26 May 2010, 4:45 pm - 6:45 pm

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Fifth International Conference on
Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics
and Symposium in Honor of Professor I.M. Idriss
May 24-29, 2010 • San Diego, California

AN EVALUATION OF GROUND VIBRATIONS INDUCED BY HEAVY FREE-FALLING STRUCTURAL ELEMENTS

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ABSTRACT

Ground vibrations generated during a large structural demolition event can be potentially damaging to nearby structures or sensitive equipment. In this paper, an approach for the prediction of the ground vibration induced by a large free-falling heavy weight is proposed based on both measured and collected data. A series of field ground vibration measurements were performed relative to the dynamic motions induced by free-falling heavy structural elements during demolition of a generating plant in the upper Midwest, USA. Using this information and the collected data, correlations between the measured PPV and normalized distance from the impact source with various ground impact energy were developed. Subsequently, an empirical PPV estimation method is suggested. This methodology will be useful in estimating dynamic effects induced by very large demolition events; especially where existing structures are located in close proximity to the impact site.

INTRODUCTION

Vibrations produced by the impact of large falling masses during the demolition of both large and heavy structures has become of concern when any sensitive structure or building is located in close proximity. Ground vibration is directly related to the impact energy and distance between the impact source and monitoring point, as well as the in-situ soil or bedrock properties. Due to damping of the in-situ soil/rock mass and attenuation, the energy transferred by wave motion is significantly reduced in relation to increasing distance from the energy source. Several efforts have been made to develop an assessment of the amplitude of ground vibrations to establish guidance for the possible risk to the exposed structure and a tolerable ground motion limit. It has been widely accepted that the use of peak particle velocities (PPV) is most useful in defining the damage criteria for the induced vibrations (Wiss, 1981, Mayne et al., 1984). Direct correlations between PPV and major factors (namely, distance and impact energy) have been developed based on empirical test data. Most of the developed correlations are based on the measured data obtained from dynamic deep compaction (DDC) sites, which have relatively low impact energy compared with the structural demolition case. Most of the time, PPV is correlated with scaled distance based on the square root of the applied energy divided by distance was used for the data analysis to normalize the related major factors; this suggested correlation was also effectively used for the low impact energy case. However, it has not been clearly proven that these previously developed correlations for PPV estimation (from dynamic compaction) can be extended for the estimation of PPV for large structural demolition cases.

In this research, a series of monitored ground vibration components data for several large structural demolition events were analyzed and combined with collected data for various impact energy to establish a closed-form correlation between PPV and normalized distance. For the monitored power plant demolition event, the weight of each of the structural elements ranged from 300 tons to 5,000 tons with fall heights ranging from about 125 ft to 576 ft. For each individual demolition event, geophones were installed at selected distances from the dynamic source to measure the induced ground vibrations and peak particle velocity (PPV). Also, the previously measured ground vibration data from six (6) structural demolition sites, as well as five (5) dynamic compaction sites were collected from published papers and incorporated for the suggested empirical correlation.

ANALYSIS APPROACH

The impact energy by free falling weight causes the in situ ground to move in an elliptical manner in three (3) dimensions. The magnitude of PPV generated by a large impact at some distanced locale is a function of the impact energy at the source, distance from the source, ground characteristic regarding vibration transferring. Since there are many uncertainties and difficulties for quantifying ground as a vibration transferring media, and the impact of the characteristics to the PPV is small compare to distance and impact energy, it is convenient to present PPV in terms of distance and impact energy as the following equation form:

$$PPV = C \cdot \frac{1}{d^k} \cdot E^l \qquad (1)$$

Where C = intercept representing ground characteristics regarding vibration transferring. d = distance from the impact source, E = impact energy. Since the vibration is transferred as ground surface wave form, PPV dissipates inversely proportional to roughly square of the distance (in this case k = 2). Mayne (1985) suggested k = 1.7 based on empirical data from 12 dynamic compaction sites where impact energies were almost similar. Wiss (1981) presented that k generally lies between 1.0 and 2.0 with a relatively common value of 1.5.

If we approach this empirical equation from an energy dissipation point of view, the value l in Eq. (1) would be between one third and half because the energy dissipation occurs cubically on the ground. Several research results based on empirical data from dynamic compaction show that l values are between 1/3 and 1/1.7 (Wiss, 1981, Mayne et al., 1984, Mayne, 1985, Eldred and Skipp, 1998, Heyerdahl et al., 2003).

In order to develop the correlation between PPV and both distance and impact energy, scaled-distance D which is a unified factor of the distance and impact energy is defined as following expression:

$$PPV = C \cdot D^m, \quad D = \frac{(W \cdot H)^n}{d} \qquad (2)$$

where W = weight of falling mass , H = drop height. Square root of the applied energy (n = 1/2) has been frequently used for dynamic compaction data and blasting data analysis (Wiss, 1981, Leonards et al., 1980, Mayne, 1985, Mayne et al., 1984, Mayne and Jones Jr, 1983). Cube root scaling (n = 1/3) is also endorsed by some researchers (Eldred and Skipp, 1998, Heyerdahl et al., 2003).

As mentioned above, if PPV is inversely proportional to roughly the square of the distance and directly proportional to roughly cube root, the value n should be positioned between 0.17 and 0.3. In this range, 0.2 is used in this study to normalize the scale.

SITE DESCRIPTION AND MEASUREMENT

Demolition activity was performed for a large generating plant located in the upper Midwest, USA. During the demolition process, the structure was split to about eight (8) main elements each with weights ranging from 300 tons to 5000 tons (with falling heights varying between approximately 125 ft and 576 ft). There was concern that the vibrations induced by demolition activities may have a detrimental effect on existing structures adjacent to the site. There are two (2) existing structures situated within about 500 feet of the primary demolition location, an electrical sub-station and a residential building. Geophones were buried near the electrical substation and the existing building. The seismographs were set-up in the trigger mode with the threshold being set at 0.05 ips to start recording. The distance from the general impact locale to the buried geophones ranged from 160 ft to 430 ft. The measured PPV ranged 0.055 ips to 0.203 ips. This ground motion data is much lower than the typically-accepted limiting safe thresholds (which generally range from 0.6 ips to 2.0 ips depending on frequency). Weight, the drop height of each structural element, and the measured PPVs are presented on Table 1.

Two (2) PPV estimation methods have been suggested using scaled distance by the square-root of the applied energy based on dynamic compaction data (Mayne, 1985, Mayne et al., 1984). Mayne et al. (1984) proposed conservative upper boundary of PPV, which is appeared as:

$$PPV\ (ips) \le 5.7 \left(\frac{\sqrt{WH}}{d} \right)^{1.4} \qquad (3)$$

Mayne (1985) also suggested the upper limit of PPV based on the data from 12 dynamic compaction sites. This empirical equation is expressed as the following from:

$$PPV\ (ips) \le 8 \left(\frac{\sqrt{WH}}{d} \right)^{1.7} \qquad (4)$$

Table 1. Field PPV Monitoring Results

Part Number	Weight (ton)	drop height (ft)	Distance (ft)	PPV (ips)
1	1920	140	430	0.155
2	1100	140	350	0.093
3	300	135	200	0.055
4	520	135	200	0.063
5	5000	576	300	0.14
6	500	125	160	0.203
7	500	125	400	0.145
8	750	170	370	0.108

The measured PPV data versus square root scaled distance are plotted in Fig. 1 on log-log scale and compared with the aforementioned upper boundaries presented as Eq. (3) and (4). As demonstrated in Fig. 1, the measured PPV values are somewhat lower than the boundaries suggested as Eq. (3) and (4). The difference between the suggested upper boundary and the measured values are more or less about a hundred times. Since the upper limit equations were developed based on dynamic compaction data, and the major difference from the measure data from the demolition case in this study is the magnitude of the falling energy, it was suspected that the scaled distance would have to be adjusted in order to properly represent a wider range of impact energy case.

Since the test results did not possess sufficient range to establish a trend for the correlation, published data regarding PPVs generated by free falling impact energy were collected from the literature and combined with the measured data. The obtained data can be divided to two major groups depending on the free falling type and energy level; the first group is the data obtained from dynamic compaction events, and the other group is the data obtained from demolition of large structures. The descriptions of the collected data are summarized in Table 2. Please note that the two groups have significantly different energy levels; the data sets obtained from the demolition cases have very high energy comparing with the dynamic compaction cases. The impact energy of the five (5) dynamic compaction cases ranged between 74 ton·ft and 864 ton·ft. On the other hand, the impact energy range of the seven (7) demolition cases range from 243,600 ton·ft to 2,880,000 ton·ft (roughly more than 1000 times larger than the ones from the dynamic compaction cases). The measured and collected PPV data versus scaled distance by the square-root of the applied energy are presented in Fig. 2.

As shown in Fig. 2, the data presented in the graph is separated to two (2) separate groups by impact energy level. It is, as discussed previously, presumably caused by the fact that the scaled distance by square root of the energy was not properly used to normalize the data to unify the PPV values for the wide range of the impact energies. The graph also indicates that the proposed upper limit of PPV (based on scaled distance by square root of impact energy) fits well for the low energy group data sets in the dynamic compaction cases, but gives too high of a boundary for high impact energy group data sets.

There was another attempt to establish a preliminary upper limit for PPV by distance from the point of impact. Mayne (1985) suggested upper limit of PPV versus distance based on the dynamic compaction data as follows:

$$PPV = \left(\frac{75}{d}\right)^{1.7} \quad (5)$$

The measured and collected PPV data versus distance from the point of impact are plotted in Fig. 3. The attenuation trend of the data with distance (as shown in Fig. 3) are too widely scattered to develop a rational correlation. Furthermore, the PPV data from high impact energy case are higher than the upper boundary previously established by Eq. (5).

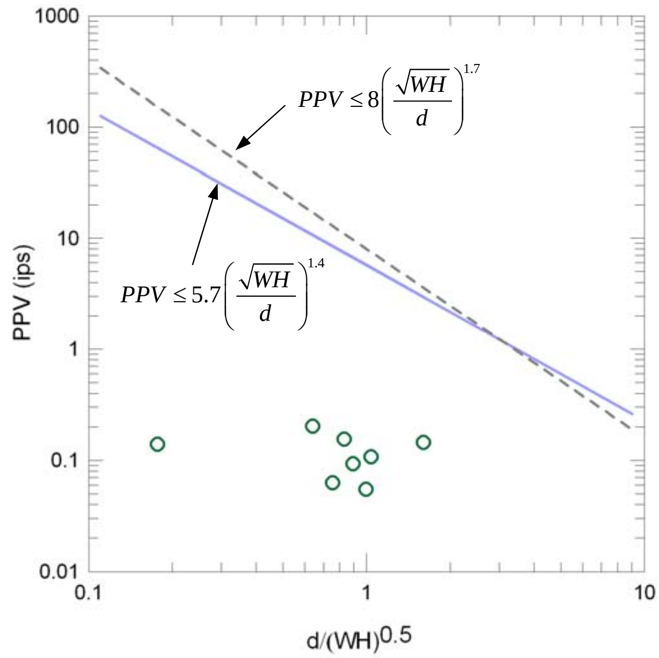

Fig. 1. Correlation between PPV and scaled distance from the field monitoring data

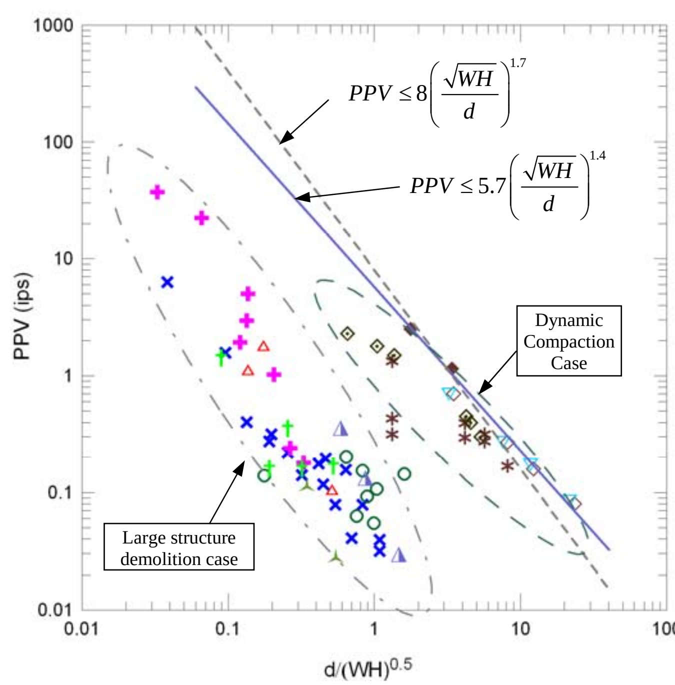

Fig. 2. PPV data versus scaled distance by the square-root of the applied energy

Table 2. Summarized cases for ground vibration data

	Test Type[1]	*Weight (ton)*	*Impact Energy (ton·ft)*	*Distance (ft)*	*PPV (ips)*	*Symbol*
Minnesota (This Study)	LSD	500~5000	40,500~2880,000	160~430	0.055~0.203	○
Cardiff (Eldred and Skipp, 1998)	LSD	2300	264,107	46~269	0.16~1.43	†
Newton Abbott (Eldred and Skipp, 1998)	LSD	2700	243,600	171~269	0.03~0.12	⅄
Crodon (Eldred and Skipp, 1998)	LSD	2500	287,073	96~240	0.03~0.36	◭
Chimmy (Eldred and Skipp, 1998)	LSD	5250	924,000	131~492	0.1~1.75	△
Cooling Tower (Eldred and Skipp, 1998)	LSD	5000	725,000	39~394	0.18~37.4	✚
Offshore Platform (Heyerdahl et al., 2003)	LSD	2300	264,500	20~558	0.03~6.3	✖
Offshore Landfill (Chen, 2003)	DDC	15	150~300	23~141	0.17~1.34	✱
Indianapolis (Leonards et al., 1980)	DDC	6	234	10~82	0.3~2.3	◈
France (Leonards et al., 1980)	DDC	12	864	52~100	1.15~2.5	◆
Chicago (Leonards et al., 1980)	DDC	3	73.8	30~200	0.08~0.7	◇
Lucas (Lukas, 1995)	DDC		80~85.7	30~200	0.08~0.7	▽

Note 1: LSD – Large Structure Demolition, DDC – Dynamic Deep Compaction

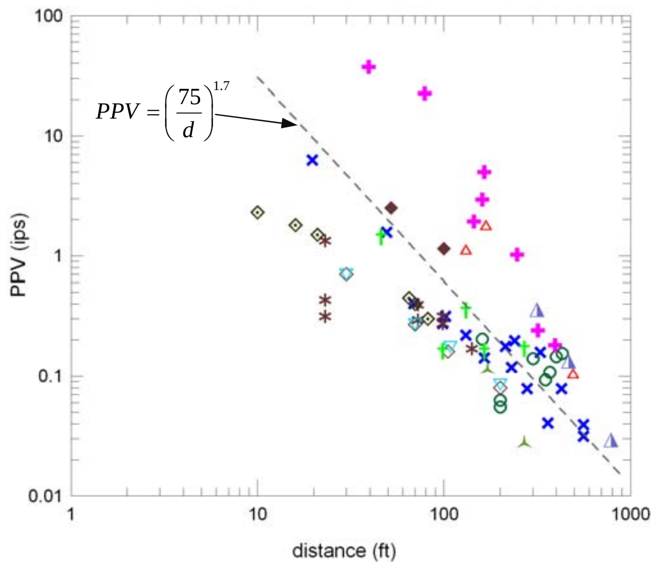

Fig. 3. PPV data versus distance from the point of impact

Based on this information, a new normalized distance is suggested in this document to unify the wide range of impact energies. The plotted data in Fig. 2 indicates that the square root of impact energy generally overstates the scaled distance in large impact energy case. When the impact energy dissipation and the distance effect are evaluated separately, the use of the mathematical 0.2 power function of the impact energy would be reasonable (n = 0.2 in Eq. 2).

The measured and collected PPV data are plotted in Fig. 4 with the scaled distance by the 0.2 power function of the applied energy. The plotted data shows that the revised scaled distance function normalizes properly for the wide range of the energy levels. Based on the plotted data, PPV and upper limit of PPV may be estimated as following equations:

$$PPV\ (ips) = 3\left[\frac{(WH)^{0.2}}{d}\right]^{1.7} \tag{6}$$

$$\text{Upper limit: } PPV\ (ips) \le 20\left[\frac{(WH)^{0.2}}{d}\right]^{1.7} \tag{7}$$

The derived prediction equations for PPV and upper limit of PPV are illustrated in Fig. 4 below:

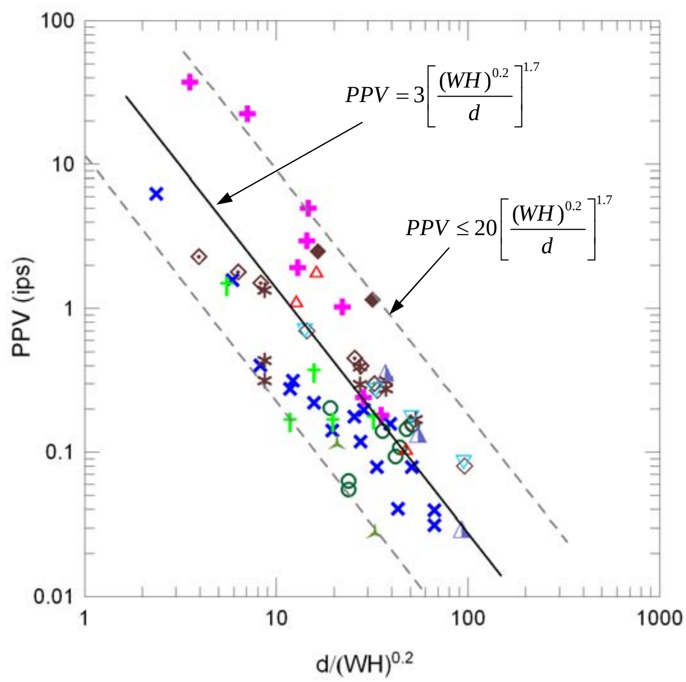

Fig. 4. PPV versus scaled distance by 0.2 power of impact energy

CONCLUSION

Given the forgoing literature review and the addition of new high applied-energy field information relative to ground motions (generated as a result of the in-situ monitoring of the recent demolition of a power plant), it was the focus of this paper to develop a new PPV prediction equations based on an improved normalized function of scaled distance. In order to unify the wide range of impact energies that are discussed in this document, a mathematical 0.2 power function of the applied energy was used as a denominator of the normalized distance. It was verified by the measured and collected data that the improved scaled distance function normalizes satisfactorily for the wide range of the energy levels. Previous such equations only existed for limited applied energy magnitudes up to the level of dynamic deep compaction (DDC) events. This improved and broader-reaching empirical approach incorporates higher applied energy events which have been normalized to establish a more encompassing PPV prediction methodology.

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NOTICE

This paper is intended as an academic discussion, not as engineering advice, and no reliance upon this paper is permitted. Independent advice by the professional of record as to the application of the concepts and opinions herein to any specific project should be sought.