Ground vibration induced by high-speed trains on bridge structures

Yit-Jin Chen
Professor, Department of Civil Engineering, Chung Yuan Christian University, Chung-Li 32023, Taiwan, e-mail: yjc@cycu.edu.tw

Ting-Jui Chiu
Kuo-Yen Chen
Master Science, Department of Civil Engineering, Chung Yuan Christian University, Chung-Li 32023, Taiwan, e-mail: sworldmark@hotmail.com; g9122104@cycu.org.tw

Ground vibration induced by high-speed trains can reach levels that cause annoyance to humans and interruption of sensitive instrumentation. To address this issue, the characteristics of ground vibration induced by Taiwan high-speed rail on bridge structures are evaluated using a wide range of field-measured data. The measurements for analysis consist of various foundation types, geological conditions, and train speeds. Both near-field vibration (25 m from track center) and far-field vibration propagation are evaluated. Specific influence factors for ground vibration assessment are also presented.

1. INTRODUCTION

At present, many high-speed rail lines have been constructed to connect major cities in many countries. High speed rail travel has become relatively competitive because of the many service advantages and the lower energy consumption of the rail system compared with other transport systems. However, ground vibration induced by high-speed trains can reach levels that cause annoyance to humans and interruption of sensitive instrumentation. [1, 2, 3] A vibration level prediction methodology for ground vibration induced by high-speed trains on various structures has been developed. Based on these suggestions, the main factors affecting vibration levels can be grouped into vibration source, vibration path, and vibration receiver. Among them, rail system, structure type, and geological condition are the most important influence factors. Numerical analysis is often used to study the rail system at various structure types. Research on this subject has progressed well in the past several decades. Other researchers [3 to 6] have studied the effect of geological and foundation conditions on ground vibration level and its propagation. These studies have shown that geotechnical-related influence factors are relatively significant on the evaluation of the vibration behavior for high-speed trains.

With these essential geotechnical influence factors, the authors conducted a comprehensive measurement scheme to evaluate the characteristics of ground vibration induced by Taiwan high-speed rail (THSR) on bridge structures. Various foundation types, soil types, and frequency dependences are applied to the field measurement data to evaluate both near-field ground vibration and far-field vibration propagation.

2. MEASUREMENT OF GROUND VIBRATION

2.1 TRAINSET

The trainset (Fig. 1) of the THSR consists of 12 train-cars with 10 cars for passengers and 2 cars as locomotives. The lengths of the passenger car (PC)

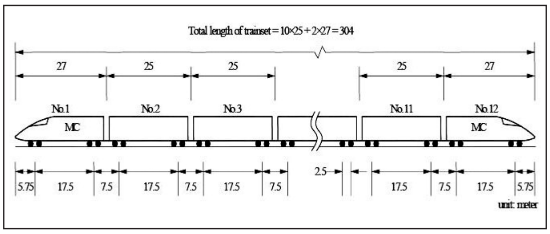


Figure 1. Configuration of trainset for Taiwan high-speed rail

and motive car (MC) are 25 m and 27 m, respectively; thus, the total length of the trainset is 304 m.

2.2 MEASUREMENT OF GROUND VIBRATION

The measuring instruments and equipment set-up is shown in Fig. 2, including accelerometers, integrator, and a data acquisition system. The following procedure is used for sensors' installation on the ground:

1. A pit with proper dimensions, which can install accelerometers, was excavated.
2. Standard sand was placed on the bottom of pit to even the excavated surface.
3. The excavated surface was compacted assuring that the surface is level.
4. Three-dimensional accelerometer was firmly placed, which connected to a steel plate as a firm base, on the ground.
5. The accelerometer direction was set: the X-direction is in the train moving direction; the Y-direction is perpendicular to the train moving direction; and the Z-direction is for the direction of gravity.

Only the vertical component (Z direction) is used in the subsequent discussion because some codes, such as Japanese code, etc., consider Z direction for analysis to simplify the process of vibration impact assessment.

Adjacent environmental conditions are also essential in avoiding any possible interruption during measurement and to make sure that all analysis data are in good quality. Microphones and digital video were installed as auxiliary instruments to record noise and any activity, and such information can be used to evaluate whether or not other vibration sources interfered with the measurement.

The vibration measuring plan includes near-field and far-field measurements. To establish the near-field vibration database in a consistent reference plane, the distance of the near-field vibration was set at about 25 m

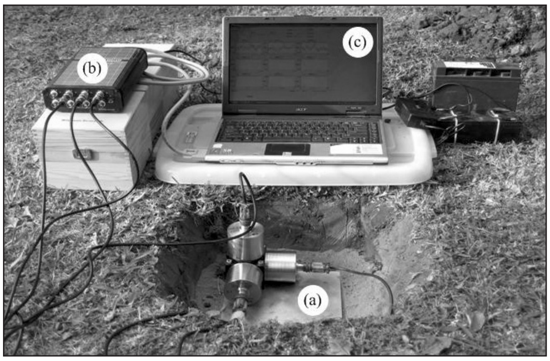
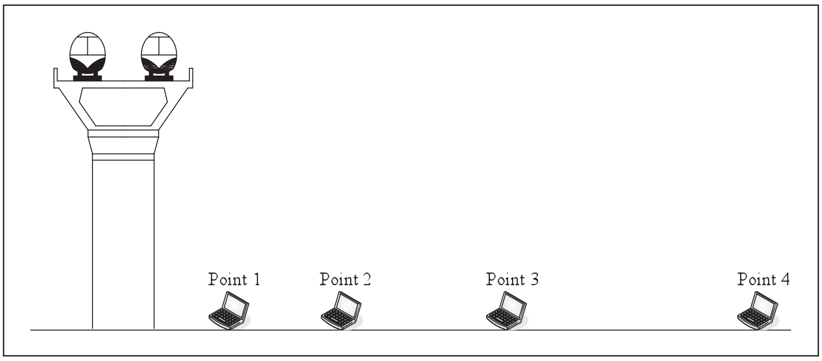


Figure 2. Measuring equipment: (a) accelerometers in x, y, and z directions; (b) integrator; and (c) data acquisition system Measurement of Site 4 and typical schematic layout

(a) Measurement Site



(b) Schematic layout

Figure 3. Measurement of Site 4 and typical schematic layout

from the track center. For far-field measurement, 4-5 measurement points in each site, which were in a straight line and perpendicular to the train alignment, were used to simultaneously measure the ground vibration when trains pass through the specific location. The first measurement point (the nearest point from the high-speed rail alignment) was located at about 25 m from the track center, whereas the distance of the last measurement point (the farthest point from the alignment) was 200 m or so, which was dependent on the field condition. The remaining points were located at average intervals. Fig. 3 is the scene of Site 4 and shows a typical schematic layout of the measurement points. All equipment was calibrated before measurement.

A range of amplitudes (10~100 dB ref. 1 micro-inch/sec) and frequencies (1~100 Hz) were needed for the assessment. To evaluate the frequency effect, the frequency domain of a 1/3 octave band for the center frequency range of 1 to 100 Hz was adopted to describe the velocity vibration level in decibel (dB).

3. GROUND SHEAR WAVE VELOCITY

The ground shear wave velocity (V_s) is used as an indicator to describe the "soil stiffness" in which, typically, the value of V_s increases with increasing soil stiffness. The National Center for Research on Earthquake Engineering (NCREE) of Taiwan measured the ground shear wave velocity all over Taiwan. The site where the ground shear wave velocity (V_s) was measured by the NCREE is adjacent to the location of ground vibration measurement and has relatively similar geological conditions. Therefore, the measured results of V_s by NCREE were adopted.

NCREE used the suspension P-S logging method (Fig. 4). This method has a single downhole probe, containing a source and two receivers, to obtain continuous high-resolution velocity measurements. Both primary wave (P) and shear wave (S) velocities can be determined through testing. A borehole is drilled and filled with water. The probe is then lowered into the borehole to a specified depth, where the source generates a pressure wave in the borehole fluid. The pressure wave is converted to seismic waves (P and S) at the borehole wall. Along the wall at each receiver location, the P and S waves are converted back to pressure wave in the fluid and received by the geophones that send the data to the recorder on the surface. Since the distances from the source to the upper and lower receivers are different, the elapsed time between the arrivals of the waves at the receivers can be used to determine the average ground wave velocity around the borehole.

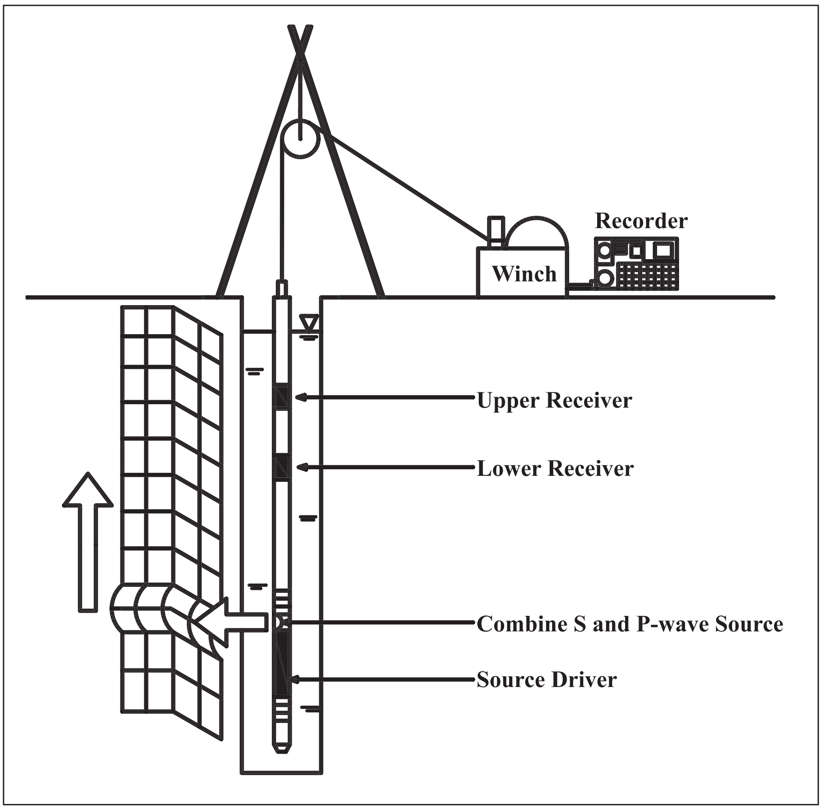


Figure 4. Schematic view of the suspension P-S logging system (modified from NCREE)

4. DATA ANALYSIS METHOD

The ground vibration level (VL) is expressed in terms of its root-mean-square (RMS) velocity. The RMS velocity level is computed using the following steps:

(1) Use Fast Fourier Transform (FFT) to transfer the velocity of time history, y(t), to the frequency domain. Then calculate the power spectrum density function (PSDF), Sy(f):

$$S_y(f) = \frac{2|Y(f)|^2}{T} \quad (1)$$

where |Y(f)| = FFT amplitude, T = time interval of y(t), and f = frequency (Hz). The suitable time interval (8 seconds in this study) which covers the ground excitation during the passing of train is selected from the time history record.

(2) Accumulate PSDF from the lower band to the upper band:

$$E_y(f_c) = \int_{f_l}^{f_u} S_y(f)\, df \quad (2)$$

where f_l, f_u, and f_c are the lower band, upper band, and center frequencies, respectively. $E_y(f_l)$ represents the energy summation from f_l to f_u. The frequencies of f_l, f_u, and f_c are based on the definition of the 1/3 octave band in ANSI [7].

(3) Calculate the RMS of σ_y (fc):

$$\sigma_y(f_c) = \sqrt{E_y(f_c)} \quad (3)$$

(4) Calculate the RMS velocity level (VL), which is represented by dB:

$$VL\ (in\ dB) = 20 \log_{10} \frac{\sigma_y(f_c)}{\sigma_0} \quad (4)$$

where the referred velocity in this study is $\sigma_0 = 10^{-6}$ in/sec (= 2.54×10^{-8} m/sec).

Furthermore, the overall vibration

level of 1/3 octave bands was used to evaluate the total vibration energy. The overall vibration level can be transferred from the RMS vibration level of each 1/3 octave band, using the following equation:

$$VL_{OA} = 10\log_{10}\sum_{k=1}^{n}10^{VL(fk)/10} = 10\log_{10}(10^{0.1\,VL(f1)} + 10^{0.1\,VL(f2)} + \cdot 10^{0.1\,VL(fn)}) \quad (5)$$

where VL_{OA} = overall vibration level in decibels, fk = each 1/3 octave band's center frequency (1 ..100 Hz for the frequency of f1 .. fn), and VL(fk) = vibration level for each center frequency.

A simple equation by Gutowski and Dym [8], modified from that of Bornitz [9], was used for estimating vibration decay. Gutowski and Dym considered both geometrical and material damping under line-source into an expression of Rayleigh wave (R-wave) attenuation as follows:

$$V_2 = V_1 \times e^{-\alpha(r_2 - r_1)} \quad (6)$$

where V_1 and V_2 are the vibration amplitudes of the R-wave at distances r_1 and r_2, respectively; r_1 and r_2 are the distances from the vibration source; and α is the vibration attenuation coefficient for the soil material.

Two kinds of ground vibration attenuations were evaluated from the measured results. Initially, attenuation was analyzed from the overall vibration regardless of the dependence of frequency. The overall vibration level (VL_{OA}) of all 1/3 octave bands in Eqn. (5) was used to evaluate the total vibration energy. With the overall vibration level of each measured point, the attenuation coefficient for high-speed trains can be back-calculated from 4 to 5 measurement points using Eqn. (6). The second approach involved the classification of the attenuation

Table 1. Measurement Scheme for High-Speed Trains on Bridge Structures

Site No.	Location	Foundation type	Soil type	Foundation dimensions[a] (m)	Symbol[b]	Ground shear wave velocity, V_s (m/s)	Concrete volume (m^3)	Measurement purpose
1	Taoyuan	Shallow	Gravel	SF: 2×10.5×10.5	SG	390	270	near-field vibration, vibration propagation
2	Miaoli	Shallow	Rock	SF: 2.8×12×12	SR	496	460	
3	Tainan	Deep	Alluvium	Cap: 3×11×11 Pile: 4-2	DA	178	590	
4	Hsinchu	Deep	Gravel	Cap: 2.5×16×16 Pile: 9-2	DG	375	1146	
5	Hsinchu	Deep	Rock	Cap: 3×18×18 Pile: 12-2	DR	470	1455	
6	Hsinchu	Shallow	Gravel	SF: 2.5×11×11	SG	379	460	near-field vibration
7	Taichung	Shallow	Gravel	SF: 2.5×12.5×12.5	SG	458	520	
8	Chiayi	Deep	Alluvium	Cap: 2×9×9 Pile: 7-1.5	DA	186	380	
9	Tainan	Deep	Alluvium	Cap:2.5×11.5×11.5 Pile: 5-2	DA	205	540	
10	Miaoli	Deep	Rock	Cap: 2×8×8 Pile: 4-1.5	DR	483	280	
11	Miaoli	Deep	Rock	Cap: 3×11×11 Pile: 5-1.5	DR	468	700	

Note: a- SF = spread footing; "Pile: 4-2" expresses 4 piles with 2.0 m diameter.

b- SG = shallow foundation in gravel; SR = shallow foundation in rock; DA = deep foundation in alluvium soils; DG = deep foundation in gravel; DR = deep foundation in rock.

based on the low, middle, and high frequency ranges. The 21 frequencies for the 1/3 octave band with 1-100 Hz were divided into three groups, including low (1-8 Hz), middle (10-25 Hz), and high (31.5-100 Hz) frequency ranges. The overall vibration level and vibration attenuation coefficient for each frequency range can then be computed using Eqns. (5) and (6), respectively.

5. DATABASE OF MEASURED GROUND VIBRATION

A comprehensive measurement scheme (Table 1) was adopted to evaluate the characteristics of ground vibration induced by the THSR on bridge structures. These measurement schemes were based on their measurement purpose. The measurements consisted of deep and shallow foundation types. The geological conditions included alluvial soils, gravelly soils, and rocks, ranging from soft ground to hard ground. The average ground shear wave velocity (V_s) was between 178 and 496 m/s. The values of average V_s were taken from ground surface to 10 m deep since it would be a representative of the surface wave analysis.

A total of 11 sites were measured for analysis. Sites 1-5 were used for both far-field vibration propagation and near-field vibration evaluation, whereas Sites 6-11 were used for near-field vibration only. The sites 1, 2, 6, and 7 have shallow foundations in hard ground (gravel or rock), while Sites 3-5 and 8-11 have deep foundations in soft to hard grounds (alluvium, gravel, or rock).

6. EVALUATION OF GROUND VIBRATION

Tables 2 and 3 present the results of vibration attenuation coefficient (α) for the overall vibration and low-mid-high frequency ranges, respectively. Results

Table 2. Statistics of a for Overall Vibration

Site 1		Site 2		Site 3		Site 4		Site 5	
Train speed (km/h)	α (10^{-3}/m)	Train speed (km/h)	α (10^{-3}/m)	Train speed (km/h)	α (10^{-3}/m)	Train speed (km/h)	α (10^{-3}/m)	Train speed (km/h)	α (10^{-3}/m)
180	1.51	245	1.92	245	0.86	120	1.15	170	1.95
180	1.90	275	2.03	265	0.90	120	1.14	180	1.43
180	1.70	280	2.03	270	0.90	130	1.25	190	2.04
200	1.64	280	1.92	280	0.74	150	1.08	190	1.58
260	2.15	280	2.18	290	0.85	150	1.04	210	1.78
260	2.08	280	2.01	295	0.91	230	0.91	210	1.87
280	2.30	280	2.31	300	0.74	250	1.16	210	1.67
280	2.20	290	1.78	300	0.90	300	1.04	210	1.88
300	1.83	290	1.91	300	0.83	300	1.02	210	1.89
300	2.30	290	1.86					290	1.76
		290	1.90						
		300	1.94						
Statistics									
n	10	n	12	n	9	n	9	n	10
Mean	1.96	Mean	1.98	Mean	0.85	Mean	1.09	Mean	1.80
SD	0.29	SD	0.14	SD	0.07	SD	0.10	SD	0.18
COV	0.15	COV	0.07	COV	0.08	COV	0.09	COV	0.10

Table 3. Statistics of a for Various Frequency Ranges

Site 1				Site 2				Site 3				Site 4				Site 5			
Train speed (km/h)	α (10^{-3}/m) L	M	H	Train speed (km/h)	α (10^{-3}/m) L	M	H	Train speed (km/h)	α (10^{-3}/m) L	M	H	Train speed (km/h)	α (10^{-3}/m) L	M	H	Train speed (km/h)	α (10^{-3}/m) L	M	H
180	0.96	2.28	2.43	245	1.22	2.41	2.83	245	0.55	1.72	3.03	120	0.41	1.42	3.48	170	0.78	2.18	3.26
180	0.89	2.61	2.89	275	0.70	2.81	3.45	265	0.48	1.71	3.16	120	0.39	1.51	3.27	180	0.32	1.81	3.74
180	0.77	2.47	3.17	280	0.90	2.29	3.27	270	0.61	1.98	4.01	130	0.33	1.63	3.56	190	0.24	1.30	3.43
200	0.95	2.30	2.92	280	0.60	2.18	3.22	280	0.52	1.39	2.64	150	0.34	1.45	2.93	190	0.67	2.53	3.64
260	0.96	2.67	3.44	280	1.01	2.57	3.47	290	0.68	1.20	3.20	150	0.28	1.41	3.58	210	0.69	2.31	3.61
260	0.88	2.60	3.21	280	0.96	2.25	3.11	295	0.76	1.23	3.72	230	0.52	1.62	3.03	210	0.60	2.37	3.24
280	0.92	2.48	3.36	280	1.00	2.66	3.55	300	0.35	1.27	3.80	250	0.33	1.57	3.66	210	0.70	2.56	3.70
280	0.32	2.45	3.36	290	0.42	2.32	3.02	300	0.75	1.73	3.32	300	0.61	1.22	2.84	210	0.68	2.27	3.43
300	0.88	2.61	3.28	290	0.88	2.27	3.08	300	0.58	1.49	3.00	300	0.60	1.42	2.64	210	0.42	1.79	3.25
300	0.42	2.42	3.88	290	0.97	2.17	3.03									290	0.41	1.67	3.25
				290	0.69	2.38	3.20												
				300	0.97	2.28	3.17												
Statistics																			
n	10	10	10	n	12	12	12	n	9	9	9	n	9	9	9	n	10	10	10
Mean	0.80	2.49	3.19	Mean	0.86	2.38	3.20	Mean	0.59	1.52	3.32	Mean	0.42	1.47	3.22	Mean	0.55	2.08	3.46
SD	0.23	0.13	0.39	SD	0.22	0.20	0.21	SD	0.13	0.27	0.44	SD	0.12	0.13	0.37	SD	0.19	0.40	0.20
COV	0.29	0.05	0.12	COV	0.25	0.08	0.07	COV	0.22	0.18	0.13	COV	0.29	0.09	0.11	COV	0.34	0.19	0.06

from each location at different train speeds are reasonably consistent, so the mean α from all train speeds was used in subsequent analyses. The statistical data are also presented to describe the quality of these analyses, including the mean value, the standard deviation (SD), and coefficient of variation (COV), which is the standard deviation divided by the mean.

6.1 NEAR-FIELD VIBRATION (25 M FROM TRACK CENTER)

Train speed factor

The relation between overall vibration level (VL_{OA}) and train speed for all foundation types and soil conditions in Fig. 5 indicates that the overall vibration level increases with increasing train speed. The trend is consistent for all foundation and soil types. The increase of overall vibration level becomes slow when the train speed is more than 270 km/h. The values of VL_{OA} range from 56 dB for low train speed (120 km/h), whereas the VL_{OA} values are between 58 and 71 dB for high train speed (270-300 km/h). On average, the difference is about 9 dB between the low and high speeds. The deep foundation in alluvial soils (DA) and shallow foundation in rocks (SR) generally show the highest vibration levels, whereas the shallow and deep foundations in gravelly soils have the

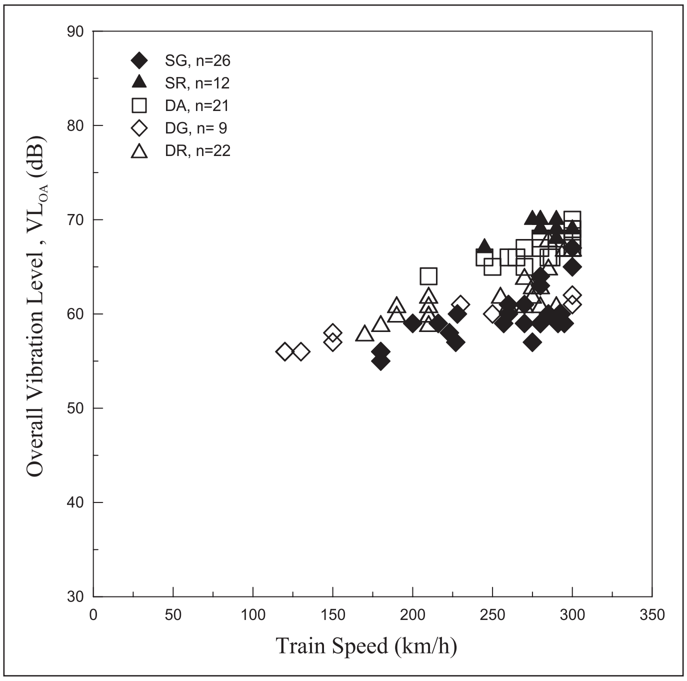


Figure 5. Relation of overall vibration level and train speed (25 m from track center)

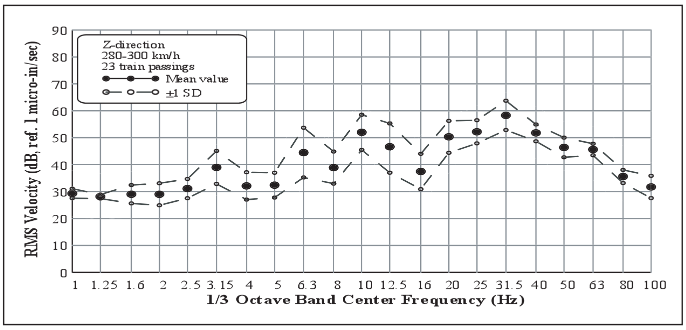
lowest vibration levels.

Dominant frequency

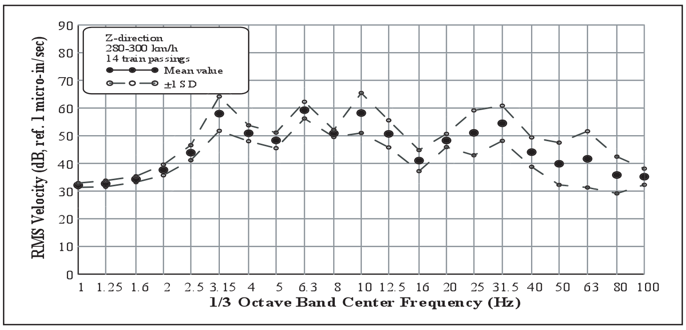
Figures 6(a), 6(b) and 6(c) show the mean vibration level versus 1/3 octave bandwidth frequency for deep foundation in soft ground, shallow foundation in hard ground, and deep foundation in hard ground, respectively. The vibrations in these figures only adopted train speeds between 280 and 300 km/h. The dashed lines express one standard deviation (SD) from mean vibration level of solid line. The number of train passing is also listed in figures. The three larger vibration levels happen at 3.15, 6.3, and 10 Hz for deep foundation in soft ground. For shallow and deep foundations in hard ground, the three main dominant frequencies are 10, 20 (or 25), and 31.5 Hz. The main dominant frequencies are low for softer ground, and the dominant frequency becomes higher when soil stiffness increases.

Concrete volume of structure

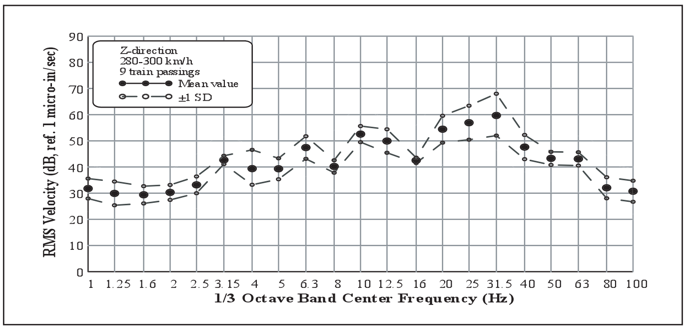
Fig. 7 presents the overall vibration level versus concrete volume (m^3) of structure for various foundations and soil types. The adopted train speeds are 280-300 km/h, which are the maximum operation train speeds for THSR. The concrete volume of structure was calculated including the volume of column, spread footing (or pile cap for



(a) shallow foundation in hard ground



(b) deep foundation in soft ground



(c) deep foundation in hard ground

Figure 6. Mean vibration level versus 1/3 octave bandwidth frequency for various foundations and soils (25 m from track center)

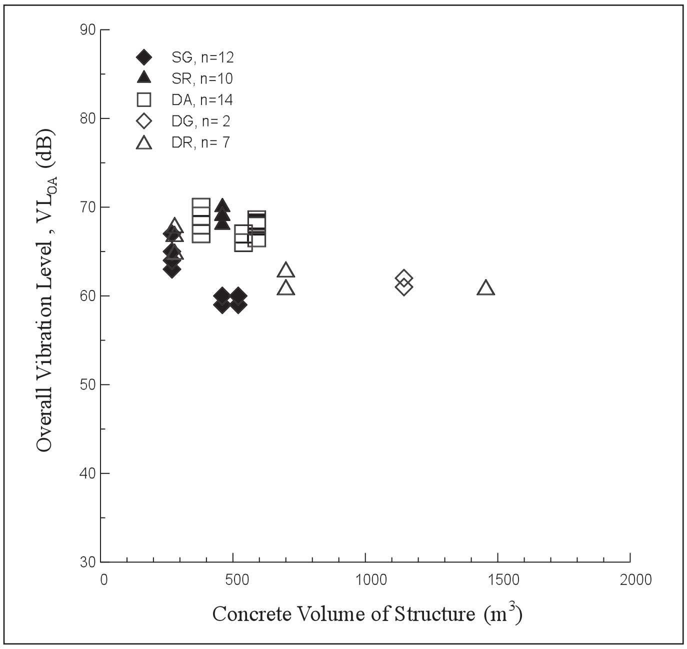


Figure 7. Relation of overall vibration level and concrete volume at 280-300 km/h (25 m from track center)

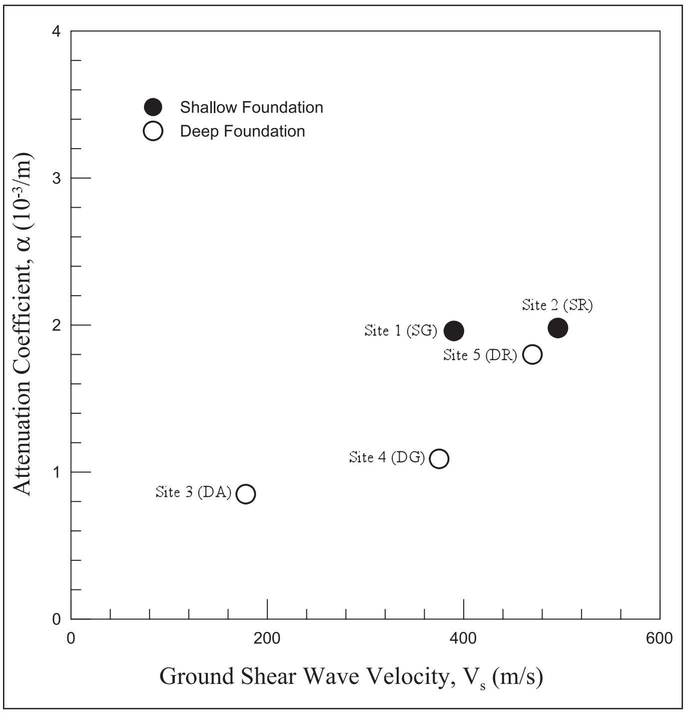


Figure 8. Relation of a and Vs for various foundation types

deep foundation), and 10 m deep pile (if any). It shows that the higher the concrete volume, the lower the overall vibration level. However, the overall vibration level converges to a constant value when the concrete volume becomes greater than 600 m^3.

6.2 VIBRATION PROPAGATION

Overall vibration

Results in Table 2 are plotted in Fig. 8 to present the relation of α attenuation coefficient versus ground shear wave velocity for overall vibration. Various foundation types are also included in the figure which shows that the α values for shallow foundations are larger than those for deep foundations. For shallow foundation in hard ground (gravel or rock), the α value is about 2.0 $\times 10^{-3}$ (1/m). For deep foundations, the average α value ranges from soft ground with 0.85 $\times 10^{-3}$ (1/m) to hard ground with 1.80 $\times 10^{-3}$ (1/m). The low α value in deep foundation may be attributed to the wave generated from deeper ground. Therefore, the decay distance of surface wave increases for deep foundation. This phenomenon is especially remarkable in soft ground. However, with increasing soil stiffness, the influence of deep foundation is relatively insignificant. Therefore, the a values for deep foundations in hard ground are close to the values for shallow foundations.

Low-mid-high frequency ranges

Table 3 lists the attenuation coefficients for the low, middle, and high frequency ranges for each site. The relationships of α and V_s for various frequency ranges are shown in Fig. 9. On average, the ranges of α values are 0.4-0.9 $\times 10^{-3}$ (1/m), 1.5-2.5 $\times 10^{-3}$ (1/m), and 3.2-3.5 $\times 10^{-3}$ (1/m) for the low, middle and high frequency ranges, respectively. Some points are noted from Fig. 9. First, the group of low frequency range has the smallest α value, whereas the group of high frequency range presents the highest value for all sites. This denotes that the attenuation in the low frequency range is less than that in the high frequency range. Previous work by Chen et al. [6] has shown the same phenomenon for high-speed trains on embankments.

Second, the difference in the attenuation coefficient for various V_s is relatively small in the low and high frequency ranges, but the middle frequency range presents a larger variation. In addition, the low frequency range has the highest COV among all frequency ranges. This is due to less vibration attenuation resulting in large variations in statistical analysis. Comparing Figs. 8 and 9, it can be observed that the factor of frequency is essential in evaluating attenuation coefficient. Therefore, the approach of overall vibration is suitable for application in general vibration assessments; the attenuation coefficient, classified as low-mid-high frequency range, is useful for cases when the estimated vibration level exceeds the criteria and vibration mitigation schemes are required.

7. CONCLUSIONS

The near-field overall vibration level increases with increasing train speed for all foundation and soil types. The values of VL_{OA} range from 56 dB for low train speed (120 km/h) to 58-71 dB for high train speed (280-300 km/h). The higher the concrete volume of structure, the lower the overall vibration level. The overall vibration level converges to a constant value when the concrete volume is greater than 600 m^3. The results also show that 3.15, 6.3, and 10 Hz are the main dominant frequencies for deep foundation in soft ground. For shallow foundation and deep foundation in hard ground, the main dominant frequencies are 10, 20 (or 25), and 31.5 Hz.

The a values for shallow foundations are larger than those for deep foundations. The average α value for shallow foundation in hard ground is about 2.0×10^{-3} (1/m), whereas the average α value for deep foundations ranges from soft ground with 0.85×10^{-3} (1/m) to hard ground with 1.80×10^{-3} (1/m). The low frequency range (1-8 Hz) has the smallest α value, while the high frequency range (31.5-100 Hz) presents the highest α.

The approach of overall vibration is suitable for application in general vibration assessments; the attenuation coefficient, classified as low-mid-high frequency range, is useful for cases when the estimated vibration level exceeds the criteria and vibration mitigation schemes are required.

The deep foundation in alluvium soils has the highest near-field vibration

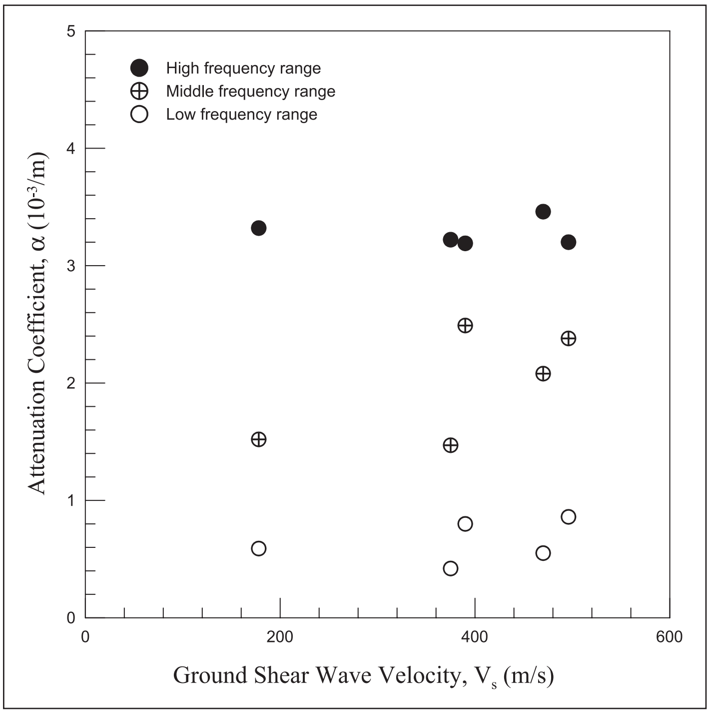


Figure 9. Relation of α and Vs for various frequency ranges

level and lowest attenuation coefficient, especially for the low frequency range. Therefore, the issue of ground vibration induced by high-speed trains for deep foundation in alluvium soils may be the most critical situation when evaluating vibration impact. On the other hand, the shallow foundation in gravelly soils presents the lowest near-field vibration level and the largest attenuation coefficient; therefore, ground vibration impact should be minimal.

8. ACKNOWLEDGMENTS

This study was supported by the National Science Council, Taiwan, under contract number: NSC 100-2221-E-033-073-MY3. The writers also acknowledge the National Center for Research on Earthquake Engineering (NCREE) of Taiwan for providing the information of ground shear wave velocity.

9. REFERENCES

1. U.S. Department of Transportation, Federal Railroad Administration, "High-speed ground transportation noise and vibration impact assessment", *Report Number 293630-1,* (1998).

2. U.S. Department of Transportation, Federal Transit Administration, Office of Planning and Environment, "Transit noise and vibration impact assessment", *Report Number FTA-VA-90-1003-06,* (2006).

3. Y.J. Chen, S.H. Ju, S.H. Ni and Y.J. Shen, "Prediction methodology for ground vibration induced by passing trains on bridge structures", *J. Sound Vib.*, 302(4-5), 806-820, (2007).

4. O. Yoshioka, "Basic characteristics of Shinkansen-induced ground vibration and its reduction measures," *Proc. Int. Workshop Wave 2000*, 219-237, (2000).

5. Y.J. Chen, Y.J., Shen, K.Y. Chen and S.M. Chang, "Some characteristics of ground vibration as induced by high-speed trains", *Proc. 4th Geotech. Earthquake Eng. and Soil Dynamics,* GSP 181, ASCE, (2008).

6. Y.J. Chen, S.M. Chang and C.K. Han, "Evaluation of ground vibration induced by high-speed trains on embankments", *Noise Control Eng. J.,* 58 (1), 43-53, (2010).

7. American National Standards Institute, "Preferred frequencies and band numbers for acoustical measurement", *ANSI S 1.6*, (1984).

8. T.G. Gutowski and C.L. Dym, "Propagation of ground vibration: A Review", *J. Sound Vib.*, 49(2), 179-193, (1976).

9. G. Bornitz, "Uber die ausbreitung der von groszkolben-maschinen erzeugten bodenschwingungen in die tiefe", *J. Springer*, (1931).

ORDINANCE AMENDED TO ALLOW NOISY SCHOOL BELL

The Kalamazoo (MI) Township Board of Trustees voted unanimously to amend the township's noise ordinance to exempt noises sanctioned or conducted by governmental units, public or private schools. The amendment also includes exemptions for emergency vehicles, and bridge or street repairs between sundown and 7 a.m. when public safety and welfare make it impossible to make those repairs during other hours. "We had an issue with a private school whose bell was causing an issue with some neighbors," said Ron Reid, township supervisor.

DELRAY'S NEW NOISE RULES TOO STRINGENT SAY RESTAURANT OWNERS

Delray Beach wants people to be quiet - all day, everyday. But a group of restaurant owners who offer live entertainment beg to differ with the city. The restaurateurs say Delray's noise ordinance is unreasonable. They say the fines are too steep and undermine a restaurant's ability to entertain patrons with live music. "If you guys are like me, we got blindsided by the whole situation," said Deck 84 restaurant owner Burt Rapoport, at a meeting with other restaurateurs. "All of us want to see a noise ordinance that is fair to the residents and fair to business owners." In September, city officials raised noise violation fines to $1,000 per day for first-time offenders, $5,000 a day for second offenses and $15,000 a day for repeat offenders. Officials also made changes to how noise is measured - the noise needs to be heard 50 feet away from the source, instead of the decibel reading the city previously used to cite violators. Rapoport said he only found out about the new rules recently when a police officer showed up at his restaurant during the day to warn him that he was in violation of the ordinance. In attendance at the meeting were owners and managers of several restaurants as well as representatives of the Downtown Development Authority, a taxing district in charge of promoting the downtown area. "From our perspective, we worked so hard to create a night-time economy," said DDA Executive Director Marjorie Ferrer. "To kill the golden goose is ridiculous." Rapoport said he created a petition he is circulating to other restaurant owners and his patrons, asking them to contact the City Commission and request the ordinance be modified. He encouraged other restaurants owners to do the same. Delray Beach's new noise fines are among the highest in Palm Beach and Broward counties, where most noise violations range from $250 for first-time offenders to $500 for repeat ones. The ordinance was crafted in response to a lawsuit the city lost against the owners of Paddy McGee's, who challenged a citation the restaurant received last year. The court ruled that the portion of the ordinance that prohibited "noise disturbances" was too vague and didn't give fair warning of when the law was being violated.