Use of in-filled trenches to screen ground vibration due to impact pile driving: experimental and numerical study

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Abstract

Vibration generated by pile driving can cause discomfort to occupants of nearby buildings and disturb the activities carried out in the buildings. The transmitted vibration will depend on both the source and the transmitting medium (soil), while the acceptable levels of vibration will depend on the receiver characteristics. Existing structures in which some sensitive processes are ongoing such as hospitals and laboratories can easily be affected due to the received vibration. Introducing a trench into the path of wave propagation has become one of the solutions. There is however little experimental data available on the effects of trenches to screen such ground borne vibration, especially that caused by pile driving. This paper describes a series of experiments conducted to investigate the characteristics of impact pile induced vibrations and the effect of coal bottom ash filled trenches to screen this vibration. In addition to experimental testing, numerical simulations are also carried out using validated model to examine the effects of in-fill material, impact load, soil characteristics

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and distance from the source to the trench on the vibration screening ability. The results of the field experiments and the numerical study are analysed and interpreted to provide guidelines for future research and design.

Keyword: Civil engineering

1. Introduction

Ground vibration from piling is inevitable during infrastructure developments in urban cities. In order to maximize the land usage, tall and heavy super structures are being constructed in urban cities in the vicinity of inhabitants and users of buildings. These building structures are mostly founded in soft soils and often supported by groups of piles. Relatively high ground vibration is induced by piling compared with the other source of vibration. Velocity magnitudes of the ground vibration from piling can vary from mild (0.7 mm/s for press-in piles), moderate (8.3 mm/s for vibratory piles) to severe (15.2 mm/s for impact piling by a diesel hammer) [1]. Once these vibration waves are generated, they are easily transferred through the soil media and eventually reach structures and cause discomfort to the occupants, disturb the activities carried out in the buildings (such as laboratory testing or operations in a hospital) and at times cause damage to the structure. Vibrations which originate from the impact piling (or pile driving) are difficult to determine and costly to mitigate. In response, regulatory authorities are compelled to impose restrictions on the use of impact pilling or to use alternative foundation methods since there is a lack of knowledge to assess the risk of vibration caused by pile driving [2].

Impact pile driving involves dropping a large mass from a particular height on top of a precast pile. The generated energy penetrates the pile into the soil but this process generates high noise levels and high impact forces on the surroundings that may not be suitable for the structures in urban areas. As shown in Fig. 1, pile driving generates body waves (P-waves) that originate from the pile toe, expanding outwards with a spherical wave front. Similarly, shear waves (S-waves) emanate from shaft friction, expanding around a cylindrical surface and Rayleigh waves (surface waves) propagate along the ground surface. However, ground vibration propagation is more complex in situations where layered soil profiles cause additional waves due to reflections and refractions at layer boundaries [3].

Ground excitation from other sources, such as, urban traffic (railway and road), machine foundations, blasting are also severe and have the potential to cause annoyance to residents and inflicting damage to structures. Low frequency vibration in the frequency range of 1—80 Hz is perceived by residents as whole body feel-able vibration whereas higher frequency vibration in the range 16—250 Hz is radiated as ground borne noise [4]. Damage to a structure is often indexed by the parameter “Peak Particle Velocity (PPV)” [5, 6], as a result, most of standards and codes of practice
prescribe permissible vibration limits using PPVs at spectral frequencies. PPV is a measurement of maximum ground particle movement speed which can be measured in all three orthogonal directions. Seismologists however use acceleration levels to quantify damage potential [7]. There is no commonly recognized standard for limiting ground vibration that is received by buildings. Threshold limits for transient ground vibration published by several standards are compared in Table 1. It can be seen that irrespective of the source of vibration, velocity amplitudes should be reduced to be around 2 mm/s for historical and important structures including hospitals, schools and universities. Generally, the limiting value for domestic areas varies between 5–20 mm/s depending on the frequency of vibration. Further, industrial buildings that mostly consist of steel or concrete frames have higher limits (between 20–50 mm/s) compared with other structures. Johnson and Hannen [8] point out that scientific explanations for limits of vibration are limited and many recommendations are based on the general experiences and judgments. A comprehensive standard with the limits of vibration is yet to be established considering the ambient vibration levels in the buildings, human perception levels, environmental effects and research studies.

In order to achieve the levels of ground vibration specified in standards, effective and efficient methods of screening the ground vibration is a growing concern. Ground vibration can be reduced by decreasing dynamic loads from the construction source [16]. Continuing this idea Massarsch and Fellenius [2] recommend to reduce hammer drop height, use of shorter piles, pre-boring and water jetting to reduce ground vibrations. However, such precautions may not be applicable in most cases due to the nature of the construction industry. Therefore, it is often suggested that

![Fig. 1. Mechanisms of energy transfer from pile.](image-url)
vibration can be screened using trenches [17]. This concept is attractive, but the execution of an effective trench system is difficult and expensive. The principle of operation of a trench is to reflect wave energy back towards the source or absorb the energy while preventing the energy from propagating beyond the trench towards a target building or other vulnerable structure or location.

Open trenches have been identified as the most effective wave barriers for screening ground vibration [18, 19, 20]. An effective wave barrier must be at least two-thirds of a wavelength to screen a seismic surface wave. For practical applications, the introduction of open trenches has several limitations. It is often difficult to install and maintain open trenches to the required depth and width due to localized collapse of the trench walls, safety issues and accidental filling due to rain or construction activities [21]. It is hence necessary to consider in-filled trenches.

In-filled trenches with appropriate sizes have found to be effective, but in no case as effective as an open trench of the same size [17]. When ground vibration waves travel through the trench, two media with different impedance are met. At this interface, the waves will undergo mechanisms such as reflection, refraction, scattering,

| Standard | Dominant excitation frequency (Hz) | Peak Particle Velocity (PPV) (mm/s) |
|----------|-----------------------------------|-----------------------------------|
|          | Domestic houses | Industrial building | Objects of historic importance and sensitive structures |
| German standards | <10 | 5 | 20 | 3 |
| DIN 4150-3 [9] | 10—50 | 5—15 | 20—40 | 3—8 |
| AASHTO [10] | Not defined | 5.1 | 25.4 | 2.5 |
| Swiss standards | 10—60 | 13.7 | 30.5 | 7.6 |
| SN 640 312,1978 [11] | 60—90 | 12.7—17.8 | 30.5—40.6 | 7.6—12.7 |
| USBM RI 8507 [8] | <10 | 12.7 | Not defined | Not defined |
| BS 7385-2 [12] | 10—40 | 12.7—50.8 | Not defined | Not defined |
| DGMS (INDIA) Buildings/structures not belong to the owner | <8 | 5 | 10 | 2 |
| DGMS (INDIA) Buildings belonging to the owner with limited span of life | 8—25 | 10 | 25 | 5 |
| DGMS (INDIA) Buildings belonging to the owner with limited span of life | >25 | 15 | 25 | 10 |
| CMRI Standard [14] | <24 | 5 | 12.5 | 2 |
| USSR [15] | Not defined | 30 | 60 | 30 |
and diffraction of wave energy. Wave barriers can exist in the form of solid, fluid and void in the ground. At a solid-solid interface, both P and S waves are transmitted; in solid-fluid interface, only P waves are transmitted while in solid-void interface, no waves are transmitted [22]. Thompson et al. [4] argue that the stiffness per unit area of the trench is the dominant parameter and not its impedance as examined by Massarsch [23]. A study conducted by Zoccali et al. [24] based on the mitigation capacity of an in-filled trench for train-induced ground vibration concluded that increment trend is strongly influenced by the properties of in-fill material used. Further, Zoccali et al. [24] stated that concrete is currently the best material to use, but in some frequency ranges it can actually increase the vibration levels and therefore this should be analyzed based on critical frequencies of the receiver. Although a concrete in-filled wave trench could effectively screen ground vibration, it would not be a cost effective method, especially for the ground vibration induced by construction activities, as the requirement is only during the period of construction. Ekanayake et al. [25] investigated the efficiency of water and geofoam as fill materials and summarized that geofoam is a more effective fill material for ground vibration attenuation. As the literature describes, the efficiency of a trench is not only a simple function of the in-fill material but also the properties of source, trench geometry and transmitting soil medium.

In the current study, characteristics of the ground vibration induced by the impact piling are first investigated experimentally. The effect of a trench filled with coal bottom ash that is rich with cementations properties [26] and the trench dimensions on screening the ground vibration are then analysed experimentally. Later, a numerical model is developed and validated using the present experiment data and then used to investigate the effect of the type of in-fill material, vibratory source, soil medium and location of trench on vibration screening. Results from the experimental and numerical studies are reviewed and the major findings summarised to aid future research and inform design.

2. Experimental

2.1. Set-up of field tests

An impact piling site that was conveniently located, was selected to conduct the experimental study. The impact load, which had a weight of 5 tons (49.05 kN), was dropped from approximately 3 m above the ground on to a reinforced concrete pile top. Varying distances (i.e., 5 m, 10 m, 15 m and 25 m) from the source along three radial directions (Fig. 2) were selected for measuring the ground vibration. The soil type of the site is identified as poorly graded sand (SP) according to the USCS [27] soil classification.
A vibration damping layer was introduced by using a trench filled with uncompacted coal bottom ash across the path of the wave propagation. A trench was excavated 6 m away from the source as indicated in Fig. 3 and its widths and depths were varied as shown in Table 2. First the width of the trench is varied keeping the depth as 50 cm. Then the depth is changed from 50 cm to 100 cm while the width of the trench was kept constant at 30 cm. This distance was selected by considering the feasibility of conducting the field measurements. The depths(s) and width(s) of the

![Fig. 3. Arrangement of the trench.](image)

| Dimension  | Size (cm) |
|------------|-----------|
| Width (W)  | 30        | 60        | 90        |
| Depth (D)  | 50        | 75        | 100       |

![Table 2. Variation of trench width and depth.](image)
trench were selected based on the site conditions. The length of the trench was fixed at 1.2 m. The trench was completely filled with coal bottom ash prior to measuring the ground vibration. Coal bottom ash, which is a waste material from coal power production, was collected from Lak Vijaya Coal Power Plant located in the North-western province of Sri Lanka. It is a hard and light-weight material, often identified as a good alternative for sand [28] and cement [29]. Since the locations of the source and the trench were the same during the measuring period (though its width and depth were varied), it was assumed that constant site conditions were maintained during vibration measurements.

A six channel seismograph (Minimate pro 6) with two geophones and a four channel seismograph (Blastmate III) with one geophone were used to monitor the ground vibration. The geophones were installed in such a way that the transverse direction was parallel to the length of the trench and the longitudinal direction was perpendicular to the trench. The arrangement of the trench and the instrumentation for vibration measurement are shown in Figs. 3 and 4, respectively.

Seismographs are capable in measuring vibrations in the traverse, vertical and longitudinal directions up to 254 mm/s with a resolution of 0.127 mm/s in the frequency range 2 Hz–250 Hz. The geophones were placed on the ground and their ground spikes were inserted (length of the spike is 65 mm) into the ground. Before measuring, they were programmed to record vibration in a continuous mode and fixed time stop mode. Arrow marks located on the top of the geophones were pointed towards the direction of the source.

2.2. Analysis of results

Magnitudes and range of frequencies of impact pile induced ground vibration were determined from the field measurements. In the three radial directions, maximum Peak Particle Velocities (PPVs) at each location were determined and average PPVs were calculated. The dominant frequency at each geophone location along the three radial directions were determined and maximum and minimum frequencies

Fig. 4. Experimental set-up for measuring ground vibration.
were extracted and then represented as the range of frequencies. The effectiveness of the in-filled trench dimensions was quantified by using Root Mean Square (RMS) value of the ground vibrations measured in-front of the trench (L1) and behind the trench (L2) (Fig. 3).

For each ground vibration, the acceleration ($a_i$) was determined from the records of ground velocity by using Eq. (1).

$$a_i = \frac{(v_{i+1} - v_i)}{\Delta t}$$

(1)

Where, $v_i$ and $v_{i+1}$ are particle velocity readings at time step $i$ and $i + 1$, respectively, and $\Delta t$ is the sampling time (i.e., 1/1024 s).

The Root Mean Square (RMS) of particle acceleration in each ground vibration was determined by using Eq. (2).

$$RMS = \sqrt{\sum_{i=1}^{n} \frac{a_i^2}{n}}$$

(2)

In Eq. (2), $a_i$ is the acceleration value of a particular time step and $n$ is the number of steps within the measured time period.

The percentage of reduction in ground acceleration was determined as the damping percentage as shown in Eq. (3). The ground acceleration at location L1 was not a unique value. Therefore, waveforms with similar ground accelerations at L1 were considered to determine the effectiveness of the in-filled trench in terms of damping percentage.

$$Damping\ percentage = \frac{RMS\ of\ acceleration\ at\ L1 - RMS\ of\ acceleration\ at\ L2}{RMS\ of\ acceleration\ at\ L1}$$

(3)

3. Results

3.1. Characterises of ground vibration induced by impact piling

Average Peak Particle Velocities (PPVs) of ground vibration in the transverse, vertical and longitudinal directions are compared in Fig. 5.

Along all three orthogonal, PPV decays with the distance from the source, as expected. In the near field (i.e., closer to the source) magnitude of the vertical vibration is greater than that in the other two directions: transverse and longitudinal. At 10 m distance from the source, the magnitudes of vibration in the vertical, transverse and longitudinal directions are closer with 4.41 mm/s, 2.67 mm/s and 3.36 mm/s, respectively. The differences in magnitude of vibration in the three directions (i.e., vertical, transverse and longitudinal) decrease with increasing distance from the vibration.
They merge at about 20 m from the source and no significant difference in the vibration magnitude could be found at about 25 m (i.e., far field).

The Fast Fourier Transforms (FFT) of the ground vibrations at 5 m, 10 m, 15 m and 25 m from the source in all three directions (shown in Fig. 2), caused by impact piling were obtained. Since the vibrations characteristics along all three directions were similar, data only along a single radial direction is shown in Fig. 6. It can be seen that the frequency range of the vibration is contained within quite a broad band from 2–30 Hz. This falls within the frequency range of 1–80 Hz which is perceived by residents as whole body feel-able vibration [30].

![Graph showing average PPV variation with distance](https://doi.org/10.1016/j.heliyon.2018.e00726)

**Fig. 5.** Average PPV variation with the distance in vertical, transverse and longitudinal directions.

![Graph showing dominant frequencies of ground vibration](https://doi.org/10.1016/j.heliyon.2018.e00726)

**Fig. 6.** Dominant frequencies of ground vibration induced by impact piling at (a) 5 m, (b) 10 m, (c) 15 m and (d) 25 m distances from source along one direction.
3.2. Effect of width of trench filled with coal bottom ash

In order to evaluate the effect of trench width, an experimental study was conducted by varying the trench width as 30, 60 and 90 cm while keeping the depth as constant (50 cm). Fig. 7(a)—(c) compare the ground vibrations at L1 (in front of the coal bottom ash in-filled trench) and L2 (behind the coal bottom ash in-filled trench) for a trench having a width of 30 cm and depth of 50 cm measured in the transverse, vertical and longitudinal directions, respectively. Figs. 8 and 9 similarly compare the ground vibrations before and after the trench (widths of 60 and 90 cm) in the three orthogonal directions. It is evident that the in-filled trench provides some degree of damping to the vibration in all three directions. The damping is more pronounced in the transverse direction than that in the other two directions. The damping of the vibration in all three directions seems to increase with the trench width. To capture these effects, the variations of damping percentages in the transverse, vertical and longitudinal directions with the trench width are compared in Fig. 10. For trench widths of 30 and 60 cm, the transverse vibration is most damped while for the trench width of 90 cm, the longitudinal vibration seems to be most damped. It can be seen that the presence of coal bottom ash in the trench reduces the ground vibration in all three directions when the trench width is increased from 30 cm to 60 cm. This trend...
continues for the vertical and longitudinal vibrations, but the damping percentage in the transverse direction decreases dramatically when the width increases to 90 cm.

In the vertical direction, the RMS of ground acceleration is reduced by 2 %, 8 % and 14 %, for trench widths of 30 cm, 60 cm and 90 cm respectively. In the longitudinal direction these reductions are 3 %, 23 % and 31 % respectively. Although a clear trend in reduction in ground vibration was not observed in the transverse direction, the RMS of ground acceleration has been reduced by 52 %, 53.5 % and 20 % for trench widths of 30 cm, 60 cm and 90 cm, respectively.

3.3. Effect of depth of trench filled with coal bottom ash

Figs. 11, 12, and 13 compare the wave form at L1 (in front of the coal bottom ash in-filled trench) and L2 (behind the coal bottom ash in-filled trench) for trenches with depths of 50 cm, 75 cm and 100 cm, respectively. Here, the width of the trench is...
kept constant at 30 cm. The variation of maximum damping percentage in transverse, vertical and longitudinal with depth of the trench is compared in Fig. 14.

From these Figures, it can be seen that for both vertical and longitudinal vibrations, the damping increases with trench depth. This trend seems to be reversed for the transverse vibration. In the vertical direction, ground acceleration has been reduced by 2%, 5% and 7% for trench depths 50 cm, 75 cm and 100 cm respectively. These reductions are 3%, 5% and 11% in the longitudinal direction for trench depths of 50

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Fig. 11. Variation of ground vibration in (a) transverse (b) vertical and (c) longitudinal directions monitored at L1 and L2 for a trench of 30 cm width and 50 cm depth.

Fig. 12. Variation of ground vibration in (a) transverse (b) vertical and (c) longitudinal directions monitored at L1 and L2 for a trench of 30 cm width and 75 cm depth.

Fig. 13. Variation of ground vibration in (a) transverse (b) vertical and (c) longitudinal directions monitored at L1 and L2 for a trench of 30 cm width and 100 cm depth.
cm, 75 cm and 100 cm, respectively. In the transverse direction, ground acceleration has been reduced by 52% and 41% for trench depths of 50 cm and 75 cm respectively. The trench with a depth of 100 cm was unable to damp the transverse ground vibration, despite a few trials. This could be due to an experimental error.

4. Model

The experimental investigation is complemented and supplemented by a numerical study on the effects of in-fill material, impact force, distance of trench from source and soil property on the ground vibration. Towards this end, the experimental investigation is simulated in an axisymmetric model (Fig. 15) utilising the Abaqus FE software and the modelling techniques are first validated. The soil type of the site is identified as poorly graded sand (SP) according to the USCS soil classification [27] and soil properties are selected as in the literature (Table 3). Rayleigh damping parameters are calculated utilising the method adopted in Zerwer et al. [31]. The soil media is modelled as an elastoplastic material with Mohr-Coulomb plasticity. Axisymmetric conditions is applied to model and 0.25 m uniform mesh elements (CAX4R) are selected for the model. Infinite elements (CINAX4) are utilised to simulate a non-reflecting boundary as the far field condition, as shown in Fig. 15.
As in the experiments, a trench is introduced at 6 m away from the source of excitation to evaluate its efficiency on vibration screening.

Prior to impact loading, gravity loading is applied to the soil elements to establish the in situ conditions. In this study, explicit scheme is used because it is suitable for high speed dynamic events such as in stress wave propagation [32]. For modelling, the impact force is calculated equating the change of momentum (MV) of the dropping weight to an impulse, with a triangular force time history and assuming an impact duration of 80 ms as shown in Fig. 16. The load is pointed directly on to the surface along the axis of symmetry. The time history for one second is considered and data is extracted at each 0.001 s interval resulting in 1000 data points.

4.1. Model validation

The model is validated by comparing the numerical results with those from the experimental study. Since an axisymmetric model is developed, only the longitudinal and vertical components of the particle vibration are compared. Material properties are listed in Table 3. Fig. 17 shows the comparison of FE model and experimental results of PPV of the free field with the distance from the source and it is evident that the two sets of results compare reasonably well. The trench filled with coal bottom ash is then introduced with the coal bottom ash modelled as linear elastic material with Mohr-Coulomb plasticity. The damping percentage for each trench configuration is obtained by using the RMS values of accelerations.

Table 3. Soil and Coal bottom ash properties [33, 34, 35, 36, 37, 38].

| Material Property          | Soil     | Coal bottom ash |
|----------------------------|----------|-----------------|
| Density (kg/m³)            | 1950     | 2320            |
| Young’s modulus (MPa)      | 150      | 18              |
| Poisson’s ratio            | 0.20     | 0.25            |
| Friction angle (degrees)   | 35       | 37              |
| Cohesion (kPa)             | 0        | 6               |

Fig. 16. Time history curve of impact load.
at the nodes where the geophones were located in the experiment. The damping percentages of different trench configurations obtained from the FE model and experimental results are illustrated in Fig. 18. It can be seen that the FE model results follow the same trends as the field test data with slight discrepancies. This may be due to the non-homogeneous and 3D nature in the experimental site. Overall, from Figs. 17 and 18 it can be concluded that the FE model results are in a reasonable agreement with the experimental data and the model is capable of simulating the ground vibration propagation and attenuation.

5. Results and discussion

The process of ground vibration propagation and mitigation with trenches involves many parameters. A sensitivity analysis is therefore performed to identify the effects of some of the controlling parameters on vibration propagation and ground barrier performance. The parameters used in the sensitivity analysis are presented in Table 4. In order to have proper comparison of results, an infilled trench having a

![Fig. 17. Comparison of FE model and experimental results for free field vibration (a) vertical (b) longitudinal.](image)

![Fig. 18. Comparison of damping percentages from FE model and experimental results for different (a) widths of trench (b) depths of trench.](image)
width of 0.3 m and depth of 3 m is considered for further investigation. Here, the in-fall material, vibration source, soil medium and trench location are varied to obtain their effects. Vertical and horizontal components of PPV variation with the distance from source and amplitude reduction ratio at selected distances are plotted. To calculate amplitude reduction ratio firstly without a trench, responses at different distances are measured as acceleration data. Secondly, the responses at the same locations are measured with the trench in place. Thirdly, the time domain acceleration data is converted to frequency domain to determine the maximum spectral amplitudes of the two data sets. Subsequently, amplitude reduction ratio for each case is defined (Eq. (4)) by considering the ratio between maximum spectral amplitudes of vibrations that are measured pre and post installation of trench for that case.

\[
\text{Amplitude reduction ratio} = \frac{\text{Maximum spectral amplitude with trench}}{\text{Maximum spectral amplitude without trench}}
\]  

(4)

5.1. In-fall material

The effect of the in-fall material is evaluated by comparing the performances of the open trench and those filled with coal bottom ash, Expanded Polystyrene (EPS) and water. EPS is modelled as an elastic material using material properties used in Motamed et al. [32]. Ekanayake et al. [25] used Mie-Gruneisen equation of state to model behaviour of water and the same model is adopted in the present study. At the trench, some amplifications of particle vibration can be observed, especially with the open trench as shown in Fig. 19. This may be due to the effects of geometric irregularities at the trench and reflected waves at the trench interface. All the trenches show some reductions of the PPVs, especially the open trench. Effects of the in-fall material is realised in the near field up to a distance 12 m and 8 m from the source for the longitudinal and vertical PPVs respectively. A clear effect of mitigation by the different trenches can be seen in the vertical far field vibration, while the trench type does seem not to have an effect on the longitudinal far filed vibration. Saikia and Das [39] concluded that the open trenches are more effective in screening vertical vibration than the horizontal components for steady state vibration and from the present study a similar conclusion can be made for impact loading. From Fig. 20, it can be seen that the open trench and water filled trench show higher amplitude

| Parameter                  | Range                        |
|----------------------------|------------------------------|
| In-fall materials          | Coal bottom ash, EPS and water |
| Peak value of impact force | 0.639, 0.959 and 1.918 MN    |
| Elastic modulus of soil    | 50, 100 and 150 MPa          |
| Distance from the source   | 4, 6 and 8 m                 |
reduction ratios and imply better performance than the other two trenches. It is somewhat obvious that open trenches are most effective as no energy transfer takes place through a void, but they are not practical for reasons stated earlier in this paper. High performance of water filled trench may be caused by interrupting shear wave propagation through a liquid phase. However, their practical applications are also limited due to wall stability and safety issues. Further, EPS material shows slightly better performance than coal bottom ash. Even though coal bottom ash was used as the fill material in the experimental study, its effectiveness was less compared to other materials (e.g. EPS) available in the industry. Since polymers tend to have higher damping than cementations material due to their viscoelastic properties [40], bottom ash which is rich with cementations properties [26] performs less effectively in vibration screening. According to Liyanapathirana and Ekanayake [21] EPS geofoam

Fig. 19. PPV variation with distance for different trench configurations (a) longitudinal (b) vertical vibration.

Fig. 20. Amplitude reduction ratio for different trench configurations.
can be considered as an effective fill material for ground barriers and hence EPS material filled trenches are considered in the subsequent study on the effects of the other parameters such as impact force, soil elastic modulus and trench location.

5.2. Impact force

Effect of the impact force is studied by varying the input force function of the model. As described in the model validation section, variations in the force function are calculated by changing the impact times as 40 ms, 80 ms and 160 ms. It is evident that with increase of impact time, peak value of load function is reduced. Consequently, resulting ground vibration is decreased significantly as shown in Fig. 21. The variations of vertical and longitudinal vibrations can be seen to be similar for the three load cases, with notable reductions in the PPVs across the in-filled trenches in all cases. As Fig. 22 illustrates amplitude reduction ratios in general increase for all three impact scenarios. However, the ground vibration resulting from the highest peak load appears to have the highest damping in the presence of trench. This may be contributed by the high drop of the longitudinal component of vibration at the trench for high impact as shown in Fig. 21 (a).

5.3. Elastic modulus of soil

The sensitivity of elastic modules of the soil media for ground wave propagation is investigated. As exemplified in Fig. 23, increase of the elastic modulus of the soil results in decrease in both the vertical and longitudinal PPVs of ground motion. A similar trend was observed by Khoubani and Ahmadi [41] who stated that even though the transmission wave velocity decrease with a reduction in the elastic modulus of the soil, level of vibration increases due to higher velocity strains. However, the amplitude reduction ratios show only small variations as shown in Fig. 24.

![Fig. 21. PPV variation with distance for different load cases (a) longitudinal (b) vertical vibration.](https://doi.org/10.1016/j.heliyon.2018.e00726)
Fig. 22. Amplitude reduction ratio for different load cases.

Fig. 23. PPV variation with distance for varies soil elastic modulus (a) longitudinal (b) vertical vibration.

Fig. 24. Amplitude reduction ratios for different soil elastic moduli.
Thompson et al. [4] observed similar trends for train induced vibration with the change of shear wave velocity of top soil layer from 100 m/s to 200 m/s. While sites with higher ground vibration levels show high reduction in the near field, far field results are comparable.

5.4. Distance from the source

The effect of trench location on vibration screening performance is studied. Three trench locations are considered and results for the longitudinal and vertical PPVs are shown in Fig. 25. There is no significant variation of the PPVs observed with the change of the trench location, except in the region (4 m–8 m) in which they were located. The location of the trench can hence be chosen depending on the proximity of the receiver to the source of vibration. However, Fig. 26 shows that the
overall performance of the trench located at 8 m has a better performance than the other trenches implying that passive isolation can be effective for impact load induced vibration. At far field conditions however, the performance of trenches are comparable.

6. Conclusions

This paper treated the ground vibration induced due to impact pile driving and its screening with the use of trenches, using experimental and numerical techniques.

At first the characterises of ground vibration and the effects of a coal bottom ash infilled trench on screening the ground vibration induced by impact piling were investigated experimentally. Free field results show that at a distance of 10 m from the source, the PPV of the vertical wave was 4.41 mm/s while the PPVs of the transverse and longitudinal waves were 2.67 mm/s and 3.36 mm/s respectively. It is hence evident that impact pile induced vibration can cause damage in vibration sensitive structures within 10 m distance from this source based on the limiting value identified as 2 mm/s in most standards. Main findings of the experimental study are listed as follows:

- The vertical ground vibration was dominant throughout the distance from the source.
- For trenches of width 30 cm and depths of 50 and 75 cm, the transverse vibration was most damped while for the trench depth of 100 cm, the longitudinal vibration seemed to be the most damped.
- When the width was increased, the ground vibration in all three directions decreased for trench widths of 30 cm—60 cm. This trend continued for the vertical and longitudinal vibrations, but the damping percentage in the transverse direction decreased dramatically when the width increased to 90 cm.
- Notable influence on screening ground vibration with the use of bottom ash filled trench was observed in the vertical and longitudinal directions, but was less in the transverse direction.

To complement and supplement the findings of the experimental investigation, a numerical study was undertaken using the validated modelling techniques. The effects of in-fill material, distance of trench from source, soil property and impact force on the ability of the trench to screen pile induced vibration were analysed. Based on the numerical study following conclusions can be drawn.

- Open trenches and water filled trenches had better performance compared to other in-filled trenches. It was also evident that soft in-fill materials contribute more towards vibration reduction compared to stiffer materials.
The amplitude reduction ratios for all trenches were reasonably unchanged with the increase in distance of trench from source.

Study on the effects of the impact force revealed that a smaller impact force at the source resulted in a significant reduction in vibration levels which may be a consideration at the design stage. However, the vibration caused by higher peak loads was damped greatly by the presence of the trench.

The amplitude reduction ratio was found to be site specific where the change of elastic modulus of soil can greatly affect vibration propagation. Sites, which have high vibrations also have lower amplitude reduction ratios at near field implying high damping.

Pile driving is a vital process in the construction industry in order to support larger structures such as high-rise buildings and bridges. Depending on the impact force, pile dimensions, site conditions and the type of the receiver, ground vibrations may cause discomfort to the occupants, disturb the activities carried out in the buildings or cause damage to the structures. Therefore, it is important to evaluate the vibration characteristics of pile driving prior to construction. The finding of this study can be used to identify limits of vibration based on the type of structures in the vicinity, characteristics of ground vibration induced by impact pile driving and the effects of trench dimensions, in-fill material, vibration source, soil medium and location of trench on vibration screening. For the case of ground vibration induced by pile driving, additional experimental and numerical investigations can be conducted to formulate a prediction model which can aid future research and inform design. Moreover, similar studies for ground vibration induced by other activities such as ground compaction and railway and highway traffic can be carried out to complement and supplement the present work.

Declarations

Author contribution statement

P. Jayawardana: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

R. Achuhan: Conceived and designed the experiments; Performed the experiments.

S. De Silva: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

D. P. Thambiratnam: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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