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Study of ground motion effect of trapezoidal valley site based on centrifuge shaking table test

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Abstract: Studying the seismic effects of valley site has critical guiding significance for site selection and aseismic design. Based on the analysis of centrifuge shaking table tests, the ground motion response pattern of the trapezoidal valley was studied. The results showed that there was a certain amplification effect of ground motion in the bedrock valley site. The amplification effect varied with the change of terrain, but the amplification effect was not significant. Different site locations had a small influence on the response spectrum. In the bedrock-overburden model, an obvious increase of the ground motion magnification was observed at the bedrock surface. Different magnifications were found under different input ground motions. The amplification effect of the ground motion was particularly evident on different sites when the frequency band was in the range of 0.5−2.5 s. In this frequency band, the frequency range of ground motion amplification was increased significantly, which was different from the pure bedrock sites. In the case of the pure bedrock sites, although the shape of the response spectrum was somewhat different for individual sites, the plateau value and characteristic period of the response spectrum were similar. Due to the terrain effect of the valley site, the amplification factors of the peak surface acceleration of the valley site changed with the change of the terrain. The higher the terrace levels of the valley, the greater its magnification, and the amplification of valley bottom was the smallest. With the increase of the input ground motion intensity, the higher the terrace levels, the higher the plateau value, and the greater the characteristic period of the response spectrum.

Keywords: centrifuge shaking table test; river valley site; ground motion; aseismic design

1 Introduction

According to the previous earthquake hazard surveys, it has been proven that the river valley sites have a key impact on the earthquake damage extent. The abnormal phenomenon of ground motion was observed for the river valley sites such as the Weihe river valley in the Haiyuan magnitude 8.5 earthquake in Ningxia province in 1920, the Qujiang river valley between Tonghai and Eshan in the magnitude 7.7 earthquake in 1970 in Yunnan province, and the Sancha river valley in the Haicheng earthquake[1] in Liaoning province. In 2005, a magnitude 7.8 earthquake occurred in the Pakistan-administered Kashmir region. Many buildings and infrastructures had severe damage and caused many casualties along the Kaghan river within the Balakot town[2]. During the "5.12" Wenchuan earthquake in 2008, Hanyuan county was damaged severely and high-intensity anomalies were observed. Studies have found that the river valley terrain had a crucial impact on the damage anomalies of the Hanyuan earthquake[3]. In addition, in the Wenchuan earthquake, different spatial sites experienced different earthquake induced damage for the river valley sites such as Anyi river in the Anchang town, Shiting river in Shifang city, Baishui river in Gansu province, Fu river in Pingwu county, Dabashan river and Dongyang river in Qingchuan, and Jian river, which further proved that the river valley site has an important impact on the ground motion distribution[4].

China is well known as a mountainous country and valley-type cities are widespread in China. For instance, many urban cities are distributed along the Guanzhong basin, Hetao plain, Fenhe valley, Hexi corridor, and Anning river valley. The main body of these valley-type cities is usually formed and developed in the valley. The layout and extension of these cities are normally followed along the terrain and rivers, which are in the gully and/or river valley areas[5]. Some of these valley-type cities are in the high earthquake intensive region (e.g. Xichang city, etc.). With the rapid development of the economy and the city, many buildings (structures) are built on the river valley site, however, the current aseismic design code of China does not have a clear provision on the design of ground motion parameter for the river valley site. A potential risk of the seismic fortification therefore exists to these buildings (structures), especially for those in river valley cities such as Xichang city in high seismic intensive areas. Due to the

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insufficient recorded data, the relevant research results obtained so far are still very limited and a large quantity of research work is still required for engineering application.

With the emphasis on the investigation of the historical earthquakes and the post-earthquake field surveys, as well as the collection and cumulation of seismic damage data from previous earthquakes, the terrain effect of river valleys has been paid broad attention by the researchers. A series of scientific studies has been conducted for the river valley terrain using various methods such as the empirical observation of strong ground motion, the analytical analysis and the numerical simulation, which provided meaningful conclusions. The empirical observation methods based on strong ground motion mainly include the traditional spectral ratio method, the generalized linear inversion method and the spectral ratio of horizontal to vertical method (H/V method). Many scholars have conducted related studies on the site effect of the river valley using the above-mentioned methods. Using traditional spectral ratio method and based on the acceleration time history records of the main and aftershock earthquake, Celebi[6] studied the magnification effects of terrain and soil layer in the seismic intensity anomalies areas in the 1985 Chile and Mexico earthquakes and the 1987 California earthquakes. Based on aftershock acceleration time history record of the 1994 Beiling earthquake, Bonilla et al.[7] studied the site magnification effect in the seismic intensity anomalies areas of the San Fernando Valley, California using the traditional spectral ratio method, genialized linear inversion method, and H/V method. Using a generalized linear inversion method, Tsuda et al.[8] investigated the soil layer magnification effect in the seismic intensity anomalies areas of the Kanto basin during 19 moderate to strong earthquakes. Based on the acquired acceleration time history at the Wei river valley of the main shock during the Wenchuan earthquake, Wang [9] studied magnification effect of river valley in the vicinity of 25 strong shaking stations by using a traditional spectral ratio method considering the geometric attenuation effect. Ren et al.[10] selected 602 sets of strong ground motion records from 28 strong earthquake stations in 96 aftershocks of the Wenchuan earthquake to analyze the site effect of the Wenchuan earthquake using a generalized inversion method. They provided an average magnification value for related sites in different frequency bands. According to the strong earthquake records, the empirical analysis method is an effective and scientific way to objectively reflect the influence of site on the earthquake. Due to the limitation of certain objective conditions, however, the deployment of many strong earthquake stations and the recording of strong earthquakes are the preconditions for the empirical method. As for the sites without strong earthquake stations, the empirical method cannot be applied, and the alternative methods are the analytical and numerical simulation methods.

The analytical method is more reliable than the numerical method in analyzing the problem nature perspective. The analytical method can be used to verify the accuracy of the numerical method and can be used to provide guiding significance for the derived results from the empirical method based on strong earthquake records. It has been a rich history for the related researches of the analytical method in the river valley site effect. In 1990, Lee et al.[11] solved the SH wave scattering problem of the semi-circular concave terrain in the frequency domain using wave function expansion approach. Liu[12] and Liu [13] et al. studied the scattering problem of a concave terrain under the seismic wave propagation using integral transformation and wave function expansion methods. They provided a solution for solving the step SH wave scattering in the semi-circular concave terrain within the time domain. Based on the Fourier-Bessel series expansion method, Liang et al.[14–18] analyzed the influence of incident P wave, SV wave, and SH wave on the arc-shaped concave terrain with a cover layer. They obtained the analytical solutions of various seismic wave scattering problem. In addition, taken the arc-shaped concave terrain as a base model, Dong [19], Yang [20], and Zhong [21] et al. also analyzed the scattering issues of P wave and SV waves. Although scholars have achieved certain results on the study of river valley topography using the analytical method, the analytical method needs higher requirements for mathematical physics calculation and poses limitations in mathematical methods, which can only lead to a simplified river valley model to analyze the problem. The analytical method is therefore used for a few simplified specific problems due to its insufficient capacity to consider the complex influence factors such as the shape and size of the river valley and the mechanical properties of the soil layers.

The numerical simulation method overcomes the above-mentioned shortcomings associated with the analytical method. However, large computation power is required during the numerical modelling and extensive storage space is needed, which requires high computation computer. Recently, high-performance computation computer is developed with the rapid development of computer techniques. The restricts of computation power is therefore solved and the numerical modelling method is used extensively in the study of strong ground motion in the river valley site. Currently, the widely used modelling methods include finite element method, Aki-lamer method, wave source method, non-linear seismic response analysis method, finite difference method, frequency domain equivalent linearization wave analysis method, characteristic line method, boundary element method, and spectral element method, etc [20−24]. Frischknecht et al. [25] built a 2D model and analyzed the Rhone valley site in Switzerland. The 2D modelling results were compared to that of 1D model results. They concluded that the 2D modelling results were roughly two times of the 1D model results. Bordoni et al.[26] conducted 2D numerical modelling for the seismic response of the L Aquila city. The 2D modelling results were compared with the spectral ratio of the recorded strong earthquake data on April 6, 2009. They obtained the magnification factors for both the low and high frequency bands for the site. With the development of computer technology and the emergence of the high-performance computation stations and the parallel computing, numerical simulation has been become the main approach of studying the seismic effect of the river valley terrain. Because each method has assumptions and/or restrictions, there will be some extent of limitations and unsuitability. These limitations could bring uncertainties to the modelling results and sometimes the modelling results even be questioned. In addition, it is gratifying that the centrifuge model test has been widely promoted and used since the 1980s. The centrifuge test has received widespread attention due to its unique features, which can make models with the prototype materials and can show the full process of soil deformation under the in-situ stress state. In China, the dynamic centrifugal model test technique has been applied in the study of geotechnical seismic engineering problems. This approach has been applied to almost all fields of geotechnical engineering and achieved meaningful research results such as the aseismic deformation of dams, the aseismic stability of slopes, the interaction between the soil and structure under seismic condition, the soil liquefaction, and the soft soil subsidence [27−31]. It is hence an alternate way to use dynamic centrifuge model test approach to study the problem of ground motion site effect in the absence of strong earthquake observation records. As Mr. Wenxi Huang pointed out that the geotechnical centrifuge model test has become a powerful method to verify the calculation method and solve the geotechnical issues [27]. Considering this, this study conducted a model test of generalized river valley site based on trapezoidal river valley site. The purpose of this study is to discuss the ground motion response law of the trapezoidal river valley site.

2 Centrifuge shaking table tests

2.1 Centrifuge system

As shown in Fig.1, the tests in this study were conducted on a shaking table of the large geotechnical centrifuge of the Tianjin research institute for water transport engineering, M.O.T (Ministry of Transport), China. The TK-C500 geotechnical centrifuge has an effective capacity of 500 *g* • t, a maximum acceleration of 250 *g*, a maximum rotation radium of 5.0 m, and a limited load of up to 5.0 t. The geotechnical centrifuge can be used for the simulation cases of different external environmental conditions such as earthquakes, waves, and the rise and fall of rainfall levels. The shaking table of the geotechnical centrifuge can realize the simultaneous shaking of the horizontal/vertical bi-directional under a 100 g acceleration. Its horizontal and vertical accelerations are 40 *g* and 20 *g*, respectively, and the frequency ranges from 20 Hz to 250 Hz. It can accurately load excitation waveforms, including sine wave, random wave, seismic wave, blasting shock wave and other vibration loads. According to the similarity ratio law, the gravity acceleration *g* increases as increasing the operation speed of the geotechnical centrifuge. In this way, the test model can reach to the in-situ stress state of the field site. The test was based on a generalized trapezoidal river valley site, two sets of test model and test plan were determined. A proper similarity ratio was then selected as 80 and the dynamic load input was applied when the gravity acceleration value reached to 80 *g* during the centrifuge rotation. Table 1 presents the related similarity ratio of the physical model test.

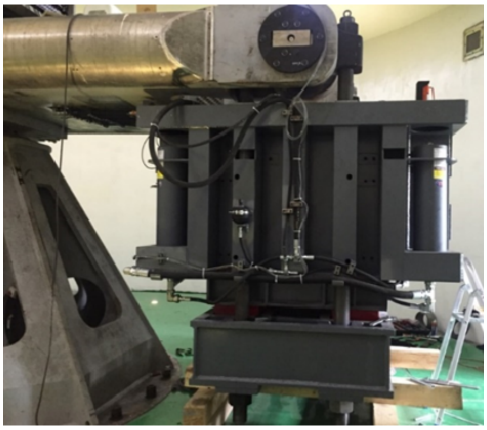


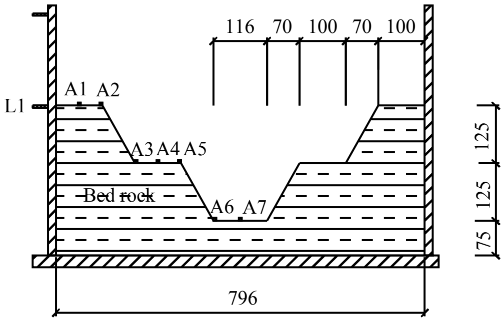
Fig.1 Horizontal and vertical centrifuge shaking table

Table 1 Similarity ratio of physical model test

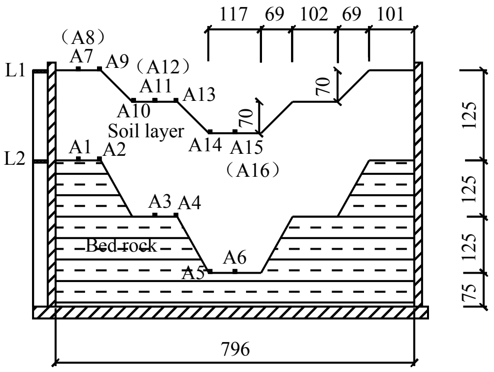
Type	Physical variable	Dimension	Similarity ratio
Dimension	Length l	L	1/80
	Displacement s	L	1/80
Material property	Density ρ	ML^{-3}	1
	Cohesion c	$ML^{-1}T^{-2}$	1
	Inter friction angle φ	—	1
	Stress p	$ML^{-1}T^{-2}$	1
	Strain ε	—	1
Dynamic property	Gravity acceleration g	LT^{2}	80
	Acceleration a	LT^{2}	80
	(Vibration) time t	T	1/80
	Frequency f	T^{-1}	80

2.2 Preparation of physical model

A layered shear model box was used as the test model box in this study. A 1 mm thick high-strength rubber membrane was arranged in the box to solve the free boundary issues. The internal dimension was 796 mm (L) x 400 mm (W) x 550 m (H) and the prepared test model is shown in Fig.3. To analyze the ground motion characteristics of the river valley site, two generalized river valley site test models were designed in this study and the test model and sensor layout scheme are presented in Fig.2. The purpose of the two generalized models is to compare and analyze the results of the two models, and further study the influence of valley topography and overlying layer on the ground motion under the earthquake for the trapezoidal valley site. In addition, the characteristics of ground motion at different locations are explored in the valley site.



(a) Bed rock



(b) Bed rock−overlying soil layer

Fig.2 Physical model (unit: mm)

The model was divided into two parts(Figs.2 and 3): the bedrock and the overlying soil layer. The bedrock portion was modelled using C60 grouting material. 12% of water was added into grouting material and the model was then cured for 7 d. After the cured material reaches the desired strength determined via testing, a series of acceleration sensors was placed on the bedrock surface, which was considered as Model 1. After the Model 1 was prepared, the overlying soil layer was made of sand with 3% clay particles. The sand soil must be dried and crushed and passed through a 5 mm sieve. The sand soil gradation curve is plotted in Fig.4. A uniform soil sample with a 15% moisture content was prepared after fully stirring using an agitator. The density of sand soil was controlled as 2.1 g/cm^3. The sand soil were compacted in layers and each layer was designed to be 30 mm. The compacted sand soil was consolidated for 1 h under the acceleration of 80 *g* centrifuge. After the model was fully consolidated, the slope was then excavated. Again, the acceleration sensors were buried within the soil surface and two LVDT displacement sensors were placed on the outside of the model box, which was viewed as the Model 2.

(a) Bedrock model (b) Bed rock−overlying soil layer model

Fig.3 Centrifuge test model

To analyze the influence of the ground motion amplitude and spectrum feature on the ground motion response of the river valley site, two seismic waves, the El Centro and Kobe, were selected as the input waves. The peak ground accelerations (PGA) of El Centro wave were set as 0.05 *g* and 0.15 *g* for the motion 1 and motion 2, respectively. Besides, the PGAs of Kobe wave were set as 0.1 *g*, 0.2 *g*, and 0.3 *g* for motion 3, motion 4, and motion 5, separately. The test was divided into two steps. The first step was to conduct a shaking table test for Model 1 and recorded the seismic response of the bedrock surface. The second step was to preform another shaking table test for Model 2 and obtained the acceleration responses for the soil surface and the soil layer−bed rock interface.

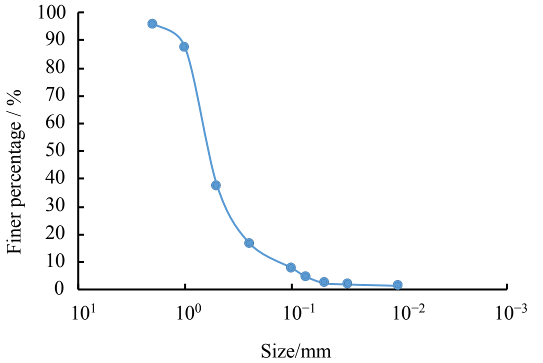


Fig.4 Gradation curve of soil

3 Ground motion response rule of Model 1

Based on the results of the physical model test and through the analysis of acceleration time history at each monitoring point from A1–A7, the amplification factor and response spectrum of peak acceleration are obtained when the peak of input seismic acceleration is in the range of 0.05 *g*–0.3 g. To analyze the amplification effect of bedrock valley site on the ground motion, Fig.5 presents the PGA amplification characteristic curve. It should be mentioned that the A1 sensor loosened during the test, resulting in abnormal data, so the data was not used in the analysis. It is seen from Fig.5 that the bedrock valley site has a certain amplification effect on the ground motion. The amplification effect varies with the changes of the terrain. In general, the amplification effect on the terrace locations is greater than that of the valley bottom. The test results are in general consistent with the previous research outcomes. However, the amplification effect is not significant, and the difference of the amplification effect of the site location is also not obvious. Under the same peak acceleration condition, for the Model 1, the amplification effect of the El Centro wave is significantly greater than that of the Kobe wave. The difference of amplification effect between the two waves is mainly resulted from the different spectral characteristics of ground motion, which indicates that the spectral features of ground motion have an obvious impact on the amplification effect.

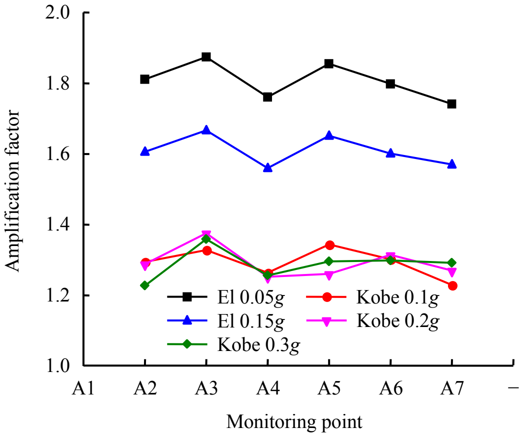
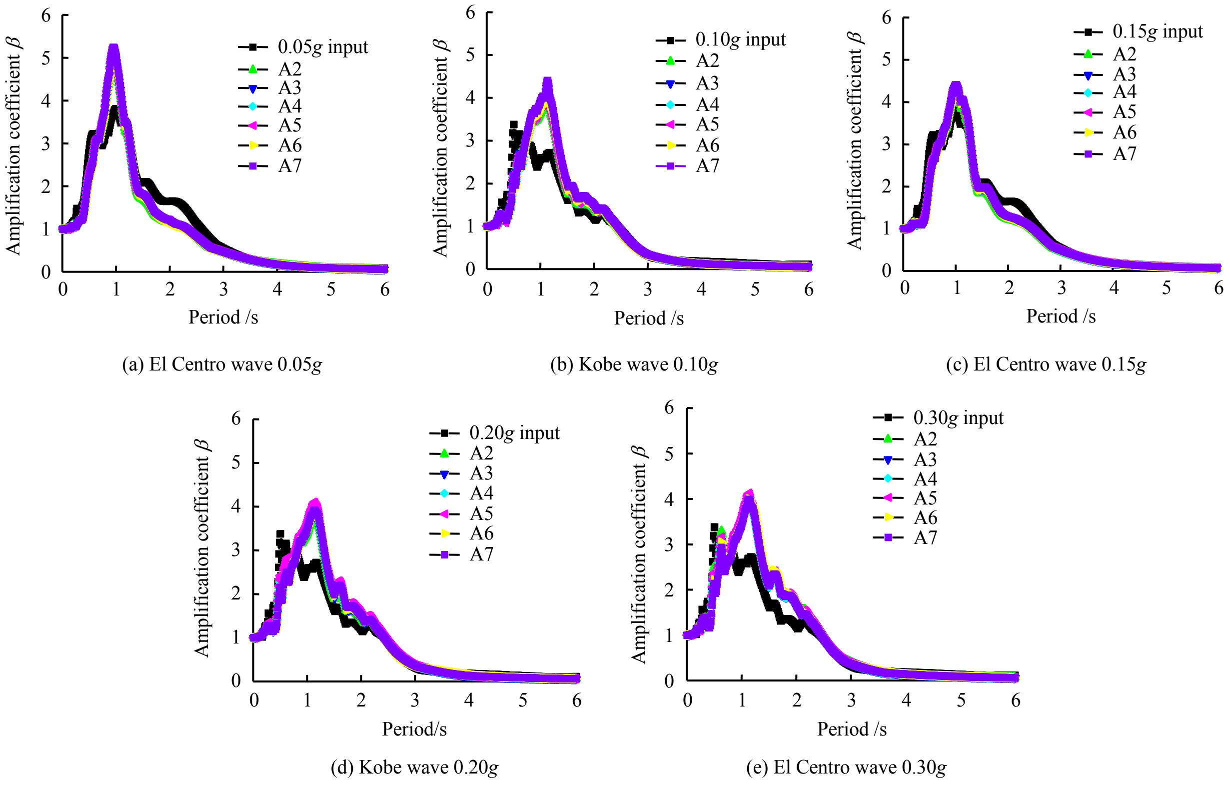


Fig.5 PGA amplification curve of bedrock site

Fig.6 shows the response spectrum curves of each monitoring point under different input ground motions. It can be seen that the spectral features are quite different between the El Centro and the Kobe waves. For the high frequency portion of the El Centro wave (period < 1 s), the amplitude is higher than that of the Kobe wave. Compared with the response spectrum of the El Centro wave, a shorter and wider spectrum is observed for the Kobe wave. This also explains the reason why the aforementioned El Centro wave has a higher magnification factor than that of the Kobe wave in Model 1. In general, the Model I site has a significant amplification effect on the ground motion within a period of 0.7–1.5 s, while it has a suppression effect on the ground motion within a period of 0.5–0.7 s. Besides,



(a) El Centro wave 0.05*g* (b) Kobe wave 0.10*g* (c) El Centro wave 0.15*g*

(d) Kobe wave 0.20*g* (e) El Centro wave 0.30*g*

Fig.6 The acceleration β spectrum curves of bedrock site under different input ground motion intensities

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small differences are observed for the shape of the response spectrum at different locations. The different locations have a little influence on the spectrum shape, which indicates that different locations of the trapezoidal bedrock valley site have little effect on the response spectrum.

4 Ground motion response rule of Model 2

To analyze the amplification effect of the trapezoidal valley site on the ground motion, the magnification factor of each monitoring point is calculated, as shown in Fig.7. Table 2 gives the mean record value of each monitoring point at different model terraces. It should be noted that the data of the A13 sensor is not included in the analysis due to the outlier data. It is seen from Fig.7 that the magnification factor of ground motion is obviously increased at the bedrock surface of the bedrock-soil model. The different magnification factors are observed under different input ground motions. Compared with the magnification factor of the monitoring point for the pure bedrock valley site Model 1, the magnification of each monitoring point of the Model 2 is higher than that of the Model 1 except the monitoring point 5. From Tab.2, the higher the bed rock terrace, the greater the magnification factor of the ground motion, while the difference is not large (the difference is about 6%). It is therefore to conclude that the valley terrain has a certain impact on the magnification effect of the ground motion, while the impact is not significant.

Fig.8 shows the acceleration β spectrum curves of the bedrock surface under different input ground motion intensities. It can be seen that the spectral curves are clearly different for different site locations, which indicates the seismic responses of different site locations are different and thus the ground motion features are also different. For the wave portion of period 0.5−2.5 s, an obvious amplification effect is observed for most of the site locations except the points A1 and A2. The frequency domain of ground motion amplification is obviously increased, which is different from the pure bedrock site case (little difference is observed for the response spectrum of each field site for the pure bedrock case). Although the shape of the response spectrum is somewhat different for each field site, the plateau values and the characteristic periods show little difference for these field monitoring sites.

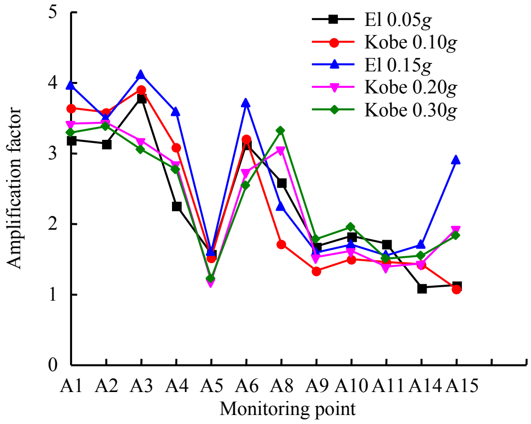


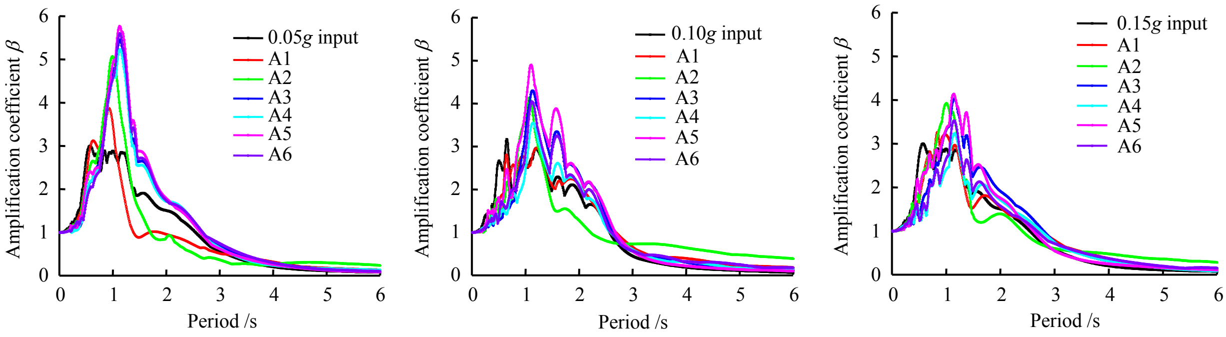
Fig.7 PGA amplification curves of river valley site

In summary, due to the reflection and refraction of the seismic wave at the interface during the propagation process, the ground motion will be significantly amplified at the interface of the dual structure site, while the magnification factor of each site location shows small variations (Tab.2). At the same time, the shape of the response spectrum is different at various locations, which also results in the different seismic characteristics.

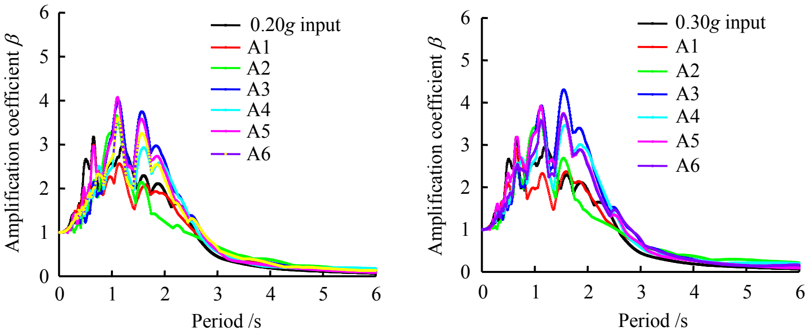
For the river valley sites, the magnification of peak acceleration changes as the valley terrain varies. In general, the higher the terrace, the larger the magnification, and the smallest magnification is found at the valley floor, which is not be influence by the input intensity of the ground motion. From Tab.2, it is seen that the mean magnification values are 2.09, 1.63, and 1.33 for the second terrace, first terrace, and the valley floor under different input ground motion intensities. Compared with the valley floor, the magnification factors of the second and first terrace are 1.57 and 1.22 times of the valley floor, respectively. According to the previous research results, obvious site amplification effect on the ground motion has been reported when the overlying cover is thicker. In this study, the overlying cover thickness of the Model 2 does not show much difference expect relatively thicker cover at the valley floor compared that with other sites. However, the magnification factor at the valley floor is relatively smaller than that of the other sites, which indicates that the valley terrain topography effect could cause the increasing of terrace magnification.

Table 2 PGA amplification of river valley site

Input seismic ground motion		PGA amplification factor					
		El Centro0.05g	Kobe0.1g	El Centro 0.15g	Kobe0.2g	Kobe0.3g	Mean value
Bed rock surface	Second terrace	3.17	3.61	3.72	3.43	3.34	3.46
	First terrace	3.03	3.50	3.85	3.01	2.91	3.26
	Valley floor	3.13	3.21	3.71	2.74	2.55	3.07
Valley site	Second terrace	2.14	1.53	1.92	2.30	2.55	2.09
	First terrace	1.78	1.48	1.63	1.51	1.73	1.63
	Valley floor	1.20	1.27	1.47	1.31	1.41	1.33



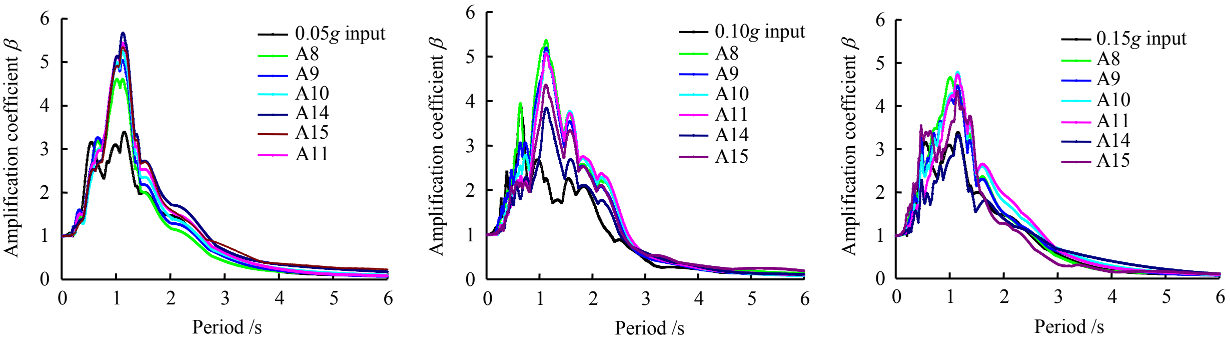
(a) El Centro wave 0.05*g* (b) Kobe wave 0.10*g* (c) El Centro wave 0.15*g*



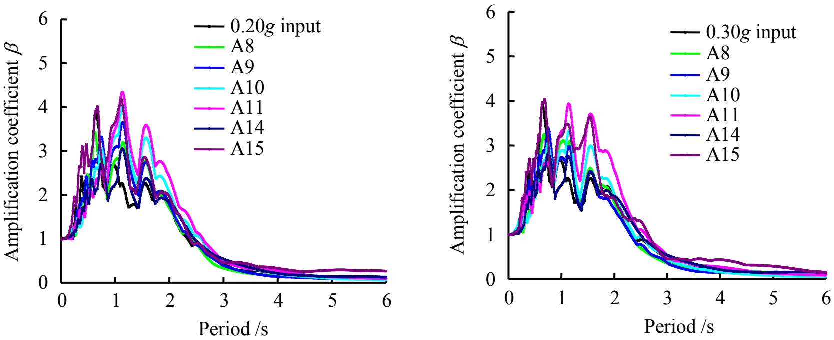
(d) Kobe wave 0.20*g* (e) Kobe wave 0.30*g*

Fig.8 The acceleration *β* spectrum curves of bedrock surface in river valley site under different input ground motion intensities

Figure 9 shows the acceleration spectrum of each monitoring point on the surface of Model 2. It is seen that the characteristics of the surface ground motion are different under different input earthquake intensities and different site locations. The input peaks of ground motion of 0.05 *g* and 0.15 *g* are set as El Centro wave, the input peaks of ground motion of 0.10 *g*, 0.20 *g*, and 0.3 *g* are all set as Kobe wave. Only the related peak values are changed for all the above-mentioned input waves without changing the corresponding spectral feature, however, the recorded surface acceleration spectrum curves show obviously differences. With the increase of the input ground motion intensity, in general, the overall shape of the response



(a) El Centro wave 0.05*g* (b) Kobe wave 0.10*g* (c) El Centro wave 0.15*g*



(d) Kobe wave 0.20*g* (e) Kobe wave 0.30*g*

Fig.9 The acceleration *β* spectrum curves of surface in river valley site under different input ground motion intensities

spectrum changes from a tall and thin shape to a short and wide shape. This observation denotes that the soil non-linearity is strengthened gradually, the amplification effect of the surface ground motion is reduced, and the amplification range of frequency domain is increased. The influence of river valley terrain on the ground motion response is reflected by the higher plateau value and the longer characteristic period of the response spectrum for a higher terrace level.

As for the trapezoidal valley sites, different terrace locations have different ground motion amplification effects and spectrum characteristics. The current aseismic design code does not have a full consideration of the site effect, nor recommend a corresponding adjustment method for the designed ground motion parameter. This will lead to a potential risk to the buildings built on the river valley sites.

5 Conclusions and discussion

(1) The bedrock river valley site has a certain amplification effect on the ground motion. The amplification effect varies with the terrain changes. In general, the amplification effect of the terrace location is greater than that of the valley floor location. The amplification effect is not significant and the difference of amplification effect in site locations is also small. However, the spectrum features of ground motion have an obvious impact on the amplification effect. Hence, only considering the designed magnitude of earthquake is insufficient in the aseismic design, which could increase the potential risk greatly.

(2) In this study, it is found that the model of bedrock river valley site has an obvious amplification effect on the ground motion within a period of 0.7–1.5 s, while it has a suppression effect on the ground motion within a period of 0.5–0.7 s. However, different site locations of the trapezoidal bedrock valley site have little effect on the response spectrum.

(3) For the bedrock-soil model, it is found that the magnification factor of ground motion is increased at the bedrock surface. Different magnifications are observed under different input ground motions. Besides, the spectral curves are different for different site locations and an obvious amplification effect is observed for most of the site locations for the wave portion within the period 0.5–2.5 s. The frequency domain of ground motion amplification is increased, which is different from the pure bed rock site case. Although the shape of response spectrum varies from site to site, the plateau values and the characteristic periods show a negligible difference.

(4) The terrace magnification increases due to the river valley terrain effect. The magnification of peak acceleration changes as the valley terrain varies. A higher terrace leads to a larger magnification factor, and the smallest magnification is found at the valley floor, which is not influenced by the input intensity of the ground motion. With the increases of input ground motion intensity, it is found that the higher terrace level, the higher the plateau value and the greater the characteristic period of the response spectrum.

For the trapezoidal valley site model in this study, it should be noted that although the ground motion response law is obtained using the designed two sets of geotechnical centrifuge shaking table test, the test results are not comprehensive to fully reflect the ground motion effect of the river valley site due to many limitations such as the few numbers of model test, the small scale of the model (i.e., simulated valley width < 64 m, simulated net estuary width < 48 m), and no water and current is considered in this study. For future studies, the model test of river valley site should be continuing to conduct. The influence of slope angle, depth-to-width ratio, and overlying layer thickness on the ground motion should be studied systematically. At the same time, the test results also should be used to test the reliability of the numerical simulation method. Once the numerical modelling is verified and calibrated, it is then used to study the ground motion systematically for the river valley site. The reasonable seismic design parameters could be obtained for the river valley sites and thus apply it to the aseismic design.

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