3-D Shaking Table Model Test Study on Dynamic Response of Composite Block Slope with Complex Structural Planes

Xu Jianrong¹, Lai Daoping¹*, He Mingjie¹, Zhang Boyan²
¹Powerchina Huadong Engineering Corporation Limited, Hangzhou, Zhejiang 311122, China
²China Institute of Water Resources and Hydropower Research, Beijing 430071, China
*Corresponding author’s e-mail: lai_dp@ecidi.com

Abstract. A large 3-D dynamic model test with scale 1:200 for block slope combined by complex structural planes is designed. The test model is composed of slope and damping boundaries. The model slope with a thickness of 1.5 m, a length of 2.95 m, a height of 1.91 m weighs about 20t, and its volume is around 6.45 m³. The block is combined by three structural planes, with volume of 0.174m³ corresponding to prototype volume of 1.39×10⁶m³. The dynamic characteristics and responses of model slope are studied by inputting white noises and different seismic waves. Test results show that natural frequencies of the slope model are almost not influenced by shaking before failure, but damping ratios increase after shaking. The distribution law of peak acceleration amplification factors along the slope height is basically similar under the action of different seismic waves. The amplification effect is significant around the crest of the slope and amplification factors are equal to 1.0 almost at the middle and bottom of the slope. Acceleration amplification effects of the block are not significant, but they are significant around the corners cut by structural planes. The test results can be used as a good reference for the seismic design of composite block slopes.

1. Introduction
Seismic-induced slope landside is one of the main types of seismic geological hazards. In mountainous and hilly areas, earthquake-induced landslides are often characterized by wide distribution, large quantities, and high damage. The 5.12 Wenchuan Earthquake in 2008 induced a large number of landslides, causing huge economic losses and casualties. According to statistics [1], the secondary disaster losses caused by the Wenchuan earthquake landslide accounted for about 1/3 of the total earthquake losses. The analysis of seismic slope stability has become one of the important topics in the geotechnical engineering and seismic engineering industry.

At present, the commonly used methods for seismic stability analysis of slopes are the rigid body quasi-static method and the dynamic finite element method [2], which have not been widely accepted. In particular, the dynamic amplification effect of the inertial force of the slope earthquake is related to the bank slope and its position. Currently, there is not much measured and systematic research data. Therefore, in order to provide a scientific basis for seismic stability analysis of slopes, it is necessary to conduct in-depth research about the dynamic response characteristics and variation patterns of slopes under earthquake action.
The dynamic response of the slope includes acceleration, velocity, displacement, dynamic strain and dynamic strain response. Among them, the acceleration response of the slope and its distribution pattern are the most fundamental data for evaluating the seismic dynamic response of the slope. The seismic dynamic response of the slope is closely related to the slope’s ground motion characteristics. The ground motion characteristics generally include three aspects: ground motion intensity, spectrum characteristics and time duration. The influence pattern of the slope’s dynamic response is a very important problem.

Some scholars [3~7] obtained the results of some seismic dynamic response patterns of slopes through mathematical simulation, but the patterns of the results are not consistent, and the verification of the actual ground motion response monitoring or test is still needed. To this end, a small number of scholars have conducted shaking table tests for ground motion response. By studying a 1:10 model with a height of about 21 m and a slope of about 38 degree, Xu Guangxing and other scholars[8] used the shaking table to study the dynamic characteristics, dynamic response, and the influence of ground motion parameters on dynamic characteristics and dynamic response. Xu Qiang [9] designed valley models composed of two single slopes to study the influence of seismic force direction, slope structure and slope morphology on the deformation and failure of slopes under strong earthquakes. Lin[10] studied the dynamic response of a 30 homogeneous mid-sand slope model. Li Zhensheng [11] studied the dynamic response of steeply stratified rock slopes using a shaking table. Wang Bin [12] designed a large-scale shaking table test for rocky high-steep slope with discontinuous joints.

The above scholars have shown that the dynamic response of the slope under strong earthquakes is affected by many factors, especially the slope structure.

Dynamic response and stability of the giant block formed by combination of structural surfaces, which locate in the left bank plunge pool slope of the Baihetan Hydropower Project, is a key technical issue. The dynamic response of the block slope formed by combination of structural surfaces have not been studied by using the shaking table. Therefore, based on the seismic stability study of the structural block of the left bank slope of Baihetan Hydropower Station, a three-dimensional shaking table model is designed to test the dynamic response of the slope under different dynamic loads. The test results are analyzed and the dynamic response pattern of the slope is proposed.

2. Dynamic model test design

2.1. The characteristics of shaking table
The equipment used in this test is the shaking table designed by the Engineering Research Center of Earthquake Research, China Institute of Water Resources and Hydropower Research. The load capacity and vibration performance of the shaking table are at the advanced level all around the world. It has been carried out for many power test for those 300m high arch dams which were successfully built in China.

The size of the shaking table is 5mx5m, the maximum load weight is 20 tons, the frequency range is 0.10 to 120Hz, and the 3-way translation and 3-direction rotation are added. At full load, the horizontal maximum acceleration is 1.0G, and the vertical maximum acceleration is 0.7G. The maximum horizontal displacement is ±400mm and the maximum vertical displacement is ±300mm.

2.2. Similarity
The slope of the left bank plunge pool of Baihetan Hydropower Station is about 550m along the river, 540m horizontally across the river, and 385m vertically. The slope stability is controlled by 1# block, which is cut by unloading cracks J110, faults f114 and shear cutting planes LS137. The size of the block is about 246m horizontally across the river, about 450m along the river, and about 240m vertically. The basic characteristics are shown in Figure 1.

The test can only be carried out under constant gravity field condition, the acceleration ratio $C_a$ is taken as 1.0, and the density ratio $C_p$ is taken as 1.0. The total weight of the model slope rock mass including 1# block and damping boundary is about 20tons, and the model geometric scale is 1:200.
2.3. Model making

The test model includes slope rock mass, 1# block and damping boundary. The size of the model slope is 220cm across the river, 295cm along the river, and is 191cm in height. The total volume of the model is 6.45 m³, of which the volume of the block is 0.174 m³. The slope rock mass and the block are made of special weighted rubber whose density is 2400kg/m³.

The shear strength of the structural face includes the shear friction coefficient f and the shear cohesion c. The similarity ratio of the friction coefficient f is 1, and the ratio of the shear cohesion c is 200. In the model, the cohesion is very small, so that it is difficult to directly measure and adjust the cohesion c, and it is easy to interact with the surface friction coefficient. The method of controlling the actual area is used in the model to show the comprehensive effect of cohesion. The parameters of the model and prototype are shown in Table 1. The bottom sliding surface LS₃₃₇ is contacted by test rubber and PTFE, and its friction coefficient is 0.38. The side sliding surface f₁₁₄ is made of test rubber and nylon smooth surface contact, and its friction coefficient is 0.5. Four circular holes with a diameter of 19 mm are arranged on the side sliding surface f₁₁₄, and 20 circular holes with a diameter of 25 mm are arranged on the bottom sliding surface LS₃₃₇. Gypsum is coated in the holes, and the bonding strength of the gypsum material is 11.87 N/cm², in order to achieve the corresponding cohesive force requirements between the side slip surface and the bottom slip surface.

| Cracks  | Strength parameters of prototype | Strength parameters of the model |
|---------|---------------------------------|---------------------------------|
| LS₃₃₇   | f = 0.38, c = 1220 Pa           | f = 0.38, c = 0.244 MPa        |
| f₁₁₄    | f = 0.50, c = 500 Pa           | f = 0.50, c = 0.100 MPa        |
| J₁₁₀    | f = 0.15, c = 0.00 Pa           | f = 0.15, c = 0.00 MPa        |

2.4. Damping boundary

As a semi-infinite body, the slope's vibrational energy is transmitted outward through the basic medium. Under the indoor test conditions, the test model can only select the limited range of the slope foundation, so the vibration energy radiation must be reasonably simulated on the finite-scale boundary of the artificial interception. This shaking table dynamic test uses the polymer viscous liquid shear damping boundary to simulate the radiation damping effect. This method has been applied in the shaking table test of the arch dam-foundation system and achieved good results, and the damping characteristics are easy to adjust. The viscous damping fluid’s damping boundary achieves a damping effect by utilizing the shear viscosity of the viscous liquid material.

The tangential damping coefficient c of the damping boundary and the liquid shear viscosity \( \eta \) has the following relationship:

\[
c = \rho v_s = \frac{\eta}{\Delta L}
\] (1)
- \( \rho \), \( v_s \) is the density and shear wave velocity of the model base medium, and \( L \) is the thickness of the viscous liquid.

The shear viscosity \( \mu \) of the measured liquid is \( 7.0 \times 10^3 \text{Pa·s} \). The elastic modulus of the basic material of this model is 169 MPa, and the thickness of the damping boundary \( L \) is 17 mm, which is slightly smaller than the actual calculation. The main compensation for the normal damping effect is considered. The outer part of the damping boundary in the test model is supported by a steel frame fixed to the shaking table, and the outer surface of the foundation is waterproofed to prevent the damping fluid from leaking. The test model and support boundaries are shown in Figure 3.

![Figure 3. Model and its support boundary](image)

![Figure 4. Installation layout of the accelerometers](image)

2.5. Earthquake acceleration response measurement

The seismic acceleration provided by the seismic department to the design refers to the peak acceleration of the surface. Therefore, the accelerometer is used to measure the acceleration response of the slope surface and the surface of the 1# block, and their installation positions are shown in Figure 4. Due to the large geometric scale of the test model, the sensors mounted on the slope surface are light in order to reduce the sensor’s influence on the model. One acceleration measurement point corresponds to three measurement channels, and the measurement points are measured along the slope direction (x direction), the transverse direction (y direction), and the vertical acceleration (z direction).

3. Input wave and loading resolution

The input wave mainly uses artificial seismic waves generated by the canonical spectrum. According to the design, the maximum horizontal acceleration is 212 gal, and the vertical acceleration is 141 gal that is \( 2/3 \) of the horizontal direction. The design seismic acceleration refers to the acceleration of the semi-infinite plane. According to the principle of seismic wave propagation, the seismic peak input at the bottom of the model should be half of the design’s peak and it can scale according to the characteristics of the shaking table and the model scale. The experimental vibration loads increased step by step. The peak acceleration of the input seismic wave is 0.778-7.0 times of the design’s acceleration, and we input the white noise to test the dynamic characteristics of the model after the earthquake. At the same time, in order to study the seismic dynamic response of the slope and the spectral characteristics of the seismic wave and the time-keeping relationship, the 1st design earthquake also uses the site wave and the Koyana wave. The x-direction design seismic wave, the site wave and the peak adjustment, the Koyana wave and the response spectrum are shown in Figures 5-7. The response spectrum of the site wave is the largest, and the response spectrum of the Koyana wave is the smallest. The test loading resolution is shown in Table 2.

| Test conditions | Relation to the design earthquake | Test conditions | Relation to the design earthquake |
|-----------------|-----------------------------------|----------------|-----------------------------------|
| 1-1             | White noise/0.05g                  | 8-1            | 2.0 times SPSW                    |
| 2-1             | 0.778 times SPSW                   | 9-1            | 3.0 times SPSW                    |
| 3-1             | 1 times SPSW                       | 10-1           | 4.0 times SPSW                    |
| 4-1             | 1 times site seismic wave          | 11-1           | 5.0 times SPSW                    |

Table 2 Seismic wave input scheme
5-1 1 times Koyana seismic wave 12-1 6.0 times SPSW
6-1 White noise/0.05g 13-1 7.0 times SPSW
7-1 1.5 times SPSW 14-1 White noise/0.05g

Figure 5 Specification seismic wave and its response spectrum

Figure 6 Site seismic wave and its response spectrum

Figure 7 Koyana seismic wave and its response spectrum

4. Dynamic characteristics of the slope model
In the beginning of this study, and after the 1 time and 7 times design seismic wave vibration input, the white noise three-way vibrations are inputted respectively, and the response accelerations are collected. The transfer function of the slope top acceleration measurement point (2xyz) to the table is calculated so that the basic dynamic characteristics of the model slope is acquired. The stimulation of white noise frequency ranges from 3.0 to 120Hz, and the data acquisition length is 180s. The FFT length in spectrum analysis is 4096, and the corresponding frequency resolution is 0.244Hz.

The frequency and damping ratio calculated from the three test conditions are shown in Table 4. It can be seen from the table that the frequency of the model slope along the x-direction, the transverse y-direction and the vertical z-direction are 18.80, 20.02 and 35.96 to 36.16, respectively. The x-direction damping ratio of the slope is 8.46% to 10.39%, the y-direction damping ratio of the transverse slope is 10.98% to 11.0%, and the vertical z-direction damping ratio is 12.21 to 12.89%. The vibration test has almost no effect on the fundamental frequency of the model slope, and has little effect on the damping ratio of the model slope. The damping ratio of the x direction and the z direction increases slightly after the 7 times design earthquake, and it can seem from the vibration test that the slope is slightly damaged.

Table 3  Basic frequency and damping ratio of the slope model

| Test conditions | x-direction |  | y-direction |  | z-direction |  |
|----------------|-------------|----------------|-------------|----------------|-------------|----------------|
|                | frequency (Hz) | damping ratio (%) | frequency (Hz) | damping ratio (%) | frequency (Hz) | damping ratio (%) |
| 1-1            | 18.80       | 8.49               | 20.02       | 11.00               | 35.96       | 12.21               |
| 6-1            | 18.80       | 8.46               | 20.02       | 10.98               | 36.16       | 12.54               |

a. SPSW means Specification seismic wave.
5. Acceleration response and pattern analysis

The investigation of the earthquake damage of the Wenchuan earthquake slope [13–15] shows that there is a very significant positive correlation between the peak acceleration of ground motion and the earthquake-induced collapse. With the increase of peak acceleration, the earthquake landslide disaster is also more serious. The dynamic amplification effect of the slope’s inertial force is related to the mountain structure and location. This paper analyzes the acceleration response of different parts of the block and the acceleration response along the height direction, and summarizes its pattern. The amplification factor of the peak acceleration PGA is defined as the ratio of the seismic peak acceleration of the slope surface to the corresponding multiple design seismic acceleration.

5.1. Block’s acceleration response and pattern analysis

The following patterns are obtained from the analysis and statistics of Figures 8 to 9:

- (1) PGA’s amplification factor is affected by block boundary characteristics

  The PGA amplification factor of the measuring point 8 in the middle of the block is the smallest among the 5 measured points in the block, the PGA amplification factor in the x direction and the y direction is between 0.7 and 0.9, and the PGA amplification factor in the z direction is about 1.0. The y-direction and z-direction PGA amplification factors of the measuring points 7 and 9 of the block’s two triangular portions are all above 1.0, and the PGA amplification factor in the z-direction is substantially larger than 1.3. It can be seen that the block boundary structure has an influence on the PGA amplification factor. The two triangle parts have weaker block constraints, and that is why the PGA amplification factor of the measuring points 7 and 9 is relatively larger than the measuring point 8.

- (2) The overall PGA amplification factor decreases as the amplitude of the input seismic wave increases

  Under the action of 2 times design earthquake to 7 times design earthquake, the x-direction PGA amplification factor of measuring points 5 and 6 at the upper part of the block is the largest, and the amplification factor reduced from 1.35-1.43 to 0.90-0.97. The z-direction PGA amplification factor of the measuring points 7 and 9 of the part reduced from 1.50-1.80 to 1.26-1.45. The PGA’s amplification factor of the measuring point 8 in the middle of the block is the smallest. The ground motion amplification factor of the weak part of the block decreases with the increase of the amplitude of the seismic wave. The reason is that the block’s damage and the damping ratio increase under the action of strong earthquake.

- (3) The PGA amplification effect of the block is not significant

  The PGA amplification effect of the measurement point 8 in the middle of the block under different multiple design seismic parameters is not significant, indicating that the coordinated deformation characteristics of the block and the surrounding slope are good.

  According to statistics, the average PGA amplification factor of the x-direction and y-direction of the five measuring points in the block is 0.92~1.08, and the average value of the PGA amplification factor in the z-direction is 1.06~1.28. Therefore, the average PGA amplification effect of the block is not significant.

![Figure 8](image_url)

Figure 8 Acceleration time history of gauging point 8 in the block under No.3-1 test condition
5.2. Analysis of acceleration response according to slope height

- (1) Analysis of response pattern of different types of seismic wave input

Under the action of three seismic waves of 1 time design earthquake, the distributions of the slope’s PGA amplification factor along slope height are shown in Figure 10. The input wave type has certain influence on the PGA amplification factor. The y-direction PGA amplification factor is less affected by the input seismic wave type and the PGA amplification factor is basically less than 1.0, because the y-direction constraint is stronger and the freedom degree is relatively low. The PGA amplification factor in the x-direction and the z-direction are relatively affected larger by the input seismic wave type. The law of seismic amplification factor under different wave type inputs is that the field wave is larger than the specification wave, and the specification wave is larger than the Koyana wave. The response spectrum of the site wave is the largest, the response spectrum of the Koyana wave is the smallest. The acceleration response is related to the response spectrum of the input seismic wave. The larger the response spectrum, the larger the amplification effect.

The PGA amplification factor in the middle of the slope body is about 1.0; the PGA amplification at the top of the slope is more obvious, especially in the x and z directions, and the amplification factor is between 1.18 and 2.22; The PGA amplification factor of the lower platform is larger than that of the middle part, which is caused by the frequency of the model platform being close to the frequency of the seismic wave. The average value of the PGA amplification factor of the measuring point 8 in the middle of the block is about 1.0.

- (2) Analysis of response pattern of seismic input with different amplitudes

Under the 0.778 times to 7.0 times design seismic wave, the distribution of slope PGA amplification factor along the slope height can be seen from Figures 11. It can be seen from the figure that under the action of different amplitude earthquakes, the variation law of the slope PGA amplification factor along
the slope height is basically the same: 1) The PGA amplification factor in the middle of the slope body is about 1.0, and the PGA amplification factors in the x, y, and z directions of the model slope with 0.6~1.8m in height are 0.77 to 1.26, 0.61 to 0.94, and 0.71 to 1.26, respectively. 2) The x-direction and z-direction PGA amplification factor of the top of the slope are between 1.47 to 1.72 and 1.46 to 1.85, respectively. The top of the slope faces the empty space, and the high degree of freedom of the slope body leads to a larger earthquake amplification factor.

As the amplitude of the input seismic wave increases, the PGA amplification factor generally shows a decreasing trend. The average value of the PGA amplification factor in the x-direction, y-direction and z-direction of the seven measuring points of the monitoring section, is reduced from 1.10, 0.87, and 1.15 under the action of 1.0 times design seismic wave, respectively, to 1.05, 0.78, 1.00 under the 7 times design seismic wave. The variation law of the PGA amplification factor is similar to that of the measured points in the block. It is also caused by slight damage and increased damping of the slope after strong earthquakes.

![Figure 11 PGA amplification factors along elevation under different seismic waves with different amplitudes](image)

6. Conclusions and discussion

In this paper, a large-scale three-dimensional shaking table model test of a complex structure face-cutting combined block slope with a scale of 1:200 is designed and completed, and key problems such as boundary condition processing and structural surface simulation in model test are discussed. We also studied the dynamic characteristics of the model slope and its variation with vibration, the acceleration response law of the slope block, the distribution law of the slope acceleration response along the slope height, and the influence of the type and amplitude of the seismic wave. The following conclusions are drawn:

1) The vibration test has no effect on the fundamental frequency of the model slope, and has little effect on the damping ratio of the model slope. The damping ratio of the x-direction and the z-direction increases slightly after the 7-times design earthquake, and the vibration test did slight damage to the slope block.

2) The PGA amplification effect of the block is not significant. The average PGA amplification factor in the x and y directions of the five measuring points in the block is 0.92~1.08, and the average PGA amplification factor in the z direction is 1.06~1.28. The boundary characteristics of the block have a great influence on the PGA amplification factor. The PGA amplification factor of the two triangular parts of the block is larger, and the PGA amplification factor of the middle part of the block is smaller. The average value of the PGA amplification factor decreases with the increase of the input seismic wave amplitude, which is related to the increase of the slope body damping ratio.
(3) Under the action of design seismic specification wave, site wave and Koyna wave, the input wave type has certain influence on the distribution law of PGA amplification factor along the slope height. The PGA amplification factor in the y direction is less affected by the seismic wave types, while its influence on the x and z directions is relatively large. The PGA amplification factor under the action of the site wave is the largest. The PGA amplification factor in the middle of the slope body is about 1.0, and the PGA amplification at the top of the slope is more obvious.

(4) Under the action of 0.778 times to 7.0 times of design seismic wave, the variation law of slope PGA amplification factor along slope height is basically the same. The PGA amplification factor in the middle is about 1.0, and the x-direction and z-direction PGA amplification factor of the slope top are between 1.47–1.72 and 1.46–1.85. As the amplitude of the input seismic wave increases, the PGA amplification factor generally shows a decreasing trend.

We can learn from the test that the distribution law of the slope PGA amplification factor along the elevation is consistent with the phenomenon of the instability of the slope ridges found in the Wenchuan earthquake slope damage investigation, that the seismic dynamic amplification effect of the slope top and the shoulder is obvious. The PGA amplification factor in the middle and lower slopes is about 1.0 on average. Therefore, when calculating the seismic stability of the slope by using the rigid body limit equilibrium method, under normal circumstances, the dynamic amplification effect of the slope inertial force can be temporarily ignored. The stability analysis of the slope top and the shoulder should adopt the dynamic method or consider the amplification effect, and adopt the anchoring support measures such as anchor bolt, anchor cable and lattice structure according to the stability analysis results. The block boundary has a significant impact on the seismic response, and it is advisable to strengthen the support of the exposed part of the structural surface.

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References
[1] Zheng Yingren, Ye Hailin, Huang Runqiu. Analysis and discussion of failure mechanism and fracture surface of slope under earthquake [J]. Chinese Journal of Rock Mechanics and Engineering, 2009, 28(8): 1714–1723.
[2] Energy Industry Standards of the People’s Republic of China. NB 35047–2015 Code for seismic design of hydraulic structures of hydropower project [S]. Beijing: China Electric Power Press, 2015.
[3] He Yunlong, Lu Shuyuan. A method for calculating the seismic action in rock slope [J]. Chinese Journal of Geotechnical Engineering, 1998, 20 (2): 66 - 70.
[4] Xu Guangxing, Yao Lingkan, Li Zhaohong, et al.. Dynamic response of slopes under earthquakes and influence of ground motion parameters [J]. Chinese Journal of Geotechnical Engineering, 2008, 30(3): 918–923.
[5] Bi Zhongwei, Zhang Ming, Jin Feng, et al. Dynamic response of slopes under earthquakes [J]. Rock and Soil Mechanics, 2009, 30Supp: 180–183.
[6] Qi Shengwen, Wu Faquan, Yan Fuzhang, et al. Rock Slope Dynamic Response Analysis. Beijing: Science Press, 2007.
[7] Massey C., Della Pasqua F., Holden, C., et al. Rock slope response to strong earthquake shaking [J]. Landslides, 2017, 14(1): 249-268.
[8] Xu Guangxing, Yao Lingkan, Gao Zhaoning, et al.. Large-scale shaking table model test study on dynamic characteristics and evolution of dynamic responses of slope [J]. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(3): 624–632.
[9] Xu Qiang, Liu Hanxiang, Zou Wei. Large-scale shaking table test study of acceleration dynamic responses characteristics of slopes[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(12): 2420–2428.

[10] M.-L. Lin, K.-L. Wang. Seismic slope behavior in a large-scale shaking table model test[J]. Engineering Geology, 2006, 86(2/3): 118-133.

[11] Li Zhensheng, Ju Nengpan, Hou Weilong, et al. Large-scale shaking table model tests for dynamic response of steep slope stratified rock slopes[J]. Journal of Engineering Geology, 2012, 20(2): 242–248.

[12] Wang Bin, Che Ailan, Ge Xiurun. Shaking table test on earthquake response of discontinuous medium high and steep rock slope[J]. Journal of Shanghai Jiao Tong University, 2015, 49(7): 951–956.

[13] Wang Xiuying, Nie Gaozhong, Wang Dengwei. Research on relationship between landslides and peak ground accelerations induced by Wenchuan earthquake [J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(1): 82–89.

[14] Xu Chong, Dai Fuchu, Yao Xin, et al. GIS based certainty factor analysis of landslide triggering factors in Wenchuan earthquake [J]. Chinese Journal of Rock Mechanics and Engineering, 2010, Supp(1): 2972–2981.

[15] Zhou Depei, Zhang Jianjing, Tang Yong. Seismic damage analysis of road slopes in Wenchuan earthquake[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(3): 565–576.