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Ground Motion Effect of River Valley Sites Based on FLAC3D Numerical Simulation

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Abstract. The study of ground motion effects at river valley sites is an important guide to site selection and seismic design. In this paper, FLAC3D numerical simulation is used to explore the influencing factors of a river valley site. By selecting four influencing factors with different input ground motion spectrum characteristics, ground motion intensities, site slope angles and depth-to-width ratios, orthogonal test forms are designed to determine the calculation conditions, and numerical simulation analysis is conducted. The study obtains the ranking of influencing factors for the top section of the slope, slope section and valley bottom section at different locations of the river valley site. The main influencing factor is the spectral characteristics of the input ground motion; the main influencing factor of the slope section and the valley bottom section is also the spectral characteristics of the input ground motion; and the overall analysis of the amplification effect pattern of the trapezoidal valley site shows that the amplification effect of the valley bottom site is the smallest and that the amplification of the slope top site is the largest.

Keywords. River valley, seismic effect, numerical simulation, influencing factors

1. Introduction

Successive seismic surveys have shown that river valley sites have an important influence on seismic damage. The Wei River valley site in the 8.5 magnitude earthquake in Haiyuan, Ningxia in 1920, the Qujiang River valley in the 7.7 magnitude earthquake between Tonghai and Eshan in Yunnan Province in 1970, and a section of the Sanji River valley in the Haicheng earthquake in Liaoning in 1975 all showed seismic ground motion anomalies [1]. The 2008 "5.12" Wenchuan earthquake caused severe damage and high-intensity anomalies in Hanyuan County, and studies have shown that the river valley topography has an important influence on Hanyuan's seismic rarity [2]. In addition, the river valley site leaves of rivers such as Anchang

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Town An Yi River, Shifang City Shiting River, Baishui River in Gansu, Ful River in Pingwu County, Daba Mountain River in Qingchuan, Dongyang River in Qingchuan and Jianjiang River in Wenchuan earthquake showed different seismic damage at different site locations, proving again that river valley sites have a predominant influence on seismic ground motion [3].

China's topography is complex, with a vast mountainous area, accounting for 2/3 of the total area of the country, and with the extension of the terrain and river development, there are a large number of river valley cities in the western part of China, such as Lanzhou, Chongqing, the Loop Plain, and the Fen River Valley. With the continuous economic development in the western region, many important buildings are built on the half-waist of river valley sites, and the current seismic design codes in China do not make clear provisions for the ground motion parameters of river valley sites, leaving potential dangers for the seismic protection of buildings. Due to the limitation of insufficient basic information and related research results, there is still a certain gap in the application of seismic design codes, and much research work is still needed. Therefore, it is necessary to carry out research on the seismic effects of river valley sites.

With the emphasis on historical large earthquake investigations and poster earthquake field investigations, as well as the collection and accumulation of the data of previous earthquakes, the effect of river valley topography has received increasing attention from the majority of scientific and technical workers, and the research methods mainly include the empirical methods of strong motion observation, analytical analysis and numerical simulation methods. With the development of computer technology, numerical methods are increasingly used in the field of engineering. Numerical methods are able to consider the effects of a variety of complex factors, which mainly include the finite element method (FEM) [4-5], finite difference method [6-7] and boundary element method. One of the advantages of the FEM and finite difference methods is the fine simulation of the medium material, so many scholars have used this type of method to study the effect of river valley sites. Corine Frischknecht & Jean-Jacques Wagner et al. [8] developed a two-dimensional model using numerical analysis of the Rhone Valley site in Switzerland, and their results were analyzed against the results of the one-dimensional model, yielding a two-dimensional model magnification result approximately twice as large as the one-dimensional model result. Paola Bordoni et al. [9] analyzed the seismic response of the city of L Aquila using two-dimensional numerical simulations and compared the analysis with the strong seismic recording spectral ratio of the actual earthquake to derive the low- and high-frequency amplification of the site. Zhang Xiaobo and Jing Liping et al. [10] simulated the topography of the Zhongxian Yangtze River Bridge valley and the expansive Jiedu Bridge valley by $FLAC^{3D}$, and the results showed that there was basically no amplification at the valley floor and that the amplification was prominent at the topographic relief; when the model soil was nonlinear, the input seismic ground motion intensity was higher and the amplification lower.

In this paper, a finite difference approach is used to explore the influencing factors of river valley sites through the $FLAC^{3D}$ numerical simulation method. Considering the influencing factors of the river valley site comprehensively, orthogonal tables are designed, and a verified numerical simulation method is used to establish the site model and analyze the site influencing factors. Using extreme difference analysis, the degree of influence of each influencing factor on the amplification effect of the river valley site is given for the slope top section, slope section and valley bottom section.

2. Calculation Method

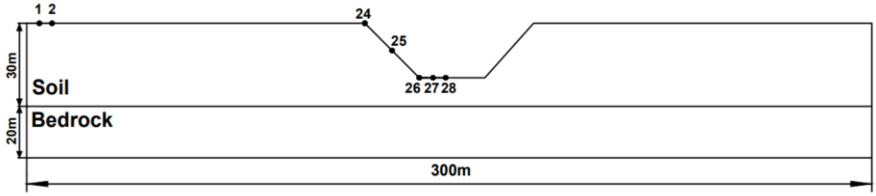
The numerical simulation program used in this paper is FLAC^{3D} (Fast Lagrangian Analysis of Continua), derived from the 3D Fast Lagrangian Analysis program developed by ITASCA Consulting Group, Inc. The mathematical model used for the calculation principle is based on the basic principles of elasto-plasticity theory.

In this paper, the bedrock material is modeled as an isotropic elastic material, and the soil is modeled as a rational elastic–plastic Coulomb-Moore intrinsic relationship material. The boundary conditions are selected as a rigid boundary at the bottom, the boundary conditions may not be set at the bottom, and the free boundary is selected on both sides. Acceleration time-course input is converted to stress time-course input. The damping form adopts Rayleigh damping, and a simple method of determining the central frequency is chosen to perform dynamic calculations in the elastic state to finally determine the minimum central frequency of the bedrock, with the critical damping ratio set at 2% and the critical damping ratio of the soil body at 5%.

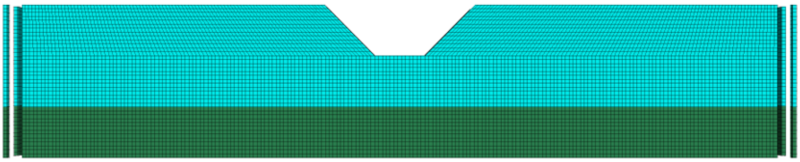
3. River Valley Site Impact Factor Study

3.1. Computational Models

At present, scholars worldwide investigating river valley site topography mainly simplify the site topography and then analyze it. This paper uses a simplified first-order trapezoidal river valley site model, as shown in figure 1. The lower part of the soil layer is bedrock, and the upper part is the soil body. The thickness of the site cover soil layer is 30 m, the depth of the valley bottom is 20 m, and the width of the valley bottom is changed to achieve a depth to width ratio of 0.5, 1 and 2. The slope angle is set to 30°, 45° and 60°. The total length of the site model is 300 m, and the thickness of the bedrock is 20 m. The monitoring points are calculated at 4 m intervals, and 24 monitoring points are set for the platform section at the top of the slope, 1 monitoring point for the slope section and 3 monitoring points for the valley bottom to analyze the difference in the ground motion response of each section of the site. The 3D model is established and meshed for the river valley site, and the maximum mesh size is determined to be 2.5 m according to the wave propagation speed, as shown in figure 1(b). According to the existing geotechnical names and properties used to determine the shear wave velocity, as shown in table 1, the bedrock, soil shear modulus, bulk modulus, and input parameters are as shown in table 2. The critical damping ratio is set to 0.05, and the center frequency is set according to the self-oscillation frequency of the site.



(a) Monitoring point location



(b) Numeral model

Figure 1. River valley site model.

Table 1. Model basic parameters.

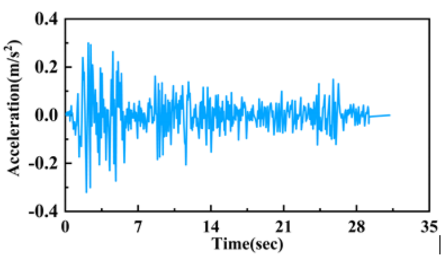
Soil type	Soil layer	Bedrock
ρ (kg/m^3)	1850	2200
Shear modulus(Pa)	250	800
Poisson ratio	0.3	0.22

Table 2. Model input parameters

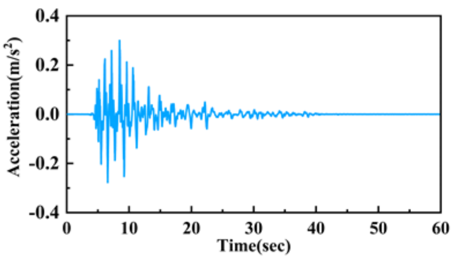
Parameters	Bedrock parameters	Soil parameters
ρ (kg/m^3)	2200	1850
Bulk modulus (Pa)	2.04E+09	2.5 E+08
Shear modulus (Pa)	1.408E+09	1.15E+08

3.2. Input Ground Motion

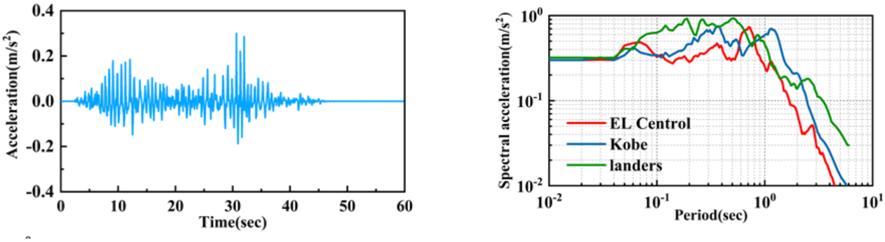
In this paper, El Centro, Kobe, and Landers ground motions are selected as the input ground motions, the original ground motions are baseline corrected and filtered using bandpass filtering to 0.1-25 Hz, and then amplitude modulation is performed to adjust the ground motion amplitudes to 0.10g, 0.20g, and 0.30g. El Centro ground shaking is taken as input for the first 35 s of ground shaking input, Kobe ground shaking is taken as input for the first 40 s of ground shaking input, Landers ground shaking is taken as input for the first 60 s of the time interval, and the time interval is set to 0.02 s, as shown in figure 2.



(a) El Centro



(b) Kobe



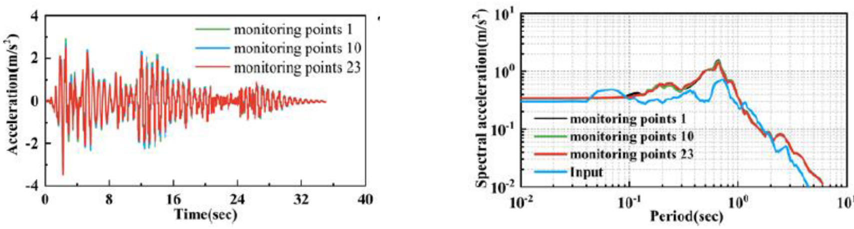
(c) Landers (d) Spectral acceleration

Figure 2. Input seismic ground motion and response spectrum.

3.3. Analysis of the Results of Influencing Factors

3.3.1. Analysis of the Results of the Top Section of the Slope

The analysis of different influencing factors of the site is carried out for the generalized first-order river valley site model. The site amplification is mainly determined by the ratio of the peak ground motion acceleration at the surface of the site monitoring point to the peak input acceleration at the monitoring point. To analyze the response characteristics of different slope sections, the site amplification effects are given for the top, slope and bottom of river valley slopes. Due to the large amount of monitoring data, only the monitored acceleration time curves of monitoring points 1, 10 and 23 are given in this paper. To investigate the spectral characteristic pattern of the site, the time-course curve is subjected to response spectrum analysis. The waveforms and response spectra of different monitoring sections in the top section of the slope are shown in figure 3 (only the time-course curves and response spectra of El Centro ground motion are given in this paper due to space limitations). The acceleration response is maximum at the monitoring position of point 1 and then shows a decreasing trend. From the analysis of the response spectrum, the shape of the response spectrum changes from "multipeak" to "single-peak" under the three seismic wave inputs, which is related to the fact that only the elastic phase is analyzed in the soil simulation, and the main period of the response spectrum is concentrated between 0.5 s and 1 s under the three ground motion inputs. The site amplification for the trapezoidal river valley site is shown in figure 4. Conditions 1, 4 and 7 have significantly smaller amplification than other conditions, and the results of the input ground motion as Kobe ground motion spectral characteristics on the river valley site are significant for these three conditions.



(a) El Centro strong ground (b) El Centro response spectrum

Figure 3. Strong ground motion time history curve at the top of slope and response spectrum.

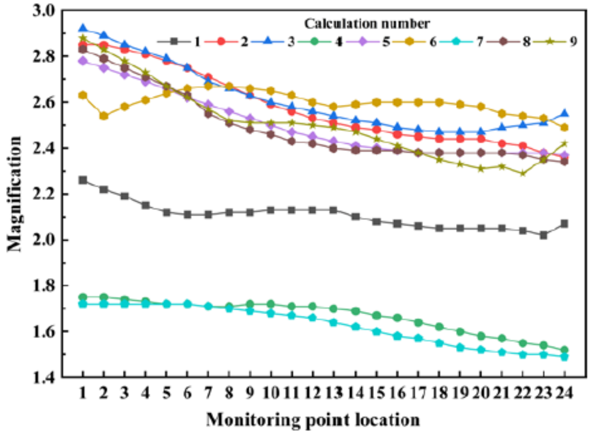


Figure 4. Magnification of each monitoring point.

According to the orthogonal test design analysis method, the test results are subjected to analysis of extreme differences and ANOVA. The results of the range at position 1 are obtained from the range as shown in table 3. In the table, K1 is the sum of the magnification of 8.03 for all working conditions at position 1 and factor level 1, and the other results are obtained in the same order. In addition, k1-3 indicates the average value corresponding to each level, and the calculation is expressed as k1=K1/S. S indicates the number of occurrences of this factor level, and the number of occurrences of this factor level is 3, so k1 can be obtained as 2.68.

Table 3. Monitoring point 1 extreme difference analysis results.

Calculated items	Factors			
	A	B	C	D
K1	8.03	5.73	7.77	7.92
K2	7.16	8.46	7.48	7.2
K3	7.43	8.43	7.42	7.5
k1	2.68	1.91	2.59	2.64
k2	2.39	2.82	2.49	2.40
k3	2.48	2.81	2.47	2.50
Range	0.29	0.91	0.12	0.24
Influence ranking	2	1	4	3

Table 4. Ranking of impact factors for different monitoring sites.

Location/m	Factors			
	Input seismic ground motion	Spectral characteristics	Inclination	Depth-width ratio
4	2	1	4	3
8	2	1	4	3
12	2	1	4	3
16	2	1	4	3

Location/m	Factors			
	Input seismic ground motion	Spectral characteristics	Inclination	Depth-width ratio
20	2	1	4	3
24	2	1	3	4
28	2	1	3	4
32	2	1	3	4
36	2	1	3	4
40	2	1	3	4
44	1	2	3	4
48	2	1	3	4
52	2	1	3	4
56	2	1	3	4
60	2	1	3	4
64	2	1	3	4
68	2	1	3	4
72	2	1	3	4
76	2	1	3	4
80	2	1	3	4
84	4	1	2	3
88	2	1	3	4
92	2	1	3	4
Inflection point	2	1	3	4

The results of the extreme difference analysis were summarized to give the ranking of the impact factors of the river valley sites for different monitoring points as shown in table 4. The overall analysis of the spectral characteristics of the input ground motion is the most influential for the river valley site, followed by the input ground motion intensity, and finally the influence of the inclination angle and the depth-width ratio, which indicates that under certain input ground motion characteristics, the slope angle and the depth-width ratio of the site will be less influential in comparison, which may be related to the site model. For the first five monitoring locations, the degree of influence of the site's depth-to-width ratio is greater than that of the dip angle. As the location is closer to the bottom of the slope valley, the degree of influence of the dip factor of the site increases. At the position of 84 m, the degree of influence of spectral characteristics > dip angle > depth to width ratio > input ground motion intensity appears; at the position of 48 m, which is far from the bottom of the slope, the degree of influence of input ground motion intensity is the greatest. With different locations from the valley bottom, the ranking of site influence factors also changes, the overall performance of input ground motion spectral characteristics has the greatest degree of influence, and the geometric parameters of the site have a weaker influence.

3.3.2. Analysis of Slope Section Results

The analysis is similar to the previous one and is not repeated here. The magnification of the slope section of the river valley site is shown in table 5, and the results of the extreme difference analysis are shown in table 6. From the analysis of the magnification of the river valley site, the magnification of the slope section of the river valley site is notably smaller than the magnification of the platform section at the top of the slope, the topographic effect of the site is prominent, and the magnification effect changes with the location. From the extreme difference analysis, the trapezoidal valley site of the slope section is similar to the platform section and still shows the greatest degree of influence of the spectral characteristics of the input ground motion, but there are changes in the ranking of the influencing factors as the degree of influence of the spectral characteristics, the depth to width ratio, the intensity of the input ground motion, and finally the change in the dip angle of the site, and the ranking of the influencing factors within the site is advanced.

Table 5. Monitoring point 25 magnification.

Location/*m*	Calculation number								
	1	2	3	4	5	6	7	8	9
25	1.34	2.09	2.19	1.37	2.1	2.09	1.36	2.33	2.17

Table 6. Results of the analysis of extreme differences at monitoring point 25.

Calculated items	Factors			
	A	B	C	D
K1	5.62	4.07	5.76	5.61
K2	5.56	6.52	5.63	5.54
K3	5.86	6.45	5.65	5.89
k1	1.87	1.36	1.92	1.87
k2	1.85	2.17	1.88	1.85
k3	1.95	2.15	1.88	1.96
Range	0.10	0.82	0.04	0.12
Ranking of influencing factors	3	1	4	2

3.3.3. Analysis of the Results of the Trough Section

Based on the analysis of the numerical simulation results, the results of the magnification of the valley bottom are shown in table 7, and the ranking of the influencing factors of the valley bottom is shown in table 8. From the analysis of the ground motion amplification, the amplification of the valley bottom section of the river valley site is smaller than that of the slope top platform section and the slope section as a whole. Under the effect of the input El Centro ground motion, the amplification does not have a significant decreasing trend in the valley section; the amplification effect is less variable in the valley section as the position changes. After the extreme difference analysis, the ranking of the valley bottom influence factors is given. As seen from table 8, the main influencing factor of the trapezoidal river valley site in the valley bottom section is the spectral characteristics of the input ground motion, and the ranking of the influencing factors is different from that of the slope section. The influence of the geometric factors of the river valley site becomes greater, the influence ranking of the dip angle and depth to width ratio increases, and the influence of the input ground motion intensity gradually decreases. At the inflection point between the slope and the valley bottom section, the degree of influence of the dip angle increases, and in the valley bottom platform section, the degree of influence of the deep to wide ratio is the main factor.

Table 7. Valley magnification.

Location/*m*	Calculation number								
	1	2	3	4	5	6	7	8	9
26	1.28	1.94	2.53	1.3	1.8	2.53	1.26	2.01	2.53
27	1.52	1.79	2.6	1.24	1.82	2.71	1.23	1.72	2.6
28	1.58	1.79	2.69	1.18	1.83	2.73	1.23	1.7	2.61

Table 8. Ranking of valley impact factors.

Location/*m*	Factors			
	Input seismic ground motion	Spectral characteristics	Inclination	Depth-width ratio
26	4	1	2	3
27	3	1	4	2
28	3	1	4	2

3.3.4. River Valley Site Magnification Analysis

Based on the above research analysis, the amplification of the entire river valley terrain is averaged, and the results of the amplification effect of the trapezoidal river valley site are given visually in figure 5. The summary of the calculated results reveals that the amplification at the bottom of the valley is the smallest and the amplification at the top of the slope is the largest. There is a tendency for the magnification of the site valley location to increase under the action of El Centro ground motion.

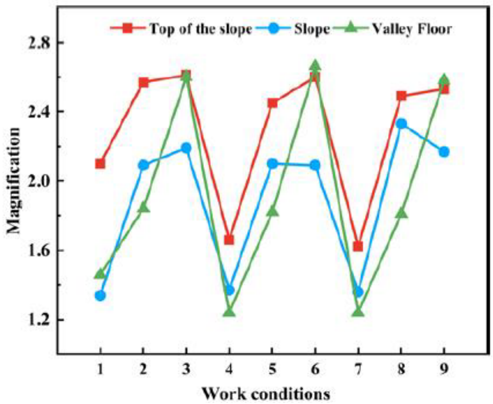


Figure 5. River Valley site magnification.

4. Conclusion and Discussion

In this paper, the FLAC^{3D} numerical simulation method is used to study the influencing factors of river valley sites. The ranking of the factors influencing a river valley site on ground motion was obtained. To input different ground motion spectral characteristics, ground motion intensities, site slope angles, and depth-width ratios, four influencing factors were selected. Using the orthogonal test form, the computational conditions were designed, numerical simulations were performed, and the following conclusions were obtained.

(1) Top-of-slope segment: The amplification of the site tends to decrease as the distance from the valley slope position decreases. The influencing factors of the slope top section, whose main influence is the spectral characteristics of the input ground motion, are followed by the intensity of the input ground motion. At a distance of 24 m, the influence ranking of dip angle and depth-to-width ratio changes, revealing the influence of the degree of site geometry parameters on the results. The spectral characteristics were analyzed for the ground motion time range of the monitoring sites, and the main period of the site is found to be 0.5 s-1 s.

(2) In the slope section as well as the valley bottom section, the ranking of the influencing factors produces changes, and the most important influencing factors are still the input ground motion spectrum characteristics, in order of the depth to width ratio, dip angle, and input seismic ground motion intensity, and the geometric parameters of the site model become more influential compared with the case of the slope top section.

(3) The overall analysis of the amplification effect law of the trapezoidal valley site shows that the amplification effect of the valley bottom site is the smallest and that the amplification of the slope top is the largest.

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