latter mitigates vibrations between the source and the structure to be protected. Passive isolation is considered to be the widely accepted method, and it is further classified as continuous and discontinuous barriers. To the best of the writer's knowledge, continuous barriers like open trenches (Barkan, 1962) and infilled trenches (Segol et al., 1978) have been proposed in the mid-20th century. Several studies are being conducted on various aspects of continuous barriers (Kavand & Khadangi, 2023; Istengun et al., 2023; Klein et al., 1997; Sivakumar et al., 2010) to assess their performance and screening efficiency. But these methods are hindered by surface waves, and as they are constrained by factors such as limited space, high water tables, and the need for constant maintenance and care, studies have sought to identify a proper alternative. In order to bridge this gap, discontinuous barriers like multi-row pile barriers (Woods et al., 1974) are considered to be a better option, as they are deeply driven into the soil and can be arranged in any desirable configuration. Geometrically, these multi-row pile barriers can be perceived as a periodic system, and hence they are referred to as periodic pile barriers.

Past research has shown that ambient vibrations in the middle frequency range can be isolated using solid concrete piles, whereas low-frequency vibrations (less than 20 Hz) can be isolated by using

soft infilled materials within the hollow concrete pile (Haung & Shi, 2015). Regarding this fact, numerous studies are being conducted analytically and experimentally to understand the effects of infilled materials on periodic pile barriers. Pu et al. (2018) studied the performance of periodic pile barriers in layered soil to isolate surface waves from the perspective of attenuation zones. Eskandarighadi et al. (2022) proposed a coupled finite-element genetic algorithm methodology to study the mitigation effect of scattered barriers on machine vibration by varying the installation pattern. Further, scattered pile response has been compared with vertical concrete walls and found that the piles perform well as compared to walls. Zhang et al. (2022) conducted experimental investigations to assess the performance of combining periodic barriers and periodic foundations in mitigating vibrations. This study concludes that the screening effectiveness of the combined system is very beneficial for vibration isolation. Meng et al. (2020) adopted the COMSOL PDE method to assess the performance of periodic pile barriers in saturated soil. Xia et al. (2011) established a new method called multiple scattering to obtain a solution for plane elastic wave scattering by an arbitrary pile configuration and diameter. Numerical analysis was conducted to understand the screening effectiveness of single and multi-row pile barriers by considering various factors like distance between pile rows, pile numbers, number of pile rows, configuration of pile rows and separation between piles. Furthermore, a 2D finite element model has been developed, and the results have been validated against field responses to assess its applicability. This paper provides an overview of the isolation effect of pile barriers by varying parameters such as pile length, pile diameter, hollow ratio, and infill materials. Similarly, an ample number of studies (Haung & Shi, 2013a; Lei et al., 2021; Pu & Shi, 2019) have been conducted on discontinuous wave barriers to obtain a better intuition on the appropriate way of effectively isolating vibrations from various sources.

India is facing tremendous issues regarding waste accumulation from several sources such as construction waste, industrial waste,

demolition waste, power houses, etc. As this waste disposal causes harmful effects on the environment, it is always advisable to utilize it as a substitute in the construction field, road pavement, and ground improvement, thereby conserving dwindling resources. Researches are being carried out in understanding different aspects of indulging industrial wastes like flyash (Malik et al., 2023; Kasiviswanathan & Govindarajulu, 2023; Hoy et al., 2016) silica fume (Senol & Guner, 2023; Tak, 2023; Elchalakani, 2015), recycled aggregates (Tejas & Pasla, 2023; Silva et al., 2019), rubber waste (Juveria et al., 2023; Senol & Guner, 2023; Yilmaz & Degirmenci, 2009), GGBFS (Hyunh et al., 2022) into construction zone, pavements and ground improvements, thereby limiting the environmental and ecological damages. Detailed literature exhibited a wide gap in utilising these waste materials as periodic pile barrier infill for improving vibration mitigation. In this booming era of industrial innovations, mitigation of vibrations generated by machines and the foundation of machines are to be given great importance because of space limitations. Therefore, this paper aims to deeply investigate the performance of infilled pile barriers in vibration isolation, using waste materials like flyash, tyre chips and geofoam. A 3D finite element model has been developed using PLAXIS 3D software, consisting of piles arranged in rows with a center-to-center spacing of 1.5m, located 10 m from the source. The screening efficiency of pile barriers infilled with fly ash, geofoam and waste tyre chips, embedded in two different soils like clay and sand is studied based on two important aspects like impedance ratios and amplitude reduction factor.

2. FINITE ELEMENT MODELLING

The finite element method is considered one of the prominent methods for analyzing piles or pile groups in layered soil, a problem that is difficult to address with analytical or semi-analytical formulations. In the present study, a 3D finite element method has been considered to model periodic pile barriers using the software PLAXIS 3D. All the requisites for validation have been taken from the studies of Pu et al. (2018).

Table 1 Soil properties (Pu et al., 2018)

Sl. No	Depth (m)	Soil Type	Young's Modulus (MPa)	Poisson's ratio	Density (kg/m ³)
1	0-1.6	Fill	37	0.4	1830
2	1.6-2.4	Clayey silt	44	0.4	1939
3	2.4-9.0	Sandy silt	57	0.4	1888
4	9.0-16.0	Silt	141	0.45	1898
5	16.5-27.5	Sandy silt	90	0.45	1837
6	27.5-30.0	Silty clay	155	0.45	1847

2.1 Numerical modelling and validation

A row of 10 fly ash piles having a diameter of 0.6 m, a depth of 9 m, and a center-to-center spacing of 1m has been placed in a soil model with six different layers whose properties are described in Table 1. All the soil properties (Table 1) and fly ash properties (Table 2) are assumed as per Pu et al., 2018. The piles have been placed in a soil model of 40m×20m×20m, and material damping introduced into the soil was 5%. Both the soil and the pile have been discretized using 10-node tetrahedral elements. The applied loading is a vertical harmonic load of 1kN at a frequency of 41Hz. The periodic pile barriers were kept 10 m from the source, and the variation of displacement amplitude with horizontal distance was plotted, as shown in Figure 1.

Table 2 Fly ash properties

Properties	Unit weight (kN/m ³)	Young's modulus (MPa)	Poisson's ratio
Value	5	25	0.35

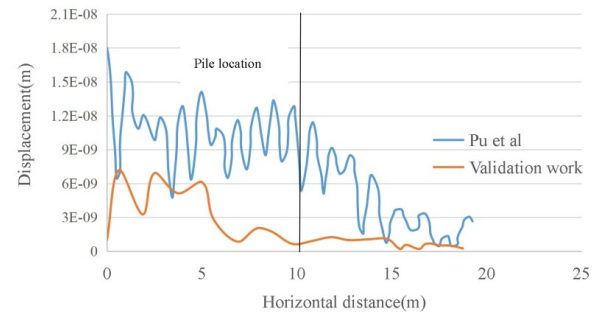


Figure 1 Validation curve

From Figure 1, it is observed that the amplitude keeps declining from the pile barrier, and the simulation results are closely consistent with the results from the literature. Hence, this model can be used for further analysing the screening efficiency of pile barriers.

2.2 Optimizing number of piles

In engineering practice, one might intuitively expect that a greater number of piles will provide better screening efficiency. But in a real scenario, the efficacy will reach its optimum at one particular point. Therefore, this section focuses on gaining intuition for this aspect from the perspective of the amplitude reduction factor (ARF), which is the ratio of the displacement amplitude with a barrier to that without a barrier (Woods, 1968). Soil models with different pile numbers (3, 5, 7, 9, and 11) have been modelled using PLAXIS 3D, Edition 20 (2013), and amplitude reduction factors are determined to assess screening efficiency as the number of piles increases. The pile numbers are selected to maintain the symmetrical arrangement.

The model consists of fly ash piles with a diameter of 1 m, a depth of 5 m, and a center-to-center distance of 1.5 m, surrounded by a clay layer of 40 m × 20 m × 20 m. To neglect all sorts of boundary effects, the model boundaries have been considered to have a width equal to 40 times the pile diameter and a depth equal to twice the pile length, as per Zhang (2018). Piles are modelled as linearly elastic, and the surrounding soil is modelled using the Mohr-Coulomb model. Model boundaries used default boundary conditions, fixing the bottom nodes in all directions and the side nodes only in the perpendicular direction. A periodic pile barrier system has been kept at a distance of 10m from the source, and the displacement amplitude at a distance of 5m from the pile has been considered for computing ARF. This optimization study has been conducted by replacing the soil model with clayey soil and fly ash piles. The properties of fly ash have been taken from Table 2. Table 3 presents the properties of clay taken from Huang and Shi (2015).

A dynamic reciprocating load of 10kN at 35 Hz is applied, and the response of each set of pile numbers is observed in terms of the amplitude reduction factor. Figure 2 illustrates the soil model with different numbers of piles (3, 5, 7, 9, 11) for analysis. All the models have been analysed to evaluate the displacement amplitude reduction with the increased number of piles and thereby optimizing the number of piles.

As discussed earlier, the amplitude reduction factor is the ratio of the displacement amplitude with a barrier to the displacement amplitude without a barrier. From Figure 3, it is observed that as the number of piles increases, ARF decreases until 7 and then almost attains a constant value, indicating that displacement amplitude decreases with an increase in pile number to a certain extent. Therefore, this study exemplified the fact that, increasing the number

of piles in periodic pile barriers will not increase the screening efficiency beyond a limit. Hence, this study performed all the analyses in the upcoming sections with 7 piles.

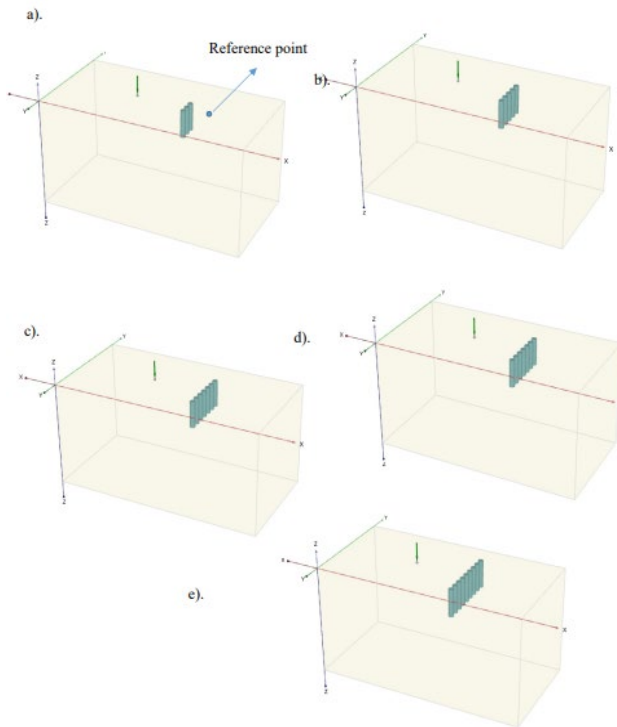


Figure 2 Soil model with different number of piles
a) 3 piles b) 5 piles c) 7 piles d) 9 piles e) 11 piles

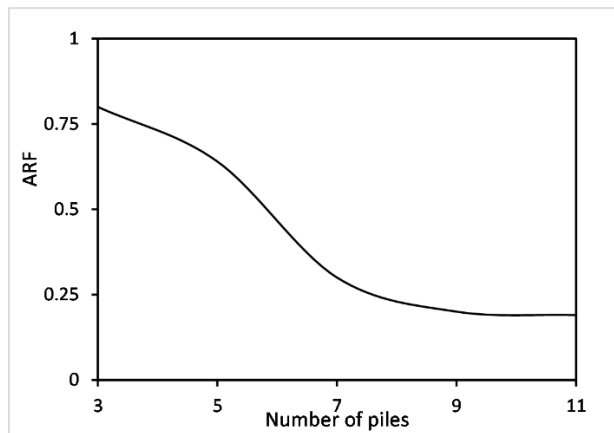


Figure 3 Variation of number of pile with ARF

2.3 Modelling of pile barrier

A 3D finite element model has been developed for understanding the vibration mitigation efficiency of periodic pile barriers with different materials like fly ash, geofoam and waste tyre chips embedded in clay and sand under vertical harmonic loading. Fly ash and tyre chips are waste materials and geofoam is lightweight fill with inherent compressive strength. As the strain levels are small, these materials are considered to be homogeneous and isotropic. Since the chosen infilled materials are softer than soil (Table 4), these barriers are expected to dissipate energy due to the disparity in impedance. From the augmentation studies described in the previous section, seven piles have been selected for the analysis. The seven piles, with a diameter of 1m, a depth of 7 m, and a center-to-center spacing of 1.5 m, have been placed in a soil model measuring 40 m × 20 m × 20 m, as illustrated in Figure 4. The model boundary or region of interest should be kept far from the reflecting zones to avoid significant boundary effects. Boundary conditions have been fixed the same as those explained in section 2.2. Absorbent boundary conditions are

specified to avoid reflections of waves, as the soil is assumed to be a semi-infinite medium. All the material properties used in the analysis have been procured from various literature (Haung & Shi, 2015; Pu et al., 2018; Tandon et al., 2023) and are given in Table 3.

Table 3 Properties of the material used

Material	γ (kN/m ³)	E (MPa)	μ	C (kN/m ²)	ϕ (°)
Clay	19	20	0.35	30	10
Sand	19	40	0.35	0	35
Flyash	5	25	0.35	-	-
Geofoam	0.61	14.6	0.1	-	-
Tyre chips	6	16.25	0.3	-	-

γ – Density, E- Young's modulus, μ -Poisons ratio, C- cohesion, ϕ - angle of internal friction

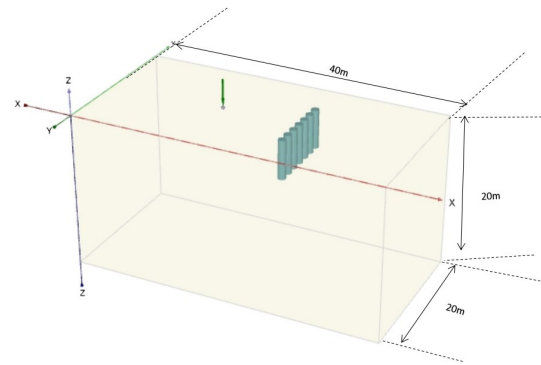


Figure 4 Soil model with periodic pile barriers

10-noded tetrahedral elements have been used to discretize both the soil and the pile. Because the certainty of results directly influences the selected mesh size, a fine mesh has been chosen for the analysis. The analysis has been done by simulating dynamic loading as sinusoidal waves in the vertical direction at varying frequencies. Soil is assumed as the Mohr-Coulomb model because soil inherently has some displacement, which can be elastic or plastic displacement. This type of behavior is reflected in the Mohr-Coulomb model, and the rest of the isolating materials are considered as linear elastic materials. Material damping of 5% is introduced for clayey soil and 2.5% for sand and Rayleigh coefficients are computed from the following Eq. (1),

$$\alpha + \beta\omega^2 = 2\zeta\omega \quad (1)$$

with the angular frequency of the excitation (ω) and material damping (ζ). The studies assumed that the predominant running frequency of machines lies between 60 rad/sec and 600 rad/sec under dynamic loading. This indicates that the damping value considered for the soil layer is constant within the assumed frequency range.

This model has been used in this study for further analysis. The technique of vibration mitigation becomes understandable with a profound understanding of concepts such as impedance ratio, attenuation zone, amplitude reduction factors, etc. Impedance ratio (IR) is a term that relates the shear wave velocity and density of barrier material and soil as expressed in the given Eq. (2):

$$IR = \frac{\text{Density of barrier} \times \text{shear wave velocity of barrier}}{\text{Density of soil} \times \text{shear wave velocity of soil}} \quad (2)$$

The effectiveness of the pile barrier was found to be significantly affected by the acoustical properties of the pile material. Recent studies have emphasized the impedance ratio, as it plays an important role in vibration mitigation; in the case of periodic pile barriers, this impedance dissimilarity between soil and barrier ultimately isolates these detrimental vibrations. Materials with an impedance ratio less than 1 are considered soft piles, and those with an impedance ratio

greater than 1 are considered hard piles (Prakash & Puri, 1987). Table 4 describes the impedance ratio of materials chosen for this study.

Table 4 Impedance ratio of different materials

Material	With respect to clay	With respect to Sand
Fly ash	0.57	0.4
Geofoam	0.034	0.024
Tyre chips	0.27	0.194

An attenuation zone, or band of frequency gap, is a range of frequencies that are efficiently screened by the pile material. Therefore, periodic materials should always be chosen with one or more frequency bands, thereby prohibiting wave propagation and ultimately reducing vibrations. This study focuses on incorporating the significance of all these parameters in vibration mitigation and thereby deciphering all the aspects in this concept.

3. RESULTS AND DISCUSSIONS

This section briefly discusses the performance of 3 pile barrier materials in clay and sand under a dynamic point load of 1 kN applied 10m from the pile location.

3.1 Periodic Pile Barriers in Clay

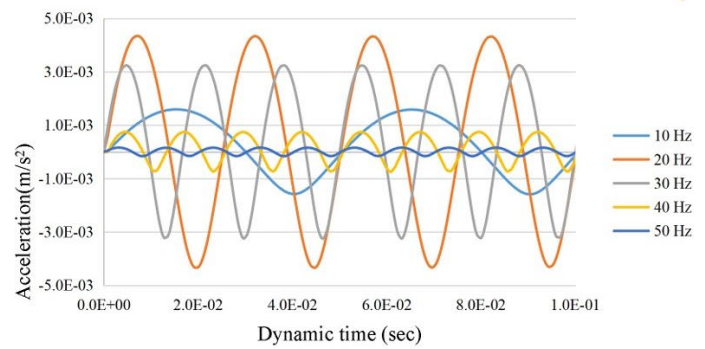
3.1.1 Acceleration time response

Analysis has been performed on the model to acquire the time acceleration response of each material in clay, thereby obtaining a better insight into their mitigation efficiency. All the responses are observed to be sinusoidal in nature, as the input load given is sinusoidal harmonic load. Figure 6 demonstrates the mitigation effect of clay alone and by intruding barriers with fly ash, geofoam and tyre chips into clay.

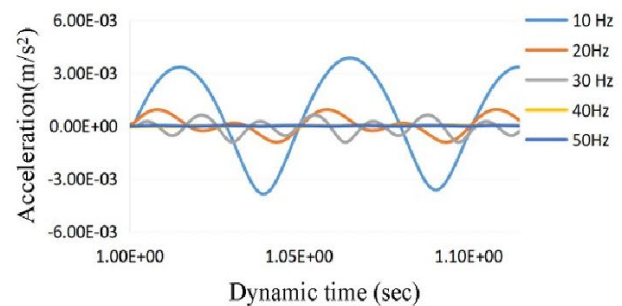
In all cases, it has been observed that the amplitude has increased at a particular frequency and then decreased, which indicates its resonant frequency. Moreover, comparing all the figures, it has been observed that geofoam reduced the acceleration amplitude to a reasonable extent. For better understanding, the response of all materials, along with clay alone, have been compared at a particular frequency of 20 Hz at 10 m from the pile location.

Figure 7 illustrates the variation of acceleration versus time for all materials, including clay alone, at a particular frequency. The curve depicts that, for a particular frequency, geofoam has performed better by reducing amplitude, then tyre chips and latter fly ash. The graph illustrates that acceleration amplitude reduced by 75% with the usage of geofoam as compared to clay alone

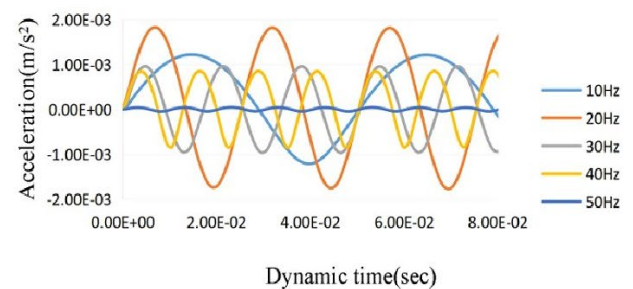
However, waste materials like fly ash and tyre chips are also found to decrease the acceleration amplitude to a reasonable extent as compared to clay alone. Hence, the relevance of impedance ratio (IR) is to be comprehended, and Table 4 illustrates the impedance ratio of materials in the order $IR(\text{Geofoam}) < IR(\text{tyre chips}) < IR(\text{Fly ash})$. Past researchers have conducted full-fledged studies in shedding light on the mitigation efficacy between soft piles ($IR < 1$) and hard piles ($IR > 1$). These studies revealed that soft piles performed better than hard piles due to their additional absorbent effect, or rather, damping effect. Therefore, this section provides guidance on selecting the material for pile barriers with respect to their impedance ratio.



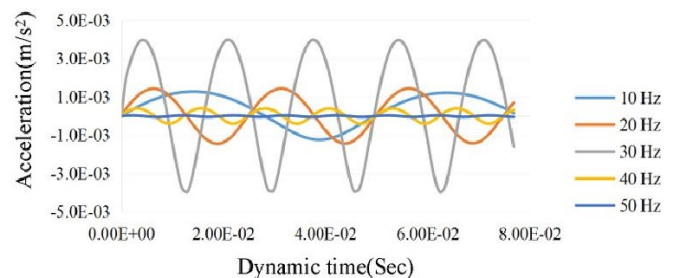
(a)



(b)



(c)



(d)

Figure 6 Acceleration versus time (a) clay alone (b) geofoam pile in clay (c) fly ash pile barrier in clay (d) tyre chips pile barrier in clay

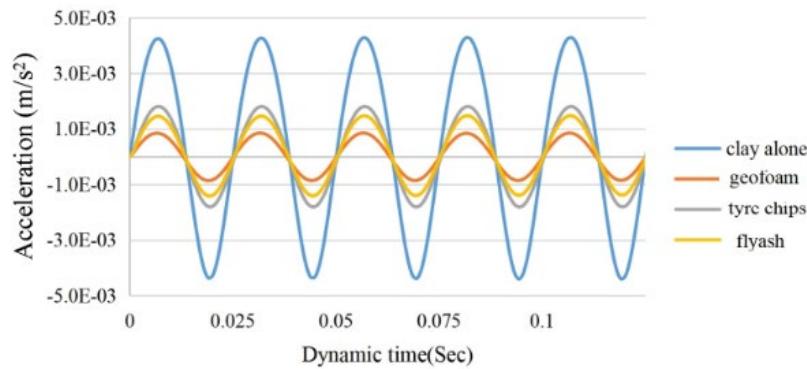


Figure 7 Variation of acceleration versus time for all materials at 20Hz

3.1.2 Maximum displacement variation with pile location

Various materials like fly ash, geofoam and tyre chips have been used as infilled materials in piles with an intention of mitigating waves in clay. Figures 8 to 10 illustrate the maximum displacement variation for each barrier material obtained from the acceleration time response

when they are kept at a distance of 10m from the source. Each figure depicts the variation in overall displacement with horizontal distance and the displacement amplitude as the wave passes through the piles (10 m to 20 m).

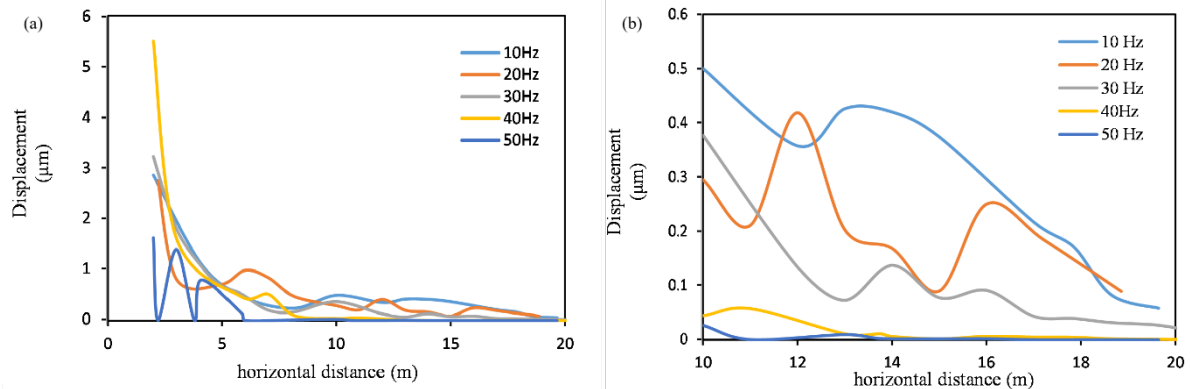


Figure 8 Variation of displacement along horizontal distance for fly ash piles in clay (a) 0-20m horizontal distance (b) 10-20m horizontal distance.

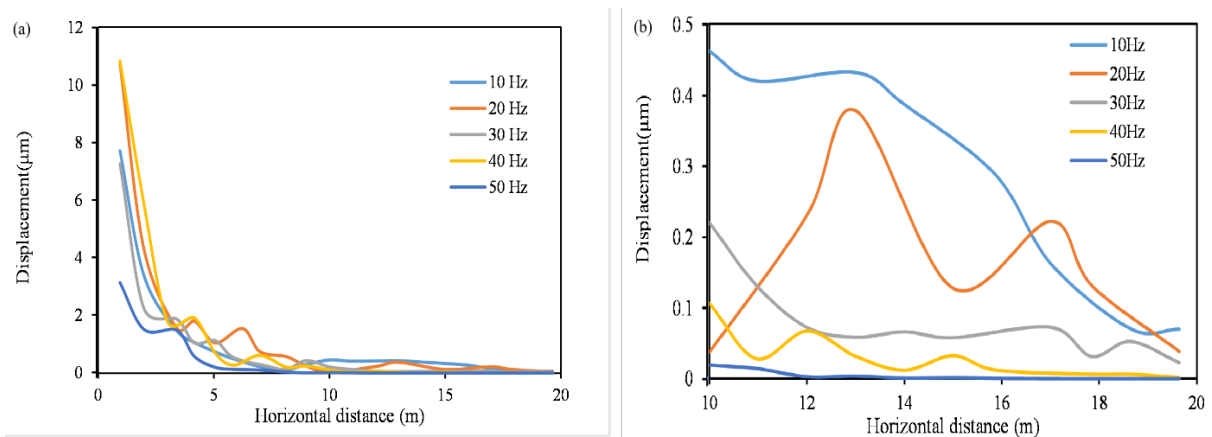


Figure 9 Variation of displacement along horizontal distance for geofoam piles in clay (a) 0-20m horizontal distance (b) 10-20m horizontal distance.

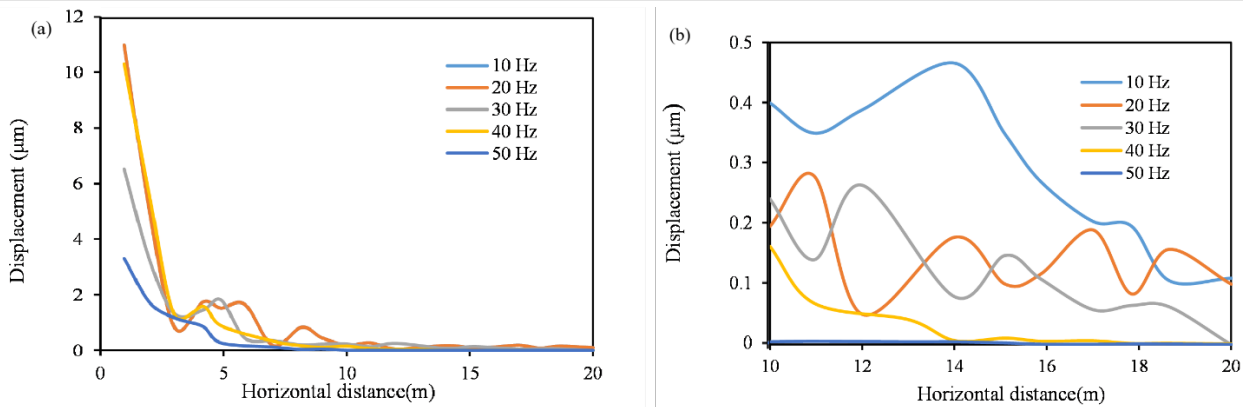


Figure 10 Variation of displacement along horizontal distance for tyre chips piles in clay
(a) 0- 20 m horizontal distance (b) 10- 20 m horizontal distance.

It is observed that displacements have reduced significantly beyond the pile location for all three materials, which further depicts that intruding pile barriers can mitigate waves in clay to a large extent. This decrement in displacement can be inferred as an inhibition of wave propagation by barrier materials.

3.1.3 Amplitude reduction curves

This section discusses the effectiveness of barriers by understanding the concept of ARF. The amplitude reduction factor (ARF) is defined as the ratio of the vertical amplitude with a barrier to that without a barrier. The wave barriers are effective if ARF is less than 0.25 (Woods et al., 1974). Therefore, drawing a line from 0.25 on the Y-axis intersects the curve at different sets of frequencies that determine the material's attenuation zone. The attenuation zone can be defined as the frequency range that is efficiently screened from propagating through the pile material.

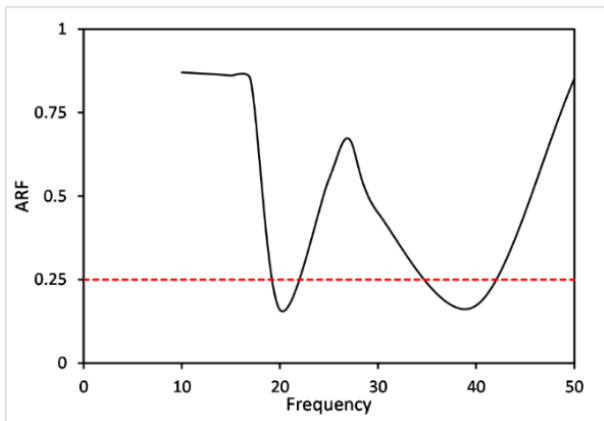


Figure 11 Amplitude reduction curves for geofoam in clay

From Figure 11, it is observed that the attenuation zones for geofoam piles in clay fall into two different frequency ranges, from 19 Hz to 24 Hz and 35 Hz to 43 Hz. It is always beneficial to choose a material with different sets of attenuation zones, as it mitigates the propagation of waves at different frequencies.

From Figures 12 and 13, it is observed that the curve is very narrow, and thereby attenuation zones fall in a limited range of 23 Hz to 27 Hz for fly ash and 21 Hz to 23 Hz for tyre chips. This minimal range of the attenuation zone can be attributed to a higher impedance ratio between the two materials compared to geofoam. Therefore, this section concludes that geofoam performs better as a pile barrier in clay when compared to fly ash and tyre chips. Table 5 illustrates the attenuation zone of each pile material used in the study.

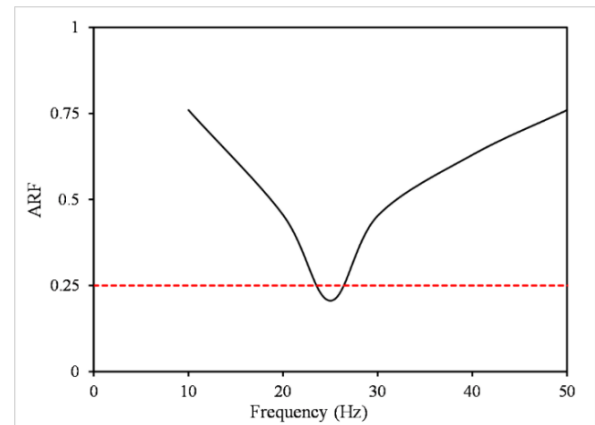


Figure 12 Amplitude reduction curves for fly ash in clay

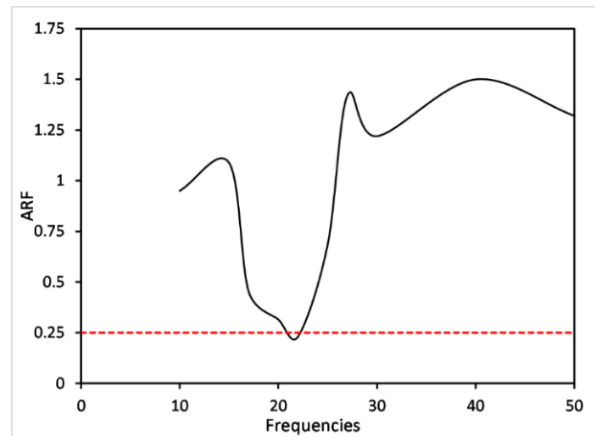


Figure 13 Amplitude reduction curves for tyre chips in clay

Table 5 Summary of Attenuation zone of different pile materials in clay obtained from analysis

Material	Attenuation range
Geofoam	19-24Hz, 35-43Hz
Fly ash	23-27Hz
Tyre chips	21-23Hz

Table 5 depicts that geofoam exhibited two different zones of attenuation ranges in clay which means that this particular range of frequencies will be bounded to propagate through the material, which makes it superior over tyre chips and fly ash in clay. Hence, it is advisable to select appropriate materials for wave isolation by being well informed about the frequency range at which the machines operate.

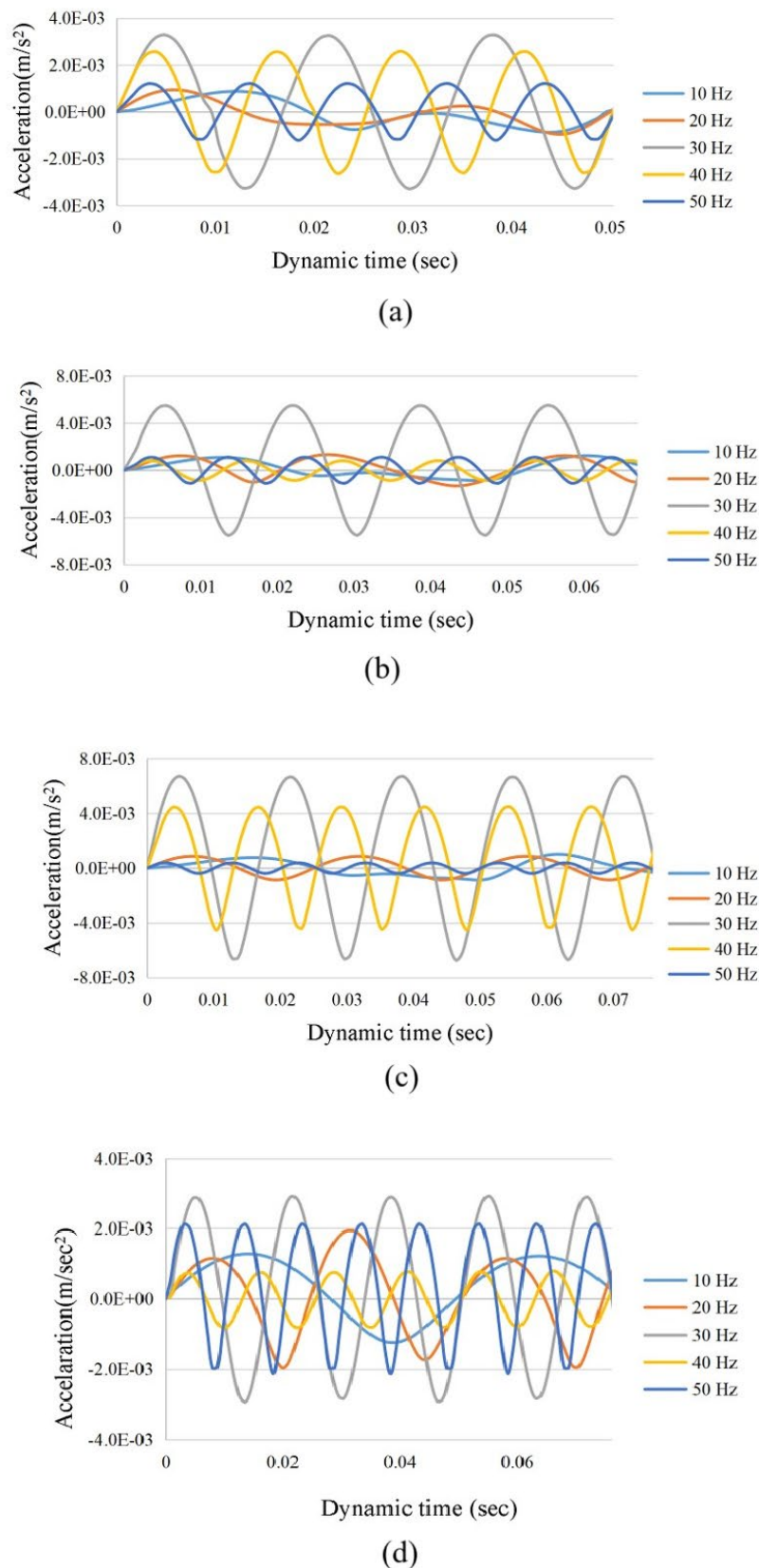


Figure 14 Variation of acceleration versus dynamic time (a) sand alone (b) geofoam pile in sand (c) fly ash pile in sand (d) tyre chips in sand

3.2 Periodic pile barriers in sand

Similar analysis has been performed in sand using different materials, such as geofoam, fly ash, and tire chips, incorporated into the pile. A dynamic load of 1 kN has been applied at a distance of 10m from the pile to assess the screening efficiency of these materials as pile barriers.

3.2.1 Variation of acceleration versus time

This section details the variation in acceleration with dynamic time for all barrier materials used in sand. The acquired response is found to be sinusoidal in nature as the input load is sinusoidal in nature.

Figure 14 illustrates the acceleration versus time response of sand and all the chosen materials as infilled materials of piles in sand. All

materials exhibited a sinusoidal output response because the input data was sinusoidal. Figure 15 shows the acceleration-time response of all materials in sand at a frequency of 20Hz and a distance of 10 m from the pile. The figure clearly depicts that there is no benefit in using these isolation materials in sand. Moreover, this plot shows an inverse effect of the chosen isolation materials, with amplitudes

higher than those of sand alone. This can be because the damping of sand is lower as compared to clayey soil. Therefore, it can be comprehended that, even though the impedance ratio is low, the performance of infilled material has a great dependency on the damping property of the soil in which the waves need to be mitigated.

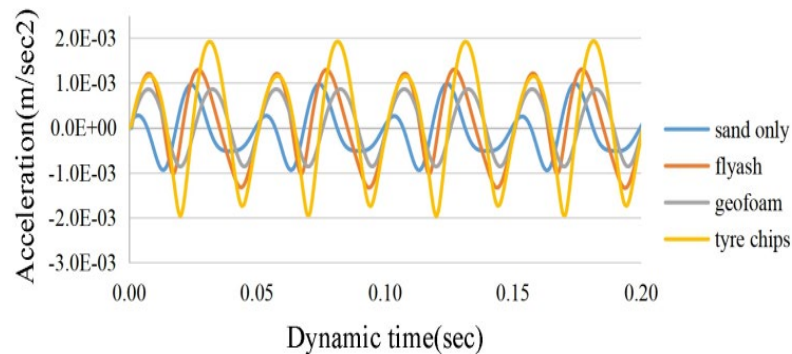


Figure 15 Variation of acceleration versus time at a particular frequency of 20Hz

3.2.2 Variation of maximum displacement with horizontal distance

Figures 16-19 illustrate the variation of displacement amplitudes with horizontal distance when sand alone, geo foam, fly ash and tyre chips

are being used as barrier materials. The pile barrier is located 10 m from the source, and the overall wave propagation up to 20 m is depicted in these figures. From the above plots, it is observed that as the waves pass through the barrier, the reduction in displacement amplitude is less pronounced in sand.

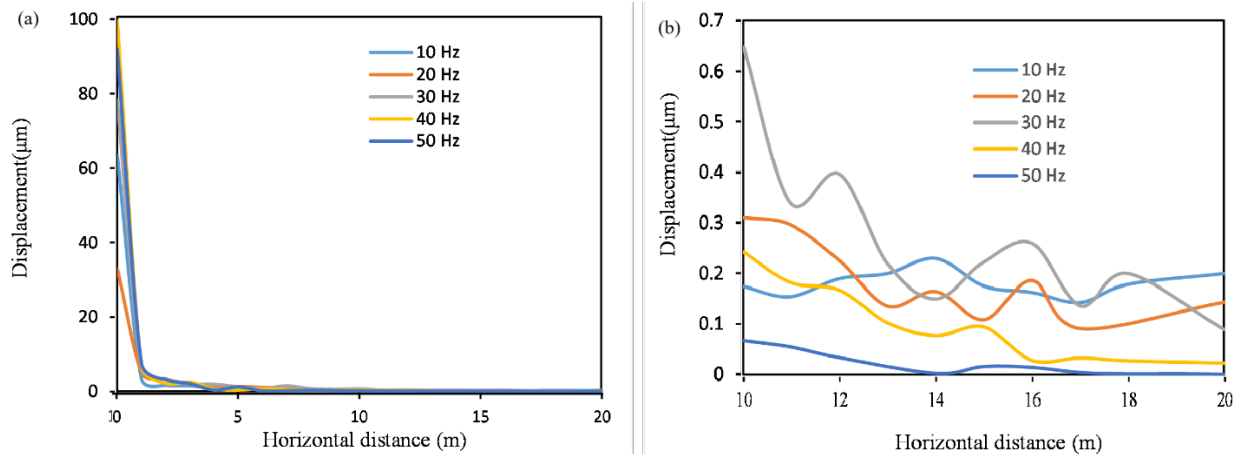


Figure 16 Variation of displacement along horizontal distance for sand
(a) 0 - 20 m horizontal distance (b) 10 - 20 m horizontal distance

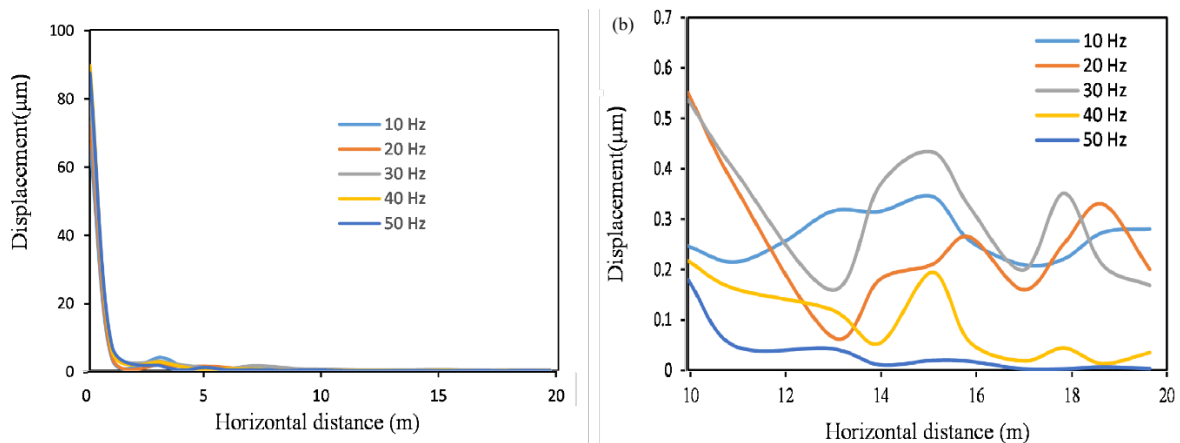


Figure 17 Variation of displacement along horizontal distance for fly ash piles in sand
(a) 0 - 20 m horizontal distance (b) 10 - 20 m horizontal distance

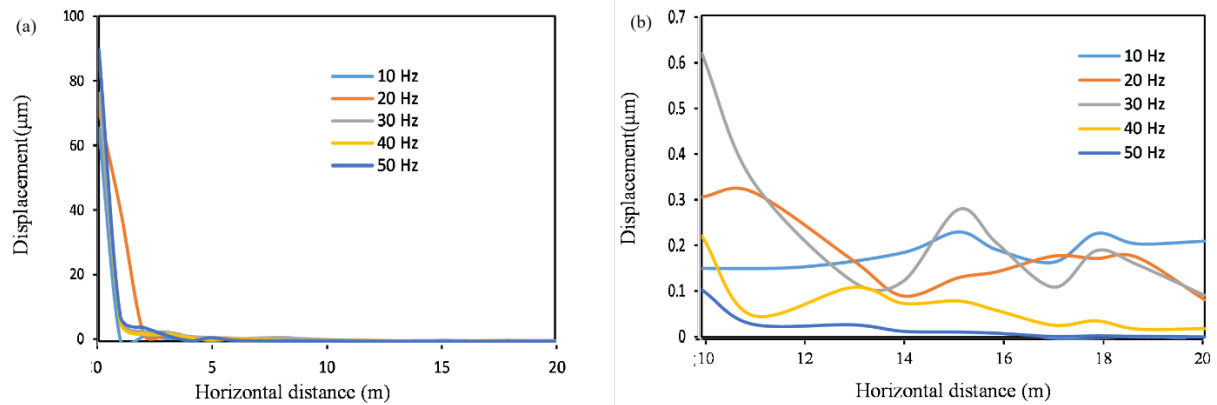


Figure 18 Variation of displacement along horizontal distance for geofoam piles in sand
 (a) 0 - 20 m horizontal distance (b) 10- 20 m horizontal distance

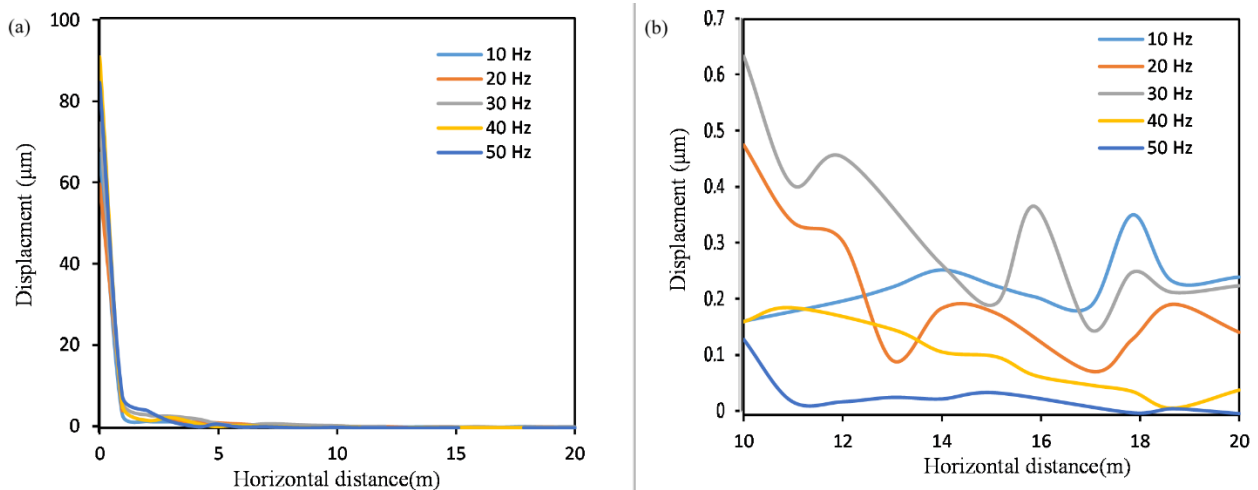


Figure 19 Variation of displacement along horizontal distance for tyre chips piles in sand
 (a) 0 - 20 m horizontal distance (b) 10 - 20 m horizontal distance

3.2.3 Amplitude reduction curves

Amplitude reduction curves are of great significance, as explained earlier, since they provide better insight into the screening efficacy of the materials used. The minimum amplitude reduction factor is 0.25, and Figures 20-22 show that these materials failed to meet this requirement. Therefore, the use of geofoam, fly ash, and tire chips as infilled materials in piles, when embedded in sand, is not recommended.

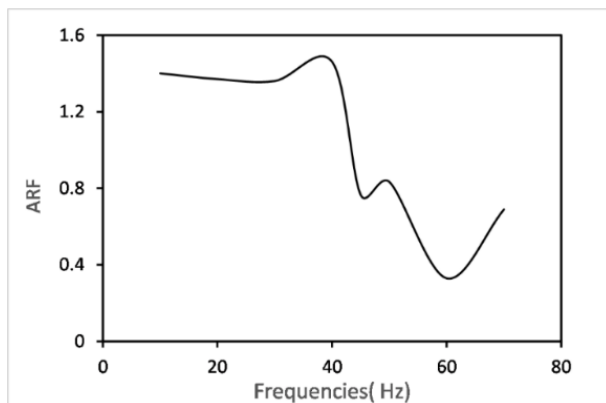


Figure 20 Amplitude reduction curve for fly ash piles in sand

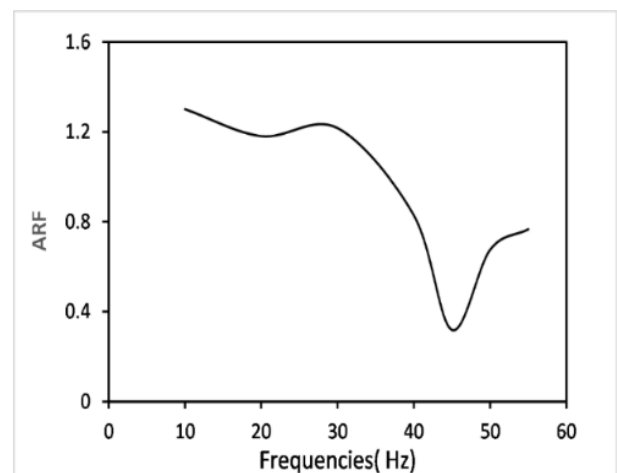


Figure 21 Amplitude reduction curve for geofoam piles in sand

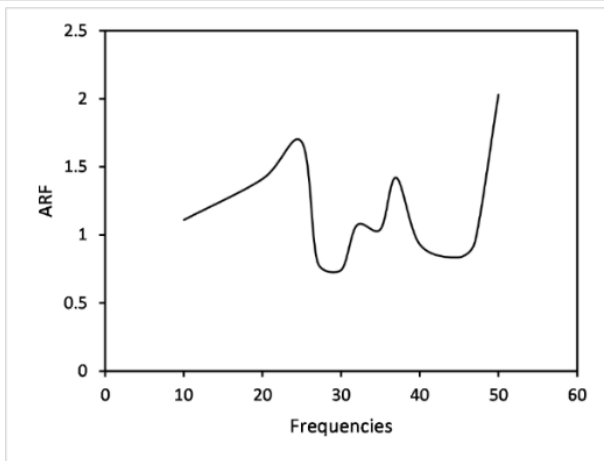


Figure 22 Amplitude reduction curve for tyre chips piles in sand

3.3 Comparative response of clay and sand with different materials

On comparing the performance of infilled materials in sand and clay, it is observed that all the chosen materials perform better in clay than sand. This can be due to high damping in clay. Figure 23 exhibits the comparative performance of fly ash in clay and sand. It is observed that in clay, fly ash exhibited an attenuation zone, whereas in sand it does not have much efficacy in mitigating waves. In sand, the efficacy of the infilled materials is not fulfilled, leading to mediocre performance.

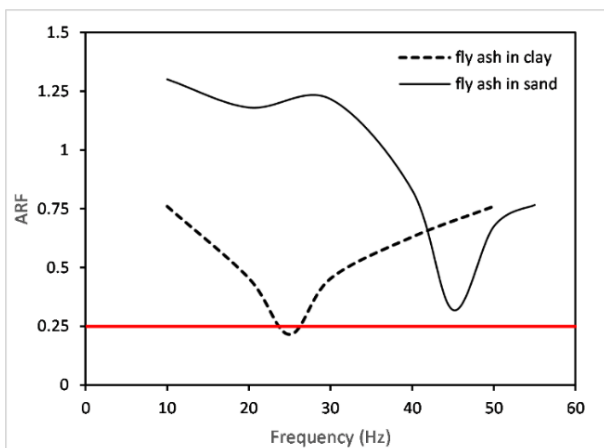


Figure 23 Comparative ARF versus frequency response of geofom in clay and sand

4 CONCLUSIONS

This study mainly focused on understanding the screening efficiency of piles infilled with geofom, fly ash, and tyre chips when embedded in clay and sand using PLAXIS 3D. The major conclusions of the study are as follows:

- The screening efficiency of periodic pile barriers does not increase with an increase in the number of piles, and this has to be optimized for better performance.
- The acceleration time response of all three infilled piles in clay has been studied and observed that geofom infilled piles exhibited better performance in clay as compared to other materials.
- The significance of impedance ratio is understood, and the study concludes that the lower the impedance ratio, the better the screening efficiency for a particular type of surrounding soil under dynamic loading.

- Amplitude reduction curves for geofom infilled piles in clay are more beneficial as they provide two attenuation zones.
- The analysis of infilled pile barriers in sand is analyzed and it is found that all three materials have not shown much efficacy in mitigating waves. In addition, tyre chips infilled piles in sand are affected negatively by increasing the amplitude as compared to sand alone.
- The damping properties of surrounding soil are as important as the impedance ratio in mitigating waves. Even though the impedance ratio is low, the soil's damping properties are significant, as high-damping soil absorbs more waves than low-damping soil.

Periodic pile barriers infilled with waste materials offer a unique, sustainable, and cost-effective solution for vibration mitigation. These pile barriers are a better option for deep and persistent vibration or when a more durable and low-maintenance solution is required. The incorporation of waste materials into pile barriers can reduce disposal costs and be considered an environmentally friendly solution if the waste material is non-toxic. Moreover, the infilled waste materials provide additional damping characteristics and can be customized based on the required vibration mitigation, soil type, and vibration characteristics. Unlike open trenches, this pile installation involves minimal surface disruption. Even if the waste material degrades over time, the pile itself remains stable, and the infilled material can be replaced or replenished as required.

However, there are certain downsides to using waste materials, such as potential degradation, settlement or compaction over time, and high installation costs. In addition, the waste materials used should be properly treated to prevent leaching and other contamination of surrounding soil or groundwater. These pile barriers seem to exhibit limited efficiency under high vibration, and long-term maintenance and monitoring are essential for their long life. Thus, utmost care should be given while choosing the waste materials for periodic pile barriers for vibration mitigation.

This study focused on utilizing waste materials in periodic pile barriers for mitigating waves, which not only protects the environment, but also makes the future more productive, sustainable, and efficient. Reusing waste materials seems to be a more appropriate solution than dumping tons of industrial waste into natural soil. For this purpose, the decision about utilized material should depend on the availability of material, potentiality of use, importance of nearby structures, and funding. For better efficacy, the preferred materials chosen as infilled materials should have high damping, low stiffness and low density. In addition, more investigations need to be conducted to comprehend the long-term efficiency of barriers in saturated and normal ground, the alteration in properties due to continuous wetting due to rain, leaching effect, etc. Regarding all these facts, concrete blocks are preferred by clients due to their high durability, despite being less effective at mitigating waves. This reduced mitigation of concrete blocks can be attributed to their low damping, which adversely minimizes performance. Hence, future studies can be extended by utilizing waste materials in construction activities by understanding their behavior in all aspects, further enhancing environmental protection. Similarly, studies can also be conducted to explore the waste materials that are beneficial as infilled materials for reducing wave propagation in sand.

5 REFERENCES

- Barkan, D. D. (1962). "Dynamics of Bases and Foundations". New York, NY: McGraw-Hill.
- Elchalakani, M. (2015). High Strength Rubberized Concrete Containing Silica Fume for the Construction of Sustainable Roadside Barriers. *Structures*, 1, 20–38.
- Eskandarighadi, M., Yarmohammadi, F., & Rafiee-Dehkharghani, R. (2022). "Vibration Isolation of Machine Foundations by Topology Optimization of Wave Barriers." *International Journal of Geotechnical Engineering*, 16(8), 1000–1012.

- G. Segol, P. C. Y. Lee, & J. F. Abel. (1978). "Amplitude Reduction of Surface Waves by Trenches". *Journal of Soil Mechanics and Foundations Division*, 104, 621441.
- Huang, J. K., & Shi, Z. F. (2013a). "Attenuation Zones of Periodic Pile Barriers and Its Application in Vibration Reduction for Plane Waves." *Journal of Sound and Vibration*, 332(19), 4423–4439.
- Huang, J., & Shi, Z. (2015). "Vibration Reduction of Plane Waves Using Periodic In-Filled Pile Barriers." *Journal of Geotechnical and Geoenvironmental Engineering*, 141(6), 04015018.
- Huynh, T. P., Ho, L. S., & Van Ho, Q. (2022). "Experimental Investigation on the Performance of Concrete Incorporating Fine Dune Sand and Ground Granulated Blast-Furnace Slag." *Construction and Building Materials*, 347, 128512.
- İstegün, B., Çelebi, E., Kırtel, O., Faizan, A. A., Göktepe, F., Zülfikar, A. C., & Navdar, M. B. (2023). "Mitigation of High-Speed Train-Induced Environmental Ground Vibrations Considering Open Trenches in the Soft Soil Conditions by In-Situ Tests." *Transportation Geotechnics*, 40, 100980.
- Juveria, F., Rajeev, P., Jegatheesan, P. & Sanjayan, J. (2023). "Impact of Stabilisation on Mechanical Properties of Recycled Concrete Aggregate Mixed with Waste Tyre Rubber as A Pavement Material." *Case Stud. Constr. Mater.* **18**, e02001.
- Kasiviswanathan, M., & Varatharajapuram Govindarajulu, K. (2023). "Experimental Study on Mechanical and Durability Properties of Fly Ash-Lime-Slag Block for Dry Stack Masonry Construction." *Journal of Materials in Civil Engineering*, 35(3), 04022479.
- Hoy, M., Horpibulsuk, S., & Arulrajah, A. (2016). "Strength Development of Recycled Asphalt Pavement–Fly Ash Geopolymer as a Road Construction Material." *Construction and Building Materials*, 117, 209–219.
- Kavand, A., & Khadangi, A. (2023). "Field Testing on Active Isolation of Vibrating Foundations in Middle-Frequency Range." *Construction and Building Materials*, 374, 130893.
- Klein, R., Antes, H., & Le Houédec, D. (1997). "Efficient 3D Modelling of Vibration Isolation by Open Trenches." *Computers & Structures*, 64(1-4), 809–817.
- Lei, L., Miao, L., Li, C., Liang, X., & Wang, J. (2021). "Locally Resonant Periodic Wave Barriers for Vibration Isolation in Subway Engineering." *KSCE Journal of Civil Engineering*, 25, 1239–1251.
- Malik, M. I., Mir, M. S., & Akhter, M. (2023). "A Synthesis on Utilization of Waste Glass and Fly Ash in Cold Bitumen Emulsion Mixtures." *Environmental Science and Pollution Research*, 30(7), 17094–17107.
- Meng, L., Cheng, Z., & Shi, Z. (2020). "Vibration Mitigation in Saturated Soil by Periodic Pile Barriers." *Computers and Geotechnics*, 117, 103251.
- PLAXIS 3D (2013) Manual for General Information, Reference and Scientific Manual.
- Prakash, S., & Puri, V. (1988). "Foundation of Machines: Analysis and Design." A Wiley Interscience Publication, John Wiley & Sons, New York.
- Pu, X., & Shi, Z. (2018). "Surface-wave attenuation by periodic pile barriers in layered soils." *Construction and Building Materials*, 180, 177–187.
- Pu, X., & Shi, Z. (2019). "Periodic Pile Barriers for Rayleigh Wave Isolation in A Poroelastic Half-Space." *Soil Dynamics and Earthquake Engineering*, 121, 75–86.
- Şenol, A., & Guner, A. (2023). "Use of Silica Fume, Bentonite, and Waste Tire Rubber as Impermeable Layer Construction Materials." *Advances in Civil Engineering*, 2023(1), 7301343.
- Silva, R. V., De Brito, J., & Dhir, R. K. (2019). "Use of Recycled Aggregates Arising from Construction and Demolition Waste in New Construction Applications." *Journal of Cleaner Production*, 236, 117629.
- Sivakumar Babu, G. L., Srivastava, A., Nanjunda Rao, K. S., & Venkatesha, S. (2011). "Analysis and Design of Vibration Isolation System Using Open Trenches." *International Journal of Geomechanics*, 11(5), 364–369.
- Tak, S., Gupta, P., Kumar, A., Sofi, A., & Yun, C. M. (2023). "Effect of Using Silica Fume as a Partial Replacement of Cement in Concrete." *Materials Today: Proceedings*.
- Tandon, K., Kumar, D., Ayothiraman, R., Manna, B., & Ramana, G. V. (2023). Numerical Evaluation of Tire Chips–Filled Trench Barriers for Effective Vibration Isolation." *Journal of Low Frequency Noise, Vibration and Active Control*, 42(1), 325–344.
- Tejas, S., & Pasla, D. (2023). "Assessment of Mechanical and Durability Properties of Composite Cement-Based Recycled Aggregate Concrete." *Construction and Building Materials*, 387, 131620.
- Woods, R. D. (1968). "Screening of Surface Waves in Soils." *Journal of Soil Mechanics and Foundations Division*, 94(4), 951–979.
- Woods, R. D., Barnett, N. E., & Sagesser, R. (1974). "Holography, a New Tool for Soil Dynamics." *Journal of Geotechnical Engineering*, 100(11), 1231–1247.
- Xia, T.-D., Sun, M.-M., Chen, C., Chen, W.-Y., & Xu, P. (2011). "Analysis on Multiple Scattering by an Arbitrary Configuration of Piles as Barriers for Vibration Isolation." *Soil Dynamics and Earthquake Engineering*, 31(3), 535–545.
- Yilmaz, A., & Degirmenci, N. (2009). "Possibility of Using Waste Tire Rubber and Fly Ash with Portland Cement as Construction Materials." *Waste Management*, 29(5), 1541–1546.