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Effect of Soil Types on Attenuation of Piled Induced Ground Vibration: Experimental and Numerical Study

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Abstract: Ground vibration induced by pile driving has become a major concern in the construction industry, mainly due to its negative impact on the structural health of surrounding structures. Therefore, it is necessary to estimate the level of vibration propagating to surroundings before processing the pile driving to avoid any adverse impact. Pile driving is usually done in different types of soils. However, experimental evaluation of ground vibration propagation and attenuation through different soil types is not feasible, both technically and economically. The objective of the current study is to investigate the ground vibration propagation and attenuation through different types of soil by using a numerical model, which is validated with experimental measurements.

A two-dimensional axisymmetric Finite Element Model (FEM) was developed by using Abaqus/CAE software. The boundary condition of the model was addressed by illustrating the application of non-reflecting boundary and fixed boundary. To minimize excessive mesh distortion during pile penetration into the soil, Arbitrary Lagrangian-Eulerian (ALE) adaptive mesh was used. The model was validated by comparing Peak Particle Velocities (PPVs) obtained from a full-scale field experiment for peat soil and laterite soil. The validated model was used to predict the ground vibration propagation and attenuation through different soil types: loess, silt, and sandy clay. A rate of vibration attenuation over a distance of 9 m was found to be 1.14 mms^{-1}/m, 0.66 mms^{-1}/m, 0.572 mms^{-1}/m, 0.5 mms^{-1}/m, and 0.41 mms^{-1}/m for laterite, loess, sandy clay, silt, and peat, respectively, indicating that among these five different soil types, the highest ground vibration attenuation was revealed by laterite soil while the least ground vibration attenuation was revealed by peat soil.

Keywords: Ground vibration, FEM, ALE adaptive mesh, Attenuation, PPV

1. Introduction

In the modern-day, rapid population growth and economic development have resulted in increased demand for urban infrastructure. However, new construction activities are often carried out near existing structures due to lack of available land. Hence, high-rise buildings are designed to make effective use of available space. These high-rise buildings are built on varying types of soils and are frequently supported by pile groups.

Piling causes high ground vibration than any other source of vibration. Pile-induced vibration can easily transmit through soil and eventually reach structures. The maximum response of the structure will mainly depend on the level of vibration reaching a building structure. Once the oscillations propagate through the structure, based on the intensity levels, the vibration can be felt by occupants (Avci et al., 2019 [1]) causing discomfort to the occupants and malfunctioning of sensitive equipment. This disrupts the activities carried out in the buildings (such as laboratory testing or operations in a hospital), and importantly, it causes damage to the structure (Massarsch et al., 2008 [2]). These effects depend on the pile driving method, soil type, pile hammer load, and the distance between the piles and nearby structures (Tavasoli et al., 2018 [3]).

The soil properties have an important role in the amount of wave attenuation. Wave attenuation during the wave propagation

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through the ground can be attributed to two components: geometric damping and material damping (Kim and Lee, 2000) [4]. The attenuation due to material damping depends on the physical soil parameters like soil type, grain size distribution, hardness (an indicator of soil compaction), and void ratio (Karmer, 1999 [5]).

Most of the investigations on ground vibration propagation is limited to experimental investigations (Kim and Lee, 2000 [4], Jayawardana et al., 2016 [6], Wanniarchchi et al., 2014 [7]). However, experimental analysis of ground vibration is not technically or economically feasible. Hence, numerical analysis can be used as an alternative and effective method to evaluate the severity of vibrations.

Using a program based on the Finite Element Method, various numerical studies have been performed and proven for the simulation of vibration propagation (Masoumi et al., 2007 [8], Khoubani et al., 2014 [9], Liyanapathirana et al., 2016[10]). The widely used formulae for approximating ground vibrations proposed by several researchers have limitations since they take into account only a few important vibration factors. Besides, it is important to evaluate the pile-induced ground vibrations before the pile driving process in different soil types, to make sure the effect of such vibrations in nearby structures.

The objective of this study is to investigate the effect of soil characteristics on the propagation of pile-induced ground vibrations, experimentally and numerically. A two-dimensional axisymmetric model was developed to simulate free-field ground vibration propagation and attenuation. This model was validated using a full-scale field experiment. Also, the model predicts the ground vibration at different distances from the source in different soil types.

2. Methodology

2.1 Experimental Analysis

2.1.1 Site Selection

Impact piling sites were chosen for measuring the ground vibration. The measurements were recorded in three radial directions at 6 m, 9 m, and 15 m distance, as illustrated in Figure 1. These distances were selected by considering the feasibility of conducting field measurements. Pile driving sites having two different soil types, namely, peat soils and laterite soils were selected for experimental investigations.

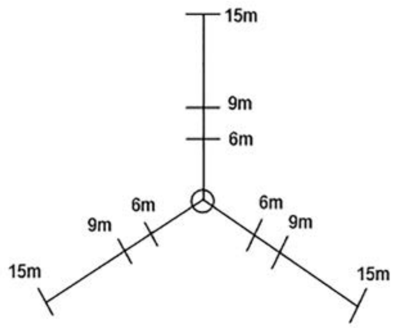


Figure 1 - Ground Vibration Monitoring Locations

2.1.2 Ground Vibration Measurement

A four-channel seismograph and a six-channel seismograph were used to take measurements in the field. Seismographs are capable of measuring vibration in the vertical (parallel to the pile driving), transverse, and longitudinal directions (perpendicular to the direction of pile driving), with a resolution of 0.127 mm/s in the frequency range of 2 Hz-250 Hz. Geophones were mounted on the ground and their ground spikes were inserted to a length of 65 mm. More details of measuring ground vibration induced by impacted pilling can be found in Subashi et al., 2020 [11].

2.2 Numerical Analysis

A finite element model was developed for the analysis of impact pile driving using the Abaqus/CAE software. Because of the possibility to utilize an accurate mesh, decreased convergence errors, and reduced computation time, 2D axisymmetric criteria were adopted.

2.2.1 Mesh and Geometry

The pile was defined as an analytical rigid surface with a single reference point for applying the load and relevant boundary conditions. The pile-soil interaction was generated when the pile was penetrating the soil. The pile tip was modeled as a conical surface with a diameter of 0.3 m.

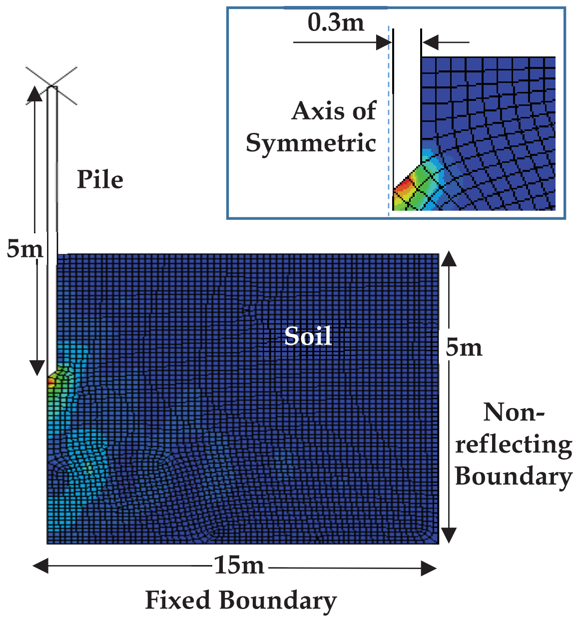


Figure 2 - Geometry and Boundary of the Model

The Arbitrary Lagrangian-Eulerian (ALE) method was used to simulate pile installation, which preserved mesh consistency during pile driving. The soil around the pile was modeled using four-node axisymmetric elements with reduced integration (CAX4R) because the ALE approach in Abaqus/Explicit is only applicable for linear components. The soil domain extends 15 m radially and 5 m vertically from the pile with a 0.02 m mesh size. It was assumed that the soil was in dry condition.

2.2.2 Soil-Pile Interaction

The relationship between the pile and the soil was defined using the master-slave, kinematic contact. The pile surface was chosen as the master surface, and the soil was chosen as the slave surface. The Coulomb friction model was developed to assume the tangential behavior of the soil–pile interface.

2.2.3 Loading and Boundary Conditions

Because this study was focused on wave propagation in the ground, it was necessary to include an effective simulation of infinite boundary conditions. The non-reflecting boundary at the end of the soil domain was simulated using infinite elements. Fixed boundary constraints were applied to represent the bedrock at the base. Figure 2 shows the boundary conditions of the model. The pile toe was initially positioned at the ground surface, and the reference node was used to apply sequential hammer hits to the pile head. The applied load of the pile was considered as 600kN during 0.01 s duration of impact. When pile driving happens, different types of waves are generated. The most significant is the Rayleigh wave, which propagates on the ground surface, outwards from the source. In this research, wave propagation was measured on the ground surface, so that only Rayleigh waves were considered for model validation and predictions.

2.2.4 Soil types and Material Properties

The elastic modulus of the pile is greater than the modulus of soil. To significantly reduce computational time, a rigid condition was assumed for a pile. A rigid body is a collection of nodes, elements, and/or surfaces whose motion is determined by the reference point motion of the rigid body (Khoubani et al., 2014 [9]). To apply the successive hammer impact load to this model, the reference point was created on top of the pile.

The soil domain was modeled with deformable surfaces. Material damping was a major consideration of this numerical model. Rayleigh damping coefficients, which provide a linear material attenuation, were used to apply material damping to the model in Abaqus. Rayleigh damping is given in Equation 1, where [C], [M], and [K] indicate the damping matrix, mass matrix, and stiffness matrix, respectively (Jayawardana et al., 2019 [12]).

$$[C] = \alpha\,[M] + \beta[K] \qquad \ldots(1)$$

Low-frequency behaviour was represented by mass proportional damping, whereas high-frequency behaviour was represented by stiffness proportional damping (Ekanayake et al., 2014 [13]). Two mass and stiffness constants were used in the Rayleigh damping method. They were known as α and β coefficients which depend on the soil profile. In the current study, the effect of the water table and porosity on the damping have not been considered.

The model was validated with the field measurements of ground vibration on peat soil and laterite soil. The validated model was used to predict ground vibration propagation through three other different soil types: silt, loess, and sandy clay.

2.2.5 Validation of Finite Element Model

The results of a full-scale experimental study were used to validate the FE model. The results of the field measurements and finite element model in terms of vibration attenuation were compared to verify that the numerical model simulates the similar field wave propagation. Due to the development of an axisymmetric model, only the lateral and vertical components of the particle vibration were compared.

The material properties found in Bowles, 1996 [14] were assigned to the model (Table 1). Peak Particle Velocity values (PPVs) of the ground vibration at 6m, 9m and, 15m distance from the pile centreline were validated with the experimental measurements. The velocity-time history of these relevant points was defined in the model to achieve the PPV value.

Table 1 - Properties of Laterite and Peat Soils

Properties	Laterite	Peat
Density (kg/m^3)	1920	1040
Poisson's ratio	0.32	0.35
Elastic modulus (MN/m^2)	30	2
Effective friction angle (degree)	41.9	17
Dilation angle(degree)	11.9	0
Cohesion (kPa)	10	12

Table 2 - Comparison of PPVs of Numerical and Experimental Analysis for Peat Soil

	Distance from the source		
	6m	9m	15m
Vertical direction			
Experimental PPV (mm/s)	3.531	1.969	0.923
Numerical PPV (mm/s)	3.794	1.980	0.637
Longitudinal direction			
Experimental PPV (mm/s)	3.019	1.755	1.122
Numerical PPV (mm/s)	3.003	1.650	0.907

For peat and laterite soils, a free field finite element model was validated by using experimental measurements. Table 2 compares the PPV values of experimental and numerical analyses for peat soil at distances of 6 m, 9 m, and 15 m, in the vertical direction and in the longitudinal direction. In peat soil, PPVs in the longitudinal direction are generally lower than in vertical direction. This may be possibly due to the lesser level of vibration magnitude induced by piling at the soil-pile interface of peat in the longitudinal direction than that in the vertical direction. As the pile is impacted in the vertical direction, a larger magnitude of vibration is expected in the vertical direction than in the longitudinal direction at the soil-pile interface.

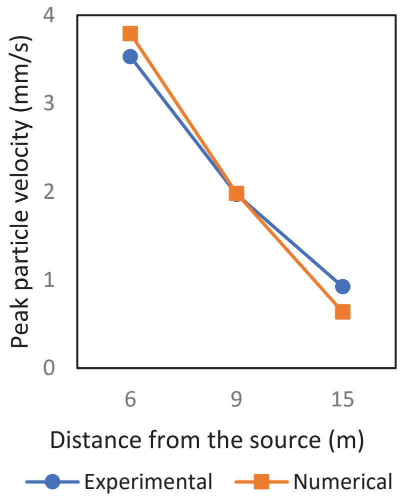


Figure 3(a) - Experimental and Numerical PPV of Ground Vibration for Peat Soil Measured in the Vertical Direction

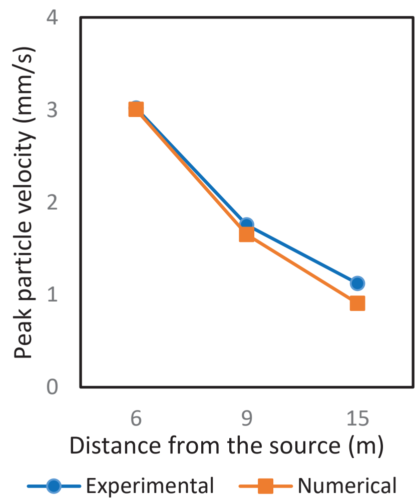


Figure 3(b) - Experimental and Numerical PPV of Ground Vibration for Peat Soil Measured in the Longitudinal Direction

PPV was defined as the maximum velocity that particles experience when applying the hammer impact. Figures 3(a) and 3(b) illustrate the comparison of PPV of peat soil in vertical and longitudinal directions, respectively. It can be seen that the numerical results and experimental results in Figures 3(a) and 3(b) are in good agreement, implying the model is validated for peat soil.

Table 3 shows a comparison of experimentally and numerically obtained PPV for laterite soils at distances of 6 m, 9 m, and 15 m from the source in the vertical direction and the longitudinal direction. Figures 4(a) and 4(b) illustrate the comparison of PPV of laterite soil in vertical and longitudinal directions, respectively.

Table 3 - Comparison of PPV of Ground Vibration for Laterite Soil Obtained by Numerical and Experimental Analysis

	Distance from the source		
	6 m	9 m	15 m
Vertical direction			
Experimental PPV (mm/s)	7.074	4.704	1.880
Numerical PPV (mm/s)	7.498	4.202	1.885
Longitudinal direction			
Experimental PPV (mm/s)	10.088	6.688	1.960
Numerical PPV (mm/s)	10.210	6.414	1.384

Material properties were assigned to the model as described in Table 1 for laterite soil and peat soil, while the loading conditions remained the same. Figures 4(a) and 4(b) confirm that PPV obtained from experimental measurements and numerical analysis is in good agreement. The numerical model developed in the current study was validated for peat and laterite soil at distances 6 m, 9 m, and 15 m from the source.

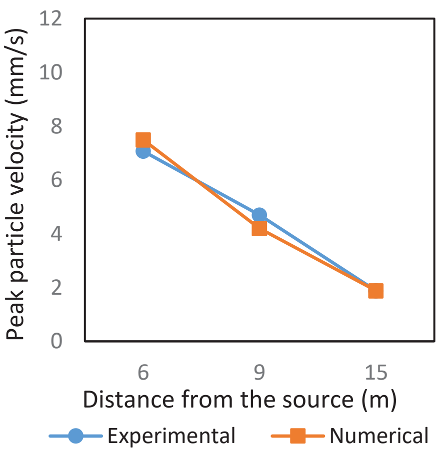


Figure 4(a) - Experimental and Numerical PPV of Ground Vibration for Laterite Soil Measured in the Vertical Direction

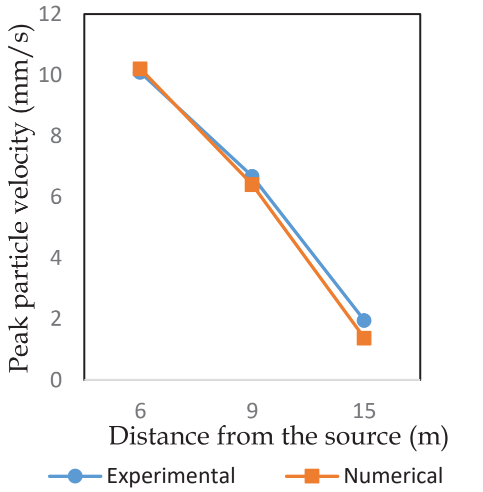


Figure 4(b) - Experimental and Numerical PPV of Ground Vibration for Laterite Soil Measured in the Longitudinal Direction

2.2.6 Free field ground vibration prediction by FEM

Free field ground vibration attenuation in different soil types was determined from the validated model. Table 4 shows the properties of the material that were assigned to the model (found in Bowles (1996) [14], Kim and Lee (2000) [4], Li (2018) [15], Li et al., 2020 [16]) to investigate the peak particle velocity induced by impact pile driving.

Table 4 - Properties of Investigated Soils

Properties	**Silt**	**Loess**	**Sandy Clay**
Density (kg/m^3)	1380	1690	1550
Poisson's ratio	0.31	0.24	0.28
Elastic modulus (MN/m^2)	15	22	20
Effective friction Angle(degree)	36.2	4	34.1
Dilation angle(degree)	6.2	0	4.1
Cohesion (kPa)	8	6	50

The model predictions were considered mainly at distances 6 m, 9 m, and 15 m from the pile centreline to compare the propagation and attenuation of ground vibration in various types of soil. For this comparison, a vector sum of PPV was considered as defined in Ekanayake et al., (2014) [13].

3. Results and Discussion

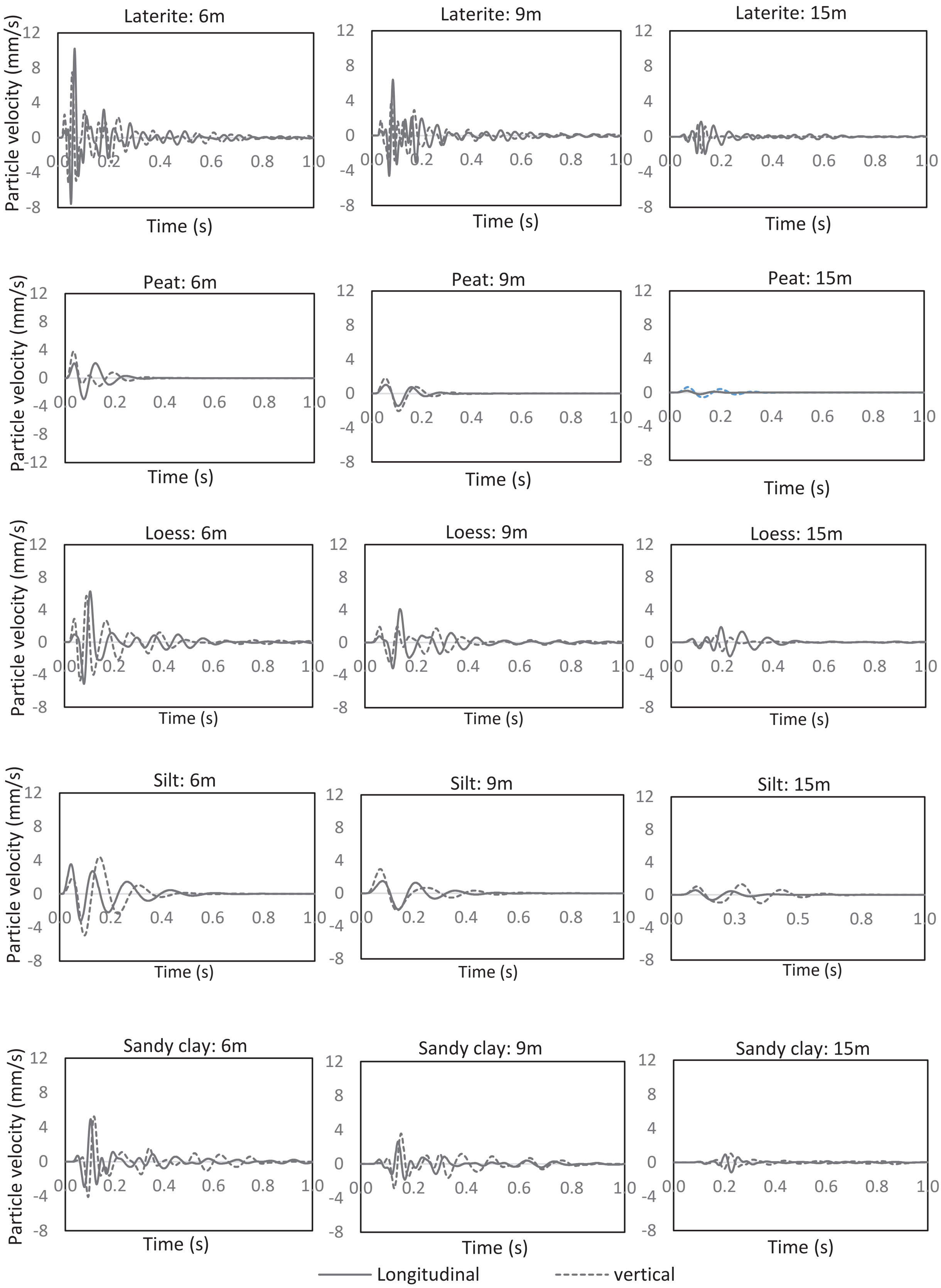


Figure 5 - Wave Propagation at Distance 6m, 9m and 15m in Five Different Soil Types: Laterite, Peat, Loess, Silt and Sandy clay

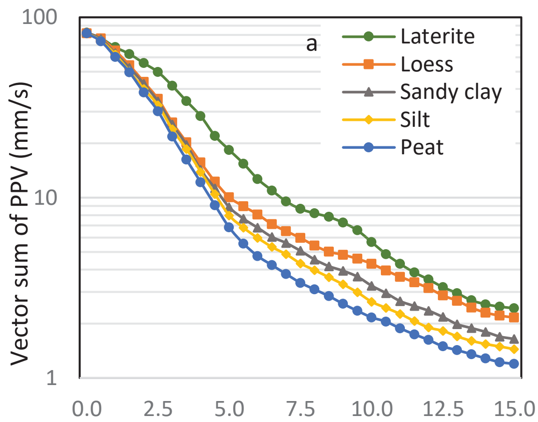
PPVs of ground vibration propagation in vertical and longitudinal directions obtained by FEM are shown in Figure 5. For each soil type, PPV reduces with increasing distance from the pile. At 6 m distance from the source, PPV of the ground vibration in the vertical direction is 3.528 mm/s, 3.794 mm/s, 4.933 mm/s 6.262 mm/s, and 7.498 mm/s for silt, peat, sandy clay, loess, and laterite, respectively (Table 5). For peat, with increasing distance from 6 m to 15 m, PPV velocity reduced from 3.794 mm/s to 0.632 mm/s, indicating 0.351 mm/s PPV attenuation per m. For silt, with increasing distance from 6 m to 15 m, PPV velocity reduced from 3.528 mm/s to 0.637 mm/s, indicating 0.321 mm/s PPV attenuation per m. The attenuation was found to be 0.416 mm/s PPV per m and 0.624 mm/s PPV per m for sandy clay and laterite soil, respectively, indicating that laterite soil shows better performance in attenuating the vibration propagation.

A similar rate of attenuation of ground vibration in the longitudinal direction was observed. Over the distance 6-15 m, the attenuation rate of PPV per m distance is 0.233 mm/s, 0.406 mm/s, 0.489 mm/s, 0.512 mm/s, and 0.981 mm/s for peat, silt, sandy clay, loess, and laterite soil, respectively, indicating better attenuation of ground vibration by laterite soil than all other soils investigated. The high stiffness of laterite soil might have contributed to enhanced attenuation and reduced transmission of the vibration.

The model predicted vibration attenuation (in terms of the vector sum of the PPV) over the distance from 0-15 m were compared for five different soil types: peat, silt, sandy clay, loess, and laterite (Figures 6 (a) and (b)). Figure 6(a) presents PPV in logarithmic scale over the distance 0-15 m, while Figure 6(b) presents PPV in linear scale over the distance 6-15 m. For all soil types, the vector sum of PPV decreases with increasing distance from the source (Figures 6(a) and 6(b)). The vector sum of the PPV attenuated at a rate of 1.14 mms^{-1}/m, 0.66 mms^{-1}/m, 0.572 mms^{-1}/m, 0.5 mms^{-1}/m, and 0.41 mms^{-1}/m for laterite, loess, sandy clay, silt, and peat, respectively, indicating the efficiency of laterite soil in attenuating ground vibration. With the distance, the attenuation rate of ground vibration is highest in laterite soil, whereas it was least in peat soil.

Table 5 - Effect of Soil Type on PPVs of Ground Vibration

Distance from the pile centreline	Peak Particle Velocity (mm/s)		
	6m	9m	15m
Vertical direction			
Laterite	7.498	4.202	1.885
Peat	3.794	1.980	0.637
Loess	6.262	4.100	1.868
Silt	3.528	1.979	0.637
Sandy clay	4.933	2.631	1.181
Longitudinal direction			
Laterite	10.210	6.414	1.384
Peat	3.003	1.650	0.907
Loess	5.707	2.539	1.099
Silt	4.950	2.953	1.299
Sandy clay	5.253	3.561	1.034



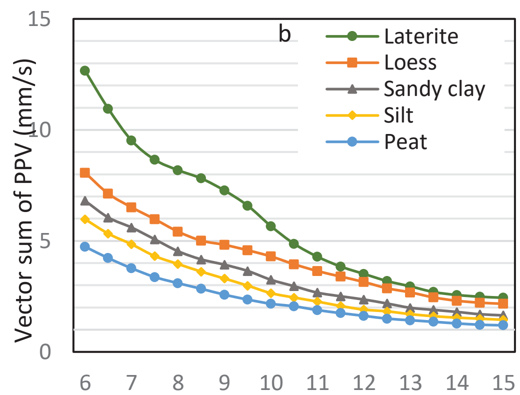


Figure 6 - PPV of the Ground Vibration With Distance From the Source for Different Soil Types (a) Logarithmic Scale Presentation From 0-15 m Distance (b) Linear Scale Presentation From 6-15 m Distance

Vibration reduction was attained by increasing the stiffness, often expressed by storage modulus, of the material (Jayawardana et al., [6], Chung [17]). For example, it was found that bottom ash was effective in screening vibration in all three directions due to its high stiffness (Jayawardana et al., [6],), metals and polymers due to their high viscoelasticity (Chung [17]).

The model developed and validated in the current study can predict wave attenuation during propagating the waves through different types of soil. The magnitude of wave predicted as PPV by the model at a location where the structure is, can be compared with the permissible PPV level for different structures, specified in standards. The determination of PPV before pile driving is important to prevent or mitigate detrimental effects on nearby structures and occupants.

4. Conclusions

The effect of soil type on propagation and attenuation of the ground vibration induced by pilling was investigated experimentally and numerically for laterite and peat soils. The FE model was validated with field measurements and used to predict the vibration propagation through different soil types: peat, loess, silt, sandy clay, and laterite.

In the vertical direction, PPV attenuation per m was found to be 0.416 mm/s, 0.624 mm/s 0.351 mm/s, 0.321 mm/s for sandy clay, laterite, silt, and peat, respectively, indicating that laterite soil shows better performance in attenuating the vibration propagation.

In the longitudinal direction, over the distance 6-15 m, the attenuation rate of PPV per m distance is 0.233 mm/s, 0.406 mm/s, 0.489 mm/s, 0.512 mm/s, and 0.981 mm/s for peat, silt, sandy clay, loess, and laterite soil, respectively, indicating higher stiffness of laterite soil contributing to the attenuation of ground vibration.

A rate of attenuation over the distance of 9 m was found to be 1.14 mms^{-1}/m, 0.66 mms^{-1}/m, 0.572 mms^{-1}/m, 0.5 mms^{-1}/m, and 0.41 mms^{-1}/m for laterite, loess, sandy clay, silt, and peat, respectively, confirming the efficiency of laterite soil in attenuating ground vibration.

To reduce the adverse impact on the surrounding structures, it is necessary to evaluate the level of vibration before commencing pile driving. The numerical simulation of pile driving developed in this study will be useful to predict the attenuation characteristics of different soil types and overcome vibration-related structural damage and people's complaints during pile driving in civil engineering construction sites.

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