A Case of Vibro Compaction Vibration Monitoring in a Reclaimed Site

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Synopsis: Vibro Compaction is a ground improvement technique in which the soil is compacted using waves generated from an equipment called a vibroflot. As the vibration magnitude is less than some other vibratory ground improvement methods this technique is sometimes preferred when the improvement zone is relatively close to existing structures and facilities. Unfortunately, not much can be found in literature on peak particle velocity (PPV) that is generated by this method. This paper reports and interprets vibration monitoring of a Vibro Compaction project that was recently performed on about 13 m of hydraulically placed sand in Palm Jumeira, Dubai. PPV was measured at different distances from the vibroflot. The depth of the vibroflot was also varied to provide a better understanding of the critical depth that creates the largest PPV. A formula is also presented to estimate Vibro Compaction generated PPV during planning stage.

Keywords: vibro compaction, vibration monitoring, peak particle velocity, PPV.

1. Introduction

1.1 The Concept of Vibro Compaction

Vibro compaction, also known as vibroflotation, is a deep ground compaction technique that was developed almost 80 years ago [1] with the invention of the first vibroprobe by W. L. Degen and S. Steuermann [2] in Germany.

This technique is best suitable for the treatment of soils with limited amounts of fines. Mitchell [1] proposes that the best desirable soils for vibro compaction are when the soil's fines content is limited to 18%. Woodward [3] suggests that best results can be achieved when fines content is less than 10%.

The vibroflot, also referred to as vibroprobe or vibrating poker is a hollow steel tube containing an eccentric weight mounted on a vertical axis in the lower part so as to give a horizontal vibration. The vibroflot itself is connected to extension tubes that are supported by a rig; usually a crane.

The vibroflot is either flushed down to the required depth in the soil using water jets or vibrated dry with air jets. When the vibroprobe reaches the required depth, material is added from the ground surface during withdrawal, and the vibroflot is moved in an up and down motion at certain intervals. The horizontal vibrations form a compacted cylinder of soil with a depression at the surface due to the reduction of void ratio in the ground. Depending on the vibroflot power, the zone of improved soil extends from 1.5 m to more than 4 m from the vibrator.

As compaction in vibro compaction is realized by the vibration of the vibroflot vibration parameters must be understood and monitored to ensure that specification limits are not exceeded.

1.2 The Development of Vibration Parameters

Effects of vibration on structures have been under investigation for more than 80 years. From 1930 to 1942 the US Bureaus of Mines (USBM) conducted an extensive research program to study the seismic effects of quarry blasting on buildings [4]. USBM's report [5] of the tests recommended an index of damage based on the acceleration. Duvall and Fogelson [6] statistically showed that these data gave contradictory results because major damage correlated with particle velocity while minor damage correlated with acceleration. Hence, the concept of implementing particle velocity in lieu of acceleration for prediction of (major) damage was formed. Langefors, Kilhstrom and Westerberg [7] also carried out extensive studies to relate between damage and ground vibrations from nearby blasting. Statistical analyses of these data show that the degree of both major and minor damage correlates with particle velocity. Similarly, Edwards and Northwood [8] carried out a number of tests and concluded that damage was more closely related to particle velocity rather than to displacement or acceleration and that damage was likely to occur with a particle velocity of 100 to 125 mm/s and recommended a safe vibration limit of 50 mm/s.

The recommended safe vibration criterion of 50 mm/s particle velocity was a probability type criterion and if the observed particle velocity exceeded the safe limit in any of the three orthogonal components there was a reasonable chance that damage would occur to residential structures. The safe vibration criterion was not a value below which damage would not occur and above which it would occur. Many structures could experience vibration levels greatly in excess of 50 mm/s with no observable damage however the probability of damage to a residential structure would increase or decrease as the vibration level deviates from 50 mm/s.

USBM [4] recommended that velocity gages should be preferably mounted on or in the ground rather than the structure because most of the data used in establishing the damage criterion were obtained in that manner. Mounting the gages in the ground was understood to alleviate the necessity of considering the response of a large variety of structures. Particle velocity should be observed in three mutually perpendicular directions. A safe vibration criterion was based on the measurement of individual components and if the peak particle velocity (PPV) of any component exceeded 50 mm/s damage was likely to occur.

According to Siskind et al. [9], Pennsylvania was the first American state to adopt the 50 mm/s PPV criterion as a safe standard in 1957; however in 1974 it was forced to adopt stricter controls because of citizen pressure and lawsuits involving both annoyance and alleged damage to residences. Consequently and in 1974, USBM began to reanalyse the blast damage problem, expand the study of [6], and overcome its more serious shortcomings. Part of the new study included emphasis on the frequency dependency of structure response and damage, recognizing that the response characteristics and frequency content of the vibrations are critical to response levels and damage probabilities. Also, an analysis was made of various studies of human tolerance to vibrations, although most data are from steady state rather than impulsive sources.

Although the study recognized that a measurement of simple peak particle velocity was an oversimplification, it concluded and recommended that peak particle velocity to continue to be the primary measure of ground motion to assess damage. A simple amplification factor was determined directly from the vibration time histories. Maximum structure velocities and their times of occurrence were noted. Ground velocities and frequencies were then picked off the records at the corresponding moments of time or immediately preceding the time of peak structure vibrations. The ratios of the two velocities were plotted against the frequency of the corresponding ground motion and as expected from the natural resonance frequencies, maximum amplifications were found to be associated with ground motions between 5 to 12 Hz.

These results suggested that frequencies below 10 Hz are most serious for potential damage from structure racking. Vibrations below about 25 Hz can excite high levels of mid-wall motion and generate most of the secondary noises, rattling and other annoyances.

Safe vibration criteria were developed for residential structures, having two frequency ranges and a sharp discontinuity at 40 Hz. There are vibrations that represent an intermediate frequency case, being higher than structure resonances (4 to 12 Hz) and lower than 40 Hz. By using a combination of measured structure amplification and damage summaries and as shown in Figure 1(a) a smooth set of criteria were developed. Three years after the publication of USBM RI 8570 [9] the Office of Surface Mining Reclamation Enforcement (OSM) also published its regulation regarding safe vibration levels [10] (see Figure 14(b)) which appears to be quite similar to USBM's regulation.

Humans notice and react to vibration at levels that are lower than the damage threshold. Vibration levels that are completely safe for structures by all standards can be quite unpleasant when viewed subjectively by people.

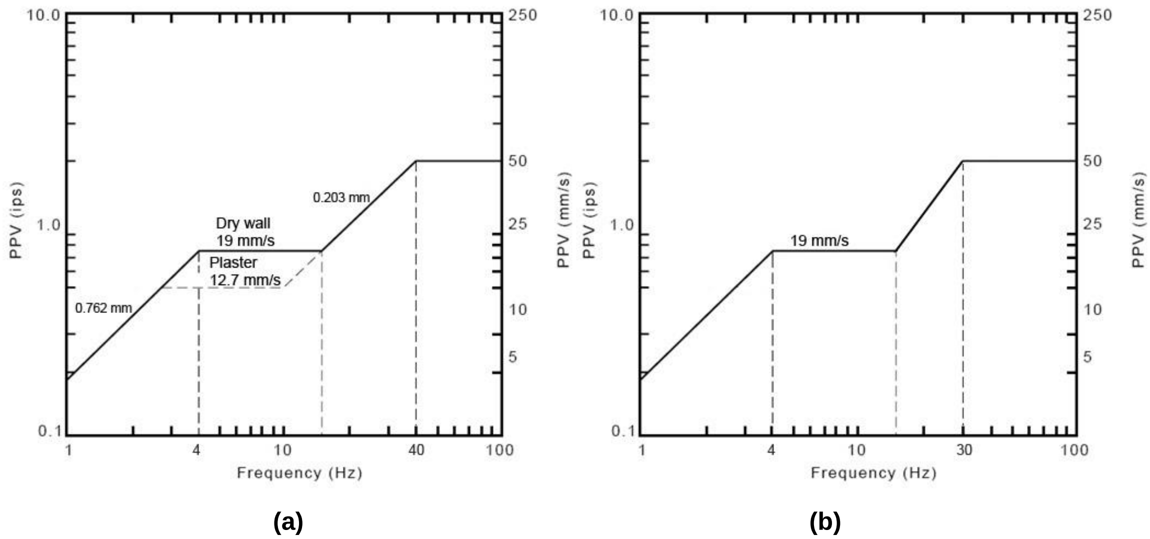

Figure 1: (a) USBM RI 8570 safe vibration limit criteria [9], (b) 1983 safe vibration level criteria modified from USBM RI 8570

2. Vibrations in Vibro Compaction

2.1 Previous Research

Similar to any other process that creates vibration, it is important and mandatory to be aware of the implications of vibrations generated by vibro compaction on structures and humans and to be able to estimate the magnitude of the determining parameters. Unfortunately not much research is available about the particle velocity generated by this technique.

Without providing details about the measurements and the scatter of data, Woods and Jedele [11] have presented the graph of peak vertical velocity (which may have been PPV) for vibroflots with motor powers of 22 kW (30 hp) and 75 (100 hp). Similarly, Dowding [12] has presented the graph for a vibroflot with a motor power of 120 kW, 18 mm vibration amplitude and 30 Hz frequency. Neither of the publications has referred to the depth of the vibroflot during particle velocity measurements.

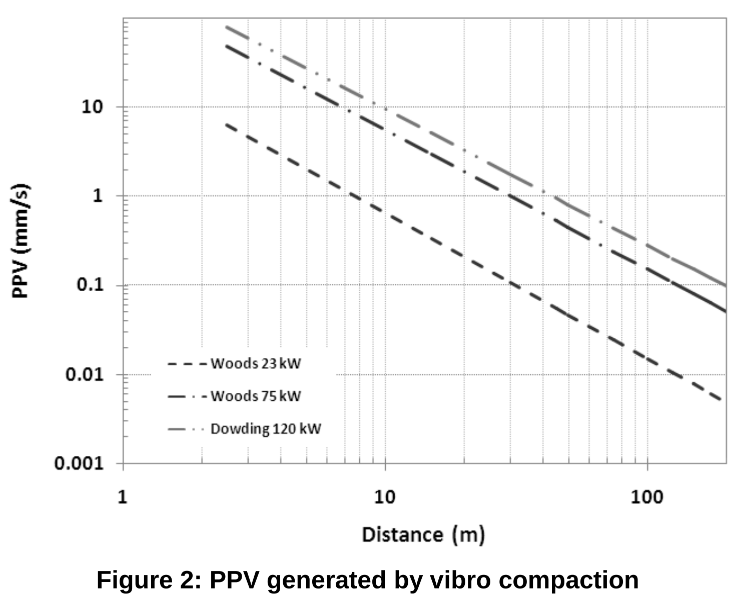

Figure 2: PPV generated by vibro compaction

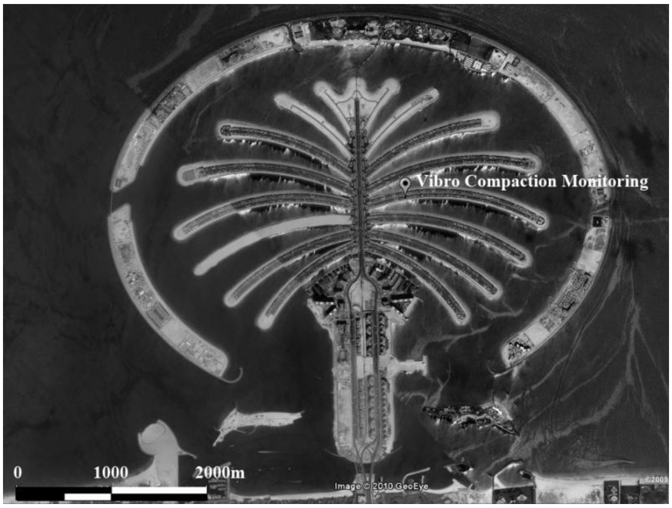

Figure 3: Location of vibro compaction vibration monitoring on Frond D of Palm Jumeira

2.2 This research: Vibration Monitoring of Vibro Compaction on Palm Jumeira

2.2.1 General Information About the Project

Palm Jumeira is a group of man-made islands that has been reclaimed off the coast of Dubai, UAE. The reclamation shape consists of a tree trunk, a crown with 17 fronds, three surrounding crescent islands that form an 11 km long breakwater and two identical smaller islands that are in the shape of the logo of project's developer on the sides of the trunk. In all, 94 million m^3 of sand and 7 million m^3 of rock has been used in this project. Calcareous sand was dredged from the Persian Gulf using trailing suction hopper dredgers [13]. When possible, the hopper was discharged by means of a big door located on the bottom of the hull, but when the water was shallow, the dredger sprayed the sand and water mixture onto the reclamation by rainbow discharge.

2.2.1. Monitoring of Vibroflot Vibrations

The power of the vibroflot's motor that was used in this study was 96 kW. The amplitude at the tip of the vibro probe was rated at 6 mm. Centrifugal force and eccentric moment were respectively 193 kN and 17 Nm. Vibration frequency was up to 53 Hz.

As shown in Figure 3, vibration monitoring was carried out on points located on Plot 106 of Frond D, now renamed to Al Barhi, using a Bruel & Kjaer model 4370 accelerometer. Vibration monitoring was done at distances of 5, 10, 15, 20, 30, 40 and 70 m along 4 lines for two treatment points. Peak particle velocity was recorded at depths ranging from seabed at approximately 12.5 m to 2 m below the ground surface.

Measured PPV at different distances from the vibroflot are shown in Figure 4. Although the scatter of data does not allow the realisation of curve fitting processes with high amounts of reliability, nevertheless it can be observed that PPV reduces not only with distance, but also with depth. The lines that are show in Figure 4 are not the best fitted curves for vibroflot depth versus PPV, and are drawn rather to demonstrate the trend of changes. What is noticeable is that the rate of PPV change during penetration is most when the vibroflot is closest to the monitoring point.

As PPV monitoring has not included data above the depth of 2 m, extrapolation must be carried out to predict PPV at shallower depths. Considering the amount of data scatter, this approach is sufficiently accurate. Using this concept, it is possible to develop a curve for PPV when the vibroflot nose is at ground level. This is shown as a dashed curve in Figure 5. It can be seen that even though the plot of the extrapolated PPV values on ground surface is not quite parallel to the other curves, the curve that best fits these points (solid line in Figure 5) is quite parallel with the other lines and falls in between the 75 and 120 kW vibroflots. This suggests that earlier research may have also measured PPV at ground surface.

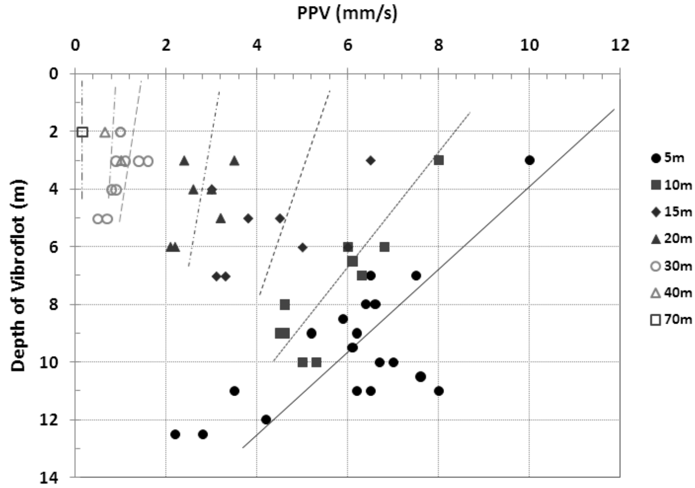

Figure 4: PPV at different distance from the vibroflot

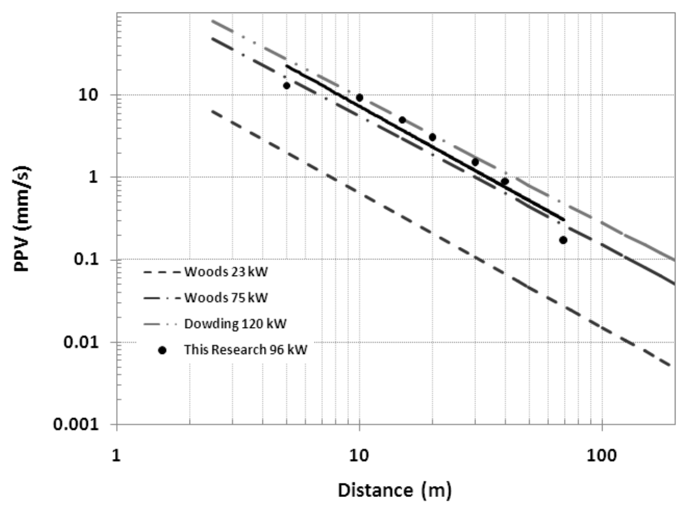

Figure 5: PPV versus distance

Wiss [14] has proposed to express PPV in terms of distance, *d*, and energy, *E*, in a single expression:

$$PPV = K\left(\frac{d}{\sqrt{E}}\right)^{-n} \quad (1)$$

K is the intercept with the ordinate and *n* is the slope or attenuation rate. The value of *n* generally lies between 1.0 to 2.0 with a relatively common value of 1.5, and $d/\sqrt{E}$ = scaled distance.

As power, *P*, is energy per unit of time, it is possible to express vibro compaction generated PPV in terms of vibroflot power and distance. By applying Eq. 1 to each of the PPV measurements by Wood and Jedele [11], Dowding [12] and this research, it can be calculated that n is from 1.52 to 1.64 with an average value of 1.59. Calculation shows that *K* ranges from 2.08 to 8.16 with an average value of 6.2 for the four set of curves. Noting that the lowest *K* value is for the 24 kW vibroflot, the average *K* for the other 3 vibroflots will is 7.5. As, the 24 kW vibroflot is less commonly used that the other types of vibro probes, and since using a large *K* value is more conservative, thus when *P* is in kW and *d* is in metres:

$$PPV = 7.5\left(\frac{d}{\sqrt{P}}\right)^{-1.59} \qquad \mathrm{mm/s} \tag{2}$$

3. Conclusions

Peak Particle Velocity measurements generated from vibro compaction is scarce. A research has been carried out to measure PPV in a reclaimed site composed of calcareous sands using a vibroflot with a motor power of 96 kW. The result of this study indicates that maximum PPV can be expected when the vibroflot is closest to the ground surface. In other words, the most critical time that vibroflot vibrations can damage a nearby structure is when it is just penetrating the ground or being pulled out of the treatment point.

The authors have proposed an equation for predicting PPV generated by vibroflots with different powers.

4. Acknowledgement

The authors would like to express their gratitude and appreciation to Menard for providing the information that has been used in this paper.

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