Research Article

Hamed S. Saher*, Haider S. Al-Jubair and Jaafar K. Ali

Measurements of induced vibrations due to steel pipe pile driving in Al-Fao soil: Effect of partial end closure

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Abstract: The experimental study investigated the impact of partially closing the end of a tubular steel pile with a diameter of 1.22 m on the induced driving vibrations. Long piles, spanning 50 m, were driven into Al-Fao soil using hammers from Daewoo Company – the PTC-110HD vibro-hammer for the initial 24 m of penetration and the IHC S-280 hydro-hammer for the remaining depth. This study established comparisons between open-end pipe (OEP) and partially closed pipe (PCP) piles concerning various parameters. These parameters included the number of blows, driving energy delivered by the hydro-hammer along the depth, and the peak soil particle velocity (PPV). Data collection was carried out using pile dynamic integral sensors for pile driving analysis, strain gauges placed along the lengths of the piles, and geophones positioned at varying distances from the pile. The results of the study unveiled a substantial effect of partial closure on the vibration response. Specifically, vibrations in the vicinity of the pile were amplified by a factor of 3–4 at depths ranging from 1 to 22 m where the vibro-hammer was employed, and by a factor of 2.5 to over 3 for the remaining depth where the hydro-hammer was utilized. Furthermore, it was observed that the rate of vibration attenuation was higher for the OEP when compared to the PCP. The vibrations are attenuated along the distance from the source where the PPV is decreased to approximately average (3.5% for OEP) and (2.3% for PCP) at a distance of around two times the penetration depth (50 m) for all embedded depths. Varied properties like stiffness, density, and damping in different soils can influence the propagation of vibrations differently. Nonetheless, as the distance from the vibration source increases, the impact of soil properties may diminish, and the vibrations tend to homogenize. Consequently, the statistical analyses yielded empirical equations that can be used for estimating vibrations in scenarios involving similar pile and hammer characteristics within comparable site conditions.

Keywords: peak soil particle velocity, driving steel pile, OEP, PCP

1 Introduction

The vibration produced from pile driving depends upon various factors such as hammer type, pile characteristics, and soil profile. This vibration has different effects on soil and nearby structures. Many codes (Such as Swedish Vibration Standard Table 1) were developed to assess and classify the intensity of vibration regarding its effects on humans, equipment, and structures [1,2] (Figure 1).

The process of transmitting the vibration is complicated, whenever the energy is transferred from the hammer into the pile, the vibration propagates into the soil due to the interaction between the soil and the pile. P-wave (pressure or spherical waves) generated from the pile toe S-wave (shear or cylindrical waves) generated from the pile's skin, and R-wave (Rayleigh or surface wave) transferred along the ground [4] and extra waves are created due to reflection and refraction, as shown in Figure 2.

The vibrations, which come from the pile driving and transferred to the soil, are influenced by the soil properties (body and shear wave velocities into the soil, layer thickness, and attenuation rate), hammer characteristics (type, energy, and vibration frequency), and pile properties (shape, material, diameter, and wall thickness).

The wave velocities depend mainly on elastic properties and bulk density of the soil [3]; hence, the wave propagates faster in stiff soil than in soft one.

* **Corresponding author: Hamed S. Saher**, Department of Civil Engineering, College of Engineering, University of Basrah, Basrah, Iraq, e-mail: hamidsalim26@gmail.com
Haider S. Al-Jubair: Department of Civil Engineering, College of Engineering, University of Basrah, Basrah, Iraq, e-mail: haider.yaseen@uobasrah.edu.iq
Jaafar K. Ali: Department of Mechanical Engineering, College of Engineering, University of Basrah, Basrah, Iraq, e-mail: jaafar.ali@uobasrah.edu.iq

Table 1: Swedish vibration standard (Swedish Standard 1991) [1]

Type of structures	Frequency bandwidth (Hz)	Blast-induced PPV (mm/s)	Traffic/machine-induced PPV (mm/s)
Steel or reinforced structures such as factories, retaining walls, bridges, steel towers, open channels, underground tunnels, and chambers	10–60	30	—
	60–90	30–40	—
	10–30	—	12
	30–60	—	12–18
Buildings with foundation walls and floor in concrete, well in concrete or masonry, underground chambers, and tunnels with masonry linings	10–60	18	—
	60–90	18–25	—
	10–30	—	8
	30–60	—	8–12
Building with masonry walls and wooden ceilings	10–60	12	—
	60–90	12–18	—
	10–30	—	5
	30–60	—	5–8
Objects of historic interest or other sensitive structure	10–60	8	—
	60–90	8–12	—
	10–30	—	3

Figure 1: Location of the tested site in Al-Fao Port (google earth).

Grizi et al. [5] reported the concept of decrease in attenuation with the increase in the distance from the wave source and confirmed the wave propagation types which propagate from the pile tip (spherical body waves) and the pile circumference (cylindrical shear waves). Massarsch et al. [6] investigated the effect of the three important factors: frequency and amplitude of vibration, eccentric moment on vibratory driving, and resistance between pile and soil's tip and skin, liquefaction areas (damage due to vibration) increase as both the load frequency and amplitude increase. Fattah et al. [8]. Massarsch and Fellenius [7] using the Swedish Standard and historical cases, reported the intensity and attenuation of ground vibration and the upper limits of vertical ground vibration by studying the energy and impedance of the driving pile in the specific stage during pile driving at a distance equal to two pile's

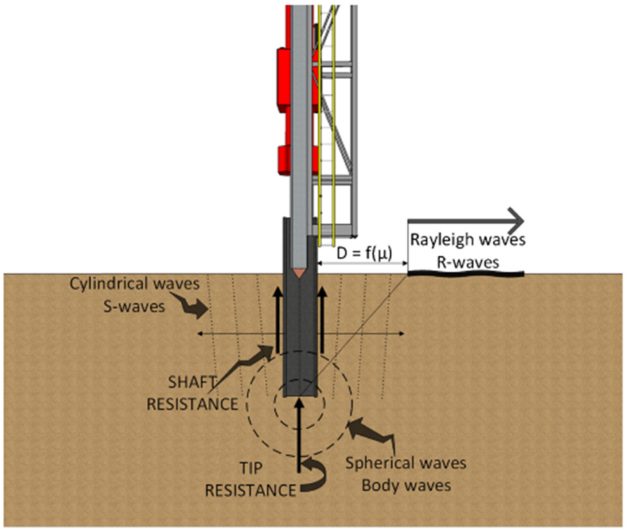

Figure 2: Mechanism of energy propagation into the soil (Grizi et al.) [5].

length. AlSheakayree et al. [9] investigated the wave propagation through the soil and the relationship between the distance from the vibration source and energy of the driving hammer and attenuation rate. Jongmans [10] found a new method to predict the ground motion produced from the driving pile by considering the geometry and dynamics characteristic of soil strata and source properties instead of previous studies that depend on empirical relationships.

The main aim of this study is to point out the influence of the presence of a shoe plate at the steel pile toe (partial end closure) on the vibration caused due to the impact of tabular steel pile, and also provide a guide to assess the safe distance from the vibration source to avoid the damage due to the impact of steel pile in Al-Fao city.

The research was carried out in a pile trial site established by the contractor, Daewoo, who provided all the necessary equipment, cranes, and hammers on the premises of the Al-Fao Grand Port. This site is supervised by Technital Company, and the necessary permissions were granted by the General Company of Ports (GCPI), the client overseeing the project.

2 Testing program

The pile testing program included ten piles of the same size. The measurements concerned two of the piles: pile #9 (open-end pipe; OEP) and #10 (partially closed pipe; PCP). The soil exploration for the test zone was conducted utilizing two boreholes (TBH-1 and TBH-2). Figures 3 and 4 and Table 2 illustrate the soil profile and layer properties.

3 Pile properties

The PCP contains a 250 mm ring shoe plate of 25 mm thickness, as demonstrated in Figure 5 and Table 3 lists the pile properties.

4 Equipment

Two types of hammers were used for pile driving: the first hammer, which is of a vibro-type, was used to penetrate

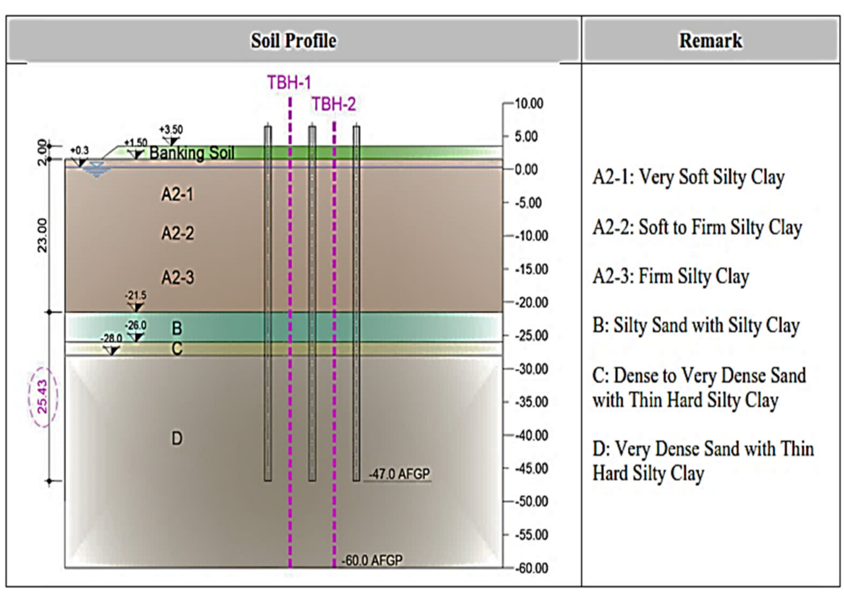

Figure 3: Soil layers properties [11].

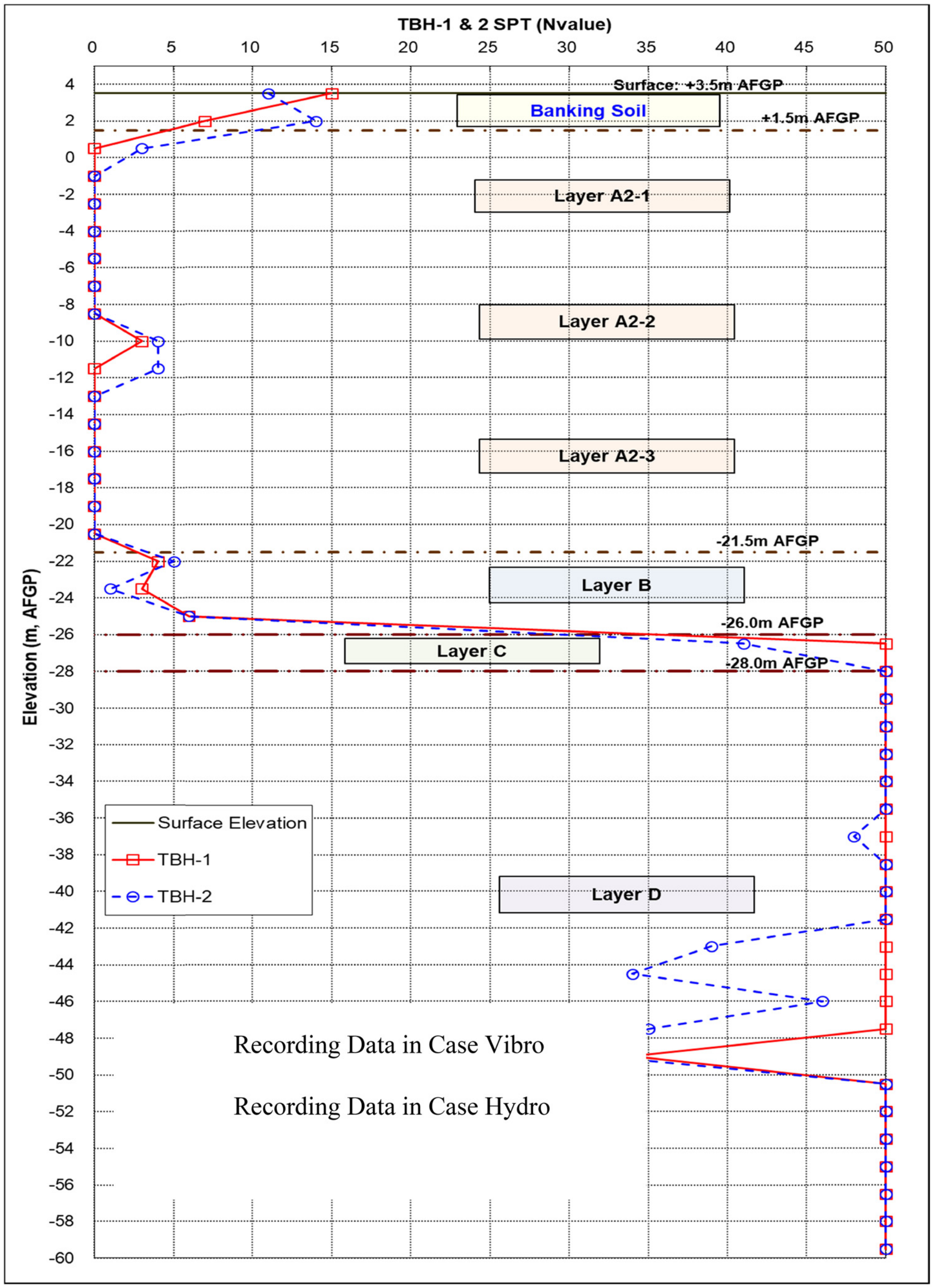

Figure 4: Soil layers description and standard penetration test blow count [11].

Table 2: Soil layers properties [11]

Layer	γ_t (kN/m^3)	c_u (kPa)	φ' (deg.)	E (kPa)
Banking	19	0	26.8	15,930
A2	19	35	0	10,000
B	19	50	0	36,060
C and D	20	0	45	54,100

the pile through a depth of 24 m; the second one, which is of a hydro-type, was used to accomplish the remaining penetration depth of 47 m. Hammer characteristics are described in Table 4.

The load amplitude of the hydro-hammer with time and waveform (pile dynamic integral [PDI] and CAPWAP output) received by the piles are explained in Figure 6.

Figure 5: Partial end closure by the shoe plate.

Table 3: Pile properties

Pile no.	Outer diameter (mm)	Thickness (mm)	Fy (MPa)	*E* (MPa)
PCP and OEP	1,220	25	460	21×10^4

The devices used to measure the surface vibration are a set of geophones with a frequency capacity of 10 Hz, connected to a seismograph data logger (PASI 16S24-U, ultra-light) [14] with (24 channels), as shown in Figure 7.

Calibration was made to check the sensitivity of the geophones, as demonstrated in Figure 8 and Table 5. This operation is conducted in the Laboratory of the Mechanical Engineering, University of Basra [15].

Table 4: Hammers properties vibro-Hammer (PTC-110HD) and hydraulic-hammer (IHCS-280) manuals (Geotechnical Interpretative Report of the container terminal in Al-Fao) [12] and [13]

	Total weight without clamp (ton)	13.3
	Max. frequency (rpm)	1,380
	Max. centrifugal force (kN)	2,300
	Max. line pull capacity (kN)	1,200

	Classification	Unit	Value	
	Operation data	Max. net energy	kJ	280
		Min. net energy	kJ	31
		Blow rate (max. energy)	Blows/min	45
	Weight	Ram	Tons	14
		Hammer (with ram in the air)	Tons	31
	Dimensions	Hammer length	mm	10,390
	Hydraulic data	Max. pressure	bar	350

5 Methodology

The geophones were placed at variable distances (from the driven pile) representing a certain percentage of the total penetration depth. Different distribution patterns are adopted for the vibro- and hydro-hammers, as shown in Figures 9 and 10.

The variation in measuring distances reflects the response of the different soil profile layers. The difference in layout is imposed by the availability of the cable's sensor length. The measurement at an angle of (45°) is associated with a horizontal distance equal to the embedment depth whereas, at 63.43°, it is associated with twice the embedment depth.

The geophones are placed on the surface of the site and connected to the data logger seismograph, and at the same time, it is connected to the battery, while the data cable connects the data logger to the laptop as shown in Figure 11.

6 Measurements and recordings

During driving the pile, the time of driving and frequency of vibration are recorded while the number of blows and energy were recorded manually or by the monitoring system in the case of hydro-hammer, as shown in Figure 12a.

On the other hand, PDI sensors recorded the required data such as force applied to the pile, velocity of the wave through the pile, maximum energy applied, and soil resistance and acceleration of the wave, as shown in Figure 12b.

Simultaneously, the distributed geophones on the site will detect a surface wave, as well as reflected and refracted body and shear waves, as shown in Figure 13.

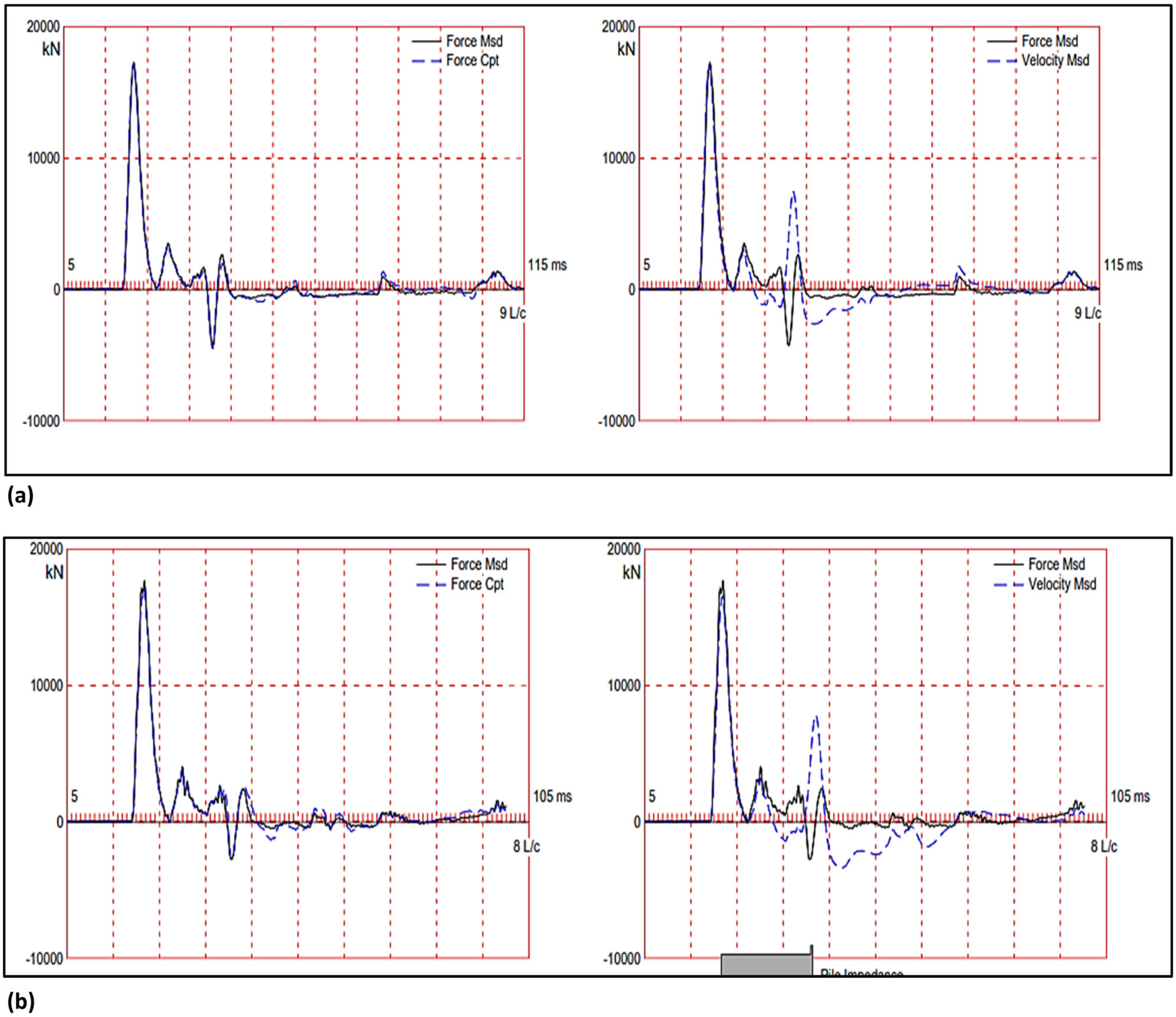

Figure 6: Load amplitude of the hydro-hammer with time and waveform for (a) OEP and (b) PCP (Geotechnical Interpretative Report of the Container Terminal in Al-Fao).

Figure 7: A 10 Hz geophone and Seismograph (PASI) data logger with 24 channels.

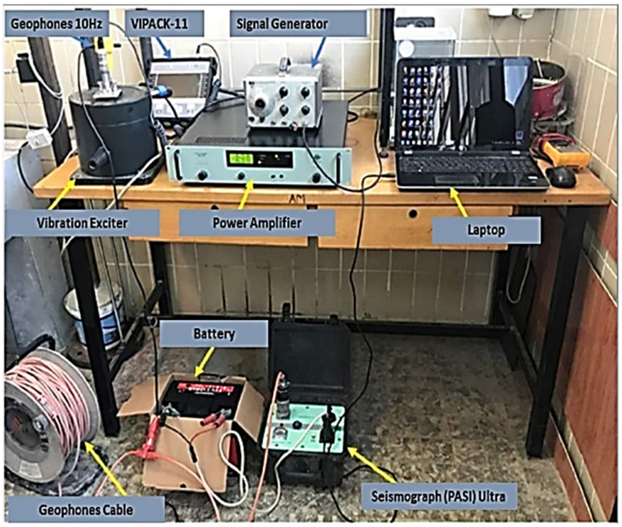

Figure 8: Calibration of a geophone [15].

The records were taken when the pile reached embedment depths of 1, 2.75, 5.5, 11, 16.5, and 22 m, in the case of using the vibro-hammer, and at embedment depths of 24.5, 29.4, 35.25, 41.13, 45.5, and 46 m in case of using the hydro-hammer. The various embedded depths in the soil profile have been carefully chosen at different depths for studying the impact of soil type on wave propagation and the depth

Table 5: Calibration of a geophone sensitivity [15]

Test no.	Frequency (Hz)	*V* (Volts)	Velocity (mm/s)	Sensitivity (Vs/mm)
1	60	1.15	42.6	0.02699
2	30	0.58	21.5	0.02697
Average	45	0.865	32.05	0.02698

of the pile's toe. These depths have been selected proportional to the final depth of the pile, resulting in a range of angles (2–63.43°) for the inclined distance from the pile's toe to the geophones on the ground. The maximum angle occurs when the horizontal distance is twice the embedded depth of the pile.

Finally, the whole raw data collected from the site from different monitoring systems are kept for analysis and study purposes. The software used to analyze the data are Geopsy, Matlab, USB Seismograph, and Excel.

7 Results and discussion

The number of blows is recorded in the site every 250 mm, for the hydro-hammer for both pile types, and the total

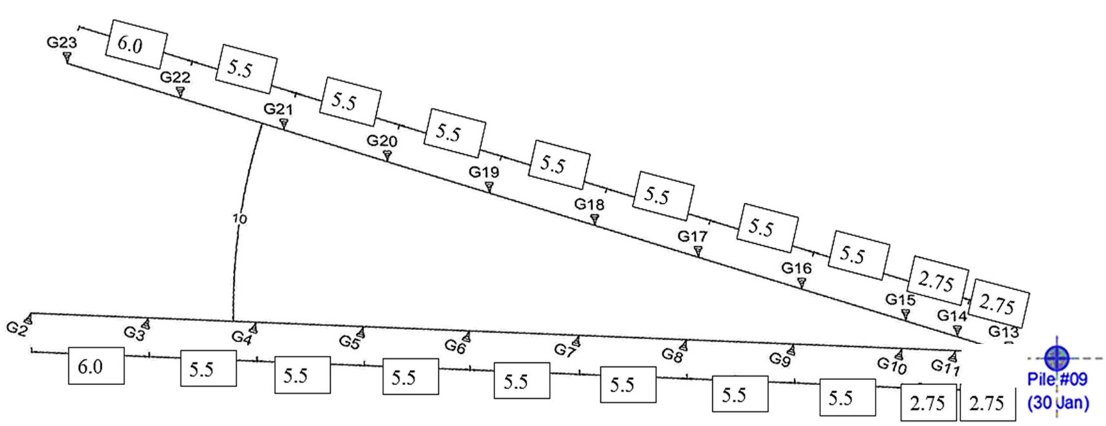

Figure 9: Distribution of geophones, in case of using the vibro-hammer.

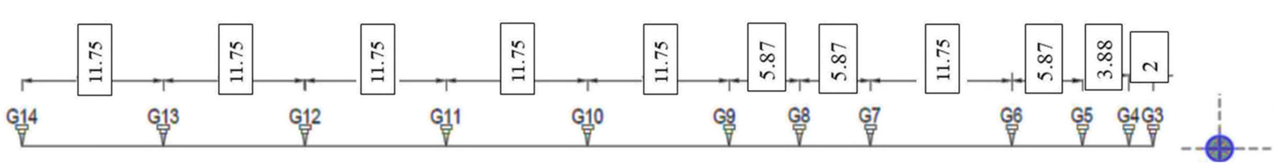

Figure 10: Distribution of geophones, in case of using the hydro-hammer.

Figure 11: Vibration monitoring system.

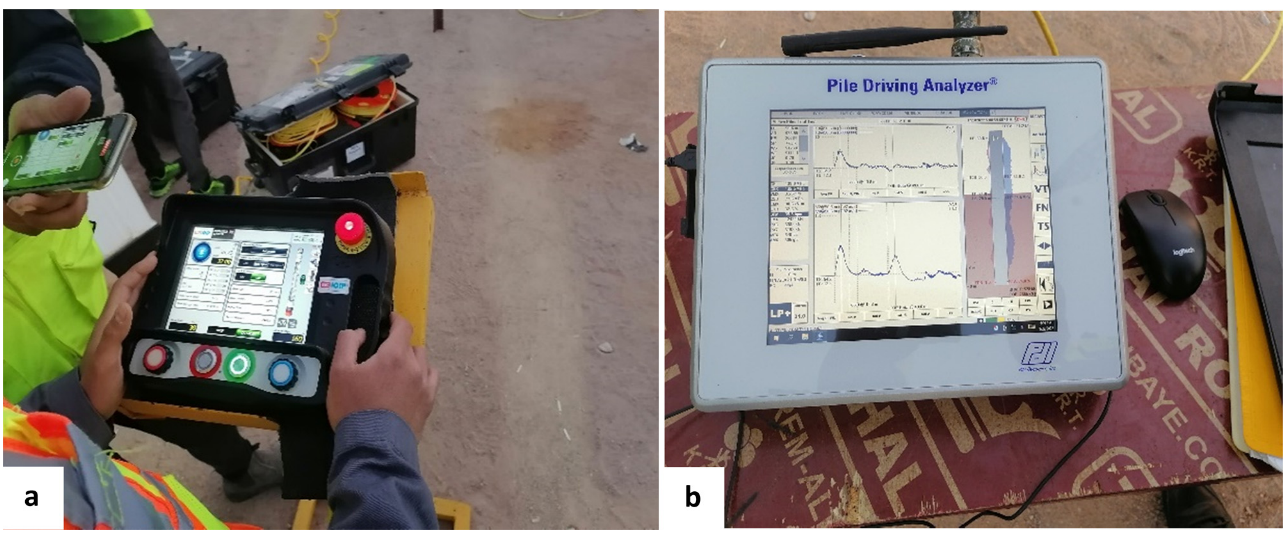

Figure 12: (a) Monitoring system of the hydro-hammer and (b) PDI monitor.

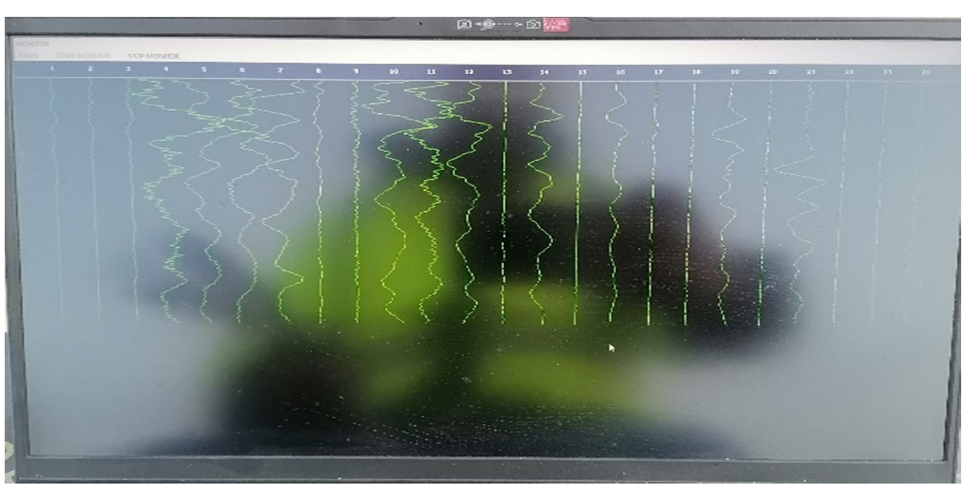

Figure 13: Monitoring of the received waves in the site.

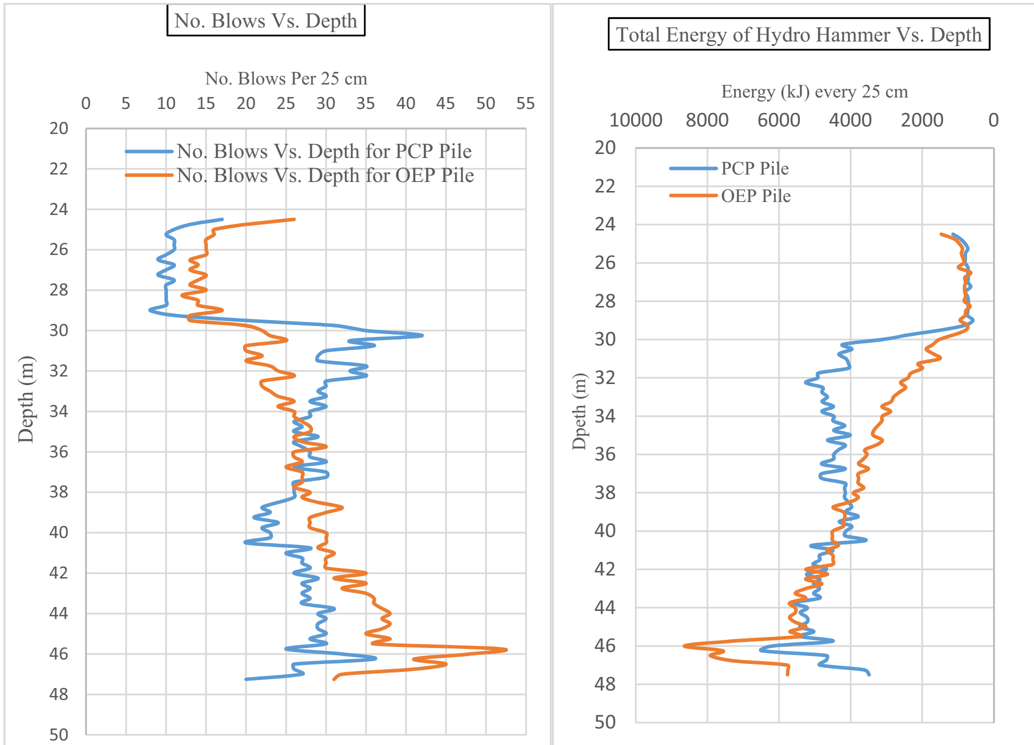

Figure 14: Number of blows and energy vs depth for hydro-hammer.

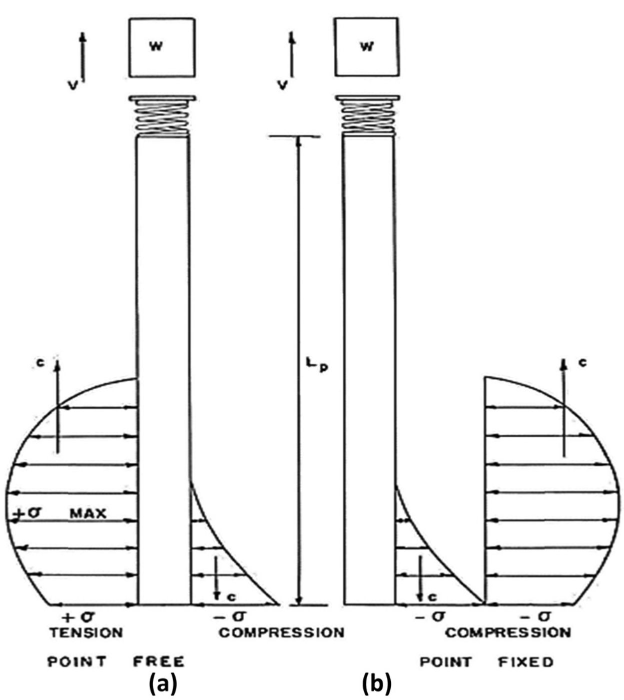

Figure 15: Stress wave reflection in long piles [16].

energy of blows is taken from the hammer monitoring system. These records are shown in Figure 14.

The number of blows and total energy required to penetrate the PCP is increased suddenly at a depth of 30 m due to the presence of the dense sand stratum (with high resistance) which led to high vibration generation. Beyond depth (38 m), the number of blows and hammer energy fluctuates with a small range because the partial closure at the end of the PCP works as an anchor (fixed point), so the compressive stress along the pile will not be reflected as tensile stress when reaching the pile's toe, instead, it will be reflected as compressive stress overlapping with previous compressive stress [16] and make the pile almost constantly driven into the soil, as shown in Figure 15. Contrary to the PCP, the number of blows and total energy is gradually increased for the OEP as the soil resistance increases.

The field measurements of voltage signals via geophones are converted to PPV and plotted against the distances from the vibration source, as demonstrated in Figures 16 and 17 for vibro- and hydro-hammers, respectively.

Tables 6 and 7 list the amplification ratios in PPV near the source, due to partially closing the pile end, for vibro- and hydro-hammers, respectively.

These ratios reduce as the distance from the source is increased for all penetration depths until they diminish at a distance close to 16.5 m from the pile.

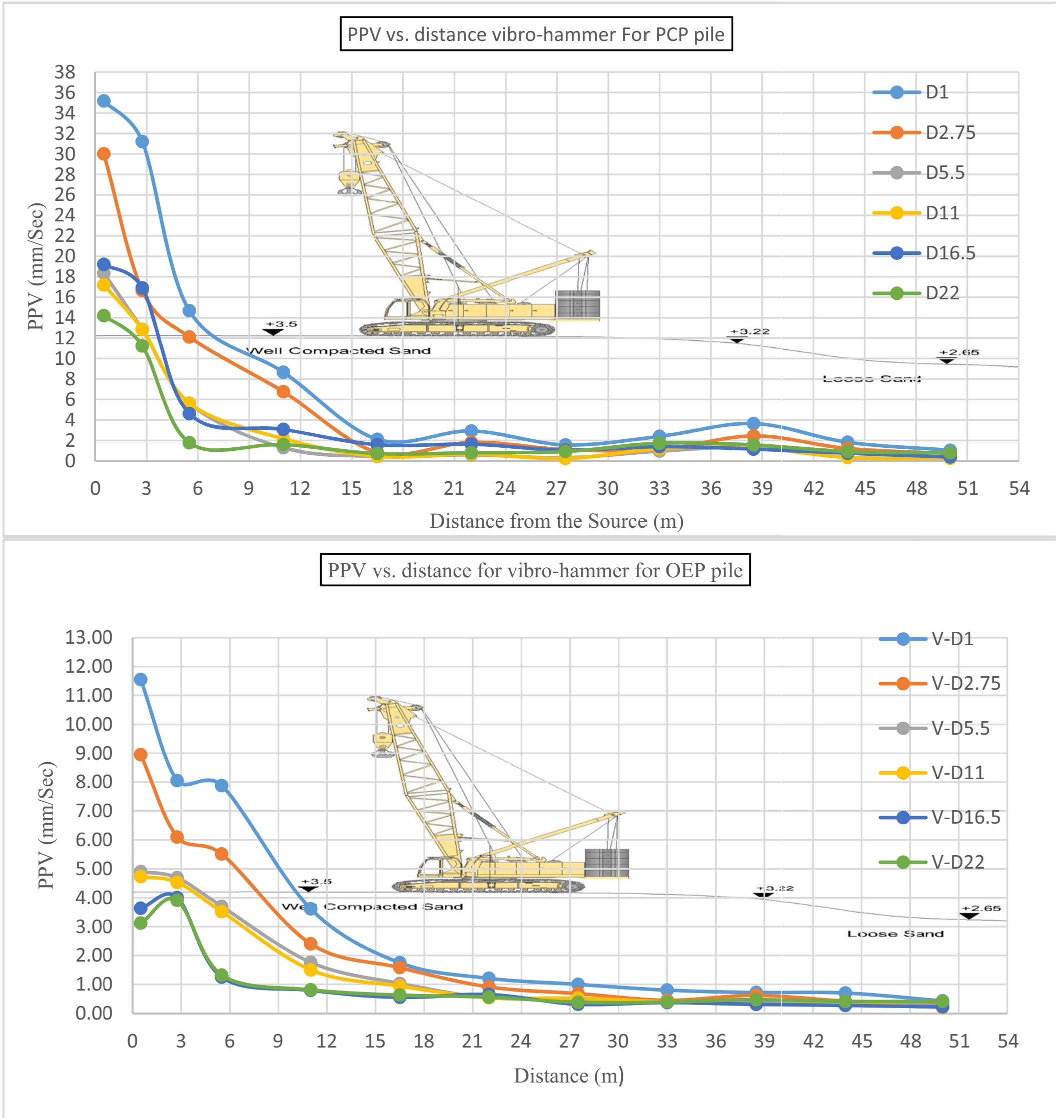

Figure 16: PPV vs distance from the source (vibro-hammer) (From this study).

During the driving of the pile on the site, a crawler crane (250 tons) was used to mount the pile. It stands near the path of geophones at a distance of about 16.5 m, and as a result, its weight is expected to affect the wave propagation in addition to the uneven level on the site, as shown in the photo of Figure 16, so the results showed that there is a slight effect for the crawler crane and uneven embankment level just in pile PCP due to the high vibration, where the vibration amplitude increases at the middle of the crane and decreases where the distance exceeds the crane location and its comeback to increase wherever the level of embankment starts to decrease.

In Figure 16, it can be observed that the amplification ratio of PCP compared to OEP ranges from 3.05 to 5.3 in the shallow depth and near the pile. This amplification is primarily due to the presence of a shoe plate at the toe of the PCP, which increases the surface area in contact with the ground. Consequently, this causes an elevation in vibrations during the pile driving process, primarily driven by surface vibrations. It is important to note that the effects of reflection and refraction play a lesser role in shallow depths compared to deeper ones. Beyond a distance of 3 m from the pile, the amplification ratio decreases significantly, ultimately becoming equivalent at greater distances.

Similarly, in Figure 17, a similar pattern is observed where the amplification ratio of PCP to OEP ranges from 2.6 to 5.04 in the shallow depth and the immediate vicinity of the pile. Once again, this effect is attributed to the presence

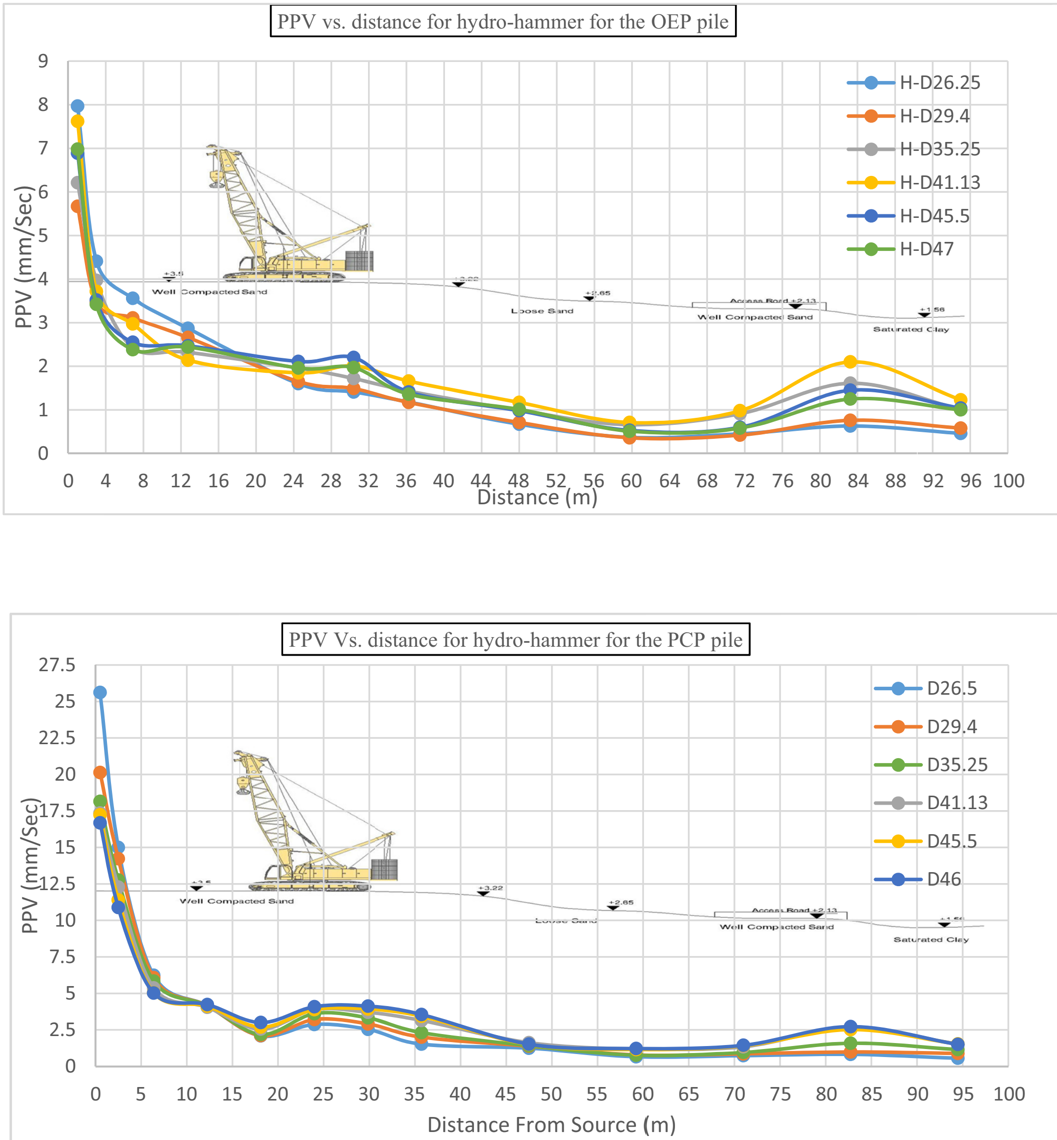

Figure 17: PPV vs distance from the source (hydro-hammer) (From this study).

Table 6: PPV amplification ratios near pile (vibro-hammer). (This work)

Pile embedment depth (m)	1	2.75	22
Amplification ratio (%)	300	>300	>450

Table 7: PPV amplification ratios near pile (hydro-hammer) (This work)

Pile embedment depth (m)	26.5–29.5	Remaining depths
Amplification ratio (%)	>300	>250

of the shoe plate at the toe of the PCP, and the same principles discussed in the case of Figure 16 apply.

The increase in vibration due to partial end closure can be attributed to the increase in soil resistance at the pile toe and hence the increase in body (spherical) waves that are reflected by the pipe to the surface.

In general, the increase in vibration close to the pile is coming from the direct effect of the surface wave from the pile's skin, while the increase in vibration in shallow depth rather than deeper nearby the pile is coming from the short path of the reflected wave from the pile's toe. Hence, a reduction in attenuation within the soil (geometric damping) correlates with lower internal damping of the soil, which pertains to the energy transmitted through it, known as material damping (Mihalache) [17], where the wavelength is small nearby the source and it causes an

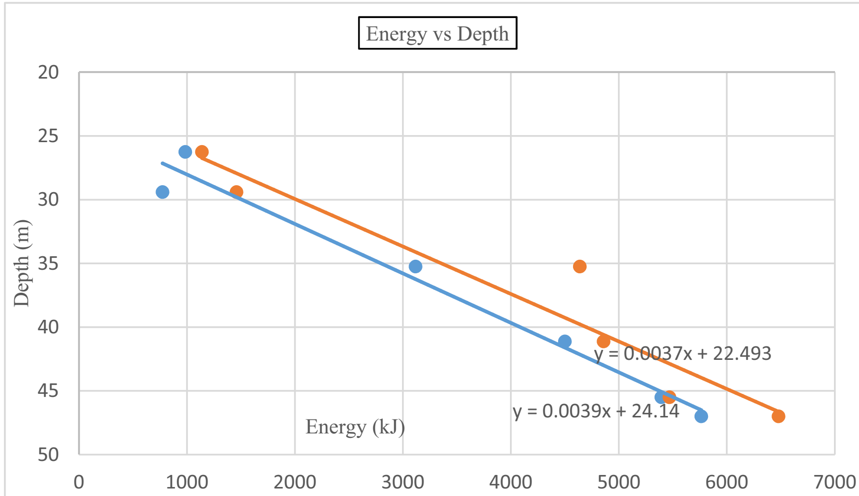

Figure 18: Blow energy vs pile embedment depth (From this study).

increase in the frequency of the vibration. Consequently, the vibration diminishes and reaches a nearly uniform level over long distances with the vibro-hammer, as the distance from the source increases, the wavelength of the waves increases, while the frequency gradually diminishes due to the effect of distance. Simultaneously, the vibration intensity and amplitude tend to stabilize at a relatively consistent level far from the source. This phenomenon is influenced not only by material and geometrical damping but also by other factors contributing to energy dissipation during wave propagation.

After a considerable distance from the vibration source, the PPVs induced by the impact of the hammer driving a pile may converge to similar levels. This convergence is a result of various influencing factors during wave propagation:

- Energy attenuation: As vibrations propagate through the ground, their energy dissipates due to various mechanisms like soil damping, scattering, and reflection. This dissipation leads to a decrease in vibration amplitudes, resulting in reduced PPVs. As vibrations travel over long distances, the energy loss is distributed, leading the vibrations to approach a similar magnitude.
- Soil influence: The characteristics of the soil through which vibrations travel play a crucial role in their attenuation. Varied properties like stiffness, density,

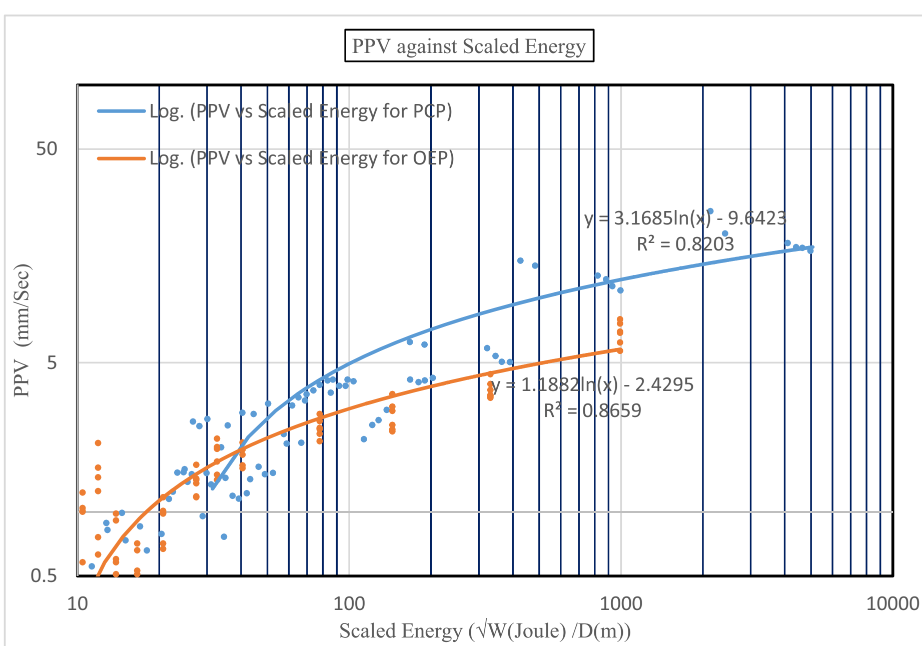

Figure 19: PPV vs scaled blow energy (From this study).

and damping in different soils can influence the propagation of vibrations differently. Nonetheless, as the distance from the vibration source increases, the impact of soil properties may diminish, and the vibrations tend to homogenize.

- Wave reflection and interference: When vibrations encounter variations in soil conditions, such as changes in soil layers or impedance, they can experience wave reflections and interference. These phenomena may lead to fluctuations in vibration amplitudes at different distances from the source. Nevertheless, these effects tend to attenuate as the distance increases, resulting in more consistent vibrations.
- The presence of water in the soil can act as a damping mechanism for vibrations. When the pile is driven into the soil above the water table, the soil's moisture content can help absorb and dissipate some of the energy from the impact, reducing the transmission of vibrations. This is particularly important for mitigating potential damage to nearby structures or the environment.

Statistical analyses are performed regarding the available data. Figure 18 shows the variation in energy with the embedment depth, whereas the vibration PPV vs scaled energy ($\sqrt{W}/R$) is demonstrated in Figure 19 for both pile types.

$$\begin{aligned} W_{(\mathrm{PCP})} &= 270.27D - 6079.189 \\ W_{(\mathrm{OEP})} &= 256.41D - 6189.744, \end{aligned} \tag{1}$$

where $W_{(\mathrm{PCP})}$ and $W_{(\mathrm{OEP})}$ are blow energies for PCP and OEP, respectively. D is the depth of the embedded Pile ($D > 24.5$ m).

$$\begin{aligned} \mathrm{PPV}_{(\mathrm{PCP})} &= 3.1685 \ln(\sqrt{W_{(\mathrm{PCP})}}/R) - 9.6423 \\ \mathrm{PPV}_{(\mathrm{OEP})} &= 1.1882 \ln(\sqrt{W_{(\mathrm{OEP})}}/R) - 2.4295, \end{aligned} \tag{2}$$

where R is the radial distance from the pile (m) and $\mathrm{PPV}_{(\mathrm{PCP})}$ and $\mathrm{PPV}_{(\mathrm{OEP})}$ are peak particle velocities for PCP and OEP, respectively. The above equations are applicable for pile and hammer characteristics and soil profiles similar to their counterparts used in this study.

8 Conclusion

The following concluding remarks are drawn from this study:

1. Although the vibro-hammer is used in the soft layers, the induced vibrations are higher than that of the hydro-hammer due to the high frequency, short wavelength, and shallow penetration use.
2. The vibrations are attenuated along the distance from the source where the PPV is decreased to approximately average, 3.5% for OEP and 2.3% for PCP, at a distance of around two times the penetration depth (50 m) for all embedded depths when the vibro-hammer is used. The PPV is decreased to approximately average, 7.25% for OEP and 4.5% for PCP at a distance of around two times the penetration depth 100 m for all embedded depths when the hydro-hammer is used. The PCP exhibited more attenuation for both hammer types.
3. Partially closing the pile tip amplified the vibrations from three times for 1 m penetration up to four times for 22 m penetration in the vicinity of the pile when the vibro-hammer is utilized. The amplification is decreased away from the pile.
4. When the hydro-hammer is used, the amplification ratio is more than three times for penetrations of 26.5 m and 29.5 m and about 2.5 times in deeper penetrations. The amplification is decreased away from the pile.
5. The amplitudes of vibration in the case of using the vibro-hammer tend to be close after a distance of 16 m from the source. The same response is noted in the case of the hydro-hammer, but at a distance of about 35 m from the source.
6. Equations (1) and (2) are proposed for estimating the induced vibrations for similar pile, hammer characteristics, and site conditions.

9 Recommendations

This study offers a reference for determining a safe distance from the vibration source to mitigate the impact of vibrations in Al-Fao city, specifically in the context of vibro- and hydro-hammers. It is important to note that the equation developed for assessing vibrations with these particular hammers and steel materials may not be applicable for evaluating other sources of vibrations.

To enhance the study's comprehensiveness, further research could be conducted, encompassing additional case studies within the same city. This might involve examining precast pipes and various types of hammers to provide a more comprehensive understanding of vibration effects.

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Data availability statement: Most datasets generated and analyzed in this study are comprised in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.

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