PEAK ATTENUATION RULE AND ENVIRONMENTAL ASSESSMENT OF GROUND VIBRATION DUE TO DYNAMIC COMPACTION

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ABSTRACT:

Being the simple constructing procedure and the low cost, dynamic compaction method was widely-used in the foundation consolidation around the world. Recently, the vibration effect due to the dynamic compaction on the adjacent structures was highlighted in the construction. Based on 207 vibration records recorded in-situ during the construction of foundation consolidation by the way of dynamic compaction, the statistical analysis respecting to the peak ground acceleration (PGA) and peak ground velocity (PGV) was performed. Referring to the earthquake intensity classification of the "China Earthquake Intensity Table"(GB/T17742-1999) and the allowable vibration velocity of the "Safe Blasting Regulation"(GB6722-2003), the vibration assessment for the dynamic compaction was carried out. The allowable safety distance for the different structures with the dynamic compaction under the specified energy grade was proposed. Furthermore, the peak attenuation rules on the vertical and horizontal direction (PGA and PGV with the horizontal distance between the recording point and the dynamic compaction point) were regressed. The peak attenuation rules of PGA and PGV accorded with the exponent attenuation rule. Finally, referring to the "Ambient Vibration Criterion in Urban Area" (GB10070-88), the ambient vibration of ground motion due to dynamic compaction was negligible and needed to be paid more attention.

KEY WORDS: Dynamic Compaction, Statistical Analysis, Peak Attenuation Rule, Allowable Safety Distance, Environmental Assessment

1 INTRODUCTION

Being the simple constructing procedure and the low cost, dynamic compaction method was widely-used in the foundation consolidation around the world. But the vibration effect due to the dynamic compaction on the adjacent structures was highlighted in the construction. The triggered controversy on the structural destruction also occurred from time to time. Generally, the particle vibration velocity was used to evaluate the structural safety. Otherwise, the particle vibration acceleration was also used to evaluate the vibration effect. So far, there are distinguished opinions and views on the determination of vibration risk due to the dynamic compaction.
Based on the detailed analysis on the recorded vibration data, it was concluded that it was mostly no harm to the building as the acceleration of the ground vibration attenuation to 0.1g (FANG Lei et al., 2001). Furthermore, the safe construction distances to buildings were proposed as 14m, 17.5m, 18.7m and 19.5m respecting to the corresponding energy grade of dynamic compaction as 1.5 MN·m, 2.0 MN·m, 2.5 MN·m and 3.0 MN·m, respectively.

Lei et al (2002) studied the vibration attenuation rule of the dynamic compaction. Referring to the maximum vibration acceleration of $PGA \leq 0.2g$, the safety distance of 10 m was proposed. Relied on the recorded data and related materials, the influence of dynamic compaction could be districted as three regions (LI Ting et al., 2003):

1) Vibration demolished region. The distance to the edge of compaction point was less than 20.4m. Within the region, the vibration acceleration, velocity and displacement are greater than 0.5cm/s^2, 5.0cm/s, 1.0mm, respectively. The vibration in the region may generally destroy the building, although the damage extent for the different structural form needs to be researched further.
2) Vibration damaged areas. The distance to the edge of compaction point is about 20.4m to 30m. Within the region, the vibration acceleration, velocity and displacement are within the interval of 0.02~0.5cm/s^2, 0.2~5.0cm/s and 0.1~1.0mm, respectively. The vibration in the region may generally damage the building in some extent.
3) Comparatively safe region. The distance to the edge of compaction point was larger than 30m. Within the region, the vibration acceleration, velocity and displacement are less than 0.2cm/s^2, 0.5cm/s, 0.1mm, respectively. The vibration in the region may not damage the building.

OUYANG Lisheng et al. (2004) measured the ground vibration response in-situ while consolidating the soft foundation by dynamic compaction in Foshan city. It was pointed that the predominant vibration frequency of the site was about 4 to 7Hz. The maximum distance to the consolidating point was about 70m as the influential intensity reached to V due to the dynamic compaction. It was pointed by ZOU Lihua et al. (2004) that the safety of the building within the distance of 15m and the comfort of the habitants reside within the distance range of 50m should be highlighted beside the energy grade of dynamic compaction, based on the experiment of consolidating the loess foundation by the way of dynamic compaction method in-situ and the analysis on vibration data. Similarly, under the specified energy grade 1000~3000kN·m of dynamic compaction, it was pointed that the distances to the compaction point of <10m, 10~30m and >30m were corresponding to the strongly distracted region, medium distracted region and slight distracted region, respectively (ZHANG Mengxi et al., 2004).

Referring to the native and foreign specifications on blasting safety, contrasting the parameter (such as the particle vibration frequency, amplitude and duration etc.) rules applying the different constructing method, GENG Guangxu et al. (2004) proposed that for dynamic compaction, the limit value of the vibration velocity was 10mm/s, the safe constructing distance was about 8~15m for the energy grade less than 3000kN·m, and 15~30m safe distance for the energy grade 3000~5000kN·m.

So far, the Blasting Safety Specification (GB6722-2003) was generally applied to assess the environmental vibration and determine the safety construction due to dynamic compaction. The different conclusions had been drawn as considering the energy grade of dynamic compaction, shape of the hamper, site condition and the adjacent structure form. The safe construction distance should be determined individually according to the conditions of the engineering item.

There were many engineering structures such as ordinary masonry buildings without seismic fortification, constructed bridge piers and culverts within the horizontal distance of 100m to the constructing expressway in Huhhot city. To acquaint the influence range of dynamic compaction, to determine the allowable safety distance to the adjacent engineering structures, the ground vibration data was measured through disposing the acceleration sensors. Based on the analysis on the recorded data, the allowable safety distance was proposed. And the environmental vibration was evaluated as well.

2 FIELD EXPERIMENT ON DYNAMIC COMPACTION

Altogether seven test lines were allocated in the experiment in-situ of the dynamic compaction. Along each test line, three test points (three acceleration sensors with their directions of east-west, south-north and vertical, respectively) were disposed to record the last three times of dynamic compaction. The test points distributed within the distance to compaction points of 10.1m to 100m. The energy grade was about 1800kN·m (the mass of the hammer was 16t, dropping height was 11.5m). The allocation sketch map of the test lines and the measuring points is shown in Figure 1. The parameters of acceleration sensors are listed in Table 1. The allocation of the test line and their test points are listed in Table 2.

Table 1 Parameters of acceleration sensors

Test points	Direction	Tab of Sensor	Sensitivity
1	Vertical	V500	0.138
	East-West	923	0.162
	South-North	1326	0.1603
2	Vertical	V558	0.134
	East-West	862	0.142
	South-North	863	0.139
3	Vertical	876	0.107
	East-West	1133	0.0973
	South-North	1136	0.0973

Table 2 Allocation of the test lines and their test points

Test line	Compaction times	Test point 1		Test point 2		Test point 3	
		magnification times	Distance to compaction point /m	magnification times	Distance to compaction point /m	magnification times	Distance to compaction point /m
1	7	5	14	20	30	100	50
	8	5		20		50	
	9	5		10		20	
	10	5		10		20	
2	8	5	12	10	28	20	48.2
	9	5		10		20	
	10	5		10		20	
3	8	5	10	10	26	20	45.7
	9	5		10		20	

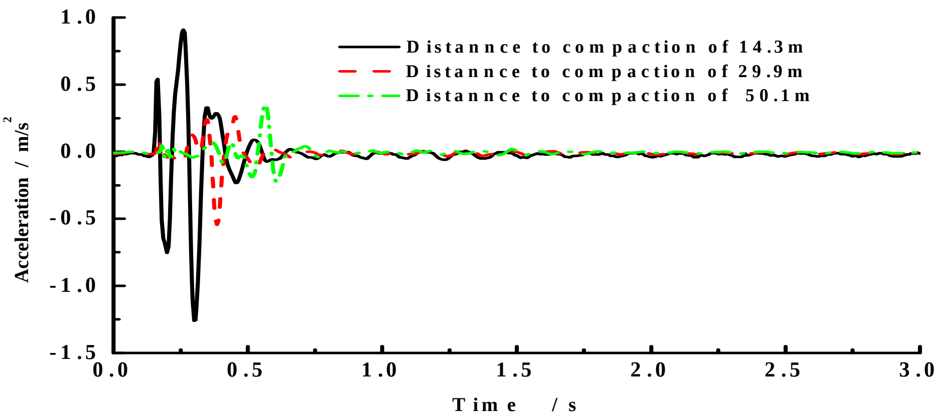
	10	2		10		20	
4	8 9 10	5 5 5	14	10 10 10	30	20 20 20	50.1
5	8 9 10	5 5 5	13	10 10 10	28	20 20 20	48
6	8 9 10	5 2 2	13	10 10 10	27	20 20 20	46.7
7	5 7 8 9	20 20 20 20	50	50 50 50 50	70	100 100 100 100	100

3 DATA ANALYSIS OF GROUND VIBRATION DUE TO DYNAMIC COMPACTION

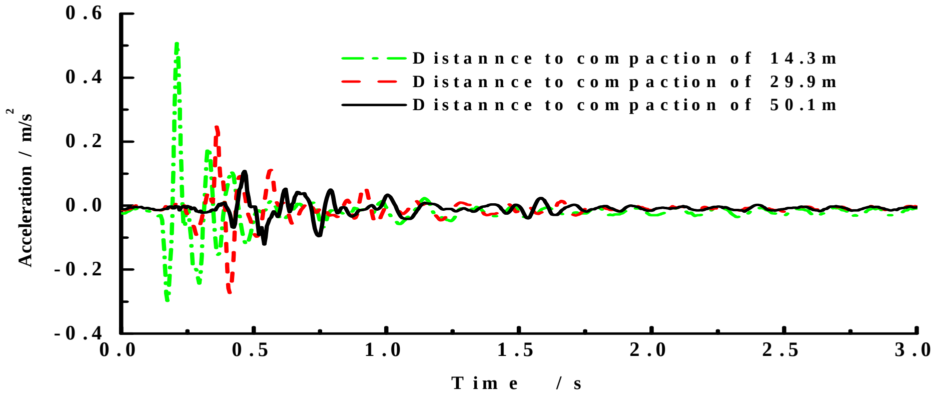
3.1 Statistical Analysis

Based on the 207 acceleration histories (with the directions of vertical, east-west and south-north) recorded in-situ, the statistical analysis was carried out. The typical vibration curves of acceleration histories are shown in Figure 2. It can be seen from Figure 2 that the duration of ground vibration due to the dynamic compaction is short. And the ground vibration is a pulse-type vibration. The attenuation of ground vibration in vertical direction is much faster than the attenuation in horizontal direction with the distance to compaction point.

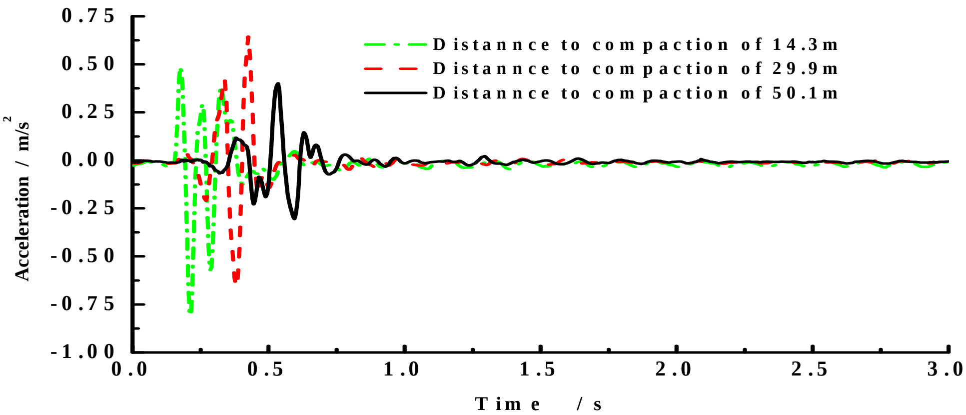
The statistical analysis respecting on the peak acceleration and peak velocity of the ground vibration was performed. The scatter graphs for the peak values of the ground vibration varying with the distance to compaction point are shown in Figure 3.



2a. Acceleration histories with vertical direction

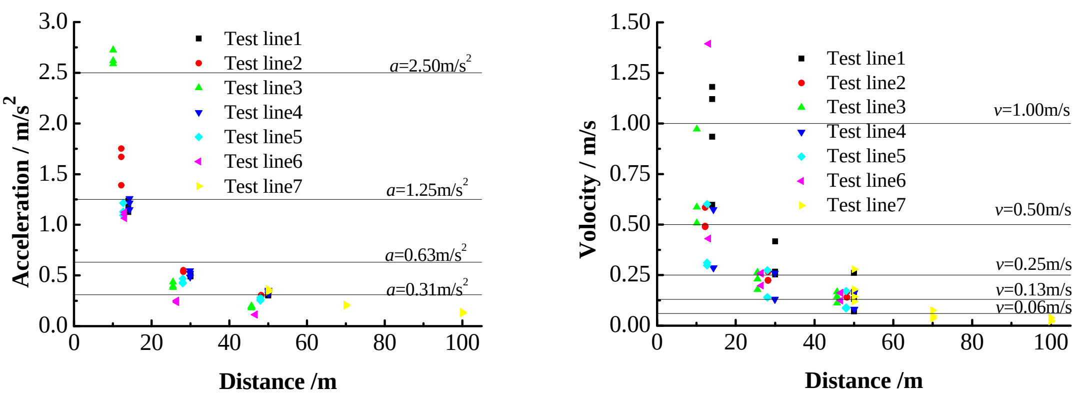


2b. Acceleration histories with east-west direction

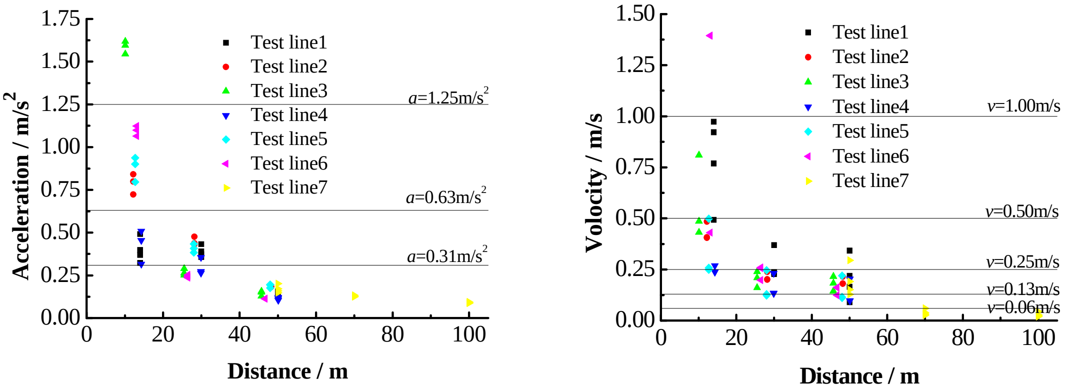


2c. Acceleration histories with north – south direction

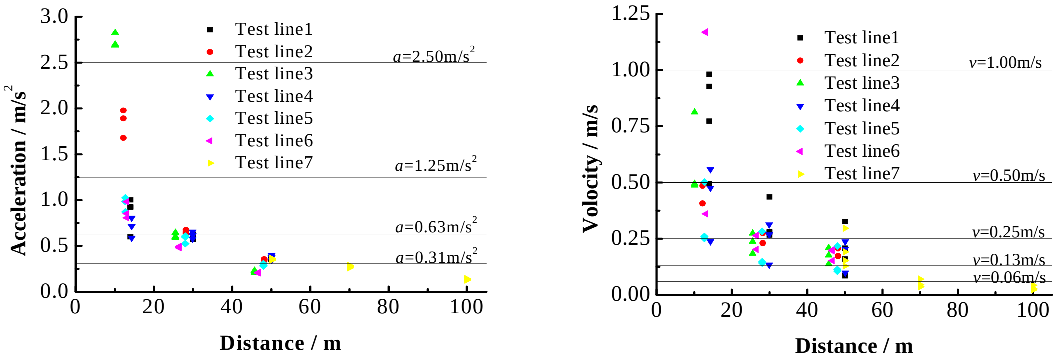
Figure 2 Typical vibration curves of acceleration histories



3 a. PGA and PGV of vertical direction with the distance to compaction point



3b. PGA and PGV of east-west direction with the distance to compaction point



3c. PGA and PGV of north - south direction with the distance to compaction point

Figure 3 scatter graphs for the peak values of the ground vibration varying with the distance to compaction point

It can be seen from Figure 3a that for vertical ground vibration:

As the horizontal distance of about 14m to the compaction point, the peak acceleration distributed within 1.0~2.75m/s^2 and was greatly dispersed. The peak velocity was also greatly dispersed within 0.25~1.40m/s.

As the horizontal distance of about 30m to the compaction point, the peak acceleration distributed within 0.31~0.63m/s^2 and the peak velocity was within 0.13~0.30m/s.

As the horizontal distance of about 50m to the compaction point, most of the peak acceleration values were less than 0.31m/s^2 but for few points. All the peak velocity values were less than 0.25m/s and within the interval of 0.06 to 0.13m/s.

As the horizontal distance of about 70m and 100m to the compaction point, all the peak acceleration values were less than 0.31m/s^2. All the peak velocity values were l within the interval of 0.02 to 0.06m/s but for few points over 0.06m/s.

It can be seen from Figure 3b that for ground vibration along east-west direction:

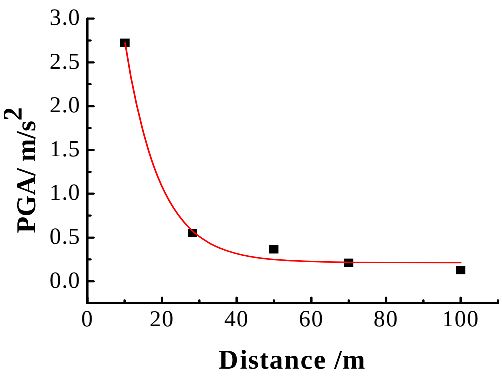
As the horizontal distance of about 14m to the compaction point, the peak acceleration distributed within

$0.31\sim1.75 m/s^2$ and was greatly dispersed. The peak velocity was also greatly dispersed within 0.25~1.40m/s.
As the horizontal distance of about 30m to the compaction point, the peak acceleration distributed within $0.25\sim0.50 m/s^2$ and the peak velocity was within 0.13~0.25m/s.
As the horizontal distance of about 50m to the compaction point, all the peak acceleration values were less than $0.31 m/s^2$. All the peak velocity values were within the interval of 0.13 to 0.25m/s.
As the horizontal distance of about 70m and 100m to the compaction point, all the peak acceleration values were less than $0.31 m/s^2$. All the peak velocity values were l within the interval of 0.02 to 0.06m/s but for few points over 0.06m/s.

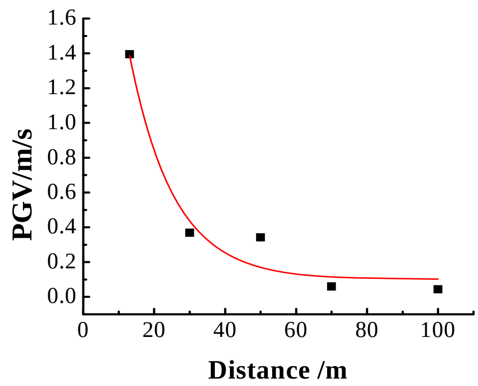
It can be seen from Figure 3c that for ground vibration along south-north direction:
As the horizontal distance of about 14m to the compaction point, the peak acceleration distributed within $0.5\sim2.75 m/s^2$ and was greatly dispersed. The peak velocity was also greatly dispersed within 0.25~1.25m/s.
As the horizontal distance of about 30m to the compaction point, the peak acceleration distributed within $0.40\sim0.70 m/s^2$ and the peak velocity was a little dispersed and within 0.25 ~0.40m/s.
As the horizontal distance of about 50m to the compaction point, much of the peak acceleration values were greater than $0.31 m/s^2$ and within $0.2\sim0.4 m/s^2$. Most of the peak velocity values were within the interval of 0.13 to 0.25m/s but for few points over 0.25m/s.
As the horizontal distance of about 70m and 100m to the compaction point, all the peak acceleration values were less than $0.31 m/s^2$. All the peak velocity values were l within the interval of 0.02 to 0.06m/s but for few points over 0.06m/s.
In summary, the ground motion due to the dynamic compaction has the strong directivity since the peak acceleration and peak velocity of the horizontal ground motion along south-north direction are greater than those along east-west direction. The direction which the strongest vibration occurred is not along the proceeding direction of construction. It is relying on the hamper shape and the distribution of ground soil.

3.2 Regression Analysis

Because of the attenuation characteristics of peak acceleration and velocity with the increase of the distance to compaction point, the attenuation trend accorded with the rule of exponent attenuation. The regression analysis respecting to the PGA and PGV was performed using the Origin7.5 software. The fitted peak curves are shown in Figure 4 to Figure 6. The parameters of the curve fitting and the corresponding correlation coefficients are listed in Table 3 and Table 4.

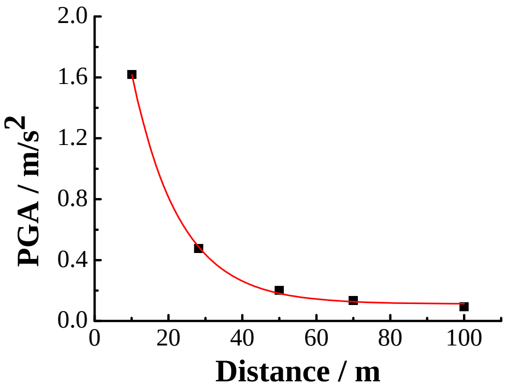


4a. Curve fitting of PGA

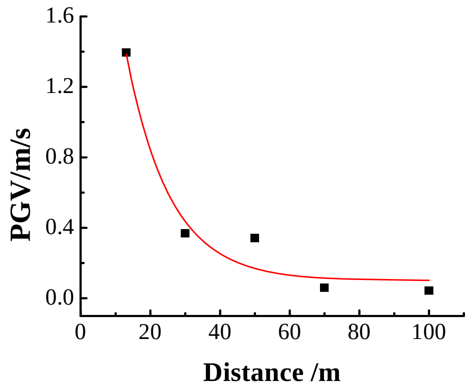


4b. Curve fitting of PGV

Figure 4 Curve fitting for peak values along vertical direction

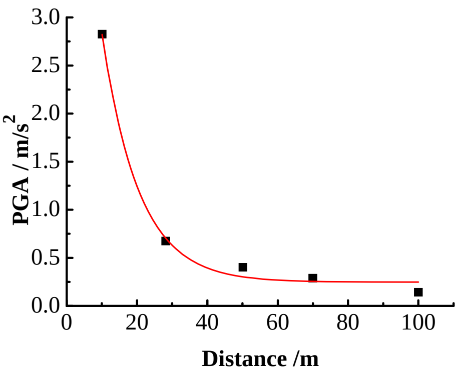


5a. Curve fitting of PGA

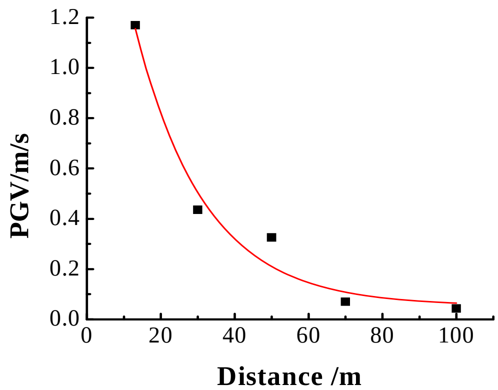


5b. Curve fitting of PGV

Figure 5 Curve fitting for peak values along east-west direction



6a. Curve fitting of PGA



6b. Curve fitting of PGV

Figure 6 Curve fitting for peak values along south-north direction

Table 3: Parameters of regression equation for PGA(in m/s^2)

Direction	Regression equation: $y = y_0 + A_1 e^{-\frac{x}{t_1}}$			
	y_0	A_1	t_1	Correlation coefficient $\|r\|$
Vertical	0.213	.402	9.337	0.99774
South-north	0.247	6.768	10.453	0.99771
East-west	0.112	3.281	12.969	0.99973

Table 4: Parameters of regression equation for PGV(in m/s)

Direction	Regression equation: $y = y_0 + A_1 e^{-\frac{x}{t_1}}$			
	y_0	A_1	t_1	Correlation coefficient $\|r\|$
Vertical	0.078	3.353	13.931	0.99323
South-north	0.054	2.202	18.934	0.98783
East-west	0.101	3.634	12.598	0.98323

It is noted that both the correlation coefficients of curve fitting for PGA and PGV are closed to 1. It can be concluded that the ground vibration due to the dynamic compaction accord with the exponent attenuation rule.

4 INFLUENCE ASSESSMENT OF AMBIENT VIBRATION

4.1 Determination of the Allowable Safety Distance

As so far, the assessment systems of dynamic compaction are still ambiguous throughout the world. The Blasting Safety Specification (GB6722-2003) was generally used to evaluate the ground vibration due to the dynamic compaction in China. As the predominant frequency of ground vibration is below than 10Hz, it is coded that the allowable safety vibration velocity is about 0.5~1.0cm/s for earth or stone building structure, 2.0~2.5cm/s for masonry building structure and 3.0~4.0cm/s for reinforced concrete building structure.

The China Earthquake Intensity Scale (GB/T 17742-1999) was also used as the evaluation criterion for the vibration assessment due to dynamic compaction. Both the earthquake damaged grade of building and the response of human body were adopted to define the earthquake intensity level. Correspondingly, both the peak acceleration and peak velocity were taken as the indexes for the ground motion parameters. It is coded that for earthquake intensity level V, the peak acceleration and peak velocity are 0.22~0.44m/s^2 and 0.02~0.04m/s, respectively; for earthquake intensity level VI, the peak acceleration and peak velocity are 0.45~0.89m/s^2 and 0.05~0.09m/s, respectively; for earthquake intensity level VII, the peak acceleration and peak velocity are

0.90~1.77m/s^2 and 0.10~0.18m/s, respectively. The detailed description of the earthquake intensity can be found in the China Earthquake Intensity Scale (GB/T 17742-1999).

Having compared the two references above mentioned, both the descriptions in the two references were considered to determine the allowable safety distance of construction by the way of dynamic compaction, since the predominant frequency of ground vibration due to dynamic compaction was below 10Hz.

It can be known from the statistical results, for the distance to compaction point less than 14m, the earthquake intensity level was taken as VII, since the most peak acceleration and peak velocity values within the distance range were greater than 1.25 m/s^2 and 0.25m/s, respectively; for the distance to compaction point about 30m, the earthquake intensity level was taken as VI, since the peak acceleration and peak velocity values within the distance range were 0.25~0.70m/s^2 and 0.13~0.4m/s, respectively; for the distance to compaction point about 50m, the earthquake intensity level was taken as V, since the peak acceleration and peak velocity values within the distance range were 0.2~0.4m/s^2 and 0.13~0.25m/s, respectively; for the distance to compaction point greater than 70m, the influence of dynamic compaction on the buildings was negligible, since the peak acceleration within the distance range were lower than 0.31m/s^2. While few peak velocity values were greater than 0.06m/s, which was higher than the allowable vibration velocity code in Blasting Safety Specification, the observation of the building was requisite during the construction of dynamic compaction.

Based on the above analysis, considering the repeated action of dynamic compaction, for the specified energy grade of dynamic compaction of 1800kN·m, the allowable safety distances for the different structure types were proposed as following:

For the ordinary stone or masonry building without seismic fortification, the allowable safety distance is about 70m;
For the reinforced concrete structures, the allowable safety distance is about 50m;
For the bridge structures with pile foundation, the allowable safety distance is about 30m.

4.2 Assessment of Ambient Vibration

The vibration grades respecting to the recorded data were calculated. The vibration grades and their mean values are listed in Table 5 and Table 6.

Table 5 Vibration grades varying with the distance to compaction point

Distance to compaction point	Direction	Test line 1	Test line 2	Test line 3	Test line 4	Test line 5	Test line 6	Mean value
14	Vertical	118.90	119.72	117.42	117.96	119.19	119.71	118.82
	South-north	111.45	110.03	110.74	111.77	111.27	110.76	111.00
	East-west	112.28	111.39	111.60	109.87	110.53	110.03	110.95
30	Vertical	117.03	116.34	116.59	116.98	116.06	116.98	116.66

	South-north	111.14	111.97	111.48	111.73	112.05	111.72	111.68
	East-west	112.71	111.92	109.41	110.80	110.49	110.59	110.99
50	Vertical	116.52	116.83	117.77	117.33	117.23	118.41	117.35
	South-north	110.80	110.44	111.82	110.48	110.34	111.57	110.91
	East-west	109.38	110.50	108.55	109.95	109.06	111.51	109.83

Table 6 Vibration grades with far distance

Distance to compaction point	Direction	Compaction times				Mean value
		No.5	No.7	No.8	No.9	
70	Vertical	116.59	116.84	116.68	116.72	116.71
	South-north	110.80	111.11	111.07	110.96	110.99
	East-west	110.93	110.86	110.26	109.85	110.47
100	Vertical	116.63	116.87	116.77	116.60	116.72
	South-north	111.64	111.70	111.79	111.70	111.71
	East-west	111.09	111.18	110.80	110.57	110.91

It can be seen from Table 5 and Table 6, the calculated vibration grades are much greater than the values coded in the “Ambient Vibration Criterion in Urban Area” (GB10070-88). The harm of the ambient vibration due to the dynamic compaction needs to be paid more attention.

5 CONCLUSIONS

Based on 207 vibration records recorded in-situ during the construction of foundation consolidation by the way of dynamic compaction, the statistical analysis respecting to the peak ground acceleration (PGA) and peak ground velocity (PGV) was performed. Referring to the earthquake intensity classification of the “China Earthquake Intensity Table” (GB/T17742-1999) and the allowable vibration velocity of the “Safe Blasting Regulation” (GB6722-2003), the vibration assessment for the dynamic compaction was carried out. The allowable safety distance for the different structures under the specified energy grade of 1800kN·m was proposed. Furthermore, the peak attenuation rules on the vertical and horizontal direction were analyzed. Both the peak attenuation rules for PGA and PGV accorded with the exponent attenuation rule. Moreover, the vibration grades of ground motion due to dynamic compaction were calculated in details. Referring to “Ambient Vibration Criterion in Urban Area” (GB10070-88), the ambient vibration was evaluated. It can be concluded that the vibration grades of ground motion due to dynamic compaction were much greater than the values coded in the existing codes. The influence of dynamic compaction on the adjacent environment was negligible and needed to be paid more attention.

REFERENCES

FANG Lei, JING Fei，LIU Songyu(2001). Influence of Vibration Caused by Dynamic Compaction and Safe Distances for Buildings [J]. *Journal of Southeast University (Natural Science Edition)*, 31(3): 29-32(in Chinese).

LEI Xuewen，BAI Shiwei，MENG Qingshan(2002). Analysis on the Vibration Produced by Heavy Tamping and Its Influence on Building[J]. *Building Technique Development*, 29(12): 20-21(in Chinese).

LI Ting. Study of vibration of dynamic compaction [J]. *Shanxi Architecture*, 2003, 29(13): 13-14(in Chinese).

OUYANG Lisheng，WANG Dijie(2004). Simple Analysis for the Seismic Effect of Dynamic Compaction [J]. *South China Journal of Seismology*, 24(3): 96-100(in Chinese).

ZOU Lihua, ZHAO Jianchang，CHEN Quanhong(2005). Experiment Study On Vibration To Improve Collapsible Loess With Dynamic Compaction[J]. Chinese Journal of Rock Mechanics and Engineering, 24(18): 3393-3397(in Chinese).

ZHANG Mengxi, WANG Yuling，FENG Jianlong(2004). Engineering properties of loess disturbed and geo-environmental damage due to dynamic consolidation[J]. *Rock and Soil Mechanics*, 25(12): 1903-1909(in Chinese).

GENG Guangxu, LI Huaping(2004)，LIU Jinchuan. Monitoring of Construction Vibration to Environment[J]. *Science and Technology of Reconnaissance*, No.4: 54-57(in Chinese).

China Society of Engineering Blasting. Blasting Safety Specfication (GB6722-2003) [S]. Beijing: China Standard Press, 2003(in Chinese).

China Quality Supervision Bureau. China Earthquake Intensity Table (GB/T 17742-1999) [S]. Beijing: China Standard Press, 1999(in Chinese).

Ambient Vibration Criterion in Urban Area (GB10070-88) [S], Beijing: China Plan Press, 1988(in Chinese)