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Experimental study of train-induced vibrations of environments and buildings

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Abstract

In this paper, the vibrations of environments and nearby buildings induced by running trains were studied through the in situ experiments at a bridge site and two buildings near railway lines. The results show that the vibration levels of the environmental ground and the building floors increase with train speed, while attenuating with the distance to the railway lines. There exists an amplifying zone of the ground vibration at certain distances to the railway track regarded as a line vibration source. For multi-story buildings, higher floors vibrate more strongly than lower ones. Heavier trains induce greater vibration than lighter trains. The measured acceleration levels for ground and buildings near the track were so big that it greatly exceeded the allowance given by the Chinese Code.

1. Introduction

As one of the main environmental pollutions, the vibration of environments that seemed to have been tolerated in the past is today increasingly being considered as a nuisance. According to the statistic investigations in several countries, traffic-induced vibration of environments is nearly the most intense in the public complaints, second only to those from industry and construction sites [1].

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With the raising of vehicle speeds, the increasing of vehicle loads and the growing of traffic flows, and the construction of urban traffic roads which are increasingly closer to buildings, the influences of traffic-induced vibrations are becoming stronger and stronger, while with the development of the society, the requirement of the public on the environments is getting more and more strict. Therefore, the influences of traffic-induced vibrations on the living and working environments of the human being have aroused the attention of the city authorities as well as engineers and researchers. Some researches on this subject have been done in China and abroad [2–14].

In this paper, two in situ experiments were carried out to study the influences of the train-induced vibrations on the surrounding environments and the nearby buildings. Some useful results have been obtained from the experiments and the measured data, such as the high vibration levels of the ground and different floors of buildings near the railway lines, the existence of vibration-amplifying zones, and the influence of train speeds and loads. The experimental results proved many of the previous theoretical conclusions about the propagating laws of vibrations in the ground and buildings [11–13], and can be referenced in the planning and designing of traffic systems in urban areas.

2. Experiments on ground vibration near bridge

The first experiment was carried out at the Daqinghe Bridge site. The purpose of this experiment was to study the vibration level and the distribution laws of the train-induced ground vibration at different distances to the bridge pier (point vibration source) and under different train speeds.

2.1. Introduction to Daqinghe Bridge site

The Daqinghe Bridge was built in 1904, located at the Shenyang–Harbin Railway Line in Northeast China. It has a full length of 750 m, composed of 22 spans and 21 piers. Each span consists of two pieces of steel I-shaped plate beams of 33.6 m in length and 2.61 m in height. The cross center-to-center distance between the two beams is 2.0 m. The web thickness of the I-beam is 12 mm. Its top and bottom flange thickness varies from 15 to 45 mm. The bracing systems connecting the two I-beams are made of angle and slot steel members. The heights of the concrete bridge piers are from 6 to 10 m. The ground soil of the site is fine sand and clay. The bridge under experiment is shown in Fig. 1.

In the experiment, the accelerations of the pier top and the surrounding ground at some points were measured by accelerometers when the test train was running on the bridge. The measurement points located on the pier top (in lateral) and the ground (in vertical) at the perpendicular distances to the bridge of 0 (foot of the pier), 20, 40 and 60 m are outlined in Fig. 2.

The dynamic loads of the experiment were the specially marshaled test train, which was composed of one locomotive, and seven freight cars. The vehicle axle-weight was 230 kN for the 6-axle locomotive and 200 kN for the 4-axle freight cars. The train speeds in the experiment were in the range of 60–80 km/h.

Fig. 1. Experiment site at Daqinghe Bridge.

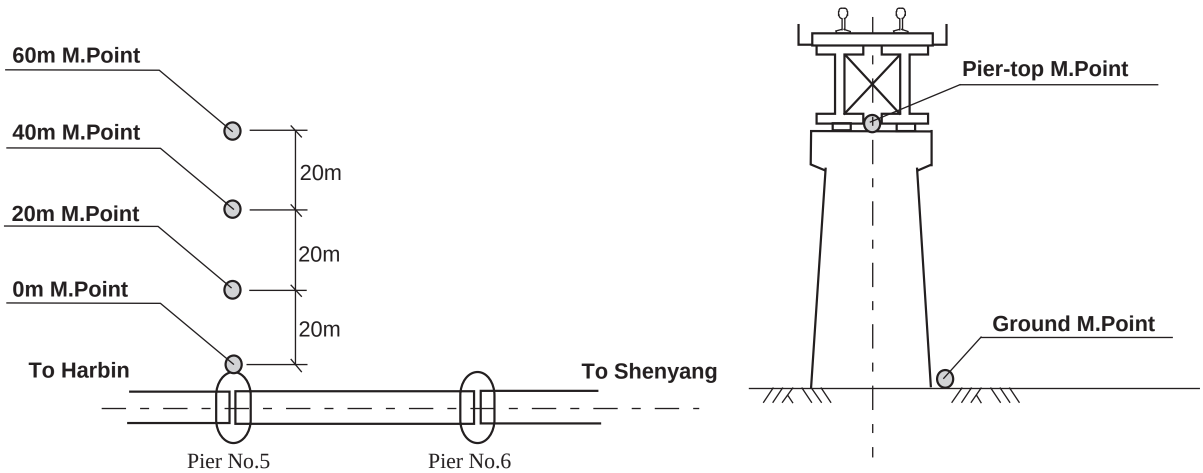

Fig. 2. Ground and pier-top measurement location arrangement.

Totally, 28 groups of measurements were carried out during the experiment. The maximum and the average vibration levels of the bridge pier and the ground at different distances under different train speeds were obtained from the measurement, which are listed in Table 1.

The vibration levels are calculated on the basis of [13]

$$G = 20\ \lg(a) + 60, \tag{1}$$

where G is the vibration level in dB and a is the measured acceleration in $\mathrm{cm/s^2}$.

2.2. Vibration of bridge pier

From Table 1 one can see that the measured maximum vibration level of the pier-top is 98.6 dB. Two of the typical measured lateral acceleration histories at the pier-top under the train speeds of 60 and 80 km/h are shown in Fig. 3. It is clear that higher train speed induced greater accelerations

Table 1
Measured pier and ground acceleration levels (dB)

Train speed (km/h)			Ground at distances to the bridge pier-foot center (m)							
	Pier top		0		20		40		60	
	Max	Ave	Max	Ave	Max	Ave	Max	Ave	Max	Ave
60	91.8	90.9	87.5	86.9	74.6	72.6	65.2	61.6	50.3	48.4
65	93.5	93.1	96.2	94.3	86.0	84.3	74.8	70.4	58.9	47.2
70	95.0	94.2	98.9	96.5	89.9	86.8	74.1	70.4	60.0	57.9
75	97.0	96.5	101.3	98.5	94.4	92.1	77.2	74.6	61.2	58.7
80	98.6	98.3	107.5	103.1	96.2	93.9	75.3	72.0	64.7	59.7

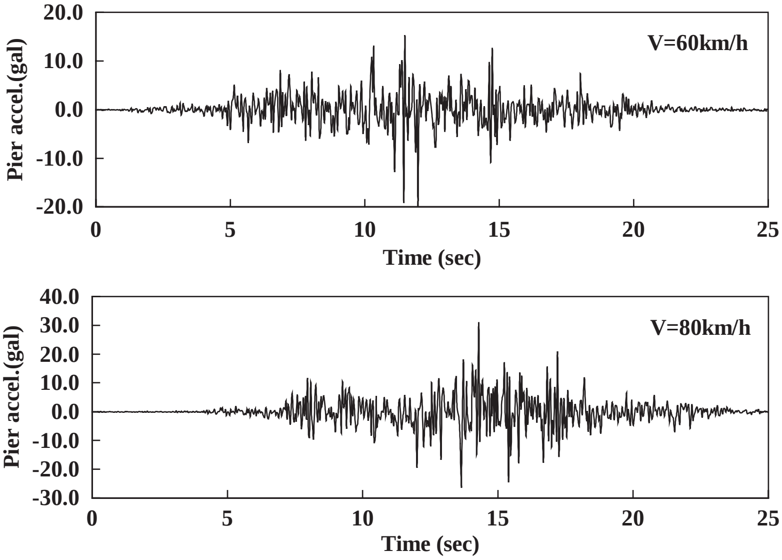

Fig. 3. Measured acceleration waves at pier top.

of the pier-top. There are 7–8 dB differences of maximum and average vibration levels of the pier under the train speed difference of 20 km/h.

2.3. Vibration of ground

The measured acceleration histories of the ground at the foot of the pier (0 m) and 40 m to the bridge under the train speed of 60 km/h are shown in Fig. 4.

The distribution of the maximum ground vibration levels induced by the passing trains at different speeds versus the distance to the bridge is shown in Fig. 5.

The main trend is that the ground vibration level attenuates linearly with the increase of the distance to the pier (point vibration source). The highest average vibration level is 107.5 dB,

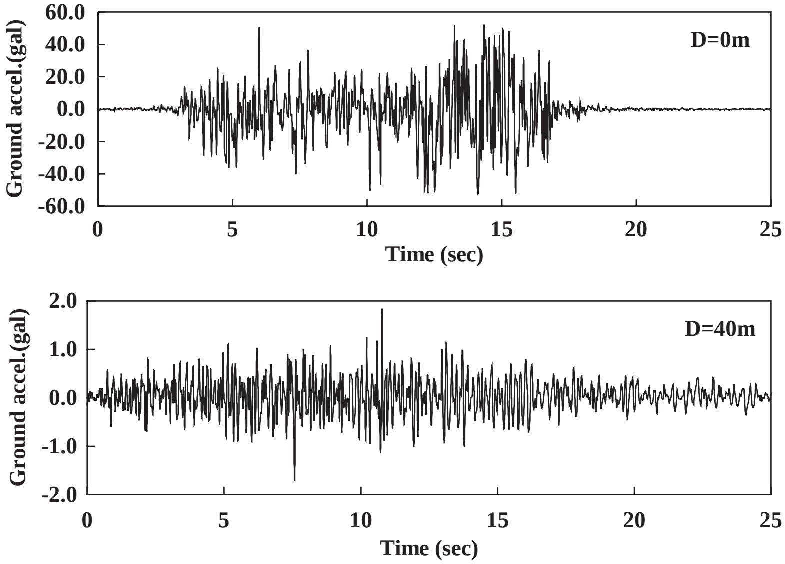

Fig. 4. Measured ground acceleration histories.

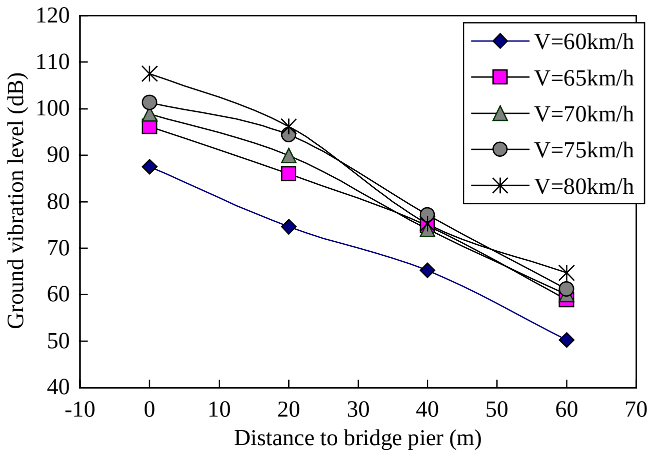

Fig. 5. Ground vibration versus distance to pier.

occurring at the foot of the pier (0 m). The measured data show 37–43 dB decrease for the vibration levels in the distances from 0 to 60 m at different test train speeds.

The distribution of the average vibration levels at different train speeds versus the distance to the vibration source has the same trends as the maximum ones, but the maximum average value is 103.1 dB.

2.4. Effects of train speed

The distribution of the maximum ground vibration levels at different distances to the bridge pier versus train speed is shown in Fig. 6. Within the train speed range from 60 to 80 km/h, the

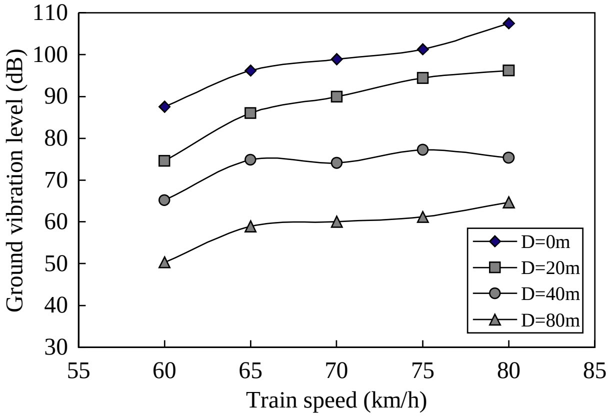

Fig. 6. Ground vibration versus train speed.

ground vibrations at different distances have the main trend of increasing with the train speed. This is because that trains with higher speed have greater dynamic impact on the ground. This conclusion can also be found in Refs. [8,10], where the train speed ranges are extended to 50–280 km/h.

When the train speed is higher than 65 km/h, the vibration level of the point less than 30 m to the pier is greater than 80 dB. The results show 10–20 dB increase for the ground vibration levels when the train speed increased from 60 to 80 km/h. The nearer the distance is, the bigger the difference is.

The distribution of the average vibration levels of the ground at different distances to the vibration source versus the train speed shows the same trends as the maximum ones, but with smaller differences than those in maximum ones.

3. Experiment of train-induced vibration of buildings

The second experiment was carried out at the site where two two-story buildings were located. The purpose of this experiment was to study the distribution laws of the train-induced vibrations of the ground and the buildings near the railway.

3.1. Introduction to the experiment

The experiment site was located by the Shenyang–Shanhaiguan railway line in Northeast China, near the Shenyang Railway Station. At the site, there are two office buildings very close to the railway tracks; see Figs. 7 and 8.

As is shown in the figures, the shortest distance from the building to the track is only 12 m; therefore, stuff working there can always feel strong vibration when a train is running on the nearby track, especially when two trains are running simultaneously.

Fig. 7. Office buildings near the railway.

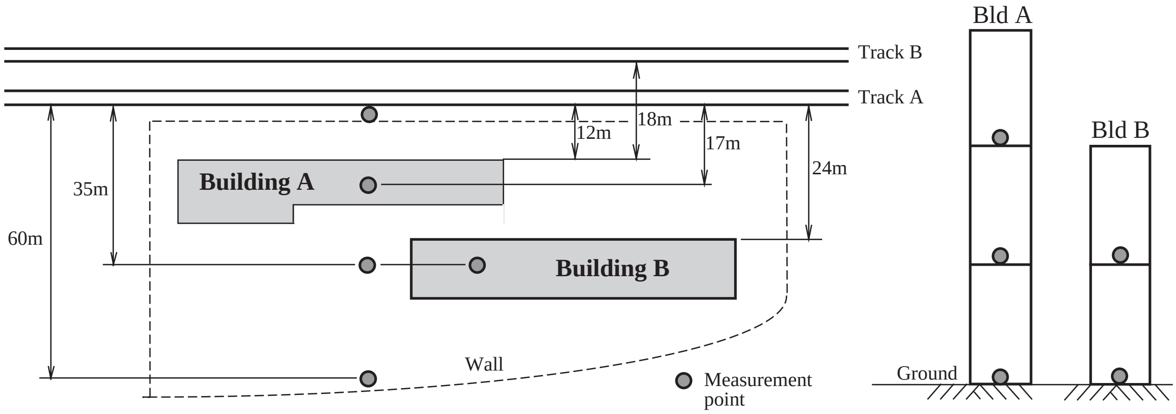

Fig. 8. Experiment site and measurement arrangement.

In total there were eight measurement points set in the experiment. The vibrations were measured by accelerometers arranged at different floors of the buildings and different points of the ground, as is outlined in Fig. 8. For buildings, the measurement points of indoor vibrations were at the centers of room floors [13].

The loads of the experiment were the trains in normal operation, including passenger trains and freight trains. The train speeds during the experiment were from 20 to 80 km/h. Totally, there were 30 groups of data measured. Because the trains on the normal railway lines were with different conformations, loads and speeds, the statistic parameters of the vibration were analyzed in the study. The maximums, averages and standard variations for the vibration levels of the buildings and the ground were obtained.

Table 2
Measured ground vibration responses (dB)

Train type	Vibration level	Distance to track			
		0 m	17 m	35 m	60 m
Freight train	Maximum	119.0	81.4	84.3	79.3
	Average	109.1	76.2	81.5	77.6
	Standard deviation	11.62	2.95	2.46	1.22
Passenger train	Maximum	106.2	70.2	75.8	71.1
	Average	97.8	67.7	74.1	70.4
	Standard deviation	6.34	1.68	1.41	0.63

3.2. Vibration of ground

The measured ground vibration responses are listed in Table 2. The maximum vibration levels near the railway track is as high as 119 dB with a rather big standard variation of 11.62, and at the point 35 m to the track, it is 78.3 dB, slightly higher than that at 17 m. The typical measured acceleration histories of the ground beside the track (0 m) and at the point 35 m to the track are shown in Fig. 9.

The measured ground acceleration levels are plotted in Fig. 10. The distribution of the measured ground vibration levels and their average versus the distance to the railway track is shown in Fig. 11. The main trend is that for different train speeds, the ground vibration attenuates rapidly with the increase of the distance, while at certain distances to the track, there appears an amplifying zone of vibration, which is at 30–45 m to the track (line vibration source).

From Table 2, one can compare the vibration levels induced by passenger trains and freight trains. Normally freight trains give heavier loads to the railway track and thus induce greater ground vibrations than passenger trains. There are 2–13 dB of differences between the ground vibrations induced by the two types of trains. The nearer the distance to the track is, the bigger the difference is.

3.3. Vibration of buildings

The measured vibration responses of buildings at different floors are listed in Table 3. The maximum vibration level at the third floor of the near building A is as high as 89.3 dB. With about 18 m longer distance but higher ground vibration, the far building B has the greater average floor vibrations than the near building A by 5–6 dB. The typical measured acceleration histories of the second and the third floors of building A are shown in Fig. 12.

Figs. 13 and 14 are the distributions of the measured vibration levels of the near building A at different floors. For such a multi-story building, the main trend is that the higher floors vibrate more strongly than the lower ones. There exists a 15 dB difference of the average vibration levels between the ground floor and the third floor. This can be explained by the fact that a multi-story

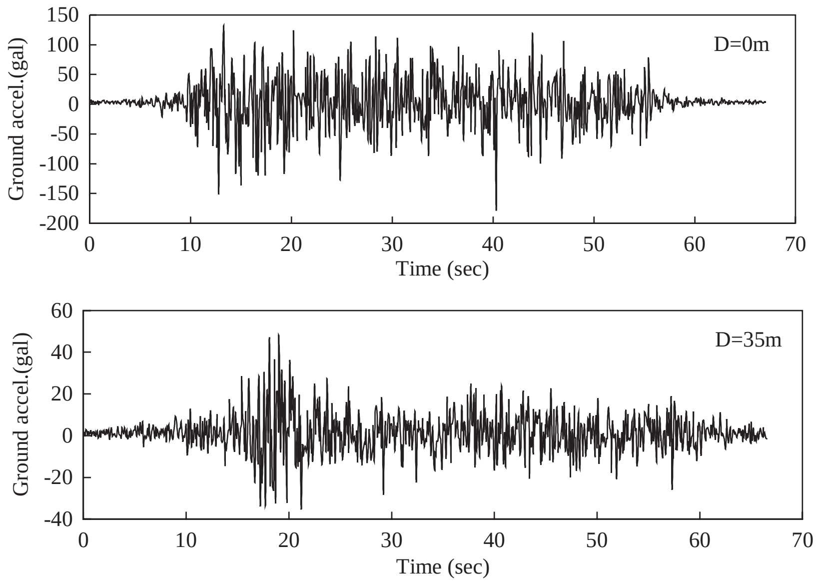

Fig. 9. Measured acceleration waves of the ground.

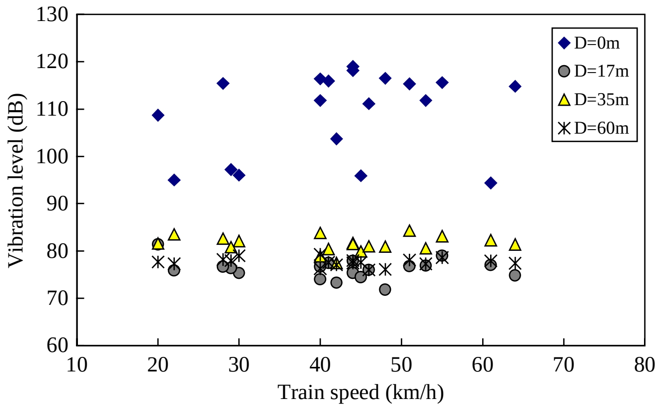

Fig. 10. Ground vibration level versus train speed.

building on the ground can be regarded as a cantilever: when excited by ground movement, it will vibrate mainly in its lowest modes, especially most easily in the first mode, producing larger vibrations at the points closer to its free end than those to its fixed end. This conclusion is in accordance with that in Ref. [1], in which the vibrations of three buildings of four–six stories were measured. However, for taller buildings, further investigations should be done.

Table 4 gives the national standard ‘‘Code for Environmental Vibration in Urban Areas [GB10070-88] issued by the National Environmental Protection Bureau of China [13], in which the allowances for environmental vibrations in different urban areas are stipulated. The code is valid to continuous steady vibrations, shock vibrations and random vibrations. For shock

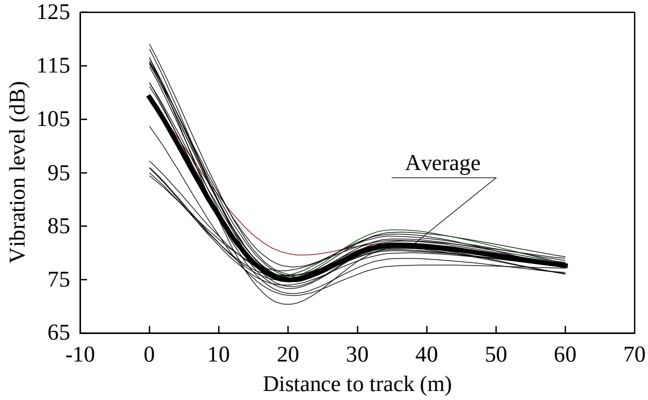

Fig. 11. Ground vibration level versus distance.

Table 3
Measured building vibration responses (dB)

	Building A			Building B	
	1st (ground) floor	2nd floor	3rd floor	1st (ground) floor	2nd floor
Maximum	72.93	76.03	89.31	79.35	93.02
Average	70.76	72.12	84.86	76.46	78.23
Standard deviation	1.982	2.063	3.011	1.711	7.312

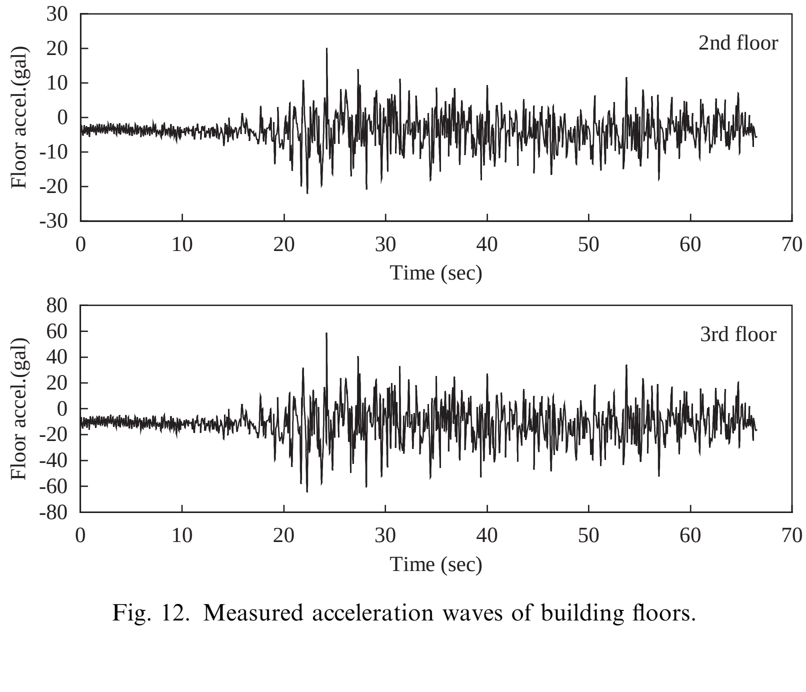

Fig. 12. Measured acceleration waves of building floors.

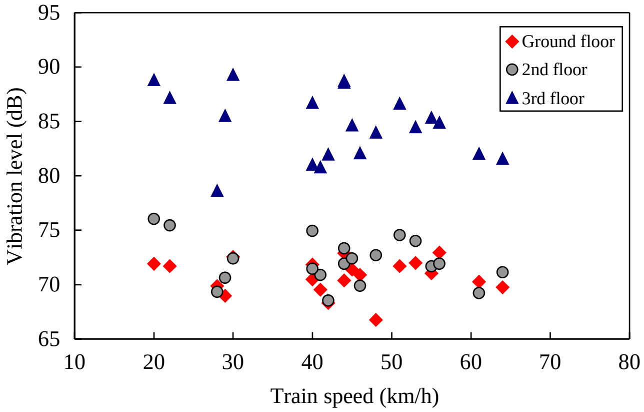

Fig. 13. Floor vibration level versus train speed.

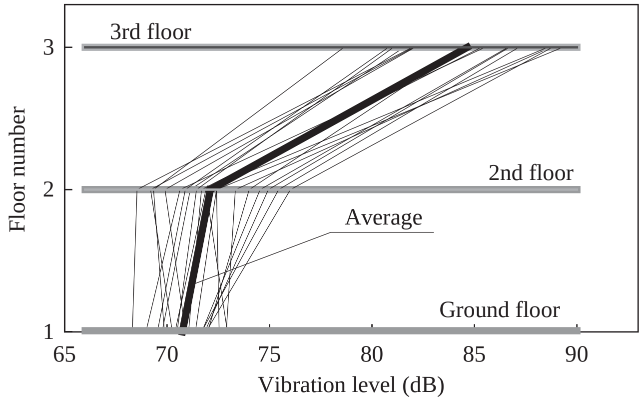

Fig. 14. Vibration level versus floor.

vibrations that take place several times a day, the maximum accelerations shall be the tabled allowances plus 10 dB during the day and 3 dB at night. One can see that the measured accelerations of the building floors have been greatly beyond the allowances of the Code.

4. Conclusions

The following points have been concluded from the above two experiments:

1. The ground vibration induced by running trains near a bridge increases with the train speed. When the speed of the test train changes from 60 to 80 km/h, the maximum vibration level of the ground near the pier foot is 87.5–107.5 dB.
2. The ground vibration induced by running trains near the bridge attenuates rapidly with the distance to the bridge pier (point vibration source).
3. For the buildings near railway tracks, the distance between the buildings and the railway track has important effects on the vibration of the buildings. With the increase of the distance, the

Table 4
Allowance for environmental vibration grades in urban areas (dB)

	Area category	Daytime	Nighttime
A	Residence districts where special silence is required	65	65
B	Districts of common residence, cultural sections and schools	70	67
C	Mixed area of residence, industry, commerce and minor traffics	75	72
D	Commercial center	75	72
E	Concentrated industrial areas	75	72
F	Road sides	75	72
G	Railway sides	80	80

vibrations of the ground and the building floors attenuate rapidly, while at certain distances to the track (line vibration source), there exists an amplifying zone (at 35–45 m to the track in the second experiment) of vibration.
4. Heavier (freight) trains induce greater vibration than lighter (passenger) trains.
5. For multi-story buildings, with the increase of floor number, the vibration level becomes higher. In the second experiment, there is a 15 dB difference between the ground floor and the third floor.
6. In the experiments, the maximum acceleration of the ground in 30 m from railway exceeded 80 dB, and the floor vibration of Building B located 35 m from the track reached 93 dB, greatly exceeded the allowance given by the Chinese Code. It can thus be concluded that the train-induced environmental vibrations are rather serious, and therefore much attention should be paid to this problem.

Acknowledgements

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References

[1] J.Ma, Railway environmental vibration and its propagation in the residential areas in China, *Journal of Environmental Science* 7(5) (1987) 70–74.
[2] M. Bata, Effect on buildings of vibrations caused by traffic, *Building Science* 99 (1) (1985) l–2.
[3] T.M. Dawn, Ground vibration from passing trains, *Journal of Sound and Vibration* 66 (3) (1979) 355–362.
[4] G. Degrande, G. Lombaert, High-speed train induced free field vibrations: in situ measurements and numerical modeling, in: *Proceedings of Wave2000*, Balkema, Rotterdam, 2000, pp. 29–42.
[5] C.H. Dowding, Effects of ground motions from high-speed trains on structures, instruments, and humans, in: *Proceedings of Wave2000*, Balkema, Rotterdam, 2000, pp. 269–288.
[6] J.A. Studer, J. Laue, Harassment and damage caused by vibrations: prediction and evaluation in theory and practice, in: *Proceedings of Wave2000*, Balkema, Rotterdam, 2000, pp. 317–324.

[7] J. Vantomme, Vibration nuisance and damage evaluation in buildings: an overview of standards, in: H. Xia, G. De Roeck (Eds.), *Traffic Induced Vibrations & Control*, NJTU Press, Beijing, 2001, pp. 313–320.
[8] G. Volberg, Propagation of ground vibrations near railway tracks, *Journal of Sound and Vibration* 87 (2) (1983) 371–376.
[9] G.R. Watts, Case studies of the effects of traffic induced vibrations on heritage buildings, Technical Report, Transport and Road Research Laboratory, Crowthorne, Berkshire, 1987.
[10] O. Yoshioka, Basic characteristics of shinkansen-induced ground vibration and its reduction measures, in: *Proceedings of Wave2000*, Balkema, Rotterdam, 2000, pp. 219–239.
[11] H. Xia, Study of vibration effects of underground trains upon surrounding environments, in: H. Xia, Y.J. Chen (Eds.), *Advances in Structural Engineering*, China Railway Publishing House, Beijing, 1995, pp. 116–122.
[12] H. Xia, Traffic-induced vibrations and their influences on surrounding environments, in: H. Xia, J.J. Zheng (Eds.), *Modern Composite Concrete & Infrastructures*, Delft University Press, Delft, The Netherlands, 2000, pp. 123–130.
[13] H. Xia, Characteristics of traffic induced vibrations and their effects on environments, in: H. Xia, G. De Roeck (Eds.), *Traffic Induced Vibrations & Controls*, NJTU Press, Beijing, 2001, pp. 83–90.
[14] Yang, et al., Train-induced wave propagation in layered soils using finite/infinite element simulation, *Journal of Soil Dynamics and Earthquake Engineering* 23 (4) (2003) 263–278.