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Variation of earthquake ground motion with depth*

HU Jin-jun[1] (胡进军) XIE Li-li[1, 2] (谢礼立)

1) *Institute of Engineering Mechanics, China Earthquake Administration, Harbin* 150080, *China*
2) *School of Civil Engineering and Architecture, Harbin Institute of Technology, Harbin* 150090, *China*

Abstract

The variation of ground motion with depth is investigated in this paper, which is essential in determining the seismic design ground motion for embedded structures and pipelines. Firstly the earthquake ground motion on surface and in subsoil recorded by Hosokura Mine array of Japan and six California Strong Motion Instrumentation Program geotechnical arrays of the United States from about fifty moderate and strong earthquakes are described. Then the arrays were classified into three different categories according to their site conditions. Finally the variation law of ground and sub-ground motion with depth is established as a result of a nonlinear regression analysis of the above-mentioned data. Through comparing the features in different sites, it is concluded that, in general, the amplitude (acceleration, velocity and displacement) of ground motion are decreasing with depth and the attenuation rate is higher in the shallow strata than that in deeper ones.

Key words: earthquake sub-ground motion; amplitude ratio; nonlinear regression analysis
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Introduction

The 21st century is the time for the exploitation and utilization of underground spaces. It is a strategic way to defeat the severe challenge that human are now confronting with, such as the lack of land, contamination of environment, traffic jam, waste of sources, and so on. The exploitation and utilization of underground space has become a global tendency, and a significant sign in evaluating the speed of modernization of cities. Facing the challenge, it is significantly necessary to learn the characteristics of earthquake sub-ground motion in different depths for the seismic design and seismic safety of embedded structures and pipelines (HU, 2003).

Researches about ground and sub-ground motion have been extensively studied in recent years (Graizer *et al*, 2000), but most of the researchers focus on the site effect, and rather less of them have concentrated on the sub-ground motion characteristics for engineering seismic input. With the worldwide rapid development of underground spaces and the subsequently increasing interest in seismic input for embedded structures, the requests for a study on sub-ground motion characteristics become imperative. In this paper based on the earthquake database, a study on the variation of earthquake amplitudes (acceleration, velocity and displacement) with depth are conducted, hoping that it would benefit to the earthquake prevention engineering especially to the

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underground earthquake prevention engineering.

1 Vertical arrays and earthquake database

Strong motion data recorded by subsurface arrays with sensors installed at different depths and geologic layers provide critical information for studies on sub-ground motion and local site effects. Records analyzed here are obtained from California Strong Motion Instrumentation Program (CSMIP, United States) and Hosokura Mine (Japan).

1.1 CSMIP geotechnical arrays and earthquake data

The CSMIP was established in 1972 by California Legislation to obtain vital earthquake data for the engineering and scientific communities through a statewide network of strong motion instruments. In this research according to the selected 6 geotechnical downhole arrays of CSMIP, totally 28 earthquakes with $2.5<M<7.1$ were recorded, including the SN, EW and UD three components. There are totally 429 seismograms.

Earthquake sensors are installed at surface and different depths in downholes. Table 1 shows the site geology and sensor depths of each array. From the table we can see that the geotechnical arrays of El Centro, Eureka Samoa, La Cienega, Vincent Thomas represent deep soil profile, with shear wave velocities increasing from approximately 150 m/s near the surface to 550 m/s at depth of about 100 m. The Treasure Island array represent fill, alluvium and rock site array.

Table 1 CSMIP Instrumented Geotechnical Arrays

Station	Depth/km	Sensors	Sensor depth/m	Geology
El Centro	4	12	0, 30, 100, 195	Deep alluvium
Eureka Samoa	5	15	0, 19, 33, 56, 136	Deep soft alluvium
La Cienega	4	12	0, 18, 100, 252	Deep soft alluvium
Treasure Island	7	21	0, 7; 16, 31, 44; 104, 122	Fill; Alluvium; Rock
Vincent Thomas East	4	12	0, 18, 46, 91	Deep soft alluvium
Vincent Thomas West	6	21	0, 15, 30, 91, 189	Deep soft alluvium

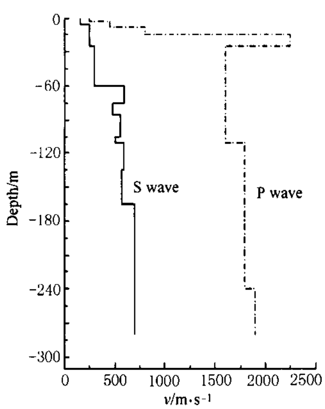

Figure 1 La Cienega downhole array P- and S-wave velocities and sensor location (Graizer *et al*, 2000)

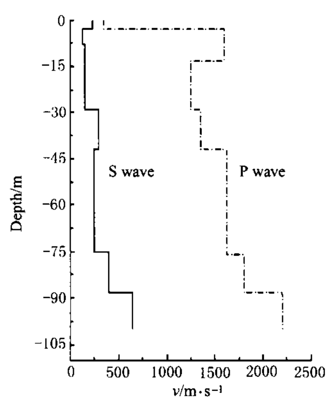

Figure 2 Treasure Island downhole array P- and S-wave velocities and sensor location (Graizer *et al*, 2000)

Figure 1 shows the P- and S-wave velocities of La Cienega array site. This kind of site is classified as a soil site (site class *D*, according to Boore *et al*, 1993). The Treasure Island array represents a soil/rock geological profile and the P- and S-wave velocities at the site are shown in Figure 2. Figure 3 shows the magnitude and epicentral distance of each earthquake.

1.2 Hosokura Mine array and earthquake data

The Hosokura Mine array is located at Miyagi prefecture in Japan, it is carried out by using an eight point three-dimensional array between surface and depth of about 400 m, for the purpose of obtaining the basic data for studying the characteristics of the seismic waves for the earthquake resistance design of deep underground disposal facility of high level waste. More than 40 low amplitude recordings from earthquakes with $3.8<M<6.9$ were recorded during the period of June of 1986 to March of 1988. In addition, in Hosokura Mine array only the acceleration amplitude data are available. Figure 4 shows the magnitude and epicentral distance of each earthquake (Graizer *et al*, 2000).

Table 2 shows the stratum geology and P-wave velocity. From surface to depth of about 400 m P-wave velocity increases from 3.5 km/s to 4.7 km/s, and the sensors are located at depth of 39.1 m (*H*-1, *H*-2), 179.3 m (*H*-3, *H*-4), 297 m (*H*-5) and 383 m (*H*-6, *H*-7, *H*-8), see Figure 5. The acceleration value at depth of 39.1 m takes the average of the two sensors *H*-1 and *H*-2, and depth of 179.3 m takes the average of *H*-3 and *H*-4.

Table 2 Hosokura array geology and P-wave velocity

Stratum	Geology	v_P/km·s^{-1}	Thickness/m
1	Andesite	3.5~4.0	140~170
2	Tuff	3.4~3.8	20~40
3	Quartzite andesite	4.0	40~50
4	Gravel tuff	3.9	20~30
5	Quartzite andesite	4.2~4.7	120~140
6	Gravel tuff	4.4~4.7	20~40

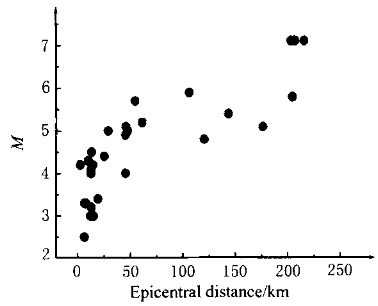

Figure 3 Magnitude and epicentral distance of earthquakes in CSMIP

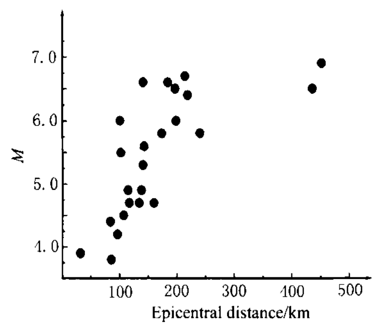

Figure 4 Magnitude and epicentral distance of earthquakes in Hosokura

To sum up, according to the site geology, the arrays were classified into three categories, *i.e.*, the rock site array (Hosokura Mine), the soil site array (El Centro, Eureka Samoa, La Cienega, Vincent Thomas), and the soil/rock site array (Treasure Island). Each category of array will be studied in sequence.

2 Method

To investigate the variation characteristics of ground motion with depth, the amplitude ratio of sub-ground/surface was conducted. Amplitude ratio means the ratio of peak ground acceleration (PGA), peak ground velocity (PGV) or peak ground displacement (PGD) of sub-ground motion in different depth compared with those of the surface. The reason why the surface ground motion was selected as the denominator is as follows. On the one hand, in general, the seismic amplitude at surface is bigger than that of sub-ground, so if we use the surface bigger value as denominator, the relative errors will be reduced. On the other hand, the on-ground recordings are much more abundant than that of sub-ground, thus we can evaluate the sub-ground earthquake parameters

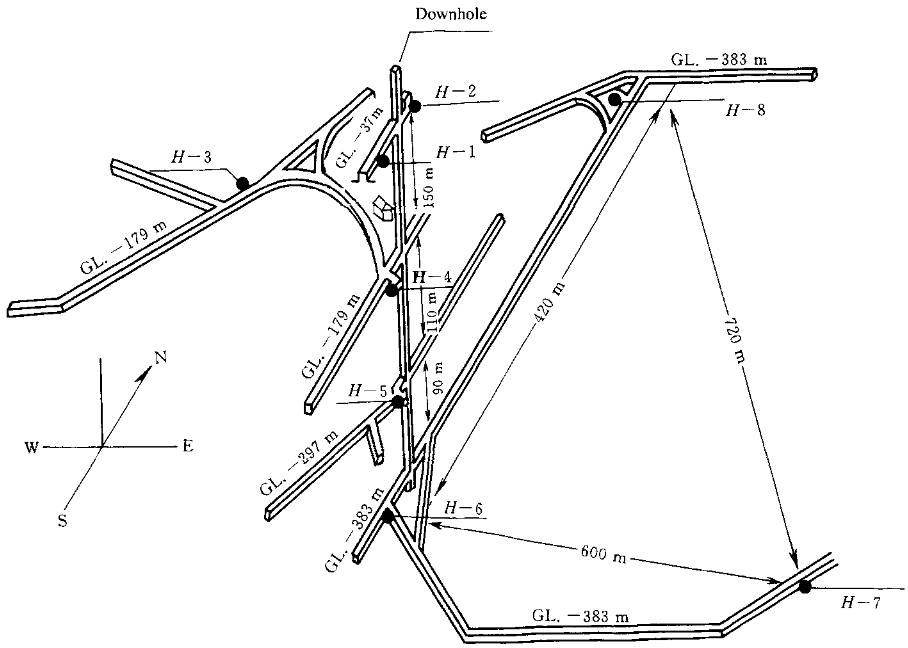

Figure 5 Hosokura Mine array and sensors location (Komada *et al*, 1989)

from the on-ground by the statistical regression curve we were to make.

Process for studying: Firstly, based on the classification of arrays, in an effort to study the effects caused by the earthquake magnitude or amplitude on the variation of ground motion with depth, all the earthquakes contained in the same kind of array were classified into different levels according to the magnitude and amplitude. Secondly, for the same earthquake level, compute the amplitude ratio of all the events. Then get the average amplitude ratio of all the events at the same depth, thus the average amplitude ratio of different depths are obtained. Thirdly, the average amplitude curves of each level are established as a result of a nonlinear regression analysis. In addition, in the research the amplitude value of horizontal component is the average of the two components.

3 Variation of ground motion with depth

The variation characteristics of acceleration, velocity and displacement amplitude with depth will be studied in sequence. For the reason that there is no PGV or PGD data in the rock site, so in velocity and displacement aspects we only compare the soil and soil/rock site results.

3.1 Acceleration aspect

3.1.1 Rock site

For the Hosokura Mine rock site array, the selected 24 earthquakes were classified into two categories according to the magnitude level, class I includes 15 earthquakes with $M<6.0$, and class II includes 9 earthquakes with $M>6.0$. Figure 6a shows the distribution of horizontal PGA ratio with depth of all the events, Figure 6b shows the average PGA ratio in different earthquake levels. According to the distribution features of the average PGA ratio points with depth, to evaluate the PGA reduction curve, the first order exponential decay function was selected by using the nonlinear least squares fitting method. Figure 6c shows the fitting reduction curve of PGA horizontal component of all events. For that the variation characteristics of vertical component are similar to that of horizontal, the figures of vertical component are not given. The fitting parameters, as well as the corresponding determinant coefficient R^2, are displayed in appendix. The fitting equation is as follows, where y is the depth, x is the PGA ratio of the corresponding depth, in addition, the fitting parameters a, b and c denote offset, amplitude and decay constant, respectively.

$$y = a + b \cdot \exp\left(-\frac{x}{c}\right) \tag{1}$$

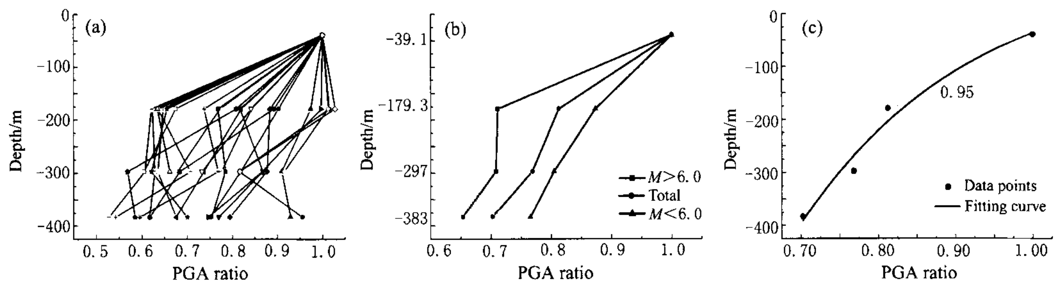

Figure 6 PGA variation of Hosokura array with depth
(a) Distribution of PGA ratio with depth; (b) Average PGA ratio of different earthquake levels; (c) Fitting curve of all events

Results indicate that PGA decreases with depth for both horizontal and vertical component; the variation characteristics of PGA with depth are affected by the magnitude level, and the decreasing extent of M>6.0 is larger than that of M<6.0; as shown in Figure 6c, the reduction curve derived from the exponential decay function can properly fit the variation of PGA with depth.

3.1.2 Soil site

The soil sites include the El Centro, Eureka Samoa, La Cienega, Vincent Thomas East, and Vincent Thomas West arrays. For similar site condition all the events recorded by the 5 arrays were put together. Similar to the procedures of rock site, firstly, all the measured values are arranged according to their depths, and the events were classified into three levels according to the magnitude. In detail, Class I for M<4.5, class II for 4.5<M<6.0, class III for M>6.0. Figure 7a shows the distribution of horizontal PGA ratio with depth of all events, Figure 7b shows the average PGA ratio of different magnitude levels. According to the distribution features of the average PGA ratio points with depth, the first order exponential decay function [see equation (1)] was selected to simulate the average PGA reduction curve. Figure 7c shows the fitting curve of horizon-

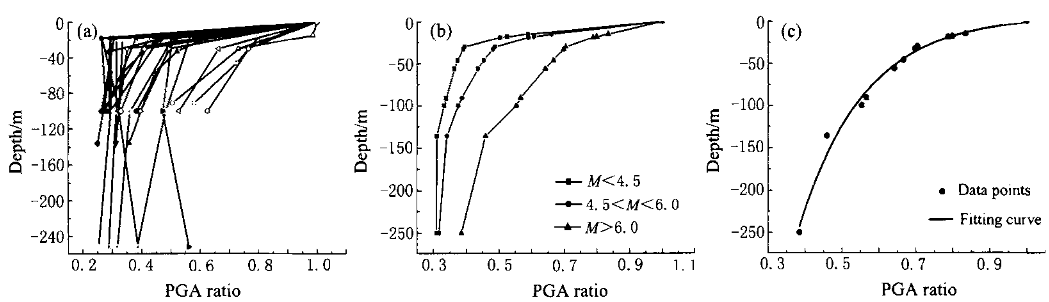

Figure 7 PGA variation with depth of soil site
(a) Distribution of PGA ratio with depth; (b) Average PGA ratio of different earthquake levels;
(c) Fitting curve of the class III events

tal average PGA ratio of the class III. Figures of vertical component are not given for its similarity to the horizontal. The fitting parameters and the corresponding determinant coefficient are also displayed in appendix.

Results indicate that PGA decreases with depth. Particularly, the decline is much more rapidly in shallower layers (depth smaller than 30 m) than that in deeper layers, which can be seen clearly in Figure 7b and c. The variation characteristics of PGA with depth are affected by the magnitude level. The decline extent decreases with the increment of magnitude. As shown in Figure 7c, the statistic reduction curve fits the distributed average PGA ratio point well.

3.1.3 Soil/rock site

The soil/rock site Treasure Island array consists of 6 moderate earthquakes of about M=4.5. For similarity of magnitude of earthquakes, all the events were put together for studying. Figure 8a shows the distribution of horizontal PGA ratio of all events. The corresponding fitting PGA reduction curve derived by the nonlinear regression analysis was shown in Figure 8b. Variation of the vertical component is similar to that of horizontal so that their figures are not given. The fitting parameters as well as the corresponding determinant coefficient are given in appendix.

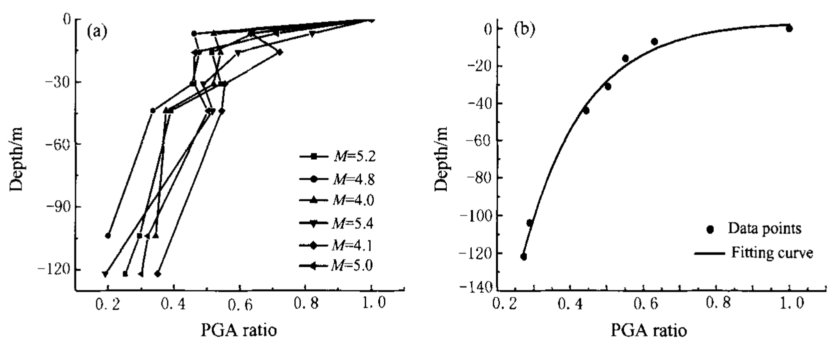

Figure 8 PGA variation of soil/rock site with depth
(a) Distribution of PGA ratio; (b) Fitting curve of all events

From the above two figures we can see that the PGA decreases with depth, and similarly to the soil site, the decline velocity is much more rapid in depth of shallower layer than that in deeper ones. The horizontal PGA in the rock is 1/3.7 of that at surface in average, and the vertical component 1/3.2. As shown in Figure 8b the first order exponential decay model agrees well with the variation characteristics of PGA in soil/rock site.

3.1.4 Comparison of PGA variation in different sites

Although the variation characteristics of PGA in different sites share some common features, as shown in Figure 9, there are still some differences which can be summarized as follows. What is needed to say is that although the events are not quite enough in soil/rock site to account for the specific reduction characteristics of PGA, in order to illustrate the essential characteristics between different site conditions we still compared the two sites.

1) The PGA decline velocity for soil/rock site is the most rapidly, for rock site it is the least rapidly, and for soil site it is in the middle of the two sites.

2) The variation of PGA with depth is affected by the magnitude of earthquakes and site geology. For soil site, the PGA decreases with the increasing of magnitude or intensity; for rock site, the decline extent of the larger earthquakes is more rapidly than that of the smaller's.

3) Different from rock site, for soil site, there is a dramatic declination in the shallower layer.

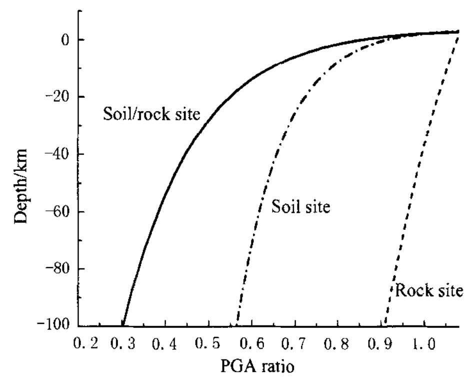

Figure 9 Comparison of PGA variations in different sites

In addition, the PGA variation characteristics in soil site is similar to that of soil/rock site.

3.2 Velocity aspect

3.2.1 Soil site

To investigate the variation of PGV with depth, we use the same procedure as that of acceleration aspect. Figure 10a and b show the distribution of horizontal PGV ratio of all events and the average PGV ratio of different magnitude levels, respectively. According to the distribution features of the average PGV ratio points, the first order exponential decay function [see equation (1)] was also selected to simulate the average PGV reduction curves. Figure 10c shows the fitting curve of horizontal average PGV of earthquakes M>6.0. The vertical component of PGV shares the similar reduction characteristics with that of horizontal. The fitting parameters of horizontal and vertical components, as well as the determinant coefficient, are given in appendix.

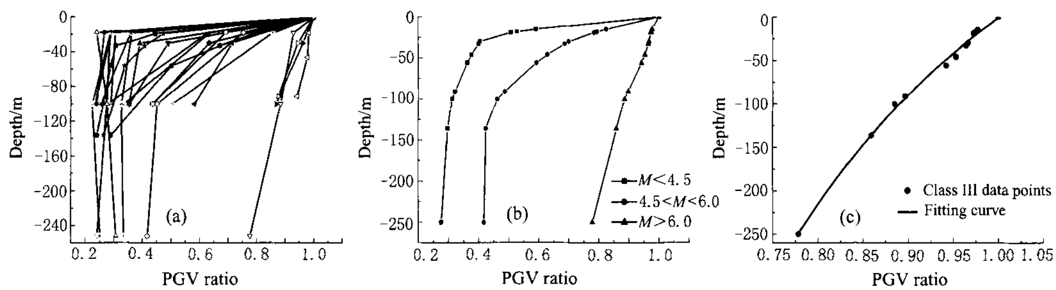

Figure 10 PGV variation with depth of soil site
(a) Distribution of PGV ratio with depth; (b) Average PGV ratio of different earthquake levels; (c) Fitting curve of the class III events

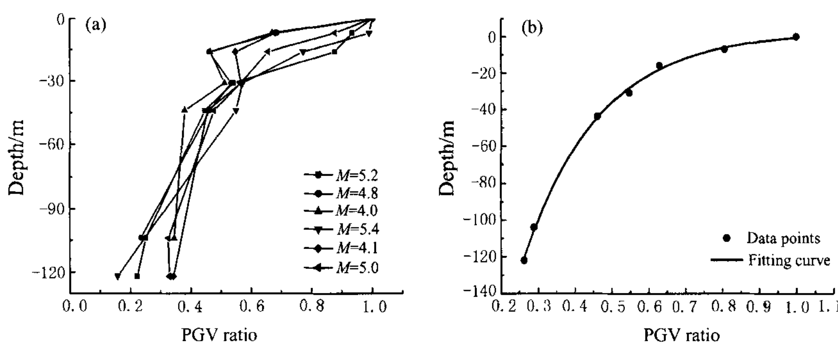

Figure 11 PGV variation with depth of soil/rock site
(a) Distribution of PGV ratio with depth; (b) Fitting curve of all events

Comparing Figure 7 with Figure 10, it is concluded that the variation characteristics of PGV for M<6.0 resemble that of PGA. But for M>6.0, the PGV decreases monotonously, while there is an obvious isolation effect in shallower soil layers in PGA, which makes the input motion smaller.

3.2.2 Soil/rock site

The same procedure as that of PGA was employed in investigating the PGV variation. Figure 11(a) and (b) show the distribution of horizontal PGV ratio and the fitting curve of average PGV ratio, respectively. The fitting model and parameters are displayed in appendix.

Results indicate that, for moderate earthquakes, the variation characteristic of PGV in soil/rock site is similar to that in soil site. The horizontal PGV in the rock is about 1/3.4 of that at surface in average, and for vertical component 1/2 that of surface. The fitting curve drawn by equation (1) can model the variation of average PGV with depth well.

3.2.3 Comparison of PGV variations in different sites

As shown in Figure 12, in order to illistrate the difference of PGV variation in different sites we selected the same level of magnitde (moderate) in the two kinds of sites. From the two simulated curves we can see that, in average, the PGV declines more rapidly in soil/rock site than that in soil site for moderate earthquakes.

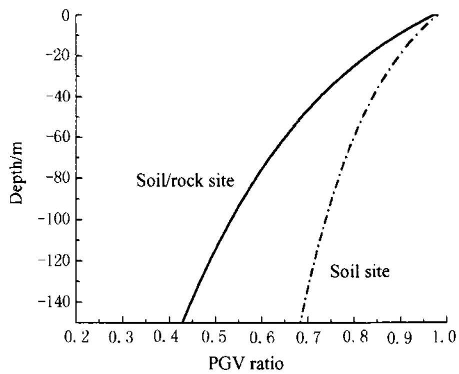

Figure 12 Comparison of PGV variations in different sites

3.3 Displacement aspect

3.3.1 Soil site

Similar to the procedure of acceleration and velocity aspects, Figure 13a~c show the distribution of horizontal PGD ratio of all events, the average PGD in different magnitude levels and its fitting curve by means of an exponential decay function, respectively. The fitting parameters and determinant coefficient are displayed in appendix.

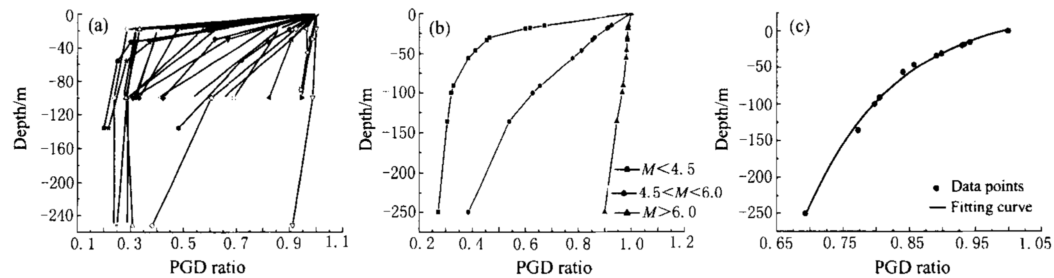

Figure 13 PGD variation with depth of soil site
(a) Distribution of PGD ratio with depth; (b) Average PGD ratio of different earthquake levels; (c) Fitting curve of all events

Results indicate that, for smaller events $M<6.0$, the reduction characteristics of PGD and PGV are similar; however, for larger events $M>6.0$, the PGD decreases monotonously and the decline extent is smaller than that of PGV.

3.3.2 Soil/rock site

The procedure for investigating the PGD variation is the same as above ones. Figure 14a and b show the distribution of horizontal PGD ratio of all events and their fitting curve of average PGD ratio respectively.

From Figure 14 and 11 we can see that the reduction characteristics of PGD and PGV in soil/rock site are very similar. Although the events are all moderate, from Figure 14a we find that the two relative larger events decrease slower than that of the smaller. The horizontal PGD in the rock is about 1/5 of that at surface in average, and for the vertical component 1/2 that of surface.

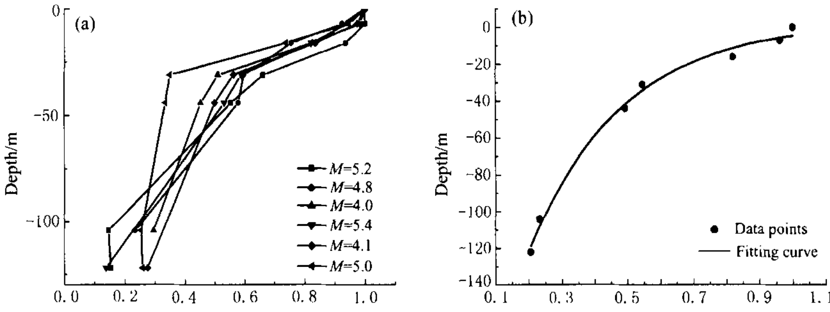

Figure 14 PGD variation with depth of soil/rock site
(a) Distribution of PGD ratio with depth; (b) Fitting curve of all events

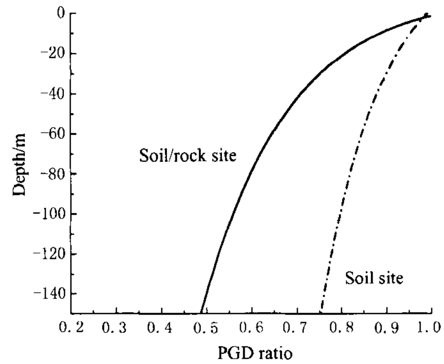

Figure 15 Comparison of PGD variations in different sites

3.3.3 Comparison of PGD variations in different sites

Figures 15 shows the PGD variation with depth in soil site differs from that in soil/rock site. From the two simulated curve we can see that, similar to the comparison of PGV in the sites, the PGD declines more rapidly in soil/rock site than that in soil site.

4 Discussion and conclusions

Based on the results of above all, we can draw some general conclusions.

1) In general, the earthquake amplitude (PGA, PGV or PGD) decreases with depth, and the decline extent is more dramaticer in shallower layers than that in deeper ones.

2) The reduction of amplitude with depth is affected by the magnitude and site geology. In general, for soil site, the decline extent decreases with the increment of magnitude as well as the amplitude.

3) For soil site, as shown in Figure 16, the decline velocities of PGA, PGV and PGD decrease in sequence. For soil/rock site, the decline velocities of PGA, PGV and PGD are similar to each other.

Results imply that PGA decreases with depth and the decline mainly focus on shallower layers. From Figure 7 it can be noticed that the PGA in depth of 25 m decreases to1/2 that of surface. That is to say, the design intensity at depth of 25 m reduces by one unit compared with that of surface. And as we all known, in seismic response analysis, the input motion for structures are generally deduced from the design intensity of surface, and then the surface motion, like PGA, PGV, PGD or time histories, are put to the bottom of the buildings. Obviously, it is inappropriate for that the depth of burial of underground structure or high-rise buildings are always more than 10 m, and the general ideas of doing so is that it would lead to an overestimate of seismic response.

In addition, the fact that PGA decreases with depth is still not taken into account in today's building code in China. While Japan's building code claimed that acceleration in depth of 20 m of

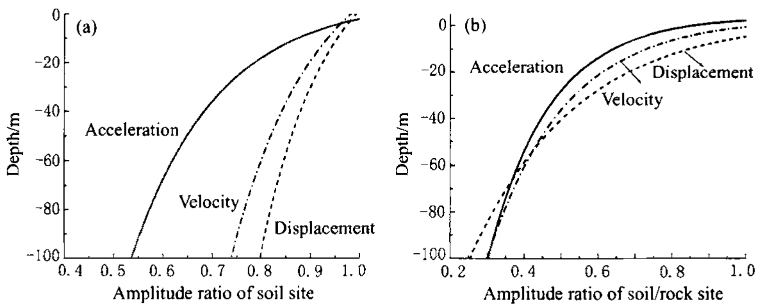

Figure 16 Comparison of variation of PGA, PGV and PGD in soil site (a) and soil/rock site (b)

soil layer was 1/2~2/3 that of surface, and accelerations at middle depths are derived by interpolation. In China there are also some suggestions on revising site classification or deducting the earthquake force for the embedded structures, but it is still unadopted by the code for lacking of practical proofs and rules. Thus for this reason, in this paper, based on the results we have made, we hope to provide some useful references or statistical rules for evaluating the seismic input for underground structure.

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Appendix

Table 1 Amplitude reduction fitting parameters and determinant coefficient R^2

	Site	Statistic events	Component	a	b	c	R^2
Acc.	Rock site	All events	Horizontal	91.128 35	−11 134.188 74	0.223 67	0.977 38
			Vertical	28.785 86	−9 339.056 79	0.201 51	0.983 15
	Soil site	All events	Horizontal	−19.091 85	−36 762.731 84	0.069 93	0.984 26
			Vertical	7.120 78	−19 784.214 55	0.107 65	0.974 31
		Class III	Horizontal	5.502 74	−2 218.336 7	0.175 81	0.986 20
			Vertical	−4.636 17	−1 660 492.752 8	0.066 91	0.966 06
	Soil/rock site	All events	Horizontal	3.859 45	−627.526 66	0.168 24	0.994 14
			Vertical	10.133 99	−530.590 75	0.230 36	0.985 49
Vel.	Soil site	All events	Horizontal	30.773 39	−10 558.251 7	0.168 07	0.997 26
			Vertical	55.404 91	−9 118.828 04	0.189 14	0.986 02
		Class III	Horizontal	208.927 23	−7 025.201 5	0.285 04	0.996 27
			Vertical	91.769 09	−1 156 994.012 9	0.105 96	0.992 57
	Soil/rock site	All events	Horizontal	2.971 86	−437.458 19	0.207 59	0.998 64
			Vertical	37.843 80	−662.134 13	0.344 74	0.998 71
Dis.	Soil site	All events	Horizontal	30.191 69	−50 400.423	0.133 71	0.995 90
			Vertical	70.147 87	−21 156.714	0.173 56	0.986 56
		Class III	Horizontal	−2 568.092 6	2 571.308 44		0.983 57
			Vertical	−1 938.683 8	1 909.919 73		0.928 60
	Soil/rock site	All events	Horizontal	3.015 21	−249.490 92	0.286 56	0.993 76
			Vertical	9.445 12	−2 060.082 3	0.190 22	0.998 39

Note: The fitting function is $y=a+b\exp(-xc^{-1})$, except for $y=a+bx$ which is used for PGD in class III in soil site.