VIBRATION ASSOCIATED WITH PILE DRIVING AND ITS EFFECTS ON NEARBY HISTORICAL STRUCTURES

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ABSTRACT
Project of constructing a bridge and a navigation lock on Dammietta Branch of Delta Barrage is currently in progress where impact and vibratory hammers are used for concrete and sheet pile driving works. Energy generated from the force pulse is dissipated either as pile penetration or as radiated wave energy. These transient wave pulses can be characterized by their peak particle velocity and its decay with distance from the pile, dominant frequency, and duration. Hammer rated energies are orders of magnitude less than ½ kg of TNT. In some situations, typical monitoring equipment is often not able to withstand the extreme environment of close-in construction machines and these motions are difficult to measure. However, Pile type controls the amount of soil displaced during insertion and thus the amount of permanent displacement, densification, and the vibration generated. Vibration analyses were focused at the construction area and at the surrounding structures. Pile vibrators used in the construction operations produce high level of vibration capable of destroying any structure close to the source; however, material damping and attenuation coefficient are at the construction sites and the vibration levels attenuates very greatly with distance from the vibration source. Dynamic analyses were done on sections from the source of vibration to the surrounding structures to study the decay of vibration wave with distance, with kind of soil, with area topography, with trenches, and with water channels. Through field study of pile driving at the construction area, effect of pile driving on nearby structures are well determined and evaluated based on predicting vibration limits at different conditions.

NOMENCLATURE

F: is principal frequency,
C_s: is propagation velocity of the shear wave.
H: is the thickness of the layer.
u_2: is peak particle velocity at distance R_2,
u_1: is peak particle velocity at distance R_1,
n: is a function of the wave type.
α: is attenuation coefficient.

1. INTRODUCTION
Implementations of construction projects involve various sources of construction vibrations such as pile driving, dynamic compaction, and operating heavy equipment. These sources generate elastic waves in soil, which may adversely affect surrounding structures. The effects range from serious disturbance of working conditions to visible structural damage and can lead to failure. The dynamic effect of construction vibrations on adjacent and remote structures depends on soil deposits at the site and susceptibility ratings of structures. It is likely that intolerable structure vibrations may be induced in close proximity of the driven piles, but foundations settlements resulting from soil vibrations in loose soils may occur at various distances from the source [1]. It is important to assess the dynamic effect before the beginning of construction activities and at the time of construction. Therefore monitoring construction vibrations have to be started prior to the beginning of construction works at the site and be continued during construction to provide the safety and serviceability of sound and vulnerable structures.

Vibrating, impacting, rotating, and rolling construction equipment is used for soil excavation, modification and improvement. Machinery with dynamic loads and blasting are sources of construction vibrations. The most prevalent powerful sources of construction vibrations are pile driving, dynamic compaction, and blasting. Blasting energy is much larger than energy of other sources of construction vibrations. The energy released by 0.5 kg of TNT is 5400 kJ, where energy released by diesel hammer is 85 kJ [2]. Such energy is 50 to 1000 times the energy transferred to piles during driving and 15 to 80 times the energy transferred to the ground during dynamic compaction of soils [3].

Ground vibrations generated by construction sources can be roughly separated into two categories: transient and steady state vibrations. Transient vibration includes single
event or sequence of transient vibrations and each transient pulse of varying duration is dying away before the next impact occurs. Such vibrations are excited by air, diesel or steam impact pile drivers, by dynamic compaction of loose sand and granular fills, and also by highway and quarry blasts. The dominant frequency of propagating waves from impact sources ranges mostly between 3 Hz and 60 Hz [3]. Where steady state vibration includes contains continuous harmonic or some other periodic forms. These forced vibrations are caused by vibratory pile drivers, double acting impact hammers operating at relatively high speeds, and heavy machinery.

Vibratory pile driving equipment is wide spread dynamic source of construction vibrations. The most important characteristics of these machines are frequency with the resultant relationships between dynamic force and eccentric moment. Low frequency machines have vibratory frequency between 5-10 Hz and used mainly for piles with big mass and toe resistance such as concrete and large steel pipe piles. Medium frequency machines have the vibratory frequency range of 10-30 Hz and used with lightweight piles such as sheet piles and small pipe piles. High frequency machines operate at frequencies of more than 30 Hz. The major advantage of these machines is their lowered transmission of ground excitation to adjacent structures [4].

It was found that structural damage could be well correlated with the peak particle velocity of structure vibrations. The same criterion for structural damage of residential buildings was set at 50 mm/s peak particle velocity in the frequency range of 3-100 Hz [5]. A conservative limit of 100 mm/s was suggested for commercial and engineered structures [6]. Although peak particle velocity is the parameter most commonly used to evaluate the effect of construction vibrations on structure, other vibration parameters can be used in assessment of vibration effects as well. Displacement of 0.1 mm, and acceleration of 2.5 m/s² is vibration limits to evaluate structural damage [7].

2. MOTIVATION

Project of constructing a bridge and a navigation lock on Dammietta Branch of Delta Barrage is currently in progress where vibrators are used for sheet pile driving works as shown in Fig. 1. There was an extended large crack at a pier of the Navigation lock of one of the most important and historical barrage in Egypt, Delta Barrage. This crack was initiated due to the construction works of sheet and concrete pile driving close to this area. The crack was developed due to vibrating and impacting construction equipment as well as dewatering process in this area. Damage or failure of this structure will have bad economic, social, and environmental impacts.

The crack was noticed during construction works, as shown in Fig. 2, but at this time there was no recording of vibration levels while vibrators were working at few steps from the pier of the navigation lock of Delta Barrage structure. Concerns were paid about Delta Barrage structure and it was requested to monitor vibration levels on the Delta Barrage structure to ensure safety of this structure where the construction area was moved more than 100 m away from the Delta Barrage structure; however, construction area becomes close to the building structures as shown in Fig. [3]. Details of measurements and analysis according to work advances are available [8].

Overall vibration levels and frequency analysis were measured in three perpendicular directions in terms of peak particle velocity, acceleration and displacement. Two dual channel pulse system of Bruel & Kjaer equipped with vibration analysis soft ware was used to record vibration spectrum in the pre-specified frequency range.

3. PREDICTION ANALYSIS

Principal frequencies of all construction vibrations depend to some extent on the transmission medium. High frequency motions tend to be filtered out or attenuated over shorter distances in soil than in rock. Layers can propagate certain frequencies further because of waveguide effects where shear waves will selectively amplify within a soil layer or rock layer at a frequency

\[ F = \frac{C_s}{4H} \]  

(1)

described by [2]:

where:

- \( F \) is principal frequency,
- \( C_s \) is propagation velocity of the shear wave, and
- \( H \) is the thickness of the layer.

As a result of these considerations, at typical distances principal frequency from blasting ranges from 1 to 40 Hz when measured on soil profiles with thicknesses greater than 2 to 3 m and 10 to 100 Hz on rock [9].

Two phenomena, geometrical spreading and damping produce attenuation or decay of vibrations. Geometrical spreading is best described by a relationship at two distances, \( R_1 \) and \( R_2 \), where peak particle velocity \( u_1 \) is

\[ u_2 = u_1 \left( \frac{R_1}{R_2} \right)^n \]  

(2)

known and \( u_2 \) unknown as [10]:

where:

- \( u_2 \) is peak particle velocity at distance \( R_2 \),
- \( u_1 \) is peak particle velocity at distance \( R_1 \), and
- \( n \) is a function of the wave type

\( n = 1 \) for body waves in the ground that spread spherically, except at the surface where \( n = 2 \), and \( n = \frac{1}{2} \) for Rayleigh waves. In some sense this power describes the decline in energy per unit area of the expanding surface over which the vibration energy is spread.

In addition to geometric spreading, for each cycle of motion or wavelength, \( \lambda \), traveled, the wave loses a small amount of energy that is required to overcome friction, and so on. This hysteretic loss of energy during one cycle of deformation is called material damping, as it is a function of the materials deformational properties. It has been shown to be proportional to the logarithm of the distance traveled:

\[ u_2 = u_1 e^{-\alpha(R_2 - R_1)} \]  

(3)

Where \( \alpha \) is attenuation coefficient. This coefficient increases with dominant frequency increases because
higher frequency signal passes through more cycles than low frequency signal when traveling same distance. Also $\alpha$ is larger in hard soil than in rock and in soft soil than in hard soil [2].

4. RESULTS AND ANALYSIS

4.1 PILE DRIVING AT SOFT SOIL AREA

In this paper, the effect of sheet pile vibrator on the nearby structures is investigated. The pile vibrator produces high level of energy, which is transmitted to the soil. The produced waves travel outward from the construction source and attenuates due to geometrical spreading and material damping. The attenuation of the vibration amplitude with distance from the vibration source is shown in Fig. 4, where the site of pile construction and its surrounding is in soft soil which has large value of material damping. The vibrator produces high level of vibration of 35-m/sec$^2$ acceleration and 130 mm/sec peak particle velocity at the driving site. These levels are dangerous and cause damage and failure at the very close structures. However, these levels attenuate very greatly with distance from the source. At 10 m from the source, peak particle velocity decreases about 98 times and reached to 15 mm/sec, where peak acceleration decreases to 2 m/sec$^2$. After 10 m, the trend of decreasing vibration level is different completely than the trend in the first 10 m. After 10 m, vibration level decreases smaller than before with distance and at 30 m, the vibration level is about $1$ m/sec$^2$ (about 10% of the gravitational acceleration) and any structure subjects to this level of vibration needs foundation support and more concern is necessary for structures subjected to higher level of vibration.

Frequency analyses done at the site of sheet pile driving and at 10 m from the construction pile site are shown in Figs. 5 & 6. The two spectra show that the dominant frequency is 18.5 Hz and its harmonics. This dominant frequency is the speed of the driving machine (1100 rpm). This dominant frequency is of high level of energy at the pile-driving site (10 m/sec$^2$) and of low level at 10 m from the driving site (150 mm/sec$^2$). The peak particle acceleration level decreases about 100 times at the dominant frequency just at distance 10 m from the source when driving at this soft soil. However, the peak level at other exciting frequencies decreases for higher frequencies and diminishes with getting far from the pile-driving source. It is apparent that vibration level associated with pile driving at the soft soil area decreases very greatly with distance from the pile driving site and the resulting wave is of periodic nature which is highly attenuated after short distance and harmonic frequencies are of low vibration level.

4.2 PILE DRIVING AT HARD SOIL AREA

On the other hand, pile driving at hard soil encounters more soil resistance and takes more time and may require larger driving machine of higher power. Variation of vibration level measured at four locations on 100 m section from the vibration source at 25 m, 50 m, 75 m, and 100 m is shown in Fig. 7, where an industrial trench was driven through concrete bed downstream of the barrage. Pile driving through concrete is very difficult and requires higher power machines and generates elastic waves of high magnitude and attenuation is of low value. Construction operations at these circumstances damaged the pier as well as dewatering operations at the near area.

Frequency analyses done at the four locations on the same section described above and the resulting spectra are shown in Figs. 8, 9, and 10 at distance 25 m, 50 m, and 75 m respectively. These spectra show that the fundamental frequency is 18.5 Hz (1110 rpm). Vibration waves attenuate with distance; however, attenuation rate is slower than rate at soft soil. Attenuation rate due to trenches is higher than without. Presence of natural or industriil trenches and water channels damp vibration level greatly and attenuates vibration wave and die out the harmonics of the fundamental frequency.

4.3 VIBRATION NEARBY HISTORICAL STRUCTURES

After analyzing vibration levels associated with pile driving vibrators and defining the problem of using such equipment close to structures, more concern was paid to the nearby Delta Barrage structure which is considered a monument and a heritage hydraulic structure. So, the study focused on the hydraulic structures in the area although they were more than 100 m from the pile driving construction area at that time. Vibration levels were monitored and recorded for some months at the nearest seven locations to the site of pile driving vibrator on the Delta Barrage structure as shown in Fig. 11. Monitoring still in continue although the vibrator gets away at far distances from the barrage and in the same time it gets closer to the building structures. At this stage of the project, measurements and analyses were focused on the building structures area where most of them are of shallow foundation and sensitive to high level of vibration. Research is in progress concerning effect of sheet pile vibrators and concrete pile hammers on the nearby building structures.

Monitoring vibration level at point (7) on the Delta Barrage structure which is 100 m away from the vibrator source, as shown in Fig. 11, is of average 0.75 mm/sec peak elocity, 110 $\mu$m peak displacement, and 27 mm/sec$^2$ peak acceleration as shown in Table 1. These low levels of vibration are mainly due to traffic loads across the surface of the barrage and the pile-driving vibrator has low effect on the structure. Most of vibration associated with pile vibrator is dumped through trenches, soil, water, and natural disconnection of the ground. The spectra measured at point (7) as shown in Fig. 12 is of random nature having low vibration level and they are mainly due to traffic and water flow across gates of the structures.

The crack of the pier of the Delta Barrage structure was occurred due to pile driving operations very close to the pier (about 3 m from pile driving operations) where sheet piles were driven through concrete bed downstream of the barrage. Pile driving through concrete is very difficult and requires higher power machines and generates elastic waves of high magnitude and attenuation is of low value. Construction operations at these circumstances damaged the pier as well as dewatering operations at the near area.

Monitoring vibration level then started where the pile-driving site moved more than 150 m away from the...
The barrage structure. Monitoring vibration behavior at the crack (point 3) is shown in Table 2 where vibration level measured is of low and safe level because vibrator at 160 m distance, as shown in Fig. 11, from the monitoring location. As indicated above, this low level is due to traffic and hydraulic flow of water on gates. The fact is that vibration level measured on the Delta Barrage structure is due to traffic, which has random nature and sometimes-transient nature due to passing trucks of different loads, characteristics, and speeds. The spectrum measured at the crack (point 3) in the horizontal and vertical directions is shown in Fig. 13. The wave is of random nature of low level of vibration amplitude and the barrage structure is dynamically safe at this stage and conditions of pile driving construction operations.

5. CONCLUSIONS & RECOMMENDATIONS

1. Delta Barrage Structure is dynamically safe for the current stage of construction operations of pile driving using vibrators.

2. Characteristics of vibration generated from pile driving vibrator is non linear according to pile type and length, soil resistance, soil type, and material damping present at each construction location and conditions.

3. Dynamic loads transmitted to the ground change in dynamic range content and intensity and generate elastic waves in the soil medium.

4. It is important to assess the dynamic effect before the beginning of construction operations by choosing the appropriate method of pile driving and avoiding sudden damage or failure.

5. Vibration generated from the pile-driving vibrator is of high dangerous level and cause damage to the surrounding structures; however, vibration level decrease greatly with distance from the source.

6. The results indicate that damping of hard soil to vibration is lower than that of soft soil and the presence of trenches and natural disconnection such as water channels, and soil can damp vibration level greatly.

7. The effect of sheet pile driving on the nearby structures using vibrators after 50 m from the source is small. Structures close to the vibrator less than 50 m should be carefully monitored and supported.

8. It is recommended to pump water at high pressure using a suitable water jet in the site of pile driving just before driving piles to decrease soil resistance and ease the operation of pile insertion. Also constructing trenches beside the construction area is necessary to absorb vibration waves and decrease vibration amplitude transmitted to the nearby structures.

REFERENCES


Fig. (1) Sheet Pile driving works beside Delta Barrage Structure

Fig. (2) Crack observed at the pier of the Navigation lock of Delta Barrage Structure

Fig. (3) Pile construction works close to the building area

Fig. (4) Vibration level change at the soft soil with distance from the Pile driving site

Fig. (5) Vibration Spectrum at the site of sheet Pile driving at the soft soil

Fig. (6) Vibration Spectrum at distance 10 m from the vibrator at soft soil
Fig. (7) vibration level change with distance from the vibrator at hard soil

Fig. (8) Vibration Spectrum at 25 m from pile vibrator at hard soil

Fig. (9) Vibration Spectrum at 50 m from pile vibrator at hard soil

Fig. (10) Vibration Spectrum at 75 m from pile vibrator at hard soil
Fig. (11) Layout of the Navigation lock of Delta Barrage structure showing vibration locations and the seven measurements points.

Fig. (12) Vibration signal measured on the Navigation lock at distance 100-m [point 7] from vibrator.
Table (1) Vibration levels measured at point [7]

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Table (2) Vibration levels measured at point [3]

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Fig. 13 Vibration signal measured at the crack on the Navigation lock at distance 160-m from vibrator source