Measurement of plate compaction-induced ground vibrations

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MEASUREMENT OF PLATE COMPACTION-INDUCED GROUND VIBRATIONS

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ABSTRACT
Plate compaction is often carried out on road and low-rise residential building construction sites to avoid the effects of differential settlements. The compaction activities generate ground vibrations, which may cause disturbance to people in close proximity and in extreme cases damage adjacent buildings if the vibrations are of a significant magnitude. Currently, in construction practice the minimum distance required between a plate compactor and an adjacent building is based on experience, rules of thumb and conservative practices. Some literature and guides are available for allowable ground vibration criteria, but little research has been carried out on ground vibrations generated by plate compactors. This study investigates ground vibrations generated by plate compactors. The vibrations are measured at various distances from the plate compactors on site to document the attenuation rate. These attenuation rates, and the allowable ground vibration criteria offered by various guides are used to determine the safe operating distances for structural safety. Discussions and comparisons on various guide criteria for structural safety are also given in this paper.

KEYWORDS
Plate compaction, ground vibration, wave propagation, vibration criteria, building structures.

INTRODUCTION
Soil compaction is a common technology used for site treatment. It is undertaken to increase the strength of the soil and decrease short and long term differential settlement. There are many methods and different machines used for compaction. Plate compactor is one of the popularly used tools to compact the site for road and low-rise building structures. Problems may arise when compaction activities occur too close to adjacent buildings, which is often inevitable for effective land use and for constructing roads to access to the buildings. The adjacent structures can be exposed to the risk of damage. The study of the risk of damage to nearby structures from plate compaction is largely absent in literature. One such study was presented by Jewell (1984), in which the attenuation rates of ground vibrations from four different plate compactors measured at a sandy soil site were determined. The measured root mean squared (RMS) and resultant peak particle velocity (PPV) were presented.

Despite a general lack of studies on plate compactor induced ground vibrations, a significant number of publications regarding construction activities, mainly blasting and pile-driving induced ground vibrations are available in literature. Many empirical formulae have been proposed to predict the peak values of construction ground vibrations. Because of the specific site conditions and construction equipment used, these empirical formulae differ from each other significantly. Dowding (1996) gives a very comprehensive review of construction-induced ground vibrations and their effects on structures. It is found that the normalized peak values at the same distance could differ by more than 100 times. Consequently, empirical formula obtained from one site may not give reliable prediction of ground vibration amplitudes and attenuation at another site, even if the two sites have similar soil properties.

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There are no universally accepted allowable ground vibration levels for building structures either. This is because structure response not only depends on ground vibration amplitude, but also on ground vibration frequencies and duration, as well as structural conditions and vibration characteristics. Different standardization organizations give different allowable vibration limits (e.g., BS5228-2:2009, BS5228-4:1992, BS7385-2:1993, CEN 2007, DIN 4150-3 1999), varying from 3 mm/s for historical and vibration sensitive structures to 50 mm/s for heavy reinforced industry buildings, depending on the vibration duration, namely transient or continuous.

This paper reviews the ground vibration attenuation relations and allowable vibration limits for building structures. Field measured ground vibrations from plate compactor compactions are then presented. Through comparisons of the ground vibration attenuation and allowable vibration limits, safe compaction distance can be determined. The results presented in this paper can be used as a guide in determining the safe distance for performing the construction activities.

GROUND VIBRATION WAVE PROPAGATION AND ATTENUATION

From the theory of wave propagation, ground vibration attenuation from a point ‘a’ on ground surface at a distance \( r_a \) from the vibration source to point ‘b’ at a distance \( r_b \) can be modelled by

\[
A_b = A_a \left( \frac{r_a}{r_b} \right)^\beta e^{\left[\alpha (r_a - r_b)\right]} \tag{1}
\]

where \( A_a \) and \( A_b \) are the peak ground vibration values at the two points, and the coefficient \( \alpha \) relates to the material damping and coefficient \( \beta \) relates to geometric spreading. \( \beta = 0.5, 1 \) and \( 2 \) correspond respectively to Rayleigh wave, body wave propagating along the surface and body wave propagating in the ground. The coefficient \( \alpha \) can be estimated by (Massarsch 2004)

\[
\alpha = \frac{2\pi f D}{C_s} \tag{2}
\]

where \( D \) is the material damping, \( f \) is the predominant vibration frequency and \( C_s \) is the shear wave velocity of the site. The above equations are derived based on the assumption that wave propagation medium is elastic, isotropic and homogeneous. In practice, the exact value of \( \alpha \) is difficult to be determined. The material damping \( D \) depends not only on soil properties but also on vibration levels, and ground vibrations contain a rather wide frequency band rather than a single frequency \( f \).

Based on field measured ground vibrations from impact pile driving at four sites, Hao and Ang (1998) derived the material damping coefficients, which varies from 0.019 on a site with fine to coarse sand to 0.125 on a site with fine sand. Amick and Gendreau (2000) summarised the available material damping coefficients obtained by different researchers through field measurements. \( \alpha \) value varies from 0.0 to 0.26, implying significantly different attenuation rates from site to site.

ALLOWABLE GROUND VIBRATION LIMITS

Many Standardization Organizations provide guidance on allowable ground vibration limits for building structures. Those commonly used in practice are reviewed and discussed in this section.

Comparison of Various Guide Values of Ground Vibration Limits

PPV is the most commonly used ground vibration parameter in defining the allowable vibration limits. In Australia, British Standards BS5228 is commonly used. Table 1 compares the ground vibration limits in the 1992 and 2009 edition of BS5228. As can be noticed, the PPV limits increased substantially in the 2009 edition. The exact reason for this increase is not known. However, reference to BS7385-2:1993 is given in BS5228-2:2009 and the PPV limits in the 2009 edition are the same as those given in BS7385-2:1993. A detailed examination of BS7385-2:1993 revealed that the vibration limits were determined mainly from blasting ground vibrations. Therefore the updated vibration limit of 50 mm/s might be unconservative for ground vibrations induced by soil compaction.
Table 1. PPV limits in BS5228 1992 and 2009 Editions

<table>
<thead>
<tr>
<th>BS5228-4:1992</th>
<th>BS5228-2:2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building Type</td>
<td>4-15 Hz</td>
</tr>
<tr>
<td>Buildings of Architectural merit</td>
<td>≤50Hz</td>
</tr>
<tr>
<td>Residential</td>
<td>2mm/s</td>
</tr>
<tr>
<td>Light Commercial</td>
<td>5mm/s</td>
</tr>
<tr>
<td>Heavy Industrial</td>
<td>10mm/s</td>
</tr>
</tbody>
</table>

Vibration limits given in Eurocode 3-Part 5:Piling (Cen 2007) are listed in Table 2, and the vibration limits given in the German Code DIN 4150 (1999) are listed in Table 3.

Table 2. Eurocode 3-Part 5 (PPV in mm/s)

<table>
<thead>
<tr>
<th>Type of structures</th>
<th>Buildings of architectural merit</th>
<th>Residential</th>
<th>Light Commercial</th>
<th>Heavy Industrial</th>
<th>Buried</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>2</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Transient</td>
<td>4</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 3. Guide Value of allowable PPV (mm/s) (DIN 4150 1999)

<table>
<thead>
<tr>
<th>Type of Structure</th>
<th>Short-term vibration</th>
<th>Long-term vibration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Foundation</td>
<td>Top Storey</td>
</tr>
<tr>
<td></td>
<td>&lt;10Hz</td>
<td>10-50Hz</td>
</tr>
<tr>
<td>Commercial and industrial</td>
<td>20</td>
<td>20-40</td>
</tr>
<tr>
<td>Residential</td>
<td>5</td>
<td>5-15</td>
</tr>
<tr>
<td>Sensitive to vibration</td>
<td>3</td>
<td>3-8</td>
</tr>
</tbody>
</table>

There are a number of other guides defined by different standardization organizations. Owing to the page limits, they are not included here. As can be noticed above, depending on the ground vibration duration and frequency contents, as well as structural types and conditions, the allowable PPV vary from 2 mm/s to 50 mm/s. Although there are reports that no structural damage was observed at PPV higher than 50 mm/s, there are also reports that damages to structures occurred at about 7.5 - 9 mm/s (Caltrans 2004), and to interior and exterior finishes such as plaster and stucco at 2 to 3 mm/s (Rainer et al. 1988). Therefore it is very important to define a credible vibration limit before construction work.

Transient and Continuous Vibration

Some guidance distinguishes allowable PPV if the vibration is continuous or transient. Blasting ground vibration is considered as transient as its duration is in an order of mini seconds, and traffic induced ground vibration is considered as continuous as its duration is in an order of seconds. German Code DIN 4150:1999 defines a short-term vibration is that it does not produce resonance in the structure, otherwise it is considered as a long-term vibration. BS7385-2:1993 states that a continuous vibration depends on the frequency and damping of the structure, implying that a ground vibration is considered as continuous if it has sufficient number of cycles to build up structural responses.

Vibration Resonance

The above allowable PPVs refer to the ground vibrations measured at or near the foundation of the structure. Using these vibration levels to assess the building performance is satisfactory for short-term excitations and non-resonant conditions for which the amplification from foundation to upper storey is close to 1.0. At resonance and when ground vibration duration is sufficiently long, the amplification ratio may be 10 or more, resulting in much greater deformations between the footing and the top of the building. BS5228-2:2009 allows a reduction up to 50% on the allowable ground vibration amplitude at...
resonance. This allowance is reasonable for a blasting ground motion with very short duration. Other codes such as DIN4150 require to adopting the same allowable PPV at all the building levels. This implies that the ground vibration level at resonance can be reduced by 10 times for a structure with damping ratio 5%. In a case study of effect of train-induced ground vibration (Rainer et al. 1988), the allowable vibration level to prevent structural damage is taken as 5 mm/s, but the allowable ground vibration level is taken as 0.5mm/s in consideration of the 10 times amplification on structural responses.

The above reviews and discussions indicate that ground vibration duration, possible structural resonance and structural conditions all need be considered when defining the allowable ground vibration levels. As plate compactor compaction usually takes place near low-rise residential buildings, and the induced ground vibrations are continuous, without losing the generality, in this study the allowable ground vibration level is taken as 5 mm/s.

MEASUREMENTS OF PLATE COMPACTOR COMPACTION GROUND VIBRATIONS

Vibration measurements were carried out at three sites in Perth Metropolitan area during plate compaction as shown in Figure 1. Two types of plate compactors were involved in the three constructions site. In this study, owing to page limit, the differences of ground vibrations induced by two types of compactors are not discussed.

High resolution (10µm/s\(^2\)) and measuring range ±3.0g Kistler accelerometers of type 8330A(X) as shown in Figure 2 were used in the measurements. Triaxial ground vibrations were measured by sticking three accelerometers on three faces of a rigid steel cube, which was pushed into the soil. The accelerometers were connected to a 4-channel signal amplifier, which was then connected to a 16-channel data logger. The sampling frequency was set to be 1000Hz. In the measurements, the ground vibrations were recorded when the compactor was at different locations between 1 m and 21 m (site 1) or 1 m and 15 m (sites 2 and 3 owing to site dimension limitation) from the accelerometer. Figure 2 shows the typical measured ground vibration time histories, the signal amplifier and data logger, and the sensor block with accelerometers used for the measurements.

The measured ground acceleration time histories were baseline corrected, and then integrated to obtain the velocity time histories. The PPVs in the three directions were extracted. The results indicate that the radial and vertical PPVs are substantially larger than the transverse PPVs. In this paper, however, only the resultant PPVs are presented. The resultant velocity time histories were obtained by square root summation of squared velocities (SRSS) in the three directions. It should be noted that the ground
vibrations in the three directions usually do not reach the peak simultaneously. Therefore the peak resultant velocity is obtained from the resultant velocity time history, instead of the SRSS of the PPVs in the three directions.

Figure 3 shows the measured resultant PPVs, their best fitted attenuation curves according to Eq. (1), and the 5 mm/s allowable PPV. As shown, among the three sites, site 1 has the relatively larger PPVs at the same distance although the same Dynapac LH700 plate compactor were used at both the site 1 and site 3, indicating the influences of site conditions on ground vibrations. Site 1 consists of fine to medium-grained sand, which is denser than site 3 with medium to coarse-grained sand. Therefore wave attenuates slower in site 1 as compared to that in site 3. If the allowable PPV is taken as 5 mm/s, the plate compactor compaction can only be carried out at a distance of 18 m from the existing building in site 1 and 15 m from the building in site 2 and site 3. If compaction needs be carried out nearer to the building, some site preparation, such as digging a trench along the building foundation to block the ground vibration wave, is suggested before the compaction work. If it is possible, monitoring the actual ground vibration levels on the foundation of existing buildings by experienced personnel is also highly recommended in case some legal disputes arise.

The best fitted attenuation coefficients $\alpha$ and $\beta$ are given in Table 4 for the three sites. Assuming the ground vibration consists of only Rayleigh wave, i.e., $\beta=0.5$, the regression analyses are carried out and the corresponding attenuation coefficient $\alpha^*$ is also given in the table.

<table>
<thead>
<tr>
<th>Site</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\alpha^*$ ($\beta = 0.5$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00441</td>
<td>0.9756</td>
<td>0.06386</td>
</tr>
<tr>
<td>2</td>
<td>0.0736</td>
<td>0.2401</td>
<td>0.03343</td>
</tr>
<tr>
<td>3</td>
<td>0.1235</td>
<td>-0.1029</td>
<td>-0.01474</td>
</tr>
</tbody>
</table>

As can be noticed, the best fitted attenuation coefficients for site 1 and site 2 are positive, indicating wave attenuation with distance. The best fitted attenuation coefficient $\beta$ is negative, or $\alpha$ is negative if $\beta$ is taken as 0.5, indicating Eq. (1) is not the appropriate relation to model wave attenuation in site 3. It should be noted that this is not uncommon, many fitted attenuation coefficients according to Eq.(1) from measured ground vibrations reported in literature give negative values. This is because of many uncertainties associated with soil conditions and surrounding structures that might influence wave propagations. For example, foundations of the adjacent structures will cause wave reflection, which may enhance the recorded ground vibrations near the foundations, and lead to recordings of wave increment instead of attenuation. Moreover, as can be noticed, the $\beta$ value at site 1 is close to 1.0, indicating the ground vibrations can be better modelled as body wave propagating along the ground surface, whereas the ground vibrations at site 2 and site 3 cannot be properly represented by any dominant wave types.
CONCLUSIONS

This paper has presented a review of allowable ground vibration levels to building structures and available attenuation relations of ground vibrations induced by construction activities. There are no universally acceptable ground vibration levels for structural safety as structural capacity to resist ground vibrations depends not only on ground vibration amplitude, but also on ground vibration frequency and duration, as well as structural conditions and vibration characteristics. Careful evaluations and assessments are needed for defining an acceptable ground vibration level for a particular structure. Ground vibrations induced by plate compactor compactions were measured at three sites in Perth Metropolitan area. The attenuation relations of the measured ground vibrations were derived and presented. Using these attenuation relations, the safe distances for conducting plate compactor compaction activities for adjacent building structures can be determined.

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REFERENCES


