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GROUND VIBRATION DURING GRAVEL PILE CONSTRUCTION

Jin-Hung Hwang* and Tung-Yueh Tu**

Key words: Ground vibration, gravel pile, attenuation, spectral analysis.

ABSTRACT

This investigation performs a field measurement of ground vibration due to gravel pile construction at a hydraulic-filled reclamation land. The ground vibrations were characterized by wave form, Fourier spectrum and response spectrum. The attenuation relation between both peak ground velocity and acceleration with distance was also derived from the measured data. An empirical method for evaluating the safe construction distance to adjacent building structures was presented based on the attenuation relation and a building vibration criterion. Vibration response spectra were also suggested for use with the spectral analysis method to determine more accurately the safe construction distance.

INTRODUCTION

Ground vibrations due to construction operations become a major concern when influencing surrounding structures. Since the need for environmental protection has increased over recent years, the impact of construction vibrations on the surrounding environment has attracted much attention from the field of geoenvironmental engineering. During the last century, much research was devoted to the ground vibrations induced by various geotechnical constructions. Most research [1-4] focused on ground vibrations due to pile driving. Some research considered construction vibrations due to dynamic compaction [5, 6] and sheet-piling operations [7, 8]. Gravel pile construction is a vibro-compaction method for improving deep, soft ground. In Taiwan, vibro-compaction with a gravel pile was first introduced to improve ground at the Kaoshing Lin-Yuan Industrial Park in the early 1980s. In the 1990s, the construction of Taiwan Plastic Miliao Industrial Park saw much ground improvement work that used the method. The gravel pile is increasingly popular for ground improvement, and so the effect of resulting ground vibrations on the surrounding environment must be thoroughly understood. A review of the literature reveals that little relevant information is available. This study involves the field measurement of ground vibration due to gravel pile construction at a hydraulic-filled reclamation site. This paper summarizes site condition and geology, vibration measurement, data analysis, suggested methods to determine the safe construction distance.

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TEST SITE AND GEOLOGICAL CONDITIONS

The test site is located at one of the industrial plants of Taichung Harbor. Figure 1 shows the layout of

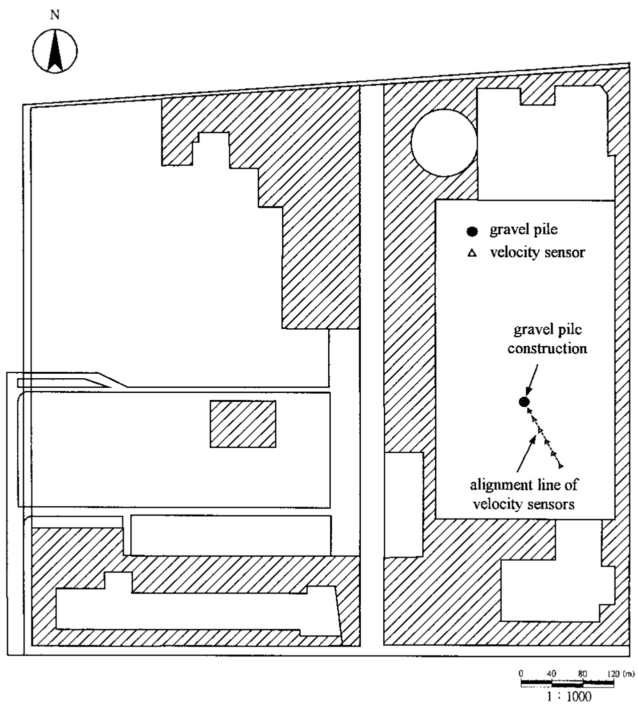

Fig. 1. The layout of the plant and the alignment of velocity sensors in the test site.

the plant and the line along which the vibration sensors were installed. Figure 2 shows the geological profile and shear wave velocity along the line. The topography of the test site is flat with ground surface elevations between +7.30 m and +7.50 m. The soil consists mainly of a deep-thick layer of gray silty fine sand, occasionally interbedded with a layer of silty clay several tens of centimeters thick. A gravelly soil with a thickness of 60 cm-120 cm was back filled on the ground surface. The shear wave velocity varied between 120 and 300 m/sec from the ground surface to a depth of 15 m below the surface.

CONSTRUCTION OF GRAVEL PILE

The construction of a gravel pile on the test site used a modified machine with a specially designed bottom feeder. Figure 3 schematically shows the construction sequences. During construction, the vibrator first generates a lateral vibratory force to liquefy the saturated sandy soils and then penetrates down to the design depth under its self-weight and external hydraulic pressure or compressed air pressure. When the vibrator is pulled up by around 0.5-1.0 m, the gravel material is poured into a vertical transport pipe using a lifting bucket which raises the gravel on the ground to a hopper mounted on the top of pipe. The gravel then goes through the pipe, and the space between the vibrator and the bottom of the construction hole is filled with gravel. When the space is completely filled, the vibrator squeezes the surrounding ground downward and laterally so as to form a compact gravel pile. The vibrator is pulled up when the vibratory compaction pressure reaches a limiting value or the vibro-compaction time reaches 2 minutes. The gravel pile is completed by repeating the above steps of pulling up the vibrator, feeding the gravel and squeezing the surrounding soil between the design depth to the ground surface.

The vibrator used in this study is a German Keller S20120 vibrator, illustrated in Fig. 4. The operating frequency of the vibrator is 30 Hz. The vibratory amplitude is 17 mm and the centrifugal force is 206 kN. The vibrator is driven by an electric motor at an operating frequency of 60 Hz, a rotation speed of 1775 rpm and a power of 120 kW. The gravel pile is 20 m long and has a diameter of 100 cm. The pile's center to center spacing is 2.5 m.

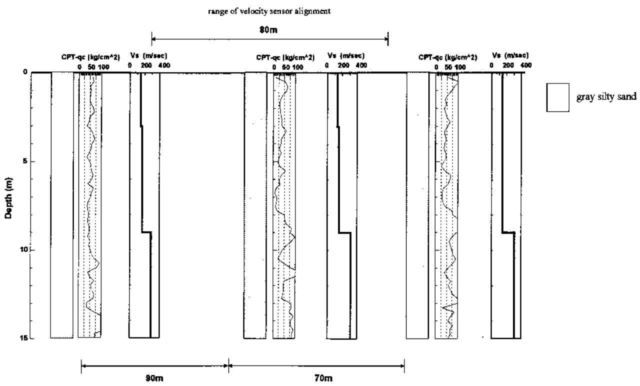

Fig. 2. The geological profile and shear wave velocity along the line of measurement.

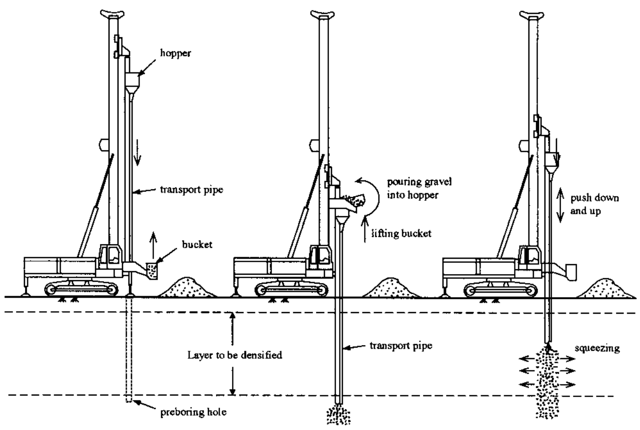

Fig. 3. The construction sequences of gravel pile with a bottom feeder design.

VIBRATION MEASUREMENT

Ground vibration was measured during the construction of a full length gravel pile. Figure 5 presents the profile of the measurement. Six stations were installed along the line of measurement. Every station had two velocity sensors, one of which measures vertical velocity and the other measures radial velocity. The closest station was 5 m distant from the center of gravel pile and the farthest one was 80 m from the center of the pile. The measurement was performed as follows.

1. The background vibration was recorded before the machine was turned on.
2. The background vibration was recorded as the vibrator and rotating rod were started.
3. The vibration during a construction cycle including feeding, compacting and squeezing, was recorded at intervals of 1-2 m from a depth of 20 m to the ground surface.

Table 1 shows the entire measurement sequence. The recording time was one minute for every event, long enough to cover a whole construction cycle.

The equipment for measuring ground vibration included velocity sensors, connectable 50 m long electric cables, and a recording and storing system. A force balanced type VSE-15D velocity sensor, manufactured by Tokyo Dynamic Test Company, was used. The frequency range of the sensor is 0.1-70 Hz. The measurement ranges of velocity and acceleration are ±10 kine (cm/sec) and ±2000 gal (cm/sec^2) respectively. The sensitivities of the velocity and acceleration sensors were 1 V/kine (Volt/kine) and 5 mV/gal (micro Volt/gal), and the resolutions were 100 μkine for velocity and 300 μgal for acceleration. The recording, storing and data processing system was a SPC-35F system, with eight channel data logging and an amplifier system connected to a PC-98 notebook computer for storing and processing data. The resolution of the A/D interface was 16 bits and the sampling rate reached a maximum of 1000 Hz.

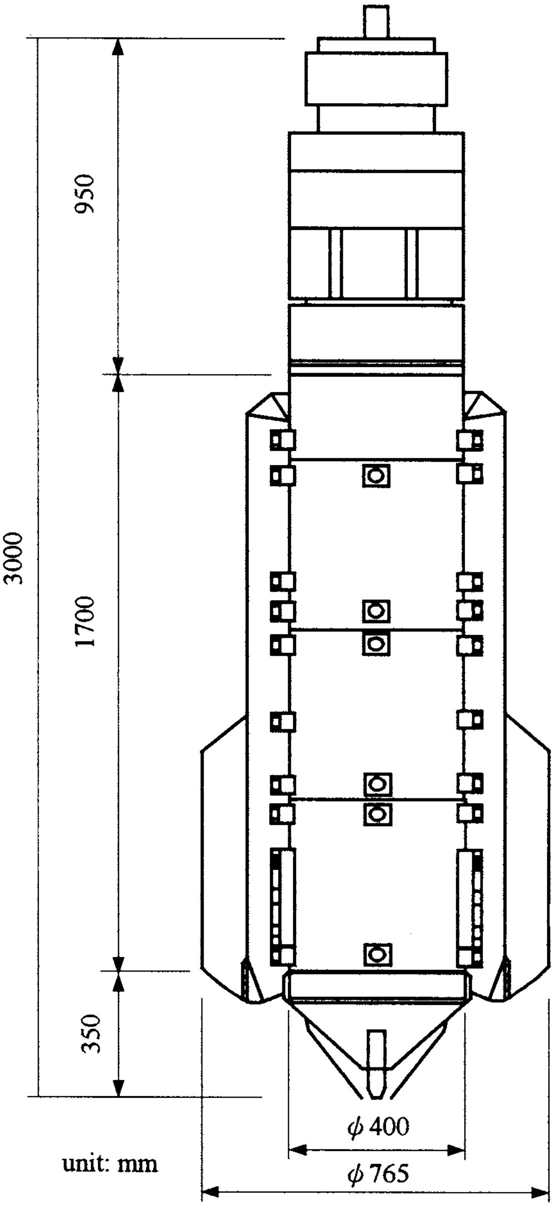

Fig. 4. The size of vibrator (German Keller S20120 type).

DATA ANALYSIS

1. Typical Vibration Wave Form

Figures 6 and 7 show the recorded radial and vertical velocity-time histories, respectively, at various

Table 1. Recording sequence of construction vibration for gravel pile

record number	Construction Stage
B1	back ground vibration (before machine is turned on)
B2	back ground vibration (machine is warming)
B3&D	back ground vibration (vibrator and pushing rod starting operation)
P011	initial feeding + compacting + squeezing at depth = 20 m
P012	start squeezing at depth = 20 m
P02	start squeezing at depth = 18.84 m
P03	start squeezing at depth = 16.96 m
P04	start squeezing at depth = 15.58 m
P05	start squeezing at depth = 13.94 m
P06	start squeezing at depth = 12.44 m
P07	start squeezing at depth = 10.70 m
P08	start squeezing at depth = 9.26 m
P09	start squeezing at depth = 7.69 m
P10	start squeezing at depth = 6.12 m
P11	start squeezing at depth = 4.61 m
P12	start squeezing at depth = 2.98 m
P13	start squeezing at depth = 1.43 m
P14	start squeezing at depth = 0 m

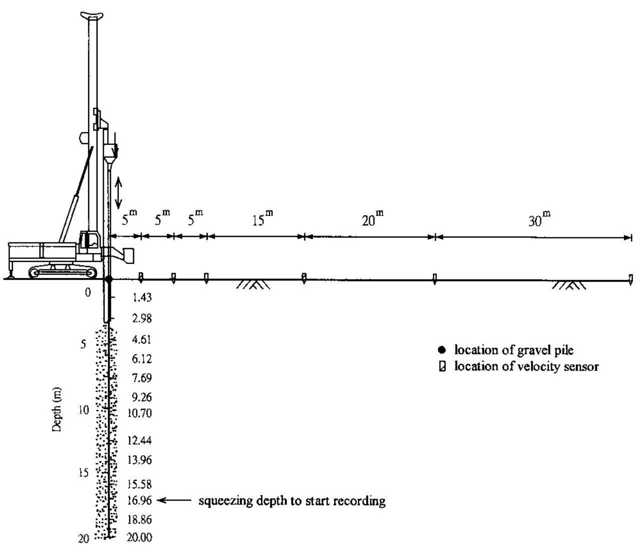

Fig. 5. The profile layout of vibration measurement.

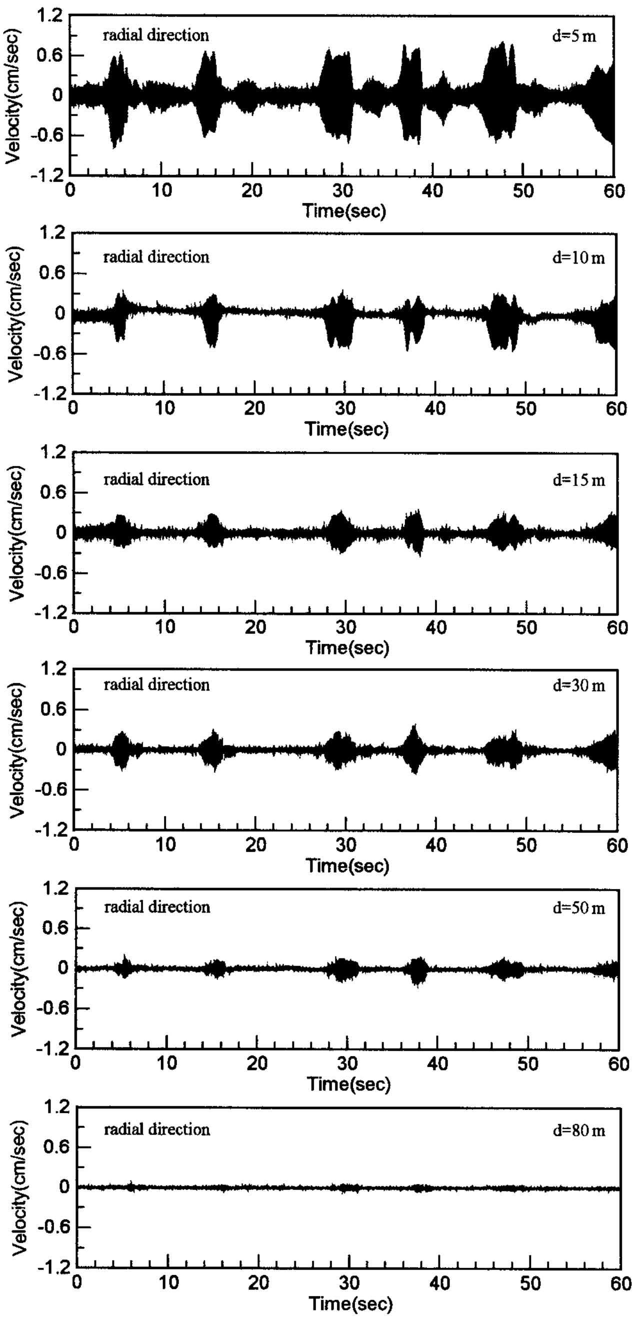

Fig. 6. The radial velocity histories at different distances when start squeezing at a depth of 2.98 m.

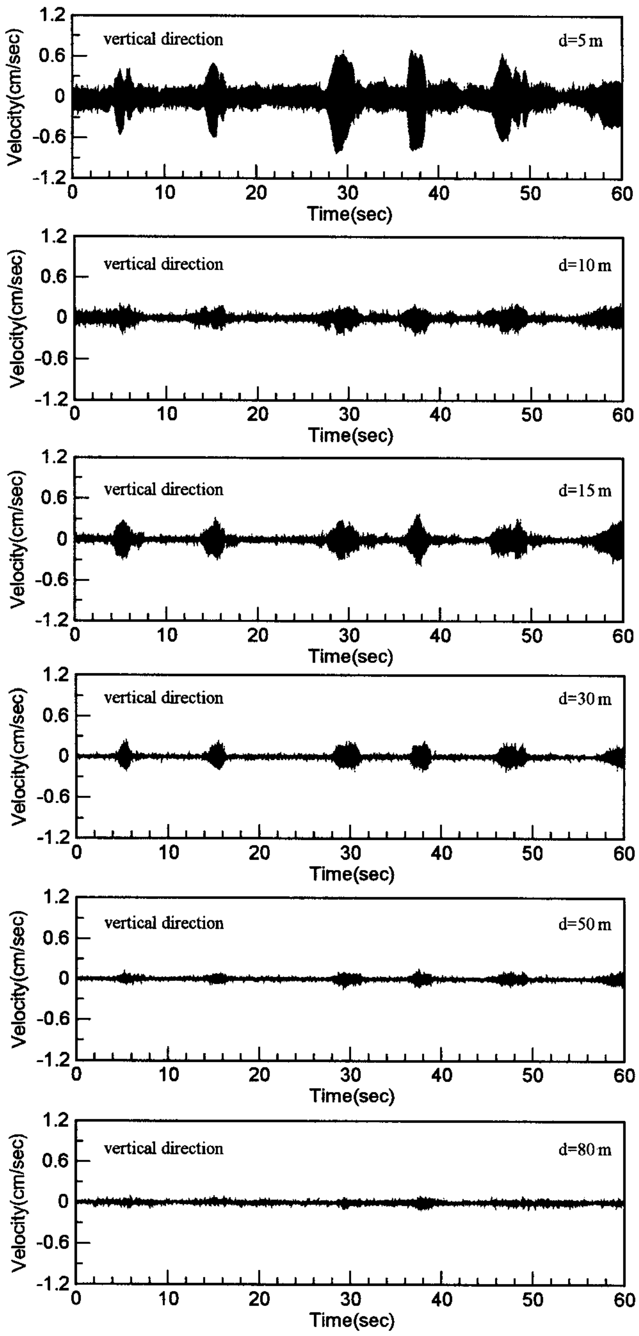

Fig. 7. The vertical velocity histories at different distances when start squeezing at a depth of 2.98 m.

distances from the vibration source, when the vibrator began squeezing at a depth of 2.98 m. The squeezing wave form propagates from near to far and the vibration amplitude quickly attenuates with distance. Figures 8 and 9 respectively show the recorded radial and vertical velocity-time histories at 5 m distance from the vibration source, when the vibrator squeezed the surrounding soils from shallow to deep. Although the periods of pulling and squeezing can be clearly identified from the velocity time history, the time histories at different squeezing depths showed no relationship, perhaps due to the uncertainties in the operational details of the vibrator and in the local soil conditions.

Figure 10 displays the paths of particle in vertical

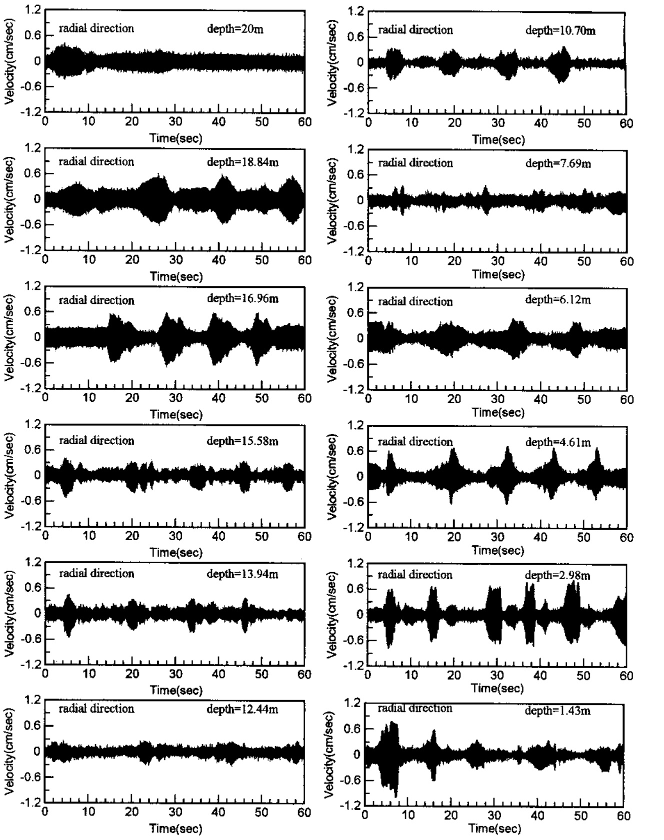

Fig. 8. The radial velocity histories at 5 m distance to vibration source for different squeezing depths.

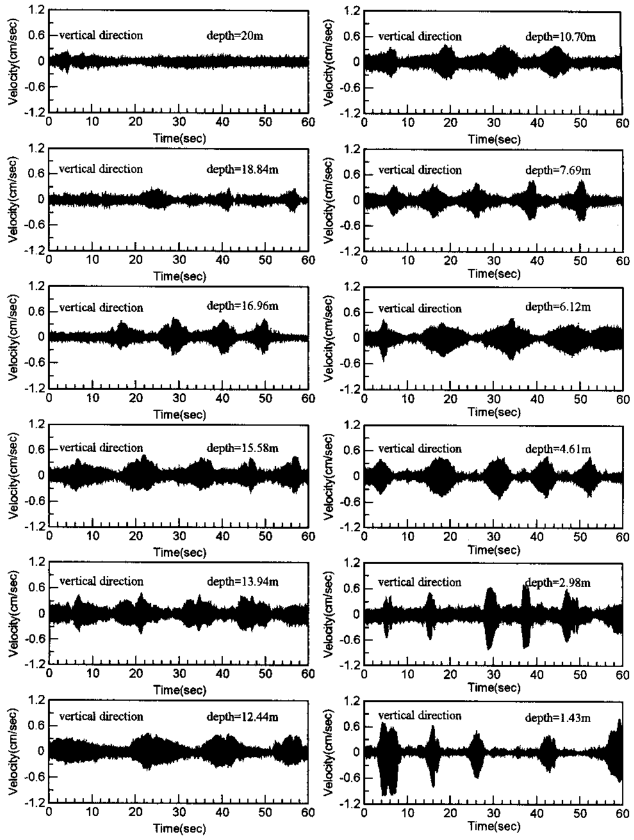

Fig. 9. The vertical velocity histories at 5 m distance to vibration source for different squeezing depths.

and horizontal planes, over various periods of vibration records, at distances of 5 m and 30 m, when the vibrator began squeezing at a depth of 2.98 m. The paths of soil particle motions look like ellipses rotating in counter-clockwise direction. The ellipse for near distance (5 m) is regular one, while the ellipse for far distance (30 m) is an oblique one. Similar observations were made at other squeezing depths.

2. Fourier Spectrum

Fourier transforming a velocity-time history over a complete operational cycle of pulling and squeezing yields an amplitude Fourier spectrum which represents the energy distribution of vibrational motion in a frequency domain. Figure 11 shows the Fourier amplitude spectra in radial and vertical directions at various different distances to the center of the vibration source when the squeezing depth is 18.84 m. The peak amplitudes were observed to be centered on two narrow frequency bands, one from 30 to 35 Hz and the other from 60 to 70 Hz. The corresponding peak amplitudes attenuate quickly with distance.

The same observation was also found for the other squeezing depths. Figures 12(a) and 12(b) are the radial and vertical Fourier amplitude spectra at 5 m from the vibration source for different squeezing depths. The peak amplitudes were also found to be centered on two narrow frequency bands. At a deeper squeezing depth, the two narrow bands were 30 to 35 Hz and 60 to 70 Hz. The narrow band gradually shifts to lower frequencies as the squeezing depth decreases; for example, the two narrow bands are 20 to 40 Hz and 50 to 60 Hz for a squeezing depth of 2.98 m. Many high frequency (>70 Hz) signals were observed in the Fourier spectra, especially at a shallow squeezing, perhaps due to some other noise from unknown surface vibration sources.

For deep squeezing, the radial Fourier amplitude seems to exceed the vertical Fourier amplitude in the first narrow band but the amplitudes are roughly the same in the second narrow band. For shallow squeezing depths, the Fourier amplitudes in the different directions do not significantly differ for the two bands.

The operating frequency of the vibrator was 30Hz

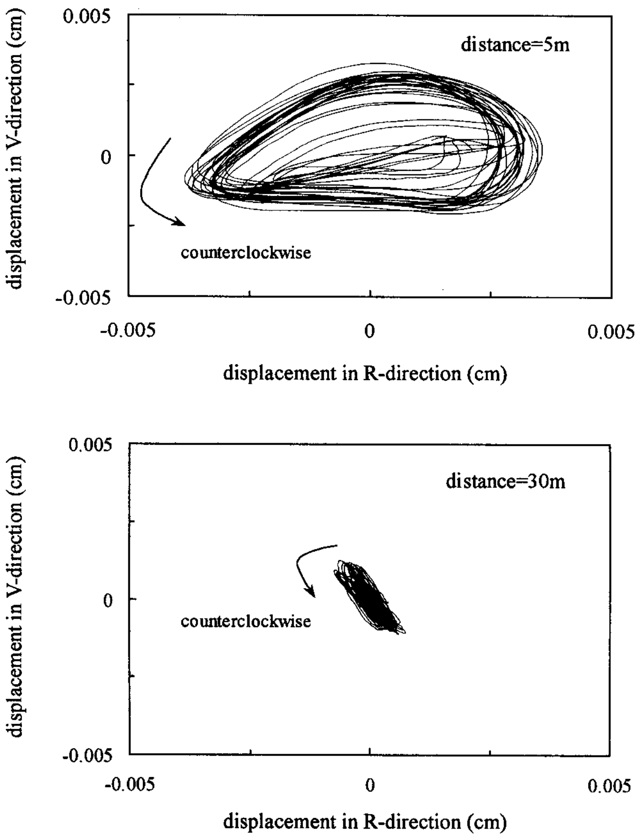

Fig. 10. The trajectories of soil particle motions.

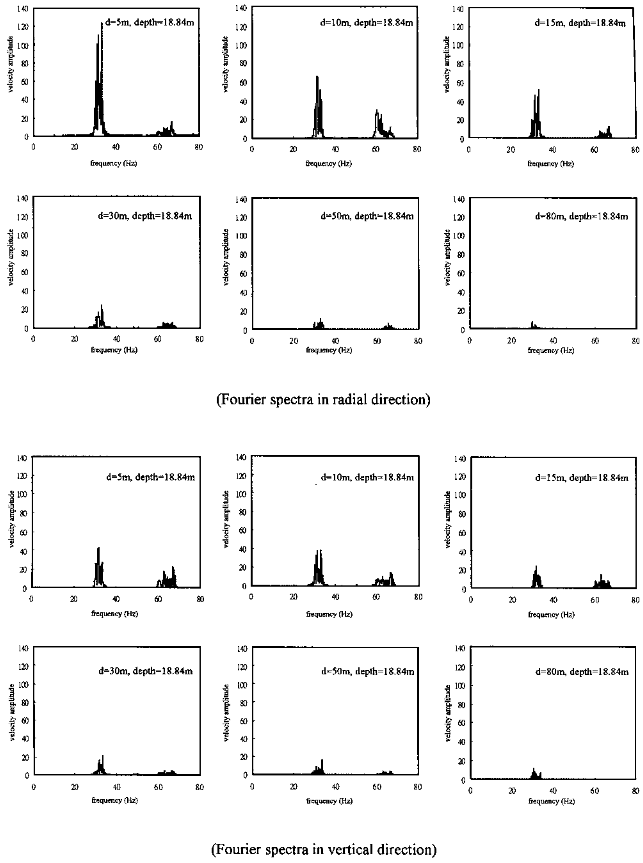

Fig. 11. The radial and vertical Fourier spectra at different distances when start squeezing at a depth of 18.84 m.

and the rotating frequency of the electric motor was 60 Hz. Since these two frequencies are close to the above narrow bands of ground vibration, the predominant vibration frequencies can be concluded to have been controlled by the operating frequencies of the construction machine. The spreading of the two operating frequencies to the two corresponding narrow bands may be caused by the vibrational interaction between the ground and the construction machine, or by the wave propagation effect through the non-linear viscous soil medium.

3. Response Spectra

Figures 13(a) and 13(b) are the normalized response spectra in radial and vertical directions, at varying distances from the center of the gravel pile. Spectral shapes were found to be rather similar regardless of squeezing depth and measuring distance. The radial and vertical spectral shapes are also quite similar. The spectral value of the long period part increases with distance. No effect of squeezing depth on the spectra can be observed.

Most of the spectral shapes show two peak responses. The primary peak occurs for the structural period of 0.031 sec with a normalized spectral value of 6-9. Most of the secondary peaks occur at the structural period of 0.011 sec with a normalized spectral value of 2-4.5. When the structural period exceeds 0.031 sec, the spectral value rapidly decays with increasing period. For near distance spectra, the spectral value is less than 0.1 when the period exceeds 0.1 sec, while for far distance spectra, the spectral value is less than 0.1 until the period exceeds 0.3-0.4 sec. Therefore, for structures with fundamental vibration periods close to 0.011 sec and 0.031 sec, possible damage to adjacent structures, due the gravel pile construction must be carefully considered.

4. Attenuation of PGV and PGA with Distance

Figures 14 and 15 show the attenuation relationship between both PGV and PGA with distance in radial and vertical vibration directions. The relationships

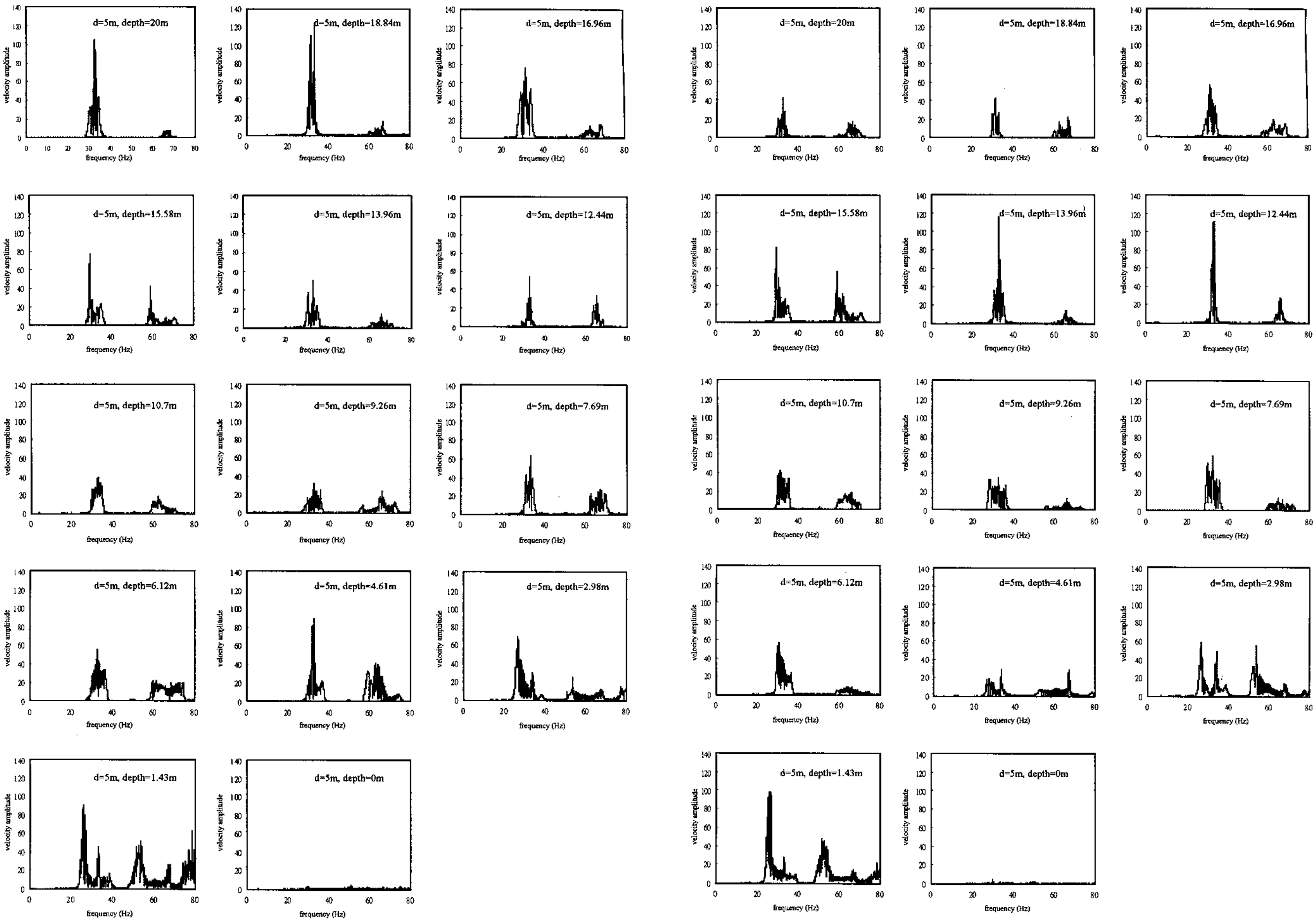

Fig. 12. (a) The radial Fourier spectra at 5m distance to vibration source for different squeezing depths; (b) The vertical Fourier spectra at 5 m distance to vibration source for different squeezing depths.

were determined by choosing the peak amplitudes from vibration histories at the various distances during squeezing. The changes in vibration amplitudes and attenuation rates with distance are similar in both directions.

SAFE CONSTRUCTION DISTANCE

1. Empirical Method

In engineering practice, determining the safe construction distance to adjacent building structures is extremely important. Following an extensive review of various building vibration criteria, a vibration control criterion for local building structures has already been suggested by the authors [9]. Table 2 elucidates the criterion. Based on this criterion and the average plus one standard deviation PGV attenuation relationships shown in Fig. 14, the safe construction distance can be simply and conservatively determined. Figure 16 presents the procedure for determining the safe construction distance for a class I building structure. Table 3 shows the safe construction distances for the other structures, which were obtained in the same way. This table can serve as a preliminary guide for evaluating the effect of gravel pile construction on adjacent structures.

2. Spectral Analysis Method

Evaluation by the method presented here is conservative because the empirical method does not account for the vibration frequency characteristics of the building structure and the ground. A response spectral analysis method has already been presented by the authors [10] to determine more accurately the safe construction distance. Using a design response spectrum, this method can automatically account for the vibration frequency characteristics of the building structure and

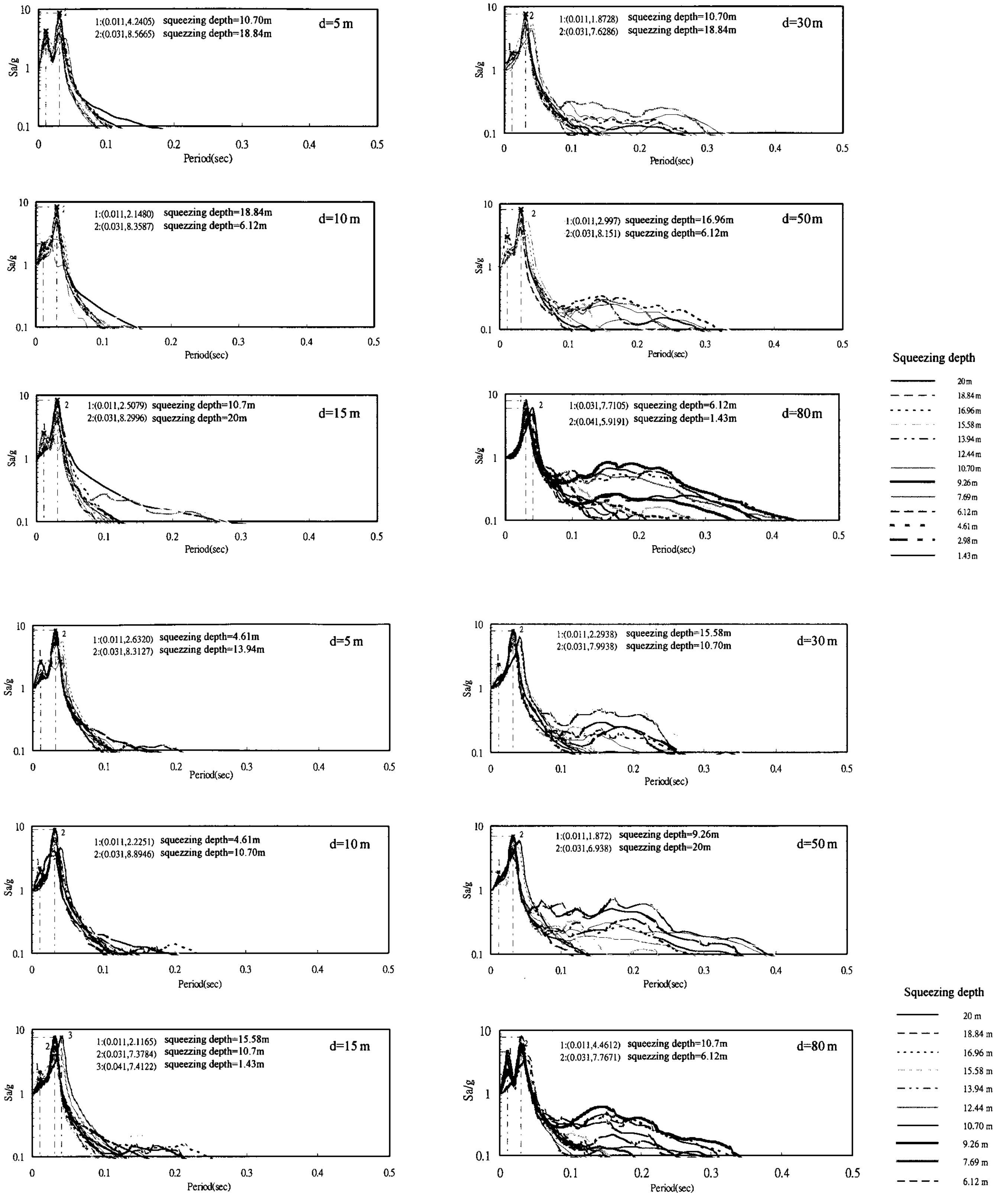

Fig. 13. (a) The radial normalized acceleration response spectra at various distances for different squeezing depths; (b) The vertical normalized acceleration response spectra at various distances for different squeezing depths.

Table 2. The vibration criterion for various building structures [9]

class	building type	allowable value peak ground surface velocity PGV (mm/sec)
I	ruins, historic buildings, old temples and buildings with high precision equipments.	4
II	masonary or reinforced masonary buildings	7
III	stiff modern reinforced concrete or structural steel buildings	25

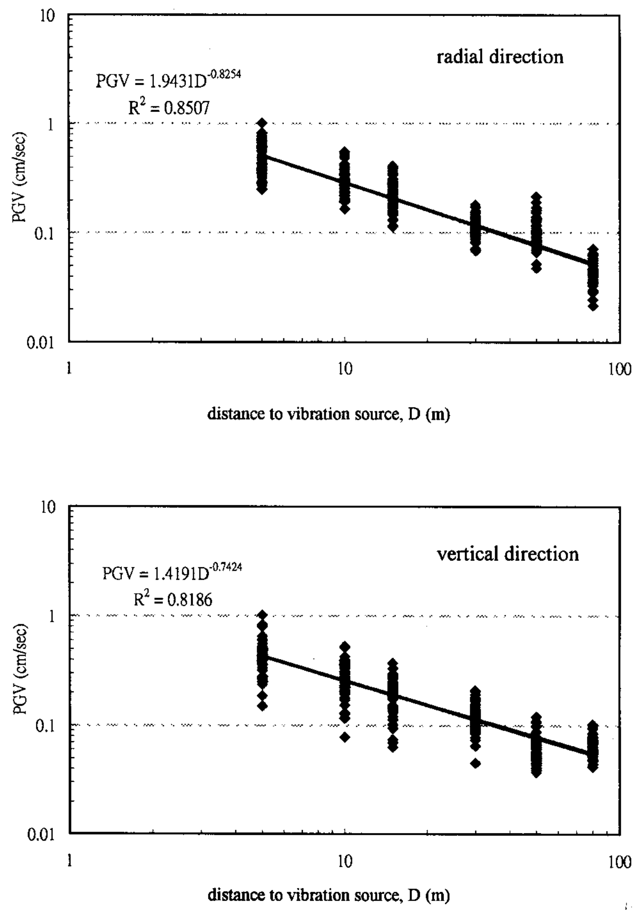

Fig. 14. The attenuation relations of PGV with distance in radial and vertical directions.

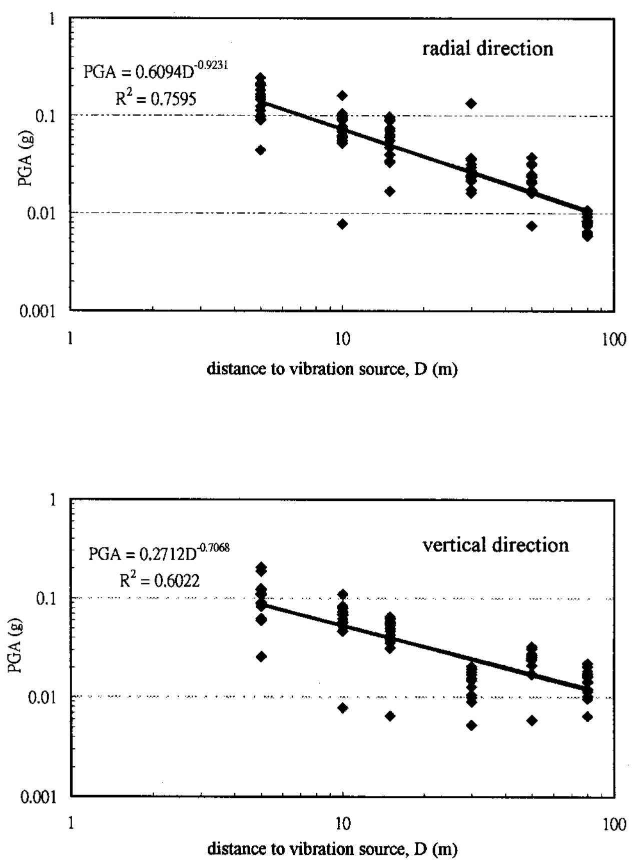

Fig. 15. The attenuation relations of PGA with distance in radial and vertical directions.

the ground. Deriving the design response spectra of the vibration records due to gravel pile construction is the most important part of applying this methods. Figure 17 is the statistical result of the response spectra of all vibration records. The suggested design spectra and their formula are also shown in the figure. Based on the design spectra and the PGA attenuation relationships shown in Fig. 15, a response spectral analysis method can be used to evaluate the safe construction distance.

CONCLUSION

Based on the study, the following conclusions can be drawn.

1) The two predominant frequency bands of the ground vibration due to gravel pile construction are excited by the two operating frequencies of the construction machine.
2) The ground vibration characteristics are similar in radial and vertical directions.
3) The construction vibration of the gravel pile is more harmful to structures with vibration peri-

Table 3. The safe construction distances in two directions for various building structures

class	building type	safe construction distance * (m) vertical direction	radial direction
I	ruins, historic buildings, old temples and buildings with high precision equipments.	9.0	10.0
II	masonary or reinforced masonary buildings	4.0	5.0
III	stiff modern reinforced concrete or structural steel buildings	1.0	1.0

* The distance is determined by the corresponding distance of the average plus one standard deviation PGV attenuation relation to the allowable PGV value. The distances are all rounded off.

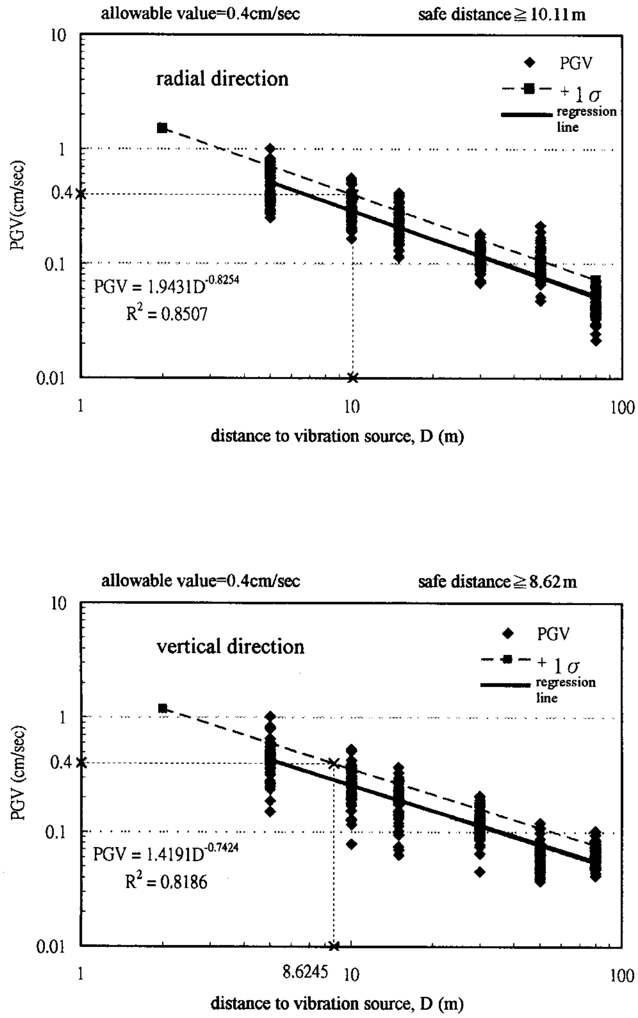

Fig. 16. The determination of safe construction distance for class I building by an allowable PGV value.

ods close to 0.011 sec and 0.031 sec.

4) An empirical method and a spectral analysis method were proposed for application by engineers to evaluate the effect of gravel pile construction on adjacent structures.

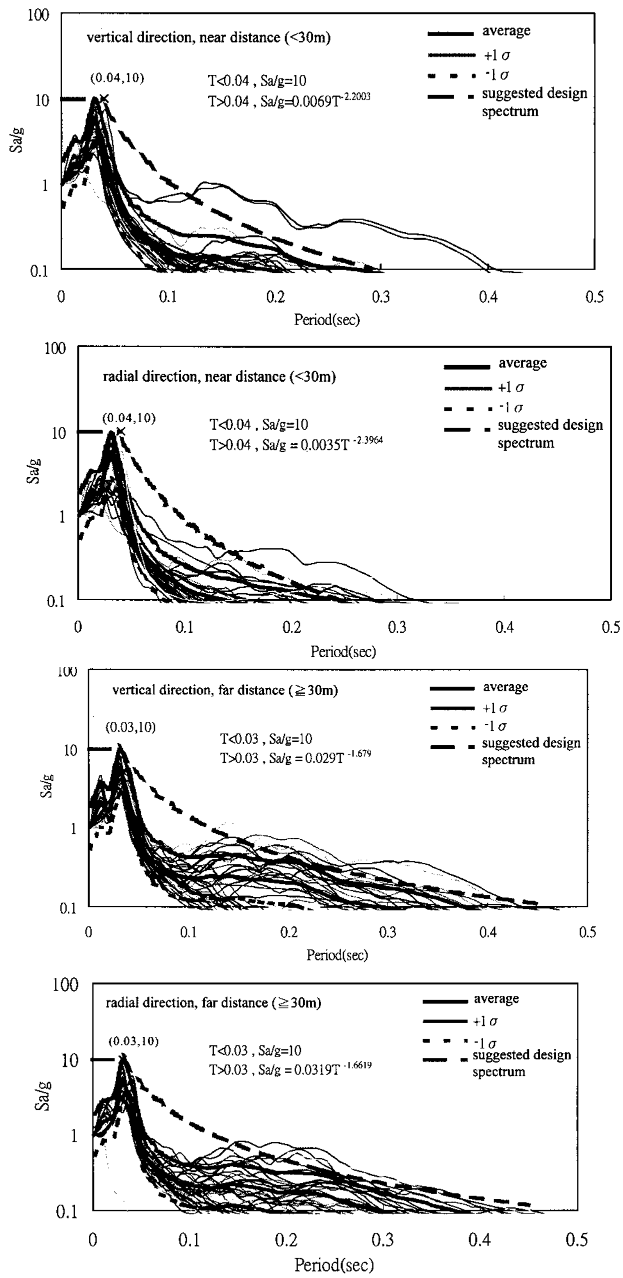

Fig. 17. The suggested design spectra for near distance (<30m) and for distance (≥30 m).

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礫石樁施工引致之地盤振動

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摘 要

本文在台灣中部某一代表性之水力回填工業區場址，成功地進行礫石樁施工引致之地盤振動量測，並以振動波形，富氏譜與結構反應譜探討此種施工之地盤振動特性。同時也整理統計出最大地表速度與加速度隨距離衰減之關係。結合地動量衰減關係與建築物振動管制準則，本文建議了一種簡單決定礫石樁施工對建築物影響安全距離之經驗評估法。本文也建議了此種施工振動之設計反應譜，可供工程師使用結構動力分析中常用之反應譜分析法，以更準確地評估礫石樁施工之安全距離。