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Construction-induced Vibration due to Pile Casing Driving

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Abstract: Ground vibration is generally caused by construction activities, e.g., pile driving, sheet pile driving, dynamic compaction of soil, blasting; natural activities, e.g., earthquake, landslide etc. In urban region, construction induced vibration is mainly caused by pile driving, sheet pile driving etc. Pile driving induces vibration in the soil which is transmitted to neighbouring structures, thereby causing potential damage, such as, differential settlements of foundations and deformations or cracks in the structures. In the present study, field observation has been conducted at two sites during pile casing driving by (i) Impact Hammer upto depth of 28 m beneath ground surface, (ii) Hydraulic Vibratory Hammer upto depth of 10 m beneath ground surface. A comparative study has been made between two sites based on the following observations. Peak particle velocity (ppv, mm/s) has been measured in the sites with varying distances from the pile driving location. Ground motion amplitude has also been acquired at different depths during pile casing driving. Based on the site observation, regression model has been developed to predict the peak particle velocity. The model is very useful for predicting PPV for site-specific parameters. Thereafter, it has been compared with the existing ground vibration model obtained from field study.

Keywords: *Construction induced vibration; pile casing driving; peak particle velocity; ground motion amplitude; regression model; site-specific parameters.*

1. Introduction

Ground vibration is a major geo-hazard, mainly caused by natural activities, e.g., earthquake, landslide, tsunami, volcanic eruption, river waterfall etc. (Huang et al., 2007); construction activities, e.g., pile driving, sheet pile driving, blasting, dynamic compaction of soil etc. (Massarsch, 1995). The other causes include vibration caused by human and technical activities, such as, noise, vehicles, shipping, trains, industrial machinery, cargo handling, war etc. (Sheng et al., 2006). It can cause significant damage to structure and foundation, e.g., excessive settlement of structure, slope instability, liquefaction of sand, collapse of trenches, excavations, and tunnels, exposure of buried pipelines etc., cracking of pipes, and severe discomfort to people.

During the pile driving phenomenon, body (shear and compressional) waves develop at the pile toe that travel externally from the tip in a spherical waveform in every direction. Vertically polarized shear waves spread from the pile shaft in a conical waveform (Woods, 1997). Surface (Rayleigh) waves are generated when P- and S- waves strike the ground level whereas some portion of the body waves are reflected back in the soil. The surface (Rayleigh) and body (P and S) waves form complex arrays of waves in the soil (Attewell & Farmer (1973), Kim & Lee (2000), Athanasopoulos & Pelekis (2000)). The amplitude of the waves reduces when distance from the source increases. The attenuation occurs because of dissipation of energy in the soil medium (material damping) and expansion of the wavefront (geometrical attenuation) (Amick and Gendreau, 2000). When these waves reach the structures via soil-structure interaction, vibrations are generated which can cause trouble to the people residing within the structures and reduction of the serviceability and integrity of the structures. The source of vibration, soil medium, soil-structure interaction and proneness of structure to vibration are the several factors which influence the intensity of damage caused by construction-induced vibration to the structures.

Construction induced vibration generally occurs due to pile driving, sheet pile driving etc. in urban environment. Piles or sheet piles are often driven for sustaining foundation or earth retention during construction and retrofit of retaining walls and bridges.

Pile driving is done by impact or vibratory hammer. The intensity of vibration caused by pile driving process at a certain location can cause immense damage to the nearby structures. Therefore, it is essential to study the vibration with the help of peak particle velocity generated during pile driving. Peak particle velocity is significantly influenced by the source of vibration and the properties of the soil media through which the wave travels. It is extremely necessary to examine whether the peak particle velocity generated during construction activities lies within the permissible limits as suggested by several researchers so that the safety of the neighboring structures can be ensured.

In the present study, field observation has been conducted at two sites located at Kolkata, West Bengal during pile casing driving by (i) Impact Hammer upto depth of 28 m below ground surface, (ii) Hydraulic Vibratory Hammer upto depth of 10 m below ground surface. A comparative study has been made between two sites based on the following observations. Peak particle velocity (ppv, mm/s) has been measured in the sites with varying distances from the pile driving location. Ground motion amplitude has also been acquired at different depths during pile casing driving. Based on the site observation, regression model has been developed to predict the peak particle velocity. The model is very useful for predicting PPV for site-specific parameters. Thereafter, it has been compared with the existing ground vibration model obtained from field study.

2. Field Study

2.1 Site I:

Test Location

Pile casing was driven using Impact Hammer upto a depth of 28 m beneath the ground surface at a site located in Newtown, Kolkata, West Bengal.

Source of Vibration

The mass of the hammers used in this investigation varies within (4.2-5) ton. The total length of the pile is 30m. The diameter of the pile casing is 500 mm. The height of fall of the hammer is (1.2-1.5) m.

Geological Profile

Fig. 1: Pile casing driving at Newtown, Kolkata by Impact Hammer

The soil condition for the site at Newtown, Kolkata has been uniform throughout the location and a typical bore log profile of the soil exploration data is given below.

Table 1: Geological Profile for the site at Newtown, Kolkata

Strata	Description of Soil	Depth of Strata
I	Greyish brown silty clay	0 m to 1 m

II	Loose or soft greyish brown silty clay or clayey silt and silty fine sand with some fragments of mica	1 m to 3.15 m
III	Loose to dense bluish grey silty clay and silty fine sand containing mica	3.15 m to 33.75 m
IV	Very dense, yellowish brown silty clay or fine sand with some fragments of mica	33.75 m to 43.25 m
V	Very stiff, bluish grey, silty clay with thin laminations of yellowish silt and very fine sand	43.25 m to 50.45 m

The ground water table is situated at a depth of about 2 m beneath the ground level. The SPT value at the site varies from 7 to 20 upto a depth of 10 m, below which, higher values of SPT varying upto about 50 at the termination depth of the pile was obtained. During the pile driving phenomenon at the site, mostly silty clay with fine sand was found.

2.2 Site II:

Test Location

A pile of length 10 m was driven by a Hydraulic Vibratory Hammer at a site situated in Baruipur, South 24 Parganas, West Bengal.

Source of Vibration

The pile casing was driven by a Hydraulic Vibratory Hammer (PTC 30H1A) of maximum frequency of 28 Hz with required power pack.

Fig. 2: Pile casing driving at Baruipur, South 24 Parganas by Hydraulic Vibratory Hammer

Geological Profile

Soil exploration was done at the site located at Baruipur, South 24 Parganas, from which the following data was obtained.

Table 2: Geological Profile for the site at Baruipur, South 24 Parganas

Strata	Description of Soil	Depth of Strata
I	Heterogeneous fill material	0 m to 1 m
II	Firm brownish grey silty clay with brown spots	1 m to 5.1 m
III	Medium dense to dense light grey silty fine or medium sand	5.1 m to 40 m

At this site, the depth of pile casing driving is nearly 10 m. The ground water table was situated at a depth of about 2.6 m below the ground surface. Thus, the soil exploration report reveals that the pile casing driving extends in stratum III containing medium dense to dense silty fine sand.

3. Test Program and Results

3.1 Site I

Test Program

At the site, the adjacent structures are located at a vicinity to the pile casing whose radial distance ranges from 20 m to 90 m. The peak particle velocity (mm/s) was measured with Vibration Meter VM-82. For detailed assessment of construction-induced vibration at a site, acceleration (mm/s^2), velocity (mm/s), and displacement (mm) can be easily measured using Vibration Meter VM-82. The current study is carried out to observe ground vibration in the eastern direction of the site for monitoring the peak particle velocity (PPV, mm/s) generated on the ground surface during single pile casing driving and simultaneous driving of two pile casings for radial distances varying between 0 m to 30 m, the depth of pile driving being 28 m.

Test Results

During the pile casing driving process by impact hammer, it has been observed that at a particular depth of driving, peak particle velocity (PPV, mm/s) decreases with increasing radial distance from the source of vibration. Figures 3 and 4 represent the variation of Peak Particle Velocity (PPV, mm/s) with increasing Radial Distance from the source of vibration at various depths(D) during single pile casing driving and simultaneous driving of two pile casings respectively.

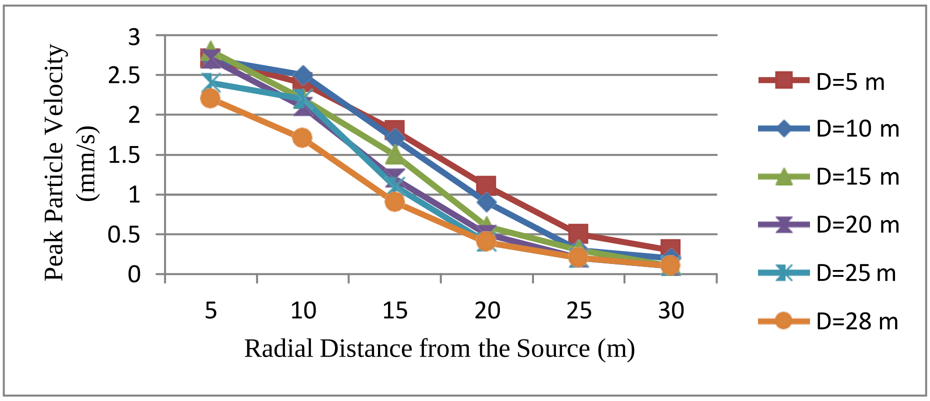

Fig. 3: Variation of Peak Particle Velocity (PPV, mm/s) with increasing Radial Distance from the source of vibration at various depths(D) during single pile casing driving

Here, the minimum and maximum values of Peak Particle Velocity (PPV, mm/s) were 0.1 mm/s and 2.8 mm/s respectively, obtained at the depths of 10-28 m, 10-15 m respectively at radial distances of 30 m and 5 m respectively from the source of vibration during single pile casing driving.

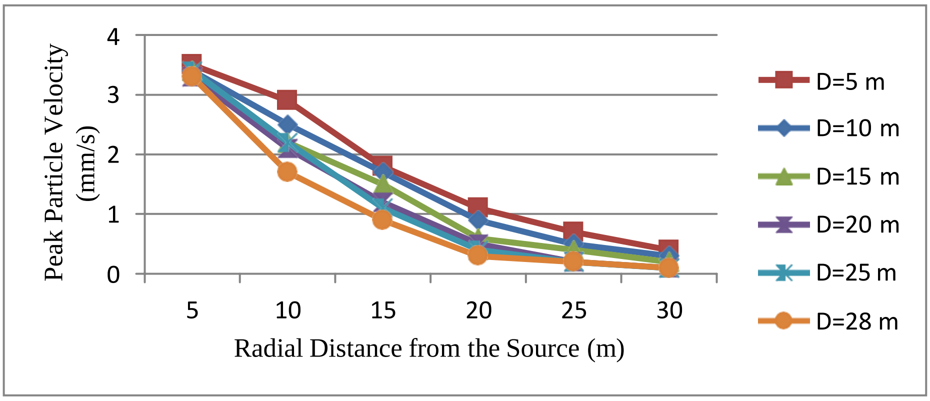

Fig. 4: Variation of Peak Particle Velocity (PPV, mm/s) with increasing Radial Distance from the source of vibration at various depths(D) during simultaneous driving of two pile casings

Here, the minimum and maximum values of Peak Particle Velocity (PPV, mm/s) were 0.1 mm/s and 3.5 mm/s respectively, obtained at the depths of 15-28 m, 0-5 m respectively at radial distances of 30 m and 5 m respectively from the source of vibration during simultaneous driving of two pile casings.

Both figures 3 and 4 indicate that the Peak Particle Velocities (PPV, mm/s) generated during simultaneous driving of two pile casings are more than that generated during single pile casing driving at certain depths at closer radial distances from the source, since greater energy is required to drive two pile casings simultaneously. It has been observed in both cases of pile casing driving that Peak Particle Velocities (PPV, mm/s) at a certain radial distance from the source of vibration generally decreases (except a few cases) with increasing depth. It may have occurred due to the presence of mostly silty clay with fine sand throughout the depth of pile driving.

A ‘scaled distance’ format which combines both distance and energy can be used to evaluate the peak particle velocity generated during construction activities to monitor the ground vibration (Wiss, 1981), (Jedele, 2005), represented by the expression given below.

$$V=k(D/(E)^{(1/2)})^{-N} \tag{1}$$

where,
V = peak particle velocity
k = intercept at 1 energy unit
D = distance from the vibration source
E = energy of the source
N = slope (given as ‘n’ in Wiss 1981)

In this site, transient vibration was generated since pile casing driving was done by impact hammer (Wiss, 1981). Therefore, the energy (E) has been obtained by the equation,

$$E=\frac{1}{2}mv^2 \tag{2}$$

where,
m=mass of the hammer,
v=velocity of the hammer

$$v=\sqrt{2gh} \tag{3}$$

g=acceleration due to gravity,
h=height of fall of the hammer

Here, m=4.2 ton, g=9.81 m/s^2, h=1.2 m.

Substituting the above values in equations 2 and 3, we get, E=49442.4 J for single pile casing driving and E=98884.8 J for simultaneous driving of two pile casings.

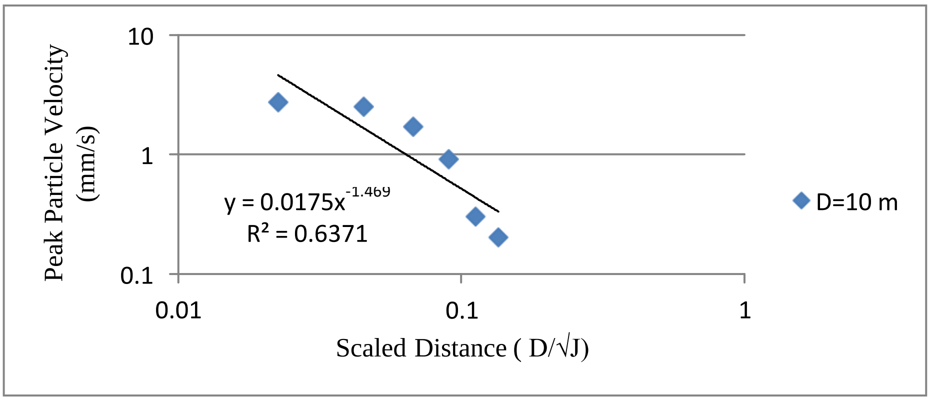

Fig. 5: Variation of Peak Particle Velocity (PPV, mm/s) with Scaled Distance during single pile casing driving at a depth of 10 m

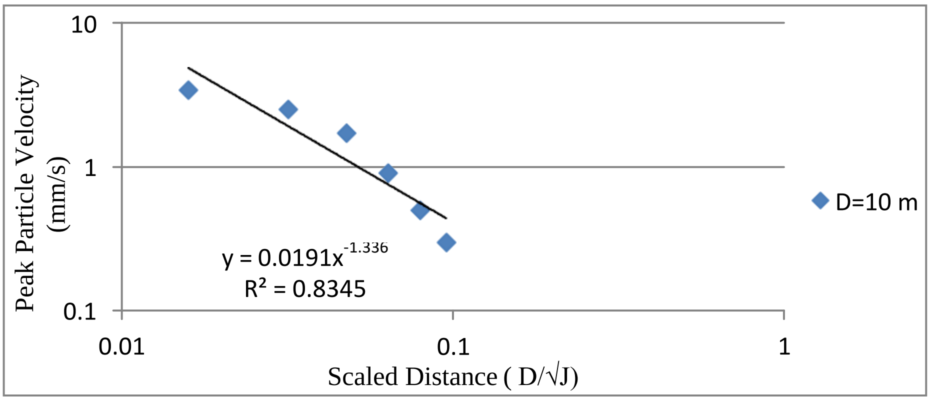

Fig. 6: Variation of Peak Particle Velocity (PPV, mm/s) with Scaled Distance during simultaneous driving of two pile casings at a depth of 10 m

Figures 5 and 6 represent the variation of Peak Particle Velocity (PPV, mm/s) with Scaled Distance during single pile casing driving and simultaneous driving of two pile casings respectively at a depth of 10 m. Here, the values of k (intercept at 1 energy unit) are 0.0175 and 0.019 and the values of N (slope) are 1.469 and 1.336 during single pile casing driving and simultaneous driving of two pile casings respectively at a depth of 10 m. Therefore, it can be concluded that k (intercept at 1 energy unit) and N (slope) are dependent on the energy of the source, peak particle velocity etc. at a particular depth of pile penetration in the soil.

3.2 Site II

Test Program

The ground vibration generated during pile casing driving was monitored by a vibrometer using vibration sensor which was placed in such manner so that the vibration parameters viz., particle velocity and amplitude could be measured in both vertical and horizontal directions. The peak particle velocity was measured on the ground surface with depth of pile casing driving being 10 m at radial distances of 9 m, 15 m and 20 m.

Test Results

During the pile casing driving process by Hydraulic Vibratory Hammer, it has been observed that at a particular depth of driving, peak particle velocity (PPV, mm/s) decreases with increasing radial distance from the source of vibration. Figure 7 presents the variation of Peak Particle Velocity (PPV, mm/s) with increasing Radial Distance from the source of vibration at various depths(D) during pile casing driving.

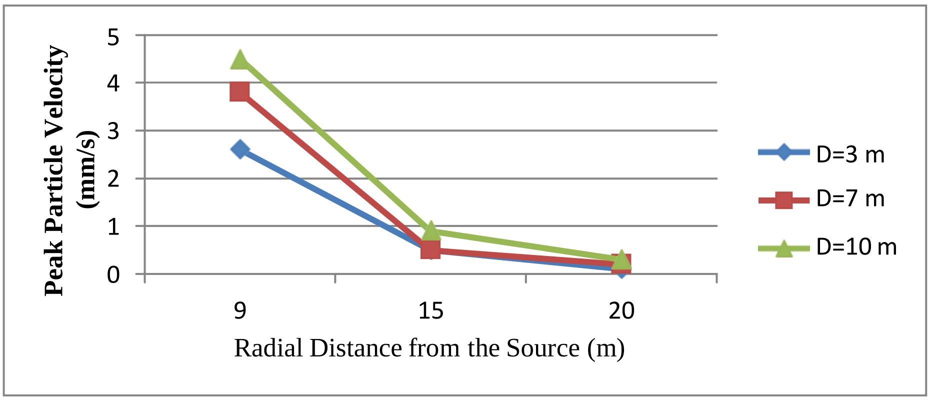

Fig. 7: Variation of Peak Particle Velocity (PPV, mm/s) with increasing Radial Distance from the source of vibration at various depths(D) during pile casing driving

Here, the minimum and maximum values of Peak Particle Velocity (PPV, mm/s) were 0.1 mm/s and 4.5 mm/s respectively, obtained at the depths of 0-3 m, 7-10 m respectively at radial distances of 20 m and 9 m respectively from the source of vibration during driving of pile casing.

Figure 7 indicates that the Peak Particle Velocities (PPV, mm/s) generated during pile casing driving at a certain radial distance from the source of vibration generally increases with increasing depth. It may have happened because during pile casing driving, the pile penetrates through a soil layer containing silty clay at shallow depth upto a soil layer containing medium dense to dense silty fine sand at greater depth.

In this site, steady-state vibration was generated since pile casing driving was done by Vibratory Hammer (Wiss, 1981). The harmonic vibration can be represented by the following equation,

$$x = X\sin\omega t \tag{4}$$

where,
ω =circular frequency in radian per unit time,
x=displacement at time 't',
X=radius of a rotating vector
The acceleration(a) can be determined by differentiating equation (4) w.r.t 't' twice.

$$a = -\omega^2 X\sin\omega t = \omega^2 X \quad \text{(taking the maximum value)} \tag{5}$$

Therefore, the vibration energy (E) has been obtained by the equation,

$$E = \frac{ma^2}{2f^2} \tag{6}$$

where,
m=mass in Kg (Total mass of vibrating object or machine),
a=acceleration, m/s^2,
f=frequency, Hz, s^{-1}
For PTC 30H1A vibrodriver, m=2258.89 kg, f=28 Hz, $X=\frac{0.7366}{2}=0.3683$ m,
Therefore, $a=28^2*0.3683=288.7472\ m/s^2$
Putting these values in equation (6), we get, E=120111.5 J

Using the 'scaled distance' approach, the Peak Particle Velocity (PPV, mm/s) with varying Scaled Distance during pile casing driving at depths of 3 m and 10 m have been plotted in the figures given below.

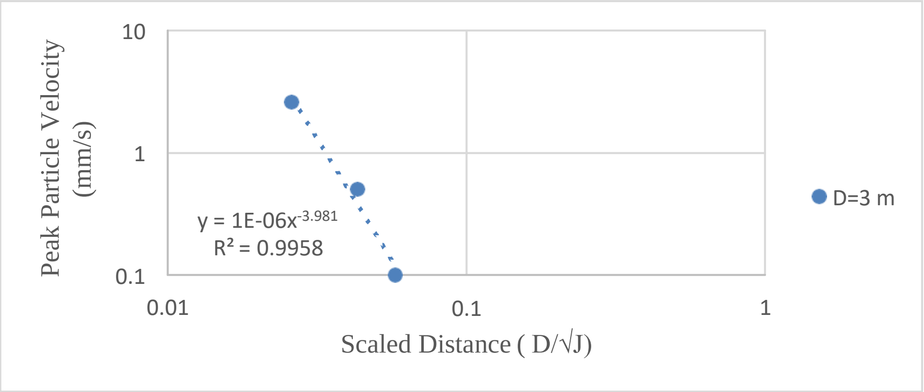

Fig. 8: Variation of Peak Particle Velocity (PPV, mm/s) with Scaled Distance during driving of pile casing at a depth of 3 m

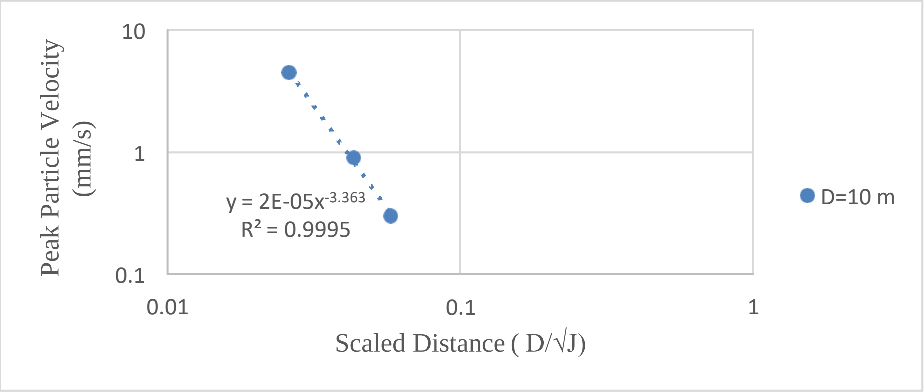

Fig. 9: Variation of Peak Particle Velocity (PPV, mm/s) with Scaled Distance during driving of pile casing at a depth of 10 m

In figures 8 and 9, the values of k (intercept at 1 energy unit) are 10^{-6} and $2*10^{-5}$ and the values of N (slope) are 3.981 and 3.363 during pile casing driving at depths of 3 m containing silty clay and 10 m containing medium dense to dense silty fine sand respectively. Therefore, it can be concluded that k (intercept at 1 energy unit).and N (slope) are dependent on the energy of the source, the type of soil through which the pile casing driving takes place.

4. Development of Statistical Model – Univariate Regression Analysis

Regression model has been developed to predict Peak Particle Velocity (PPV, mm/s) at different distances from the source of vibration with varying energy level. The observed data for different soil profiles have been considered while developing the models.

Here, the univariate regression analysis has been done with Peak Particle Velocity (PPV, mm/s) as the dependent variable and Scaled Distance (D/√J) as the independent variable.

Table 3: Regression Models for determining PPV (mm/s) for varying Scaled Distance (D/√J) during Pile Casing Driving

Type of Pile Casing Driving	Source of Vibration	Description of Soil	Depth of Pile Casing Driving	Regression Model y=PPV (mm/s) x=scaled distance (D/√J)
Single pile casing driving	Impact Hammer having mass of 4.2 ton	Silty clay with fine sand	10 m	$y = 0.0175x^{-1.469}$
Simultaneous driving of two pile casings				$y = 0.0191x^{-1.336}$
Pile casing driving	Hydraulic Vibratory Hammer (PTC 30H1A)	Silty clay	3 m	$y = 1E\text{-}06x^{-3.981}$
		Medium dense to dense silty fine sand	10 m	$y = 2E\text{-}05x^{-3.363}$

These models can be used for prediction of peak particle velocity for the respective soil profiles as presented in table 3.

5. Summary

In this study, it has been observed that the intensity of ground and structural vibrations caused by pile casing driving mainly depends on the type of hammer, heterogeneity of the stratified soil media, distance from the source of vibration, characteristics of wave propagation at site etc. The damage of nearby structures may take place mainly due to the strain that develops in the structure as well as the settlement in the foundation media due to vibration caused by driving of pile casing. The damage also depends on the type of structure. Based on these aspects, vibration criteria for vibration induced building damage are published by competent authorities in several nations. Considering all important aspects stated above, site-specific field observation has been taken to compare the relevant parameter with standard criteria.

From the observed values of peak particle velocity, it may be noted that the values attenuate with increasing distance from the source. Based on different existing standards and specification, it has been found that the permissible value of particle velocity for no cosmetic cracking of building ranges from 2 to 100 mm/s with lower values pertaining to historic and ancient buildings and the higher values pertaining to modern large size commercial and industrial buildings. The corresponding frequency range is 2 to 50 Hz.

6. Conclusion

The current study can be summarised as given below.

1) Pile casing driving was done using impact hammer and vibratory hammer at two different construction sites in Kolkata. This study has been carried out to monitor the ground vibration generated during pile casing driving to predict whether Peak Particle Velocity (PPV, mm/s) lie within permissible limits so as to ensure the safety of the nearby structures and residents.
2) During the pile casing driving process by both hammers, it has been observed that at a particular depth of driving, peak particle velocity (PPV, mm/s) decreases with increasing radial distance from the source of vibration.
3) At Newtown, Kolkata, single pile casing driving and simultaneous driving of two pile casings were done by impact hammer, the depth of pile driving being 28 m. Here, the minimum and maximum values of Peak Particle Velocity (PPV, mm/s) were 0.1 mm/s and 2.8 mm/s respectively, obtained at the depths of 10-28 m, 10-15 m respectively at radial distances of 30 m and 5 m respectively from the source of vibration during single pile casing driving. The minimum and maximum values of Peak Particle Velocity (PPV, mm/s) were 0.1 mm/s and 3.5 mm/s respectively, obtained at the depths of 15-28 m, 0-5 m respectively at radial distances of 30 m and 5 m respectively from the source of vibration during simultaneous driving of two pile casings.
4) At Baruipur, South 24 Parganas, pile casing driving was done by vibratory hammer, the depth of pile casing driving being 10 m. Here, the minimum and maximum values of Peak Particle Velocity (PPV, mm/s) were 0.1 mm/s and 4.5 mm/s respectively, obtained at the depths of 0-3 m, 7-10 m respectively at radial distances of 20 m and 9 m respectively from the source of vibration during driving of pile casing.
5) Since the structures adjacent to the site may not be treated as engineered structure, thus the PPV values should be kept less than 2.0 mm/s from safety point of view by adopting appropriate measures.
6) Using the 'scaled distance' approach, the Peak Particle Velocity (PPV, mm/s) with varying Scaled Distance during pile casing driving at certain depths at both sites have been plotted. Few univariate regression models have been developed for predicting PPV (mm/s) for varying soil type and different energy level at different depths of pile casing driving. However, the expressions are valid for the ranges of the values of the parameters considered during development of the models.

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