Analysis of Energy Features of Strong Ground Motion Induced by Short Delay Blasting in Unsaturated Loess Field

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SUMMARY:
Based on in-situ observational data, we analyzed energy features of strong ground motion induced by short delay blasting in unsaturated loess field through three aspects of time history, frequency spectrum and attenuation. For time histories, the data show exploding ground motion has two essential characteristics, i.e. larger peak ground acceleration (PGA) and shorter duration. Analysis results reveal the effective duration (ground acceleration exceeding a certain magnitude) is the pivotal factor influencing design effects of the blasting. The spectral response, meanwhile, attenuates with the increase of observational distances (apart from the centre of exploding field), especially for those higher frequency components. Values of H/V figured relative features of horizontal component to vertical one of frequency spectrum of exploding ground vibration become greater while distances widen. As exploding energy accumulated, moreover, lower frequency energy distinctly increases and the feature of frequency spectrum of the strong shock gradually approaches an actual seismic oscillation.

Keywords: loess field, exploding ground motion, time history, frequency spectrum, attenuation

1. INTRODUCTION

Since exploding techniques are widely applied in practices of engineering constructions, features of exploding ground motion and effects caused by explosions on rock-soil grounds and structures have become hot topics in the field of geotechnical earthquake engineering. In many seismic-prone areas around the world, meanwhile, the record data of natural earthquakes always cannot safety the needs to investigate non-linear response characteristics of the foundation and structure at dangerous conditions of strong ground motions induced by near-field earthquakes. For these serious cases, moreover, the explosive ground motion is a fine reference to the natural seismic vibration. Consequently, scientists and engineers from related research fields take more attention onto those problems associated with ground shocks induced by explosions.

Analysis results of exploding ground motion from Negmatullaey et al (1999) indicated that explosive vibrations could be used to investigate the responses of full-scale structures on near-field earthquake. Kumari et al (2000) reported that a small fraction of explosive energy about 3% results in the generation of strong ground motion in the near region. Lou et al (2003) analyzed characteristics of blasting seismic waves and adopted integral values of response spectrum curves to investigate the relation between response spectrum and blasting vibration velocity/frequency. Yu et al (2004) suggested empirical relations to predict the acceleration and velocity of ground motion excited by explosions. Langston et al (2006) analyzed the spatial variation of strong ground motions induced by two explosions within unconsolidated sediments of the Mississippi embayment because there are no comparable strong-motion data from natural earthquakes in this area. Tian (2007) proposed the evolutionary power spectra density function of exploding ground motion by means of non-stationary random evolutionary theory. Zong et al (2008) investigated essential laws of propagation and attention of explosive ground shocks.

In field effects of exploding ground motion, Wang et al (2002) investigated liquefaction features of saturated loess by means of experimental explosive test with micro-time intervals. Qian et al (2004) found out structural damages are associated with the maximum acceleration or velocity of blasting vibration whereas geotechnical disasters mainly with the maximum velocity of exploding ground motion. Yang et al (2005) analyzed explosive seismic effects in a complex field using finite element method. Jemberie (2008) studied nonlinear site responses during strong ground motion and proved the non-transportability of weak motion attenuation results to estimated ground motion from a future large earthquake that take place in similar areas.

In aspects of structural damages caused by exploding ground motion, Ma et al (2002) adopted a numerical method of wave propagation in nonlinear and composite media to assess wave motion and structural damage, in which a fracture indicator determined by equivalent tensile strain was defined to estimate concrete damage, and a plastic indicator based on effective plastic strain was used to identify the plastic state of reinforcement. Cui et al (2003) experimentally investigated the elastic-plastic dynamic response and buckling mechanism of steel columns under vertical ground excitation caused by underground explosions and simulated the explosion by shaking table test. Chen et al (2006) reported that the response of structures enduring one dimensional excitable load is smaller than those enduring 3D excitable loads especially for the case of blasting vibration based on results of structural response under multi-dimensional movements by time-order analysis. Liu et al (2006) established the blasting dynamic equation of multi-particle system architectural structure and then provided the solution of the equation.

Because of the lack of record data of strong ground motions induced by both of natural earthquake and explosion in loess areas, and the fine reference of exploding ground shock to near-field seismic effect, the author here analyzed essential features of time history, frequency spectrum and attenuation of artificial ground vibrations based on in-situ observational data generated by a short delay blasting within a typical unsaturated loess field in the region of Loess Plateau, China.

2. FIELD CONDITIONS AND EXPLOSIVE DESIGN DETAILS

2.1. Target Field of Unsaturated Loess

The observational field of unsaturated loess for explosive ground motion is nearby at Lijiawan village of Lintao county in Gansu province, China. This target field is a kind of typical loess ground, which could suffer dynamic settlement under an enough strong seismic loading, located in the region of Chinese Loess Plateau.

The sedimentary sequence in the target field can be roughly seen at terrace’s basset. Data collected from two exploratory wells both with the depth of 28m shows from top to bottom there are four kinds of soil layers overlaying Tertiary red bed, i.e. arable layer, seismic loess, redeposit loess and pebble bed. Within the range of buried depth from 1m to 15m, the loess layer has typically physical characteristics of collapsible loess, e.g. loosen soil mass, high porosity and great void ratio. For this layer, the water content often exceeds 12% and slight clay particles could be in sight at some places. The next layer, redeposit loess, has a thickness of 13m. Its properties differs from the overlain soil by that water content is roughly less than 10% and clay content is much more and the horizontal bedding is distinctly visible increasing with the depth gradually. The average data of physical parameters of the soil mass above the burial depth of 20m in the target field are summarized in Tab. 2.1 (ignored other soil layers due to the explosive source depth of 23m).

Table 2.1. Parameters of loess layers in the target field

Soil type	Burial depth (m)	Density (g/cm^3)		Water content (%)	Observational depth (m)	V_s (m/s)
		Natural	Dry			
Seismic loess	4	1.47	1.32	12.5	1	197
					2	241

					3	249
					4	256
	8	1.48	1.29	15.2	5	267
					6	268
					7	272
					8	269
	12	1.49	1.28	14.8	9	276
					10	283
					11	290
					12	294
Non-seismic loess	16	1.48	1.33	10.3	13	307
					14	312
					15	320
					16	368
	20	1.54	1.42	8.4	17	376
					18	392
					19	396
					20	402

2.2. Explosive Source Design

As shown in Fig. 2.1, the explosive source includes 30 single-shot points. Here, shot points are the projections of explosives (with the same burial depth of 23m) on the ground surface. All points are disposed as a circle and depart the same distance of 15m from the centre of the target field and the interval of adjacent points is about 3.14m.

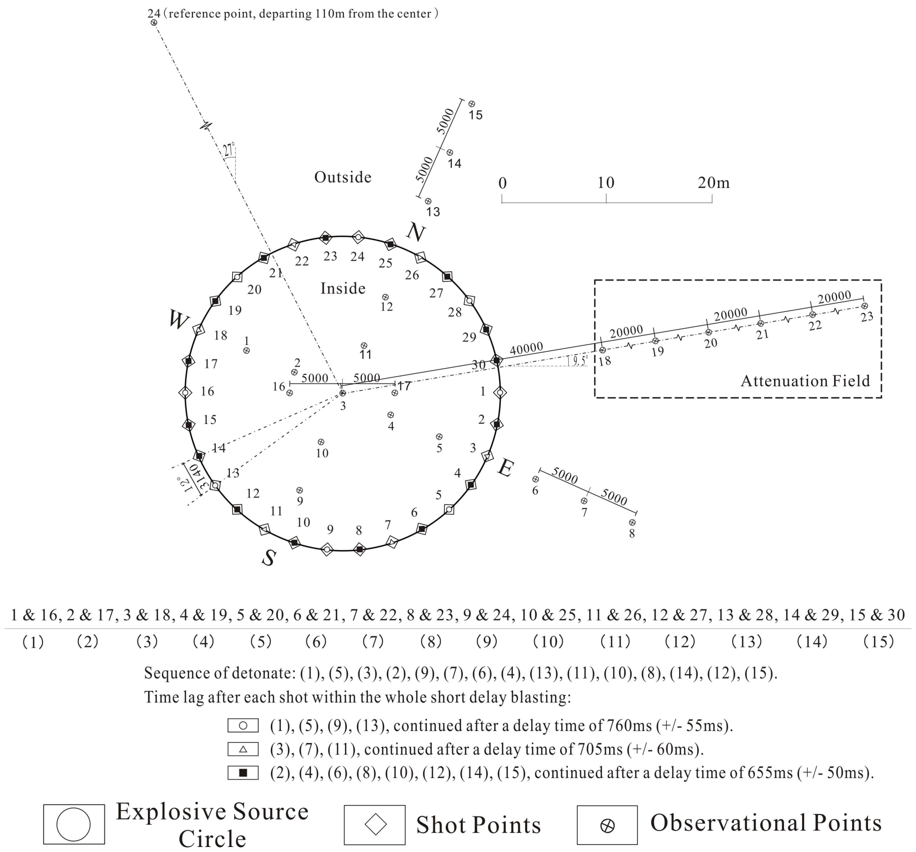


Figure 2.1. Design of the short delay blasting and observational points of exploding ground motion

Because explosives are symmetrically detonated, the intensity design of exploding ground motion could be calculated by the reference distance of shot point apart from the centre of the target field. The design formula after Zhang (1981) is

$$a = \kappa(\sqrt[3]{Q} / R)^{\alpha} \tag{2.1}$$

where Q is the mass of explosive, kg; R is the spatial distance between explosive and observation point, m; a is the peak ground acceleration (PGA) induced by explosions, m/s^2; κ and α both are attenuation coefficient of explosive vibration, here taking values as 90 and 1.55 respectively after Wang et al (2003).

The expectation intensity of exploding ground motion adopted by authors is from 0.35g to 0.40g. Therefore, the single-explosive source need to be filled 40kg middle-power explosive based on Eqn. 2.1 (Zhang, 1981).

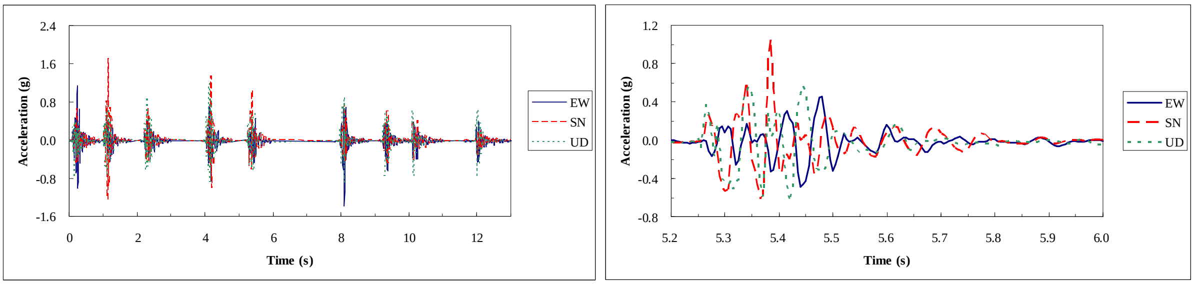
2.3. Observational Points of Exploding Ground Motion

In order to comprehensively observe distributional features of exploding ground motion, 24 observational points are arranged in the target field (see Fig. 2.1). Here, 11 points are located inside the circle of the explosive source, and 6 points outside the circle along directions of E-W and S-N respectively. Others of 6 points are scattered in the east part of the field to obtain attenuation information of explosive ground motion, with a 20m interval and the first point departing 40m from the centre along the azimuthal angle of 80.5°. The point of No. 24 is located at the position with a departing distance of 110m from the centre along the azimuthal angle of 333°.

3. FEATURES OF TIME HISTORY AND FREQUENCY SPECTRUM

3.1. Time Histories

Because of the orbicular design of single-explosive sources, the record at the centre of the target field may be the best data to investigate the actual effect of the blasting and the essential feature of exploding ground shocks. Figure 3.1 shows the time-history data recorded at the centre position (UD, vertical component; SN and EW, horizontal components). The whole time-history obviously caught 9 individual vibrations (blasting duration greater than 12s) whereas other 6 single-explosive sources unfortunately failed to be detonated due to indistinct reasons.



(a) whole blasting (9 pulses) (b) individual vibration (the fifth pulse)

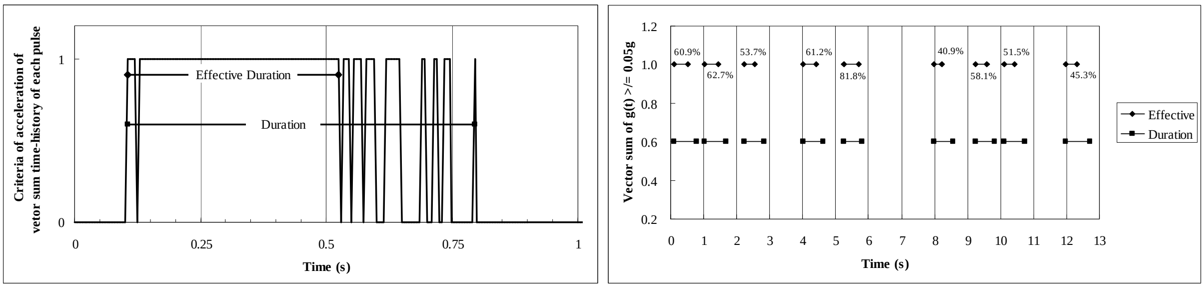
Figure 3.1. Time histories of strong ground motion induced by short delay blasting

For actual duration features of exploding ground motion, we adopted a quantitative criteria of acceleration (C_a) to analyze the time-history data as the follow.

$$C_a = \begin{cases} 1, g_{vs}(t) \geq 0.05g \\ 0, g_{vs}(t) < 0.05g \end{cases} \tag{3.1}$$

where $g_{vs}(t)$ is the vector sum of three components of recorded accelerations.

Using Eqn. 3.1, duration features of recorded data (see Fig. 3.1) are summarized in Fig. 3.2 (the percentage representing the ratio of effective duration to duration).



(a) individual (the first pulse)　　(b) whole (9 pulses)

Figure 3.2. Duration features of recorded ground motion induced by short delay blasting

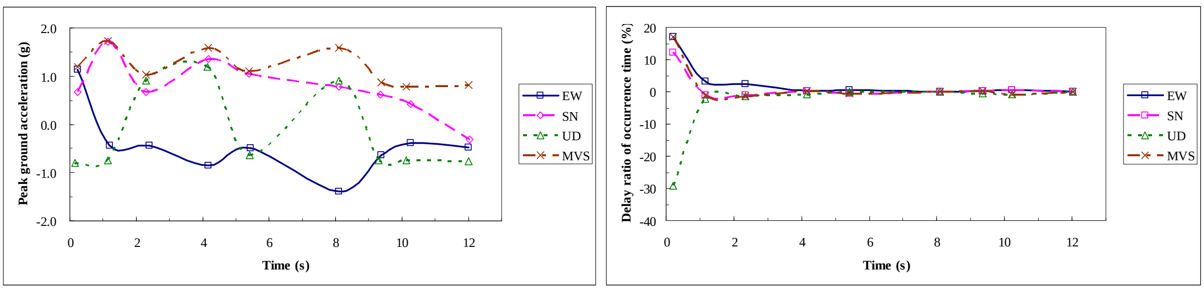
The previous result showed there is only a small part of explosive energy contributing to the generation of ground motion (Kumari et al, 2000). Figure 3.2 reveals that the explosive pulse energy could cause greater peak ground acceleration (PGA), but the subsequent energy would merely maintain a shorter duration. These essential features prove that although the PGA inside explosive source circle exceeds 1g (the double of the expectation intensity) the effective energy of whole exploding ground shocks is relatively small due to the shorter effective duration (3.23s, around with a percentage of 57.3% contrast to the duration, 5.67s).

The occurrence time of PGA for individual exploding pulse includes the contribution information of each component (UD, EW or SN) to the whole explosive energy. Here, therefore, we introduce two concepts of delay ratio of occurrence time (DROT) of PGA for three components and DROT of the maximum vector sum (MVS) for vector sum time-history due to three components. For PGA of each component and MVS of three components of individual exploding vibration, the value of DROT is calculated by the follow equation.

$$DROT_{PGA/MVS} = 100\% \times (OT_{PGA/MVS} - OT_{mean-PGA-3cs}) / OT_{mean-PGA-3cs} \quad (3.2)$$

where OT_{PGA} and OT_{MVS} is respectively occurrence times of PGA of three components and of MVS of vector sum time-history; $OT_{mean-PGA-3cs}$ is the mean of occurrence times of PGA of three components.

By this treatment, analysis results of the time-history records at the centre position of the target field are shown in Fig. 3.3.



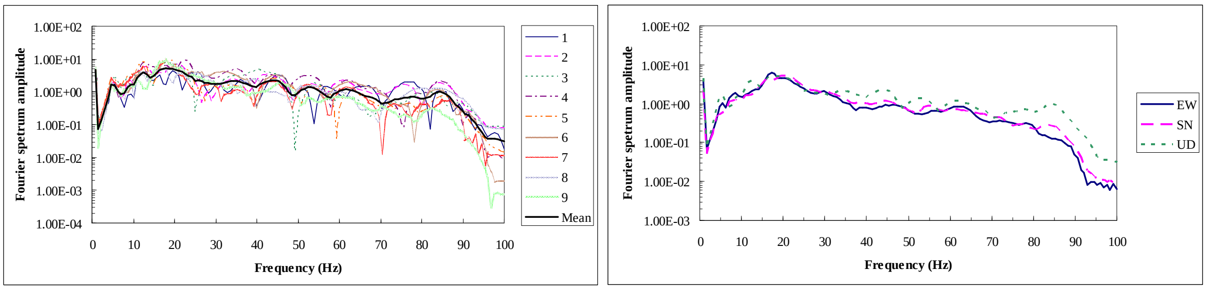
(a)　　(b)

Figure 3.3. Contribution analysis of three components of exploding ground motion

At the beginning of the short delay blasting, the contribution of SN component to explosive shock energy is greater than other ones (see Fig. 3.3). After the duration of 1s, energy contributions of three components become close, and the horizontal component of EW is the minimum one. During the explosive process later than 4s, the individual energy contributed by single component is alike each other due to almost same occurrence times. This phenomenon reveals the initial static status of soil ground needs an enough time to follow the vibration induced by explosions. Within the early stage (in this case, 4s), the soil ground vibrates by an inharmonious way along different directions; its vibration obviously differs from the later stage, in which the ground motion obviously keeps stable. The analysis result clearly indicates any reasonable design of exploding ground motion must maintain an adequate length of duration.

3.2. Frequency Spectrum

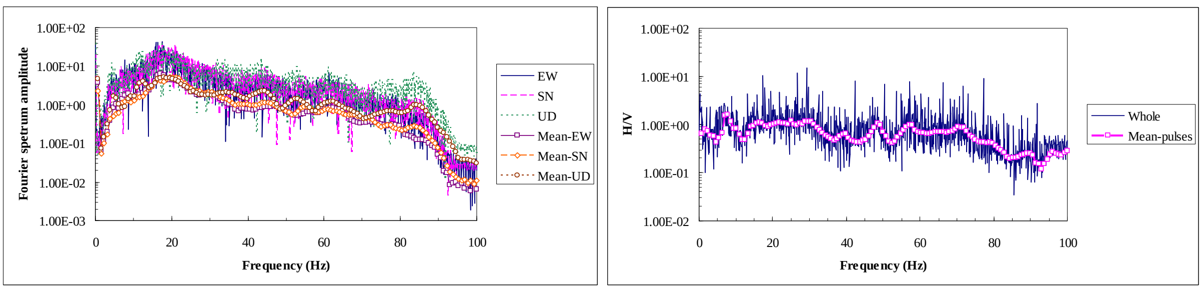
As shown in Fig. 3.4, the frequency spectrum curve of individual pulse vibration is alike each other and there is no an obvious sequence. This phenomenon indicates ground motions caused by single-explosive sources with certain detonated energy tend to possess similar random-features. For each one of individual pulse vibration, however, frequency spectrum characteristics of three components are distinctly different and the frequency of 32Hz (near the double of the predominant frequency) may be the particular point dividing the spectral curve into two parts, the left one differing from the right one. In the right case, UD component response is greater than horizontal ones (more and more distinct with increase of frequency), according with distributional patterns of explosive energy in aspects of the frequency and reference-vibration direction (component of UD, EW or SN).



(a) individual (b) mean

Figure 3.4. Frequency spectrum features of individual ground motions induced by the short delay blasting

The whole response magnitude of the short delay blasting is obviously greater than the mean of individual pulses, but spectral shapes of associated components in two cases are alike each other (see Fig. 3.5(a)). Meanwhile, there is almost no difference of H/V values between the frequency spectrum of whole time histories and the mean of individual ones (see Fig. 3.5(b)).



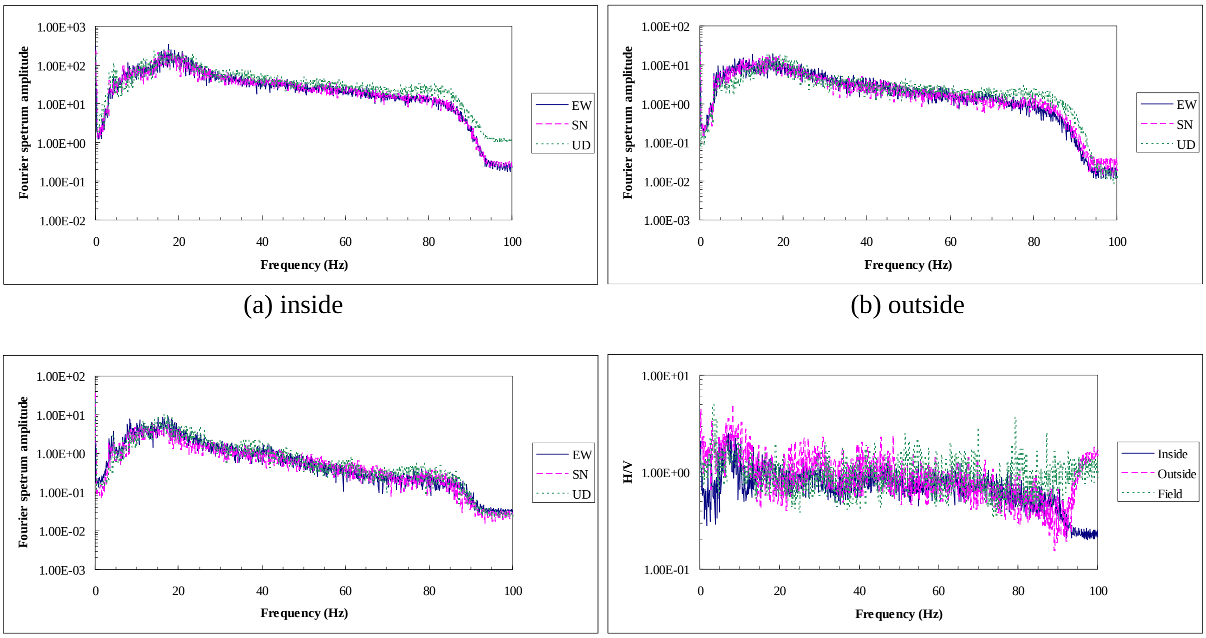
(a) (b)

Figure 3.5. Difference of frequency spectrum features between whole and individual time-histories of exploding ground motion

In Fig. 3.5, analysis results reveal the essential feature of frequency spectrum of exploding ground motion, both cases of whole blasting and individual pulse, may be mainly influenced by the single-explosive sources because each one is filled the certain mass of explosive to generate similar intensity of individual pulse energy.

The frequency spectrums within different observational areas (inside, outside and attenuation field, see Fig. 2.1) of the target field disclose that the mean response of short delay blasting inside explosive-source circle is the maximum, whereas the case within attenuation field is the minimum (see Fig. 3.6). Moreover, three components and H/V values share the same distributional characteristics at different positions with above mean responses.

Within three areas, vibration responses of higher frequency components gradually decrease with the increase of observational distances. Meanwhile, horizontal components of EW and SN are almost alike, and UD component varies between them. Although variations of UD components at different observational positions have a little difference, it is general that the vertical component suffers a larger response. As shown in Fig. 3.6(d), values of H/V at three positions are nearly similar. Within the domain below the predominant frequency, horizontal components are distinctly dominant; to the contrary, the vertical vibration is the dominant component in the greater domain. This means the principle frequency of horizontal component is relatively lower than the vertical one. Generally, the ground vibration induced by explosions has a typical feature of high frequency. Considering the design pattern of the explosive source adopted in the target filed, therefore, the dominant vertical-component indicates the energy is in an accumulative condition at the observational position inside the explosive-source circle; whereas cases of other observational positions are associated with the reduction of explosive energy. In the observational point apart from the centre of the target field far away, the feature of vibration time-history is relatively closer to the ground motion induced by natural earthquakes than those ones near the centre.



(a) inside

(b) outside

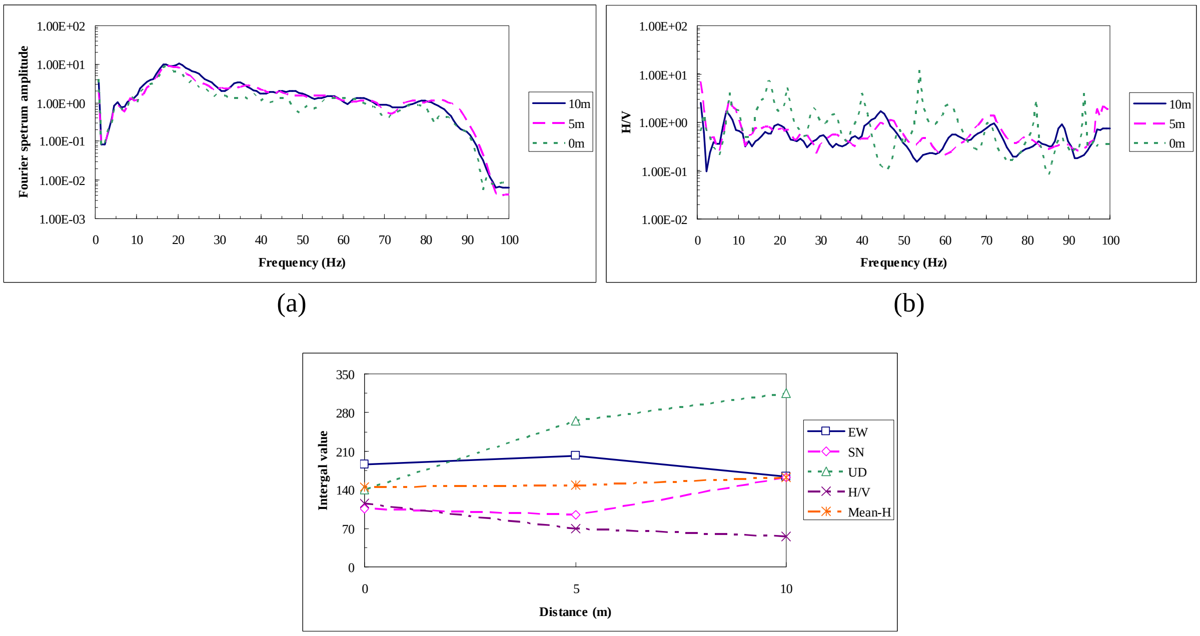
(c) field

(d) H/V

Figure 3.6. Different features of frequency spectrum of exploding ground motion in the target field

Because of the particularity and significance of exploding ground vibration inside the explosive-source circle, we analyzed the distributional characteristic of explosive energy base on the mean of spectral data of the first pulse at different observational points within the special area (see Fig. 3.7).

In Fig. 3.7, the distance of observational point is apart from the centre of the target field. Integral results of spectral curves show the mean response of horizontal components maintains stable at different positions, and the vertical component becomes greater while the distance widens. As a result, the value of H/V gradually decrease follow the increase of the vertical response.



(a) (b)

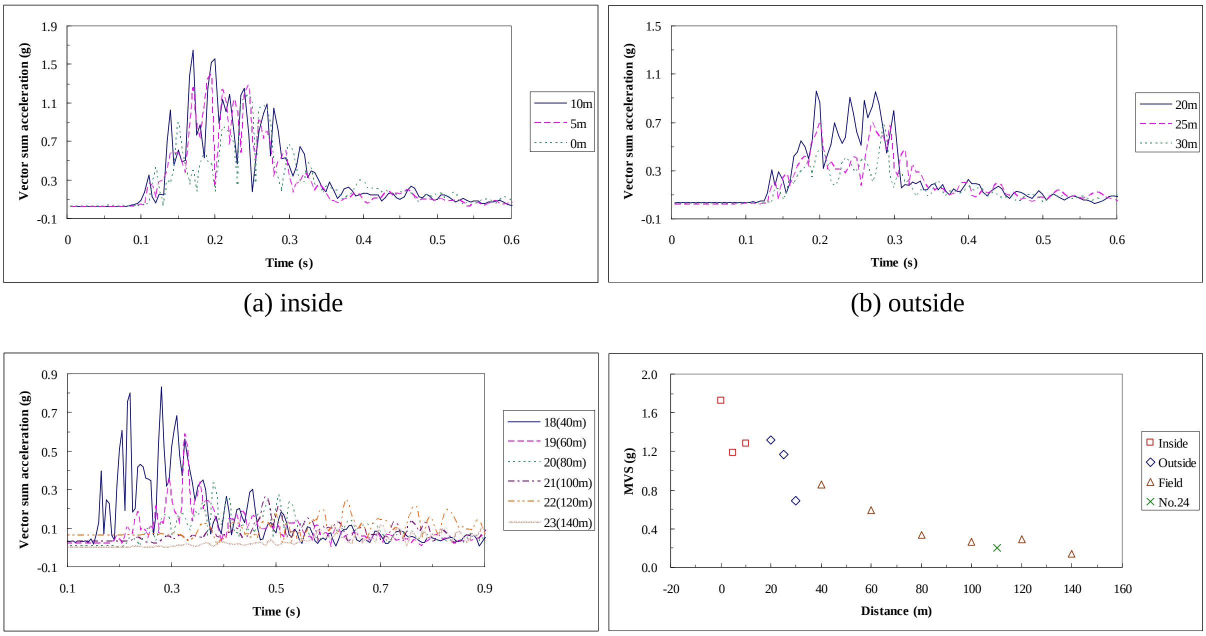
(c)

Figure 3.7. Frequency spectrum features of exploding ground motion inside explosive-source circle

4. ATTENUATION CHARACTERISTICS

4.1. Explosive Energy Attenuation

Figure 4.1 provides attenuation relations between explosive energy and observational distances.



(a) inside (b) outside

(c) field (d) attenuation

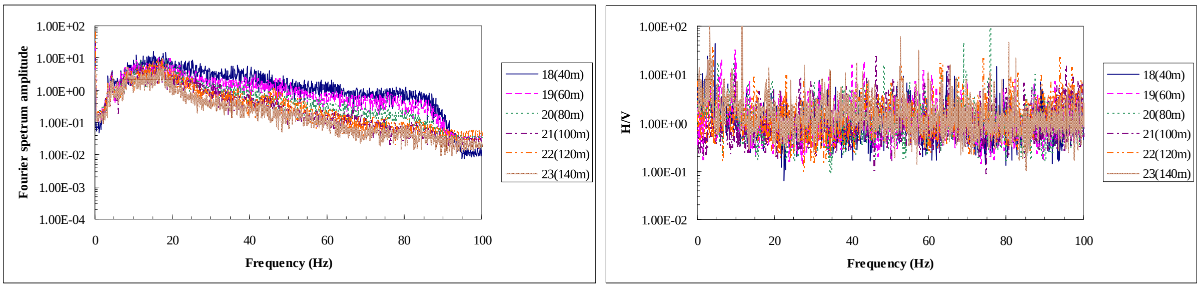
Figure 4.1. Attenuation characteristics of vibration energy induced by the short delay blasting in the target field

Attenuation features differ with observational positions due to accumulative or reduced explosive energy (source design pattern) and at the position of field the reduction gradually becomes slow while the distance increases (see Fig. 4.1(d)). According to Fig. 3.7(d), the energy of horizontal components associated with particular low-frequency is obviously dominant at the observational point apart from the centre far away. This phenomenon of slow reduction may accord with that the low-frequency vibration could propagate a longer distance as known in the research field of seismology.

4.2. Vibration Frequency Attenuation

Taken the record of exploding ground motion within the attenuation field as the analysis example of reduction characteristics of different frequency-domain vibrations, Figure 4.2 displays the response of each frequency-domain vibration tend to reduce while observational distances widens, especially for those cases with higher frequency. The variation of H/V values, representing the relative relation of the horizontal-component energy to the vertical one, discloses the similar result with the spectral alteration at different observational points.

The response magnitude of exploding ground motion obviously differs with the frequency. At a farer position apart from the centre of the target filed, meanwhile, high-frequency components could suffer a more severe reduction than low-frequency ones. Therefore, horizontal components become more and more abundant with the increase of observational distances (see Fig. 4.2(b)).



(a) (b)

Figure 4.2. Attenuation characteristics of frequency spectrum of exploding ground motion

5. CONCLUSIONS

(1) There is merely a small fraction of the explosive energy to generate the exploding ground vibration whereas the other of most energy contributes to compress the soil mass around the explosive source. This could cause artificial ground shocks induced by explosions having the essential features of a greater pulse of PGA and a shorter duration. The effective duration (ground acceleration exceeding a certain magnitude) is the most important factor influencing design effects of explosions. After the explosive is detonated, the soil mass needs an enough time to gradually alter its initial static state and then follows the exploding vibration. During the adjustment period of vibration status of the exploding field, the ground inharmoniously vibrates along three reference-directions. The beginning stage may make some explosive energy waste due to the inharmonious tremor of soil mass in the target explosive field. After the vibration of the soil mass relatively maintains stable, the effective energy induced by explosions could be constantly amplified.

(2) Symmetrical single-explosive sources could advance the energy response of exploding ground vibration at the centre position of the target field while the explosive energy is dominantly accumulative. From the view of seismic energy, it is a better expression of distributional characteristics of energy field caused by explosions that the vector sum of three components of exploding ground motion reduces with observational distances. For the high-frequency ground vibration caused by explosions, the attenuation is more obvious than the low-frequency one; this means the effective energy within high-frequency domain could propagate a shorter distance.

Furthermore, the attenuation characteristic of H/V values due to frequency spectrums with the increase of the observational distance contains the variation information of relative relation of the average horizontal-component to the vertical one.

(3) Individual exploding ground vibrations caused by certain detonated energy of explosive mass have alike random-features within frequency domain. For the exploding ground motion, the principal frequency of horizontal components differs from the vertical one. The former is obvious lower than the latter. Low-frequency components of exploding ground motion become more and more abundant while the explosive energy gradually accumulates. As a result, the explosive vibration tends to approach the actual ground motion induced by natural earthquakes. That is why explosive vibrations can be used to investigate referential responses of foundations and structures with full-scale sizes under near-field earthquake.

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