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Dynamic Compaction Vibration Monitoring in a Saturated Site

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Synopsis: Dynamic Compaction is a well established ground improvement technique in which a heavy pounder is dropped from a significant height to improve the soil's mechanical properties. The pounder impact creates waves that compact the soil; however these waves may also be a nuisance to and damage neighbouring structures and facilities. Peak particle velocity (PPV) has been identified as the most suitable parameter for assessing vibration associated risks. Previous researchers have proposed a number different equations for predicting PPV. Dynamic Compaction has recently been used for soil improvement in Oman's Blue City Project. Particle velocities and vibration frequencies in three directions have been monitored at several distances during the different phases of ground treatment. In all phases PPV has been recorded to be in the radial direction. It has been observed that although it appears that vibration frequency is not influenced by the deep compaction phase, does increase with the progression of work and application of later phases of Dynamic Compaction. This increase is more pronounced at farther distances, but becomes negligible when impact point is closer than a critical distance.

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

1. Introduction

1.1 Wave propagation in Dynamic Compaction

Dynamic Compaction is a well established ground improvement technique in which the mechanical properties of the soil is improved by dropping a heavy weight (pounder) from a significant height a number of times onto a point and in a predetermined grid [1]. The impact creates body and surface waves that propagate in the soil medium.

The body waves, the compression and shear waves, propagate radially outwards from the pounder's impact point along a hemispherical wave front. Likewise, the Rayleigh or R-waves propagate radially outwards along a cylindrical wave front.

The volume of material that is encompassed by each of the waves increases as the wave travels away from the source. Hence, the energy density, or the energy per unit volume, in each wave front decreases with distance from the source. This decrease in energy density and consequently the decrease in displacement amplitude is called geometrical damping.

Material damping is the result of energy loss due to hysteresis damping and internal sliding of soil particles [2], and is the decrease in vibration amplitude with distance from a source due to energy losses in the soil.

The amplitude of the R-wave decreases proportionally with the inverse of the distance from the vibration source [3]; however in soil the wave amplitude decreases faster as soil is not an ideal elastic medium and because there is an internal or material damping. As expressed in Eq. (1), both geometrical damping and material damping can be taken into account for R-wave attenuation [4]:

$$w = w_1\sqrt{\frac{r_1}{r}}e^{-\alpha(r-r_1)} \qquad (1)$$

The coefficient α increases with dominant frequency, as a higher frequency wave will pass through more motion cycles than will low frequency waves when travelling the same distance [5]. For material damping, decay is a function of energy loss per cycle of deformation. This explains why in a general sense dominant frequency declines with distance for the same wave type. The lower frequency components have travelled fewer deformation cycles and have lost proportionally less energy.

1.2 Prediction of Relevant Wave Parameters in Dynamic Compaction

Although the basis of Dynamic Compaction and the improvement that the ground undergoes is the direct result of wave propagation in the soil medium, nevertheless vibrations can be disturbing to humans and hazardous to structures, buildings, pipelines and other facilities.

Statistical research [6] has shown that major damage correlates with particle velocity while minor damage correlates with acceleration. Hence, it is common practice to use particle velocity in lieu of particle acceleration for prediction of damage potential.

Particle velocity should be observed in three mutually perpendicular directions [7]. While damage criteria developed by USBM (US Bureau of Mines) and other organizations have been based on the maximum single value of the three directional components, since real waves are three dimensional and the transducer axes may not be exactly in line with the source of vibrations, Mayne [8] notes that some engineers prefer to calculate the true vector sum (TVS) of the triaxial components; i.e. the square root of the summation of the squares of the particle velocities in the three orthogonal directions at the same time. Mayne has also noted that several individuals have mistakenly expressed the vibration levels in terms of the pseudo vector sum (PVS) whereas in lieu of the values at the same time, the square root of the summation of the squares of the maximum values in each of the three directions is calculated. It can be noted that the maximum values in the three orthogonal directions rarely, if ever, occur at the same time, and application of TVS is neither justifiable nor recommended in any reputable standard.

In 1974, USBM began to reanalyse the blast damage problem [9]. 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. The study showed that maximum amplifications were associated with ground motions between 5 to 12 Hz when the vibration frequency caused resonance with the natural frequencies. 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.

Field observations indicate that Dynamic Compaction generates peak particle velocity with a frequency in the range of 2 to 20 Hz [8, 10, 11, 12, 13].

Prior to performing Dynamic Compaction, peak particle velocities (PPV) should be predicted to determine the probability of exceeding specification limits and the application of contingency methods to reduce PPV values.

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

$$PPV = K\left(\frac{d}{\sqrt{E}}\right)^{-n} \qquad (2)$$

where *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.

Mayne et al. [15] compiled the results of 14 Dynamic Compaction sites. Soil types at these sites included silty sands, sandy clay, rubble, coal spoil and debris fill. For preliminary estimates of ground vibration levels, a conservative upper limit appeared to be:

$$PPV \le 70\left(\frac{\sqrt{WH}}{d}\right)^{1.4} \qquad (3)$$

PPV is in mm/s, *d* and *H* (pounder drop height) are in meters and *W* (pounder weight) is in tons. Later and based on a mix of single maximum component and TVS measurements of 12 sites, Mayne [8] proposed an upper limit conservative PPV in the form of:

$$PPV \le 92\left(\frac{\sqrt{WH}}{d}\right)^{1.7} \qquad (4)$$

In order to get a close trend and based on information accrued by monitoring vibrations realized by different drop heights from a site in Alexandria, Virginia, Mayne [8] has also postulated that while pounder weight may affect vibration frequency, the magnitude of particle velocities is slightly more influenced by the drop height of the pounder.

Thus as formulated in Eq. (5), Mayne proposed to estimate PPV by normalization (dividing by the theoretical impact velocity of the falling weight) and plotting it against the normalized distance to impact (by dividing d by the pounder radius r_0). In Eq. (5) PPV and impact velocity have consistent units.

$$\frac{PPV}{\sqrt{2gH}} \leq 0.2\left(\frac{d}{r_0}\right)^{-1.7} \qquad (5)$$

For impact energies in the range of 250 to 300 tm, Chapot et al. [16] estimated PPV using Eq. (6); however Hamidi et al [13] have found this equation to generally underestimate PPV and have instead proposed Eq. (7). Noting that the pounder and maximum drop height in Hamidi's vibration monitoring were respectively 15 tons and 20 m, Eq. (7) can be re-written in the modified (by rounding up the coefficient from 24.3 to 25) and more general form of Eq. (8)

$$PPV = 340d^{-1.1} \text{ mm/s} \qquad (6)$$

$$PPV = 560d^{-1.1} \text{ mm/s} \qquad (7)$$

$$PPV \leq 25\left(\frac{\sqrt{WH}}{d}\right)^{1.1} \qquad (8)$$

2. Vibration Monitoring at Blue City Dynamic Compaction Project

2.2 Description of Project and Ground Conditions

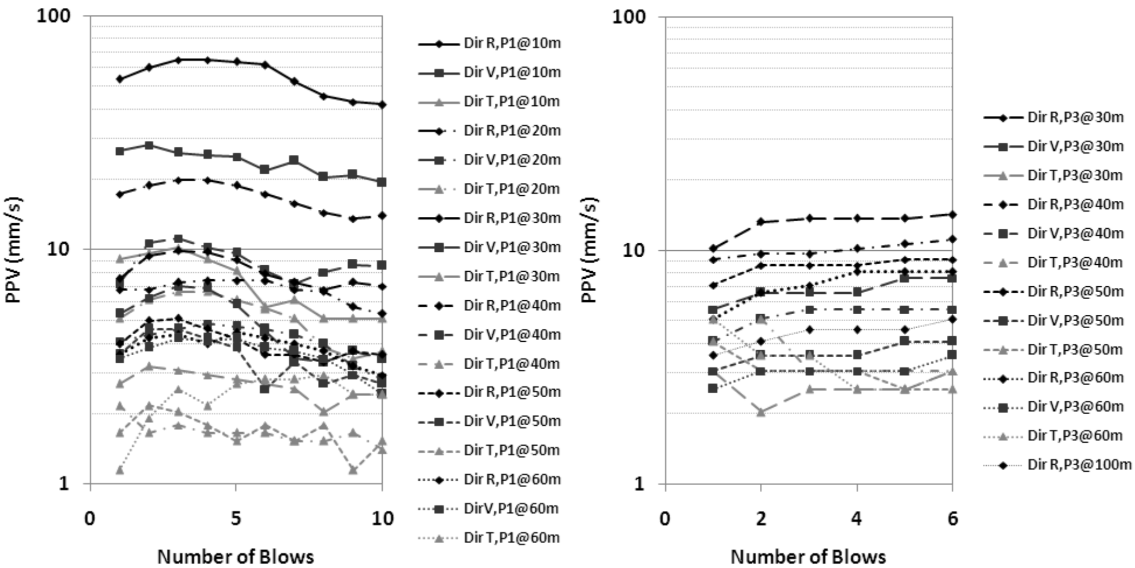
Al Madina A'Zarqa, translating to Blue City, is a multibillion dollar megacity project in Oman that spreads over an area of 32 km^2 with 16 km of coastline southeast of Al Sawadi and along the Gulf of Oman. The multiple phases of the project are to be built over a period of several years. Phase 1 of this project is located within an area that is 3 km along the coastline and measuring 2 km inland.

Plots No. 1.1.2, 1.4.2, 1.3.1 and 1.3.2 with an approximated area of 225,000 m^2 is the first construction area. Based on the topographical survey, original ground level of the site as a whole was from +0.8 m to +2.7 m MSL (Mean Sea Level). Average ground level in Plot No. 1.1.2 and 1.4.2 was approximately +1.5 m MSL. The same level was approximately +2.3 m MSL in Plot No. 1.3.1 and 1.3.2. Minimum, maximum and average groundwater levels were reported to be respectively -0.4 m, +0.25 m and ±0.0 m MSL.

A summary of the generalized ground conditions is tabulated in Table 1.

Table 1. Summary of ground conditions

Description	Top elevation (m MSL)	Average Thickness (m)	Qc (MPa)	Rf (%)	N SPT
Medium dense slightly silty sand	2.5	8.5	2-12	0.5-1	2-35
Soft very silty sand to sandy silt and clay	-6	2.5	2	2	
Interbedded medium dense silty sand and firm to stiff silt and clay	-8.5	15.5	3-20	1-4	
Substratum	-24		refusal		



(a) **(b)**

Figure 1. PPV versus number of blow (a) Phase 1, (b) Phase 3

The buildings in the mentioned plots were anticipated to be 2 to 7 stories excluding their partial basements. Preliminary calculations indicated that the presence of loose sand layers in the upper 8.5 m of ground stipulated the application of ground improvement to allow the construction of raft foundations. Among the proposals that were received during tender, the method of Dynamic Compaction was deemed as the most appropriate and competitive solution for improving the ground and allowing the construction of raft foundations.

2.3 Vibration Monitoring

Dynamic Compaction was carried out from elevation +1.8 m MSL in three deep phases using a 23 t pounder that was dropped from 20 m followed by ironing using a 15 t pounder that was dropped from 15 t.

Vibration monitoring by recording the peak particle velocities and associated frequencies in the radial, vertical and tangential directions was performed using a Nomis 7000 seismograph. Measurements were carried out at different distances, from 10 to 100 m during the three deep and ironing phases for every single drop that was applied to a specific print.

Peak particle velocities versus the blow number for Phases 1 and 3 at different distances are respectively shown in Figures 1(a) and 1(b). As can be observed, regardless of the blow number, distance to pounder impact point and phase of Dynamic Compaction, peak particle velocity was always in the radial direction. Similarly, particle velocity in the tangential direction was always the least value among the three directions. The comparison of the two figures also indicates that at equal distances, PPV in Phase 3 is higher than Phase 1. The PPV ratio between the two phases appears to be less at closer distances and more at further distances.

Also noticeable in Figure 1(a) is that in most case of Phase 1 monitoring, at a constant distance from impact, PPV initially increases with the number of blows, but then reduces to values lower than what was measured in the first blow. This is most observable in all three directions in the closest distances. As lesser blows were applied per impact point in Phase 3 it cannot be said that the same has happened in the later phase, but Figure1(b) shows that PPV of the first blow in this phase was also smaller than subsequent blows.

Plotting PPV versus distance for Phases 1, 2 and 3 produces very interesting results. It can be seen that although there is PPV scatter for records made at the same distance during each phase, the upper limit value of PPV for each phase appears to fit reasonably well with a line drawn in a semi logarithm scale. It can also be understood that the slope of PPV attenuation in the earlier phases is more than the later phases. This suggests that there is greater material damping in loose soils than dense soils. As already noted in Figure 1, Figure 3 also clearly indicates that the difference between PPV values of earlier and subsequent phases of Dynamic Compaction becomes greater as distance from impact point increases. In fact, it appears that at distances closer than a critical distance, seemingly about 19 m in this study, the value of PPV becomes insensitive to the compaction phase.

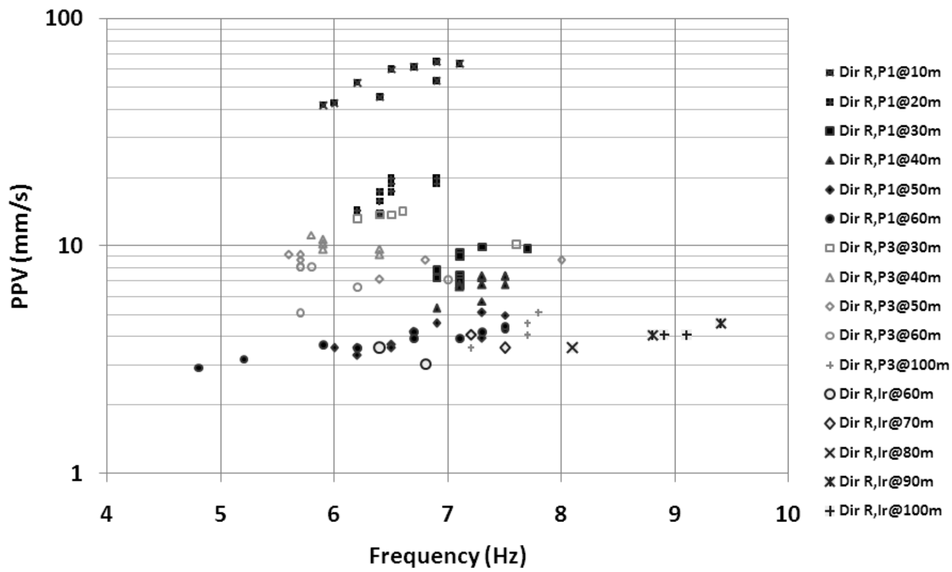


Figure 2. PPV versus frequency in Phase 1, Phase 3 and Ironing

Comparison of measured PPV in Figure 3 with the prediction equations of Mayne ([8] and [15]) and the modified and rewritten form of the equation proposed by Hamidi et al.; i.e. Eq. (8), indicates that, as expected, Mayne's predictions are quite conservative, perhaps too conservative. Eq. (8) appears to be much closer to the results of this study and can predict PPV more accurately.

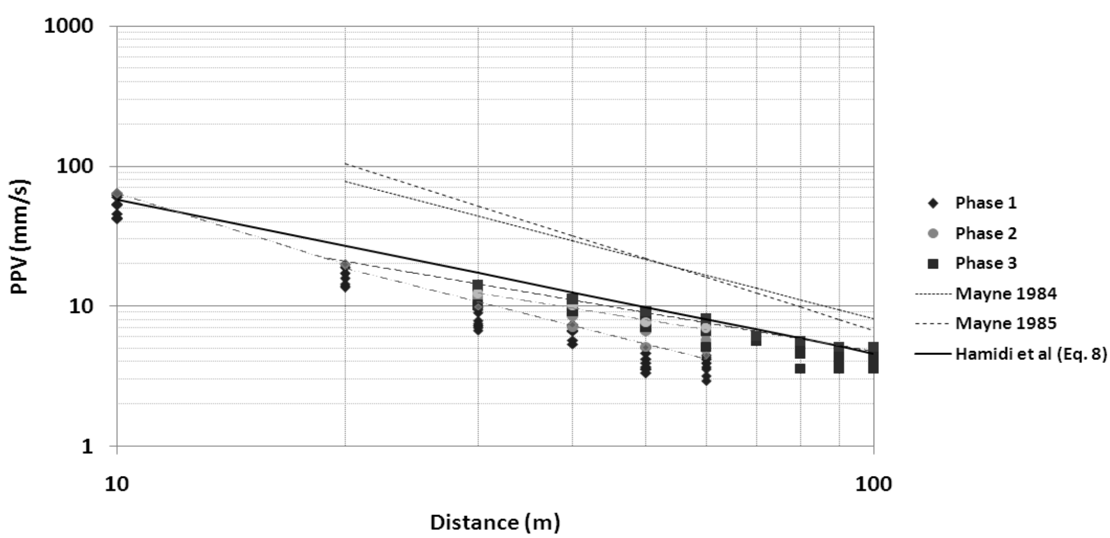


Figure 3. PPV versus distance and comparison with prediction equations

3. Conclusions

Vibration parameters have been monitored for different number of blows and distances during several phases of Dynamic Compaction. It has been observed that peak particle velocities are greater during later phases of compaction as compared to the earlier phases. The differences are greatest at farther distances, and it appears that when the distance is closer than a critical value, compaction phase influence becomes unnoticeable. The modified and rewritten equation of Hamidi et al [13] , presented in Eq. (8), that had quite satisfactorily predicted PPV values for a 15 ton pounder dropped from 20 m has here equally been successful for modelling PPV for a 23 ton pounder dropped from 23 m.

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