

# Geological Characteristics and Stability Evaluation of Wanjia Middle School Slope in Wenchuan Earthquake Area

Tian-shun Hou · Xin-gang Wang · Sibel Pamukcu

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**Abstract** To investigate the formation mechanism and the stability of Wanjia middle school slope in Wenchuan Earthquake Area, the macroscopic geological characteristics and the failure process of the landslide are researched by engineering geology analysis method, limit equilibrium method, and finite element method. The results show that after the Wenchuan Earthquake, retaining walls, houses and other infrastructure on the foot of Wanjia middle school slope were severely destroyed, 10 cm wide tension fracture appeared at the trailing edge of the slope. Wanjia middle school slope is a type of medium-sized soil landslide. The area of the deformation body is about 19,314 m<sup>2</sup>, the total volume of the deformation body is about  $23 \times 10^4$  m<sup>3</sup>. There may be two potential sliding surfaces in the unstable slope: shallow and deep landslide. The analysis results of the limit equilibrium method and the finite element method show that:

under dead weight, dead weight + rainstorm, dead weight + earthquake conditions, the plastic zone occurs mainly at the middle part or the trailing edge of the slope, and it doesn't fully cut through the deep landslide body, so the deep landslide is stable. However, under rainstorm or earthquake conditions, the plastic zone almost completely cut through the shallow landslide body, it shows that the shallow landslide is in the understable–basic stable state. It is found that the results of finite element method is concordant with the results of the limit equilibrium method ( $F_s = 1.06$ – $1.29$ , the shallow landslide is in the basic stable–stable state). The calculation results show that shallow landslides are likely to occur in Wanjia middle school slope during a rainstorm or an earthquake, so monitoring and control of the slope should be strengthened. The shallow landslide should be managed by some measures, such as anti slide pile retaining structures and drainage works, and the dangerous rock bodies on the slope surface should be cleaned up.

T. Hou (✉)

College of Water Resources and Architectural Engineering, Northwest A&F University,  
Yangling 712100, Shaanxi, China  
e-mail: houtianshunyx@sina.com

X. Wang

State Key Laboratory of Continental Dynamics,  
Department of Geology, Northwest University,  
Xi'an 710069, Shaanxi, China

S. Pamukcu

Department of Civil and Environmental Engineering,  
Lehigh University, Bethlehem, PA 18015, USA

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## 1 Introduction

The Wenchuan M8.0 earthquake occurred in Wenchuan County, Sichuan Province, at 14:28, May 12, 2008. The epicenter is located in the Yingxiu Town of

Wenchuan County, the seismic intensity is 11°, and the earthquake destroyed lots of mountains and houses. Wenchuan Earthquake in Sichuan Province caused very serious casualties and property losses. At the same time, the earthquake has caused a large number of secondary geological disasters, which have a serious threat to the traffic, houses and settlements. According to estimates, the total number of the earthquake triggered landslides and all kinds of geological disasters is more than 50,000 (Huang et al. 2008), secondary disasters (collapse, landslide, debris flow) caused approximately 20,000 deaths (Yin 2008). According to history record, there are some outstanding characteristics on the Wenchuan Earthquake triggered landslides: in a single earthquake, the most intensive landslides distribution, the largest number of landslides, the most widely landslides area.

After the Wenchuan Earthquake, the mechanism of earthquake induced landslide, the stability evaluation and forecast of landslide during earthquake are researched by a large number of scholars (Yin 2008; Huang et al. 2008; Wang et al. 2009; Du et al. 2010; Tang et al. 2011; Xu and Dong 2011; Sun et al. 2011; Mu et al. 2012; Yue et al. 2013; Highland and Sun 2013; Guo and Hamada 2013; Wang 2014; Xu et al. 2014; Dai et al. 2014). The failure characteristics of more than 20 large scale landslides induced by Wenchuan Earthquake are researched by Xu and Dong (2011), it is found that the deformation modes and mechanical mechanism of Wenchuan Earthquake induced landslides is very different from the landslide mechanism under normal gravity. Under the strong seismic condition, the most basic failure unit of the rock mass is tensile and shear slip, the tensile failure is the main. There are five formation models for large scale landslides induced by Wenchuan Earthquake: tensile-along the strike slip type, tensile-bedding slip type, tensile-horizontal sliding type, tensile-discrete sliding type, tensile-shear off sliding type. The geological model of Donghekou landslide before Wenchuan Earthquake was established according to the field survey results, then input the observed Wenchuan Earthquake wave, the static and dynamic stability were analyzed by FLAC finite difference method (Sun et al. 2011). Vertical peak acceleration caused a large area of tensile failure in the trailing edge of the slope, and it is a very important factor for collapse and throw-type landslide in southwest mountain area which are induced by Wenchuan Earthquake. Collapses and tensile cracks

occur in the Longnan red clay landslide caused by Wenchuan Earthquake, the landslide has obvious hierarchical sliding characteristics, the main factors of the landslide are as follows: earthquake, rainfall, poor rock-soil medium (Mu et al. 2012). According to basic topography and geomorphology, using Mohr–Coulomb failure criteria, the safety factor of Tangjiashan landslide was calculated by the strength reduction method. Moreover, the stability of Tangjiashan landslide under earthquake wave was analyzed. Guo and Hamada (2013) investigated various influential factors on the slope stability of 119 landslides in Wenchuan County. They separately developed acceleration attenuation laws for both the hanging wall and footwall side from 183 seismic stations. The formulae confirmed the hanging wall and footwall effect had notable influence on landslide distribution density and occurrence probability. Further, it is found that slope height, horizontal peak ground acceleration and geological structure had a stronger effect on the sliding area and volume than slope angle and rock type. The epicenters of the 2013 Lushan Earthquake and the 2008 Wenchuan Earthquake were both in the Longmen Mountains, but it is found that there are some differences between the landslides triggered by the two earthquakes (Wang 2014). More landslides were triggered by each earthquake close to the seismogenic fault and in areas with higher seismic intensities. The number of landslides was closely related to the effects of seismic amplification and peak ground acceleration, and had no obvious relation with the age of the rock. Dai et al. (2014) proposed that a three-dimensional model based on smoothed particle hydrodynamics to simulate rapid landslide motion across 3D terrain. The Navier–Stokes equations in a CFD framework are used as governing equations, and artificial viscosity is incorporated into the pressure terms in the momentum equation to dissipate energy to avoid numerical oscillation and particle penetration, thus improving the stability of the numerical results. The prediction of the fluidization characteristics of earthquake-induced flow-like landslides can notably reduce sudden loss of life, as it provides a means for mapping hazardous areas, for estimating the hazard intensity, and for identification and design of appropriate protective measures.

Wanjia middle school slope is located in Wanjia Town, Chongzhou City. Wenchuan Earthquake caused severe deformation of the slope, external expansion of the retaining wall, and tensile cracks of the road and

houses. Under the action of the heavy rainfall, the slope has serious threat to many government houses, such as Wanjia middle school, Wanjia town government, hospital. If the landslide occur, the direct economic loss would be nearly 10 million Yuan. So the failure mechanism and stability of the slope are analyzed by engineering geology analysis method, limit equilibrium method, finite element method, then it can provide some theory evidence for landslide control.

## 2 Natural Geography and Geological Environment of Exploration Area

### 2.1 Natural Geography

Wanjia middle school slope is located in Chongzhou City, it is about 30 km away from northwest Chongzhou, and it is about 85 km away from the south of Wenchuan County. The slope is located in the north of the road from Huaiyuan Town to Jiguanshan Village, the distribution of the elevation is 751–860 m, the length is about 250–400 m, the width is about 300 m, the area is about 0.1 km<sup>2</sup>, and the specific content is shown in Fig. 1. In the heavy rainfall or continuous rainfall, Wanjia middle school slope has serious threat to Wanjia middle school, Wanjia Town government, hospital, and so on.

### 2.2 Meteorology and Hydrology

Chongzhou enjoys a tropical humid monsoon climate of Sichuan basin, the annual average temperature is



**Fig. 1** Wanjia middle school slope and residents

16.1 °C, the average annual rainfall is 1015.2 mm. Rainfall is mainly in the summer, mostly in July, the average month rainfall is 252.4 mm. The rainfall in December is the least 7.2 mm. The flood season rainfall from from May to September is 829.2 mm, it is about 82.0 % of average annual rainfall. From June to July in 2005, local heavy rain occurred many times in Chongzhou, one of the greatest rainfall in 4 h is to 169 mm (Wanjia Village), and it didn't induce debris flow disaster, but it triggered a large number of floods, landslides, collapses. The river system of exploration area belongs to the Minjiang River system, the main river is Xihe River (Wenjingjiang River). Wenjingjiang River goes through southwest of the landslide area, and the highest flood level doesn't reach the slope area.

### 2.3 Geological Environment

Chongzhou is located in the southwest edge of Sichuan basin, its back rely on Longmenshan mountain, its front is Chengdu plain, the terrain gradually reduced stepwise from northwest to southeast. The mountains area whose altitude is more than 1000 m is 38.4 % of the total city area, the Low mountains and hills area is 8.7 %, and the level ground area is 52.9 %.

The terrain of Wanjia middle school slope is very steep, its front is Wenjingjiang River, there are many klints whose height is about 20 m, and the bedrock expose in the open air obviously. The middle-front edge of the slope is platform shaped, the slope angle is 0°–5°. The terrain of the middle-back edge is very steep, the slope angle is 5°–40°, there are many dangerous rock masses on the slope surface. The stratum consists of quaternary holocene colluvium layer, alluvial layer, and Jurassic ziliujing group. Colluvium layer is silty clay with sandstone, and its colour is gray and brownish red. Alluvial layer is pebble soil and sand, and its colour is gray and brown gray. Ziliujing group is mainly gray sandstone, purple mudstone, dark gray mudstone.

The exploration area is mainly located in Wuzhongshan fold belt. The crustal movement is very intense in neogene period. With the frequent intermittent crustal ascending movement, many terraces appear in the valley. The earthquake magnitude is less than M4.75 before Wenchuan Earthquake, and no serious harm occur. The biggest failure strength earthquake is Wenchuan Earthquake, the magtitude

is M8, the earthquake intensity of the epicenter is 11°. The seismic fortification intensity in the landslide area is 7°, the peak ground acceleration values is 0.10 g, and the Eigen period is 0.35 s. Surface water catchment area is 7.5 ha. According to the type of storage medium, there are pore water in loose deposit and bedrock fissure water. Because the slope is very steep, so atmospheric precipitation can discharge very quickly, the groundwater is poor in the slope.

### 3 The Basic Characteristics of Landslide and the Mechanical Parameters of Rock-Soil

#### 3.1 The Basic Situation of the Landslide

The longitudinal length of Wanjia middle school slope is 110 m, the transverse width is 300 m, the posterior elevation is 860 m, the front elevation is 789 m. The thickness of the middle-front soil in the slope is 12.0–15.3 m (according to the drillings), the thickness of the trailing edge soil is 0.8–2.9 m (according to the exploration troughs). The area of the deformation body is 19,314 m<sup>2</sup>, the volume of the deformation body is  $23 \times 10^4$  m<sup>3</sup>. It is found that the boundary of the trailing edge isn't very clear for the landslide, the plane modality of the landslide is like a round-backed armchair, the main sliding direction is 225°. The specific conditions are shown in Fig. 2.

After Wenchuan Earthquake, some deformation signs are observed: (1) Outward expansion of the retaining wall is 5–10 cm. (2) There are some cracks in the houses and the road at the foot of the slope. (3) According to filed survey, the crack at the foot of the B–B' profile has been covered by planting activities. The raining effect and excavation would induce lots of landslides which have serious threat to the local residents.

#### 3.2 Material Composition and Structural Characteristics of the Landslide

There is mainly gravel soil in the slope body, the layer is widely distributed, and the thickness of the soil in the middle section is 0.8–15.3 m. On the whole, the thickness of the soil in the East and West is thin, the thickness of the middle section is thick, and the thickness of the trailing edge is thin. The gravel soil mainly consists of silty clay with sandstone and

conglomerate. The shape of gravels is mainly angular, the diameter of the stone is about 0.1–1.2 m, a handful of up to 4.2 m. The silty clay is brown, gray–brown, purple red, and it is in the state of plastic-hard plastic, the ratio between soil and gravel is about 4:6–2:8. The gravel content in the middle-tailing edge is higher, and it is lower in the middle of the slope. There are some pebble soils in the front of the slope, which is near the Wenjingjiang River, the sorting feature is poor, and the psephicity is medium. The Material composition of the slope is shown in Fig. 3.

The slide bed of Wanjia middle school slope is made of sandstone, mudstone, conglomerate. The longitudinal shape of the bedrock surface is broken line shape, the trailing edge is very steep, and the front edge is gentle. The shape of the bedrock surface is the same as the shape of the surface morphology. The Dip angle of the bedrock surface is about 5°–58°.

According to the drillings and exploration troughs, the slope perhaps slides along the weak structure plane between the loose accumulative layer and the bedrock, and the sliding direction is 225°. The shape of the potential sliding surface is broken line shape, the slope gradient of the front edge is 2°–8°, and the slope gradient of the trailing edge is 10°–58°. The slip zone is made of brown silty clay, the soil is in the state of plastic-hard plastic under natural state. Because the trailing edge is very steep, so some shallow landslides may occur, and the altitude of the most unfavorable shear outlet position is about 785–791 m. Namely, there may be two potential slip zone: shallow slip zone and deep slip zone. So the overall stability and local stability of Wanjia middle school slope need to be calculated.

#### 3.3 The Mechanical Parameters of Rock-Soil

##### 3.3.1 Slip Body

In this exploration process, six groups of slip body soils are fetched. There are lots of conglomerates, sandstones in the slip body soil, the ratio between the soil and the gravel is 3:7. According to the laboratory tests, the average natural bulk density of the silty clay is 19.20 kN/m<sup>3</sup>, the average saturation bulk density is 19.90 kN/m<sup>3</sup>. According to field tests, the average natural bulk density of the gravel soil is 19.87 kN/m<sup>3</sup>, the average saturation bulk density is 20.20 kN/m<sup>3</sup>. On the basis of the indoor and field test

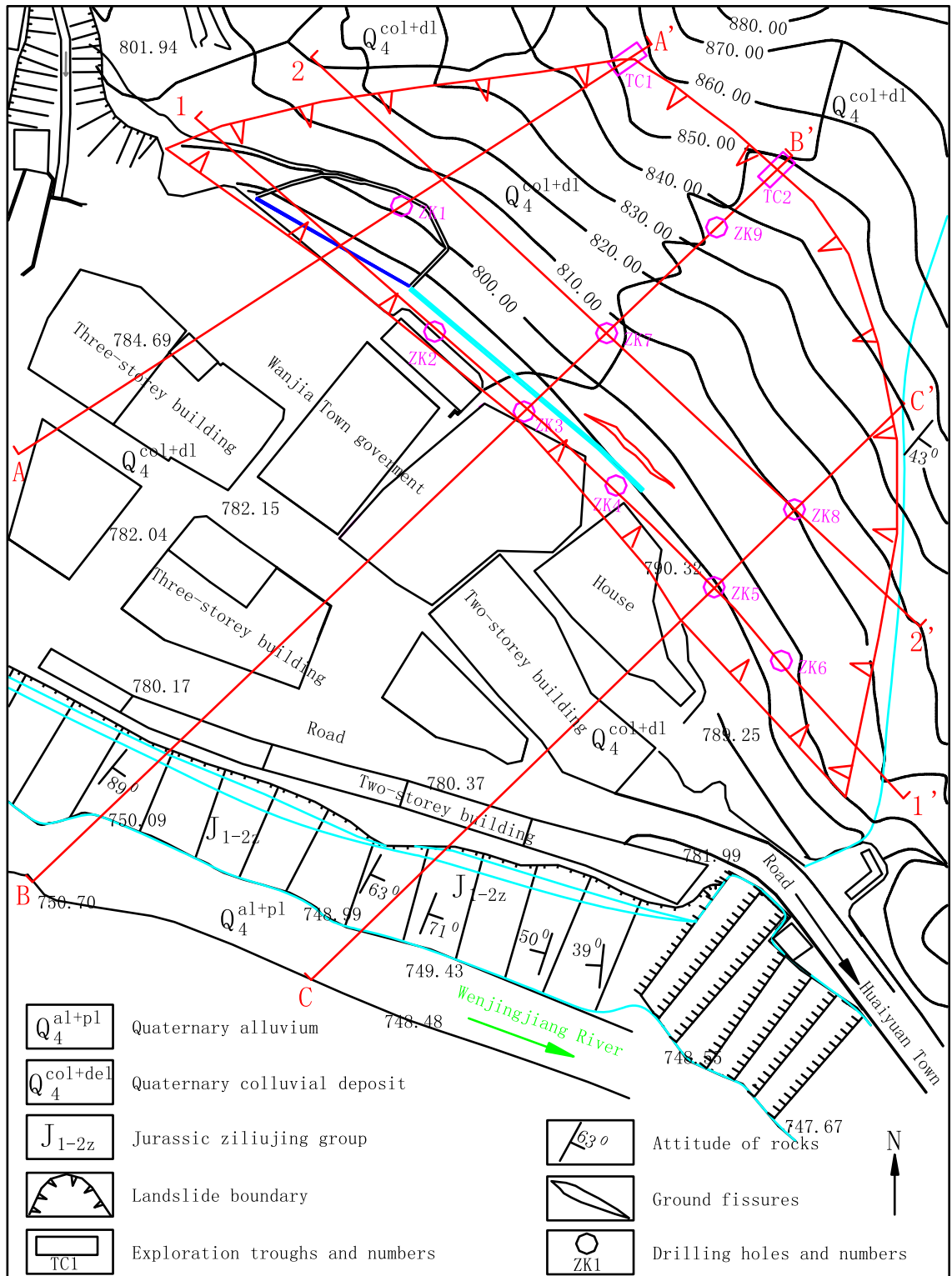
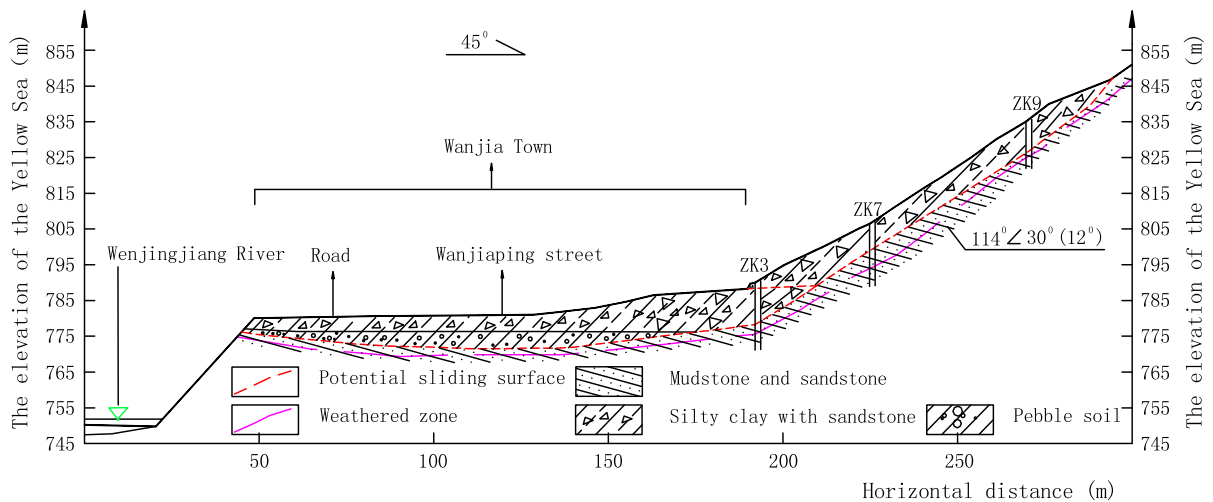


Fig. 2 Engineering geological map of Wanjia middle school slope



**Fig. 3** B–B' longitudinal profile of Wanjia middle school landslide

results, the average natural bulk density of the gravel soil is  $20.10 \text{ kN/m}^3$ , the average saturation bulk density is  $20.20 \text{ kN/m}^3$ . There are many gravels in the slip body, according to the quick shear tests, natural state:  $c = 33.90 \text{ kPa}$ ,  $\varphi = 22.30^\circ$ ; saturation state:  $c = 32.10 \text{ kPa}$ ,  $\varphi = 21.60^\circ$ .

### 3.3.2 Slip Zone

The choice of calculation parameters is reasonable or not is the key factor to safety analysis of slope. The shear strength parameters are decided by indoor tests, back analysis, and engineering analogy method.

Six groups of specimens (slip zone) are analyzed by soil routine tests. The natural bulk density is  $19.40\text{--}20.10 \text{ kN/m}^3$ , the void ratio is  $0.642\text{--}0.813$ , the natural water content is  $20.90\text{--}27.70 \%$ , the plastic limit is  $17.40\text{--}24.00 \%$ , the liquid limit is  $28.10\text{--}38.20 \%$ .

According to the quick direct shear tests, the peak shear strength parameters of slip zone under natural state:  $c = 29.60\text{--}38.30 \text{ kPa}$ ,  $\varphi = 12.10^\circ\text{--}15.50^\circ$  (the average value:  $c = 32.80 \text{ kPa}$ ,  $\varphi = 13.87^\circ$ ); the residual shear strength parameters of slip zone under natural state:  $c = 19.30\text{--}24.00 \text{ kPa}$ ,  $\varphi = 9.00^\circ\text{--}13.00^\circ$  (the average value:  $c = 31.90 \text{ kPa}$ ,  $\varphi = 11.10^\circ$ ). The peak shear strength parameters of slip zone under saturation state:  $c = 21.70\text{--}24.10 \text{ kPa}$ ,  $\varphi = 10.20^\circ\text{--}13.10^\circ$  (the average value:  $c = 23.27 \text{ kPa}$ ,  $\varphi = 11.40^\circ$ ); the residual shear strength parameters of slip zone under saturation state:  $c = 14.50\text{--}17.60 \text{ kPa}$ ,  $\varphi = 7.40^\circ\text{--}$

$10.30^\circ$  (the average value:  $c = 15.77 \text{ kPa}$ ,  $\varphi = 8.53^\circ$ ). Some results can be got from the above, the shear strength of slip zone is higher under natural state, the strength decreases with increased water content. The potential slip zone hasn't cut through the slope body, so the peak shear strength is used for stability analysis.

Because there are many gravel soils in the slope, so undisturbed specimens can't be obtained easily. Some disturbed specimens which have fewer gravels than the true situation are fetched in the field, so there is difference between the test results and the real situation. Back analysis of shear strength parameters is very important for stability analysis of slope. According to the slope deformation, B–B' profile shallow landslide is back analyzed. The potential slip zone doesn't cut through the slip body thoroughly in Wenchuan Earthquake, but some deformation can be observed in the shear outlet. Under dead weight + earthquake condition, when B–B' profile shallow landslide is in the state of limit equilibrium, some worth parameters can be got:  $c = 29.00 \text{ kPa}$ ,  $\varphi = 18.80^\circ$ . B–B' profile shallow landslide are back analyzed under natural state and saturation state, the specific calculation results are shown in Fig. 4 and Table 1.

On the basis of Table 1, the shear strength parameters of rock-soil interface (shallow slip zone and deep slip zone) are obtained. Under natural state:  $c = 28.30 \text{ kPa}$ ,  $\varphi = 17.2^\circ$ ; under saturation state:  $c = 27.35 \text{ kPa}$ ,  $\varphi = 14.60^\circ$ .

### 3.3.3 Bedrock

According to the test results of four groups of rocks, some measured value can be got. The natural density of the mudstone is  $2.45 \text{ g/cm}^3$ , its saturation density is  $2.48 \text{ g/cm}^3$ . The natural uniaxial compressive strength of the mudstone is 0.61 MPa, its saturated uniaxial compressive strength is 0.36 MPa. The natural density of the sandstone is  $2.59 \text{ g/cm}^3$ , its saturation density is  $2.63 \text{ g/cm}^3$ . The natural uniaxial compressive strength of the sandstone is 22.80 MPa, its saturated uniaxial compressive strength is 16.18 MPa.

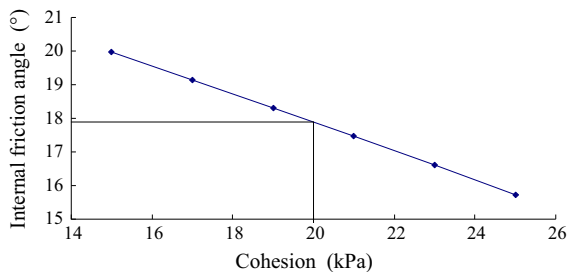
## 4 Stability Analysis of the Landslide

### 4.1 Calculation Model

According to the technical requirement, the landslide stability are calculated by Geological Hazard Exploration Information System of three gorges reservoir area—landslide stability analysis system. The specific calculation method is transfer coefficient method. The shape of the potential sliding surface is broken line shape, the profiles are calculated by slices method.

### 4.2 Calculation Situations

The exploration area is located in earthquake prone area, the seismic force is a very important factor that affects the landslide stability. In addition, the influence rainstorm on the slope stability can't be ignored, three situations should be considered for stability analysis: (1) Dead weight; (2) Dead weight + rainstorm; (3) Dead weight + earthquake, the seismic fortification intensity of the landslide area is  $7^\circ$ , the peak ground acceleration values is 0.10 g. Moreover, considering



**Fig. 4** Back analysis of shallow sliding surface of B–B' profile under saturation condition

Wanjia Town government and many houses are located at the foot of slope, so overall and local stability all should be calculated.

### 4.3 Calculation Results

The landslide stability is defined as follows:  $F_s < 1.00$ , instable;  $1.00 < F_s < 1.05$ , understable;  $1.05 < F_s < F_{st}$ , basically stable;  $F_s > F_{st}$ , stable. Combining the practical situation, the slope stability is calculated.

#### 4.3.1 Overall Stability Calculation of Wanjia Middle School Slope

Some results can be got from Table 2: the deep landslide is always stable under different conations (dead weight, dead weight + rainstorm, dead weight + earthquake). A storm or continuous rainfall will not induce overall instability of the slope.

#### 4.3.2 Local Stability Calculation of Wanjia Middle School Slope

Table 3 shows that the safety factors of A–A' profile shallow landslide are 1.22, 1.12, 1.16 under different conditions (dead weight, dead weight + rainstorm, dead weight + earthquake), it indicates that A–A' profile shallow landslide is in the state of basically stable–stable. The safety factors of B–B' profile shallow landslide are 1.16, 1.06, 1.10 under the three different conditions, it shows that B–B' profile shallow landslide is in the state of basically stable–stable. The safety factors of C–C' profile shallow landslide are 1.38, 1.26, 1.29 under the three different conditions, it indicates that C–C' profile shallow landslide is in the state of stable.

In summary, Wanjia middle school deep landslide in whatever conditions is stable, overall instability won't occur. C–C' profile shallow landslide under the three conditions is stable, but A–A' and B–B' profiles shallow landslides are in the state of basically stable–stable, it indicates that a storm or earthquake may induce some shallow landslides and other new geohazards.

### 4.4 Numerical Simulation Analysis

#### 4.4.1 Model Building

On the basis of engineering geological analysis, B–B' profile is chosen to establish a numerical model. There

**Table 1** Recommended values of shear strength of slide zone soil for Wanjia middle school landslide

Items	Natural state		Stauration State		Bulk density $\gamma$ (kN/m <sup>3</sup> )	
	$c$ (kPa)	$\varphi$ (°)	$c$ (kPa)	$\varphi$ (°)	Natural state	Stauration State
Laboratory tests	32.8	13.87	23.27	11.4	20.1	20.2
Engineering geological analogy						
Wangyuezhai landslide in Wenchuan Earthquake area	16	37	13	35	19.5	20.5
Longnan red soil landslide in Wenchuan Earthquake area	20	18	17	16.5	20.3	21.1
Back analysis	27	14.85	20	17.88	20.1	20.2
Recommended values	28.3	17.2	27.35	14.6	20.1	20.2

**Table 2** The stability calculation results of the deep landslide

Calculation profiles	Conditions	Calculation results and estimation		
		Safety factor	Safety factor	Stability estimation
Deep lanslide of A–A' profile	Dead weight	2.29	1.25	Stable
	Dead weight + rainstorm	1.99	1.15	Stable
	Dead weight + earthquake	1.45	1.05	Stable
Deep lanslide of B–B' profile	Dead weight	2.38	1.25	Stable
	Dead weight + rainstorm	2.07	1.15	Stable
	Dead weight + earthquake	1.25	1.05	Stable
Deep lanslide of C–C' profile	Dead weight	1.88	1.25	Stable
	Dead weight + rainstorm	1.65	1.15	Stable
	Dead weight + earthquake	1.13	1.05	Stable

**Table 3** The stability calculation results of the shallow landslide

Calculation profiles	Conditions	Calculation results and estimation		
		Safety factor	Safety factor	Stability estimation
Shallow lanslide of A–A' profile	Dead weight	1.22	1.25	Basically stable
	Dead weight + rainstorm	1.12	1.15	Basically stable
	Dead weight + earthquake	1.16	1.05	Stable
Shallow lanslide of B–B' profile	Dead weight	1.16	1.25	Basically stable
	Dead weight + rainstorm	1.06	1.15	Basically stable
	Dead weight + earthquake	1.10	1.05	Stable
Shallow lanslide of C–C' profile	Dead weight	1.38	1.25	Stable
	Dead weight + rainstorm	1.26	1.15	Stable
	Dead weight + earthquake	1.29	1.05	Stable

are two potential slip zones in the slope: B–B' profile shallow landslide and B–B' profile deep landslide. A numerical model is established by the finite element

software—Phase<sup>2D</sup>, the model is shown in Fig. 5, there are 2289 elements and 4757 nodes. B–B' profile shallow and deep landslides can share a model, the



difference is that they have different slip zone positions. The boundary constraint conditions are defined as follows: the bottom of the model is fully restricted, normal constraint is adopted for the left and right surfaces which are perpendicular to the X axis, and the natural slope surface is free.

#### 4.4.2 Parameters Selection

For B–B' profile shallow and deep landslides, there are three conditions: (1) dead weight; (2) dead weight + rainstorm; (3) dead weight + earthquake. Under the situation of dead weight, use the natural state parameters which are shown in Table 4. Under the condition of dead weight + rainstorm, select the saturated state parameters which are shown in Table 5. In the state of dead weight + earthquake, the anti-seismic fortify intensity of the landslide area is  $7^\circ$ , the peak ground acceleration is 0.10 g, so the earthquake acceleration (0.10 g) is imposed to the free surface, and related mechanical parameters are shown in Table 4.

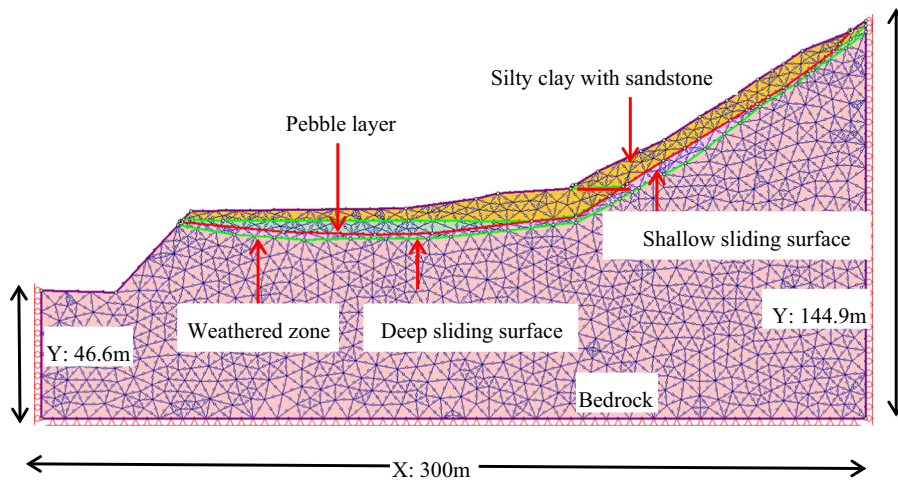
#### 4.4.3 Landslide Evolution Mechanism

The plastic zones of B–B' profile shallow landslide under different conditions are shown in Fig. 6, it indicates the evolution mechanism of Wanjia middle school landslide. (1) Under the condition of dead weight, local plastic zone occurs in the trailing edge and shear outlet of the landslide, but a large area of plastic failure isn't observed for the shallow landslide. Meanwhile, the maximum horizontal displacement of the slope is 0.48 mm by numerical simulation, and the location is in the trailing edge of the slope, the area is smaller, there is no large-scale collapse and slope sliding problems. (2) Compared with the condition of dead weight, when B–B' profile shallow landslide is in the state of dead weight + rainstorm, the plastic zone increases, but it doesn't cut through the slope. Moreover, the maximum horizontal displacement of the slope is 4.8 mm, the location is in the middle of the landslide body, the area is larger, but the slope as a whole does not exist large-scale continuous slip problem. (3) Compared with the condition of dead weight + rainstorm, when B–B' profile shallow landslide is under the situation of dead weight + earthquake, the plastic zone enlarges furtherly, but it doesn't cut through the slope. At this moment, the

maximum horizontal displacement of the slope is 96 mm by numerical simulation, the location is in the middle of the landslide body, the area is larger. A small range of sliding occurs in the middle of the landslide body, so the monitoring and prevention of the slope should be paid more attention before and after the earthquake.

The plastic zones of B–B' profile deep landslide under different conditions are shown in Fig. 7, some results can be got. (1) Under the condition of dead weight, local plastic zone occurs in the trailing edge and middle of the slope, it indicates a small amount of tension or shear slip perhaps occur in the trailing edge and middle of the slope. At this time, the maximum horizontal displacement of the slope is 360 mm by numerical simulation, the location is in the trailing edge of the slope, the area is smaller, large-scale collapse and slope sliding won't occur. (2) Compared with the condition of dead weight, when B–B' profile deep landslide is in the state of dead weight + rainstorm, the plastic zone increases in the middle of the slope. The maximum horizontal displacement of the slope is 480 mm by numerical simulation, the location is in the trailing edge of the slope, the plastic zone doesn't cut through the slope, and the overall slope is stable. (3) Compared with the condition of dead weight + rainstorm, when B–B' profile deep landslide is under the situation of dead weight + earthquake, the plastic zone enlarges a little, the maximum horizontal displacement of the slope is 600 mm in the middle and trailing edge of the slope, the area is larger, it shows that local landslides may occur.

In a word, when the deep landslide is in the state of the three conditions (dead weight, dead weight + rainstorm, dead weight + earthquake), the plastic zone mainly occurs in the middle and trailing edge of the slope, it doesn't cut through the slope, so the overall slope is stable. However, when the shallow landslide is under rainstorm and earthquake conditions, the plastic zone almost completely goes through the slope, it shows that the shallow landslide is in the state of understable–basically stable, the calculation results and the limit equilibrium analysis results are basically consistent. According to the results obtained by the two methods, when Wanjia middle school slope is under the situation of rainstorm and earthquake, shallow landslides are very likely to occur.



**Fig. 5** Finite element mesh of B–B’ profile

**Table 4** The physical and mechanical parameters under natural state

Items	Density $\rho$ (g/cm <sup>3</sup> )	Cohesion $c$ (MPa)	Internal friction angle $\varphi$ (°)	Tensile strength $\sigma_t$ (kPa)	Elasticity modulus $E$ (kPa)	Poisson ratio $\mu$
Silty clay with sandstone	2.01	0.0339	22.3	10	42,000	0.30
Sliding surface	1.9	0.0283	17.2	0	38,000	0.32
Weathered zone	1.92	0.032	20.5	5	39,000	0.31
Pebble	2.4	0	52.5	0	14,000,000	0.19
Bedrock	2.59	9.5	35	5500	16,000,000	0.18

**Table 5** The physical and mechanical parameters under saturation state

Items	Density $\rho$ (g/cm <sup>3</sup> )	Cohesion $c$ (MPa)	Internal friction angle $\varphi$ (°)	Tensile strength $\sigma_t$ (kPa)	Elasticity modulus $E$ (kPa)	Poisson ratio $\mu$
Silty clay with sandstone	2.02	0.0321	21.6	8	33,600	0.32
Sliding surface	2.28	0.02735	14.6	0	34,200	0.34
Weathered zone	2.15	0.0256	16.4	4	331,50	0.33
Pebble	2.64	0	42	0	112,000,000	0.19
Bedrock	2.63	8.075	28	4730	12,800,000	0.18

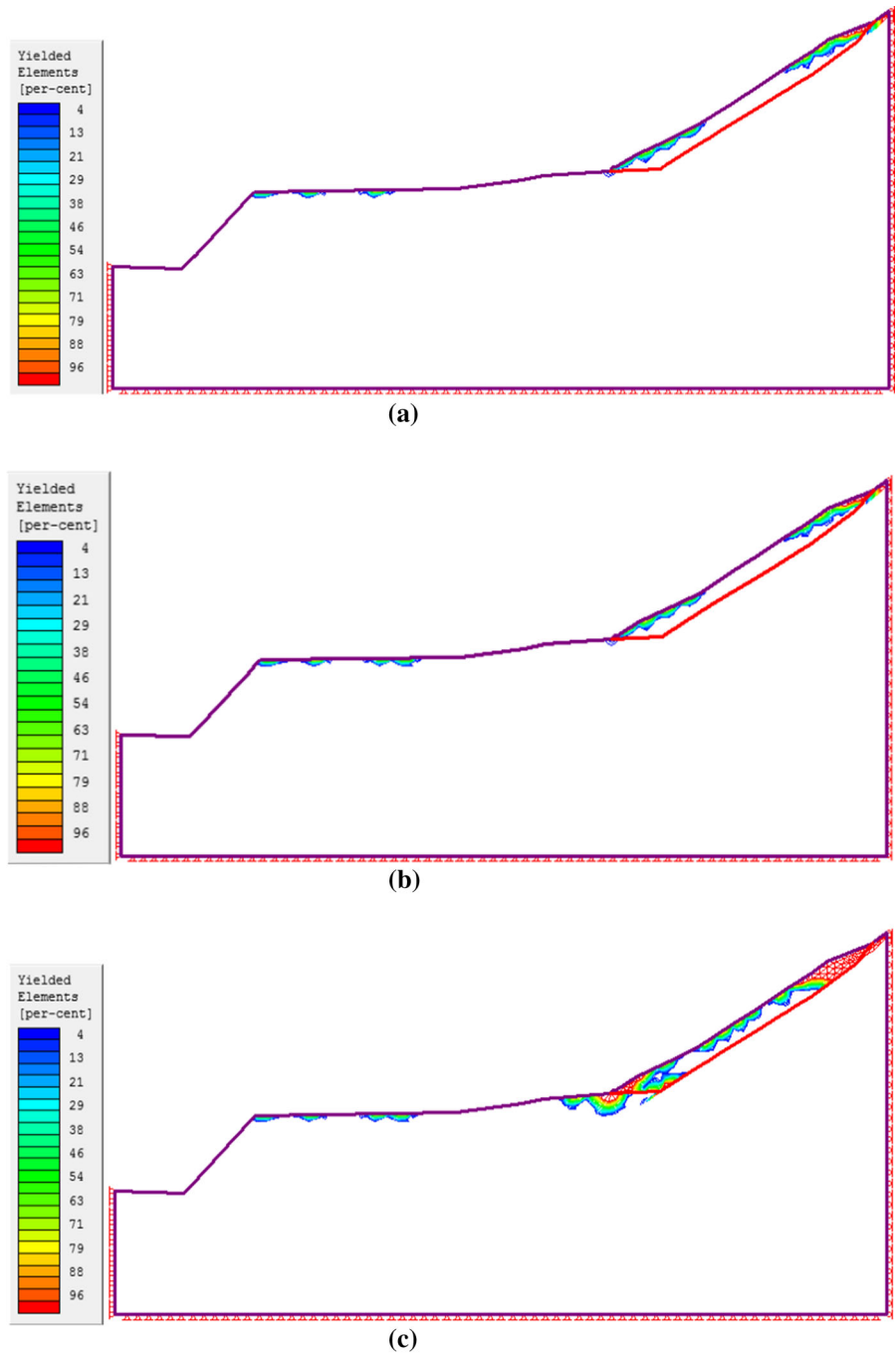
**5 Conclusions**

1. Wanjia middle school slope is located in Wenjingjiang Town, Chongzhou. Wenchuan earthquake caused severely damage to the retaining wall at the foot of the slope and the houses. According to field survey, the longitudinal length of the slope is 110 m, the transverse width is 300 m, the elevation of the trailing edge is 860 m,

the elevation of the front is 789 m. Wanjia middle school slope belongs to medium-sized soil landslide, the area of the deformation body is about 19,314 m<sup>2</sup>, the total volume of the deformation body is 23 × 10<sup>4</sup> m<sup>3</sup>. There are two potential sliding surfaces in the slope: shallow and deep slip zones.

2. Shear strength parameters of the slip zones are decided by laboratory tests, back analysis,

**Fig. 6** Numerical simulation results of plastic zone for B–B' profile shallow landslide. **a** Dead weight. **b** Dead weight + rainstorm. **c** Dead weight + earthquake

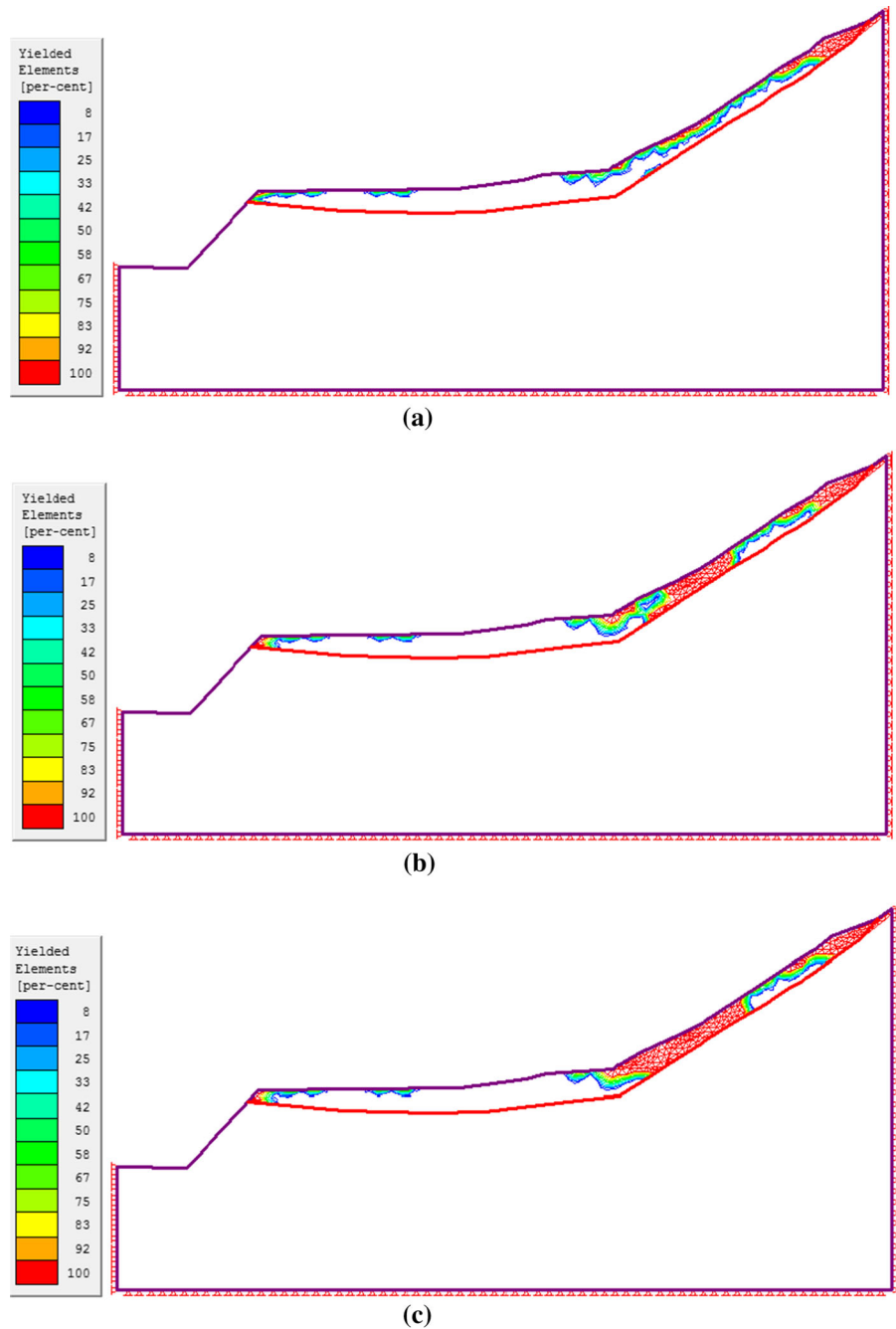


engineering analogy method and so on. Under natural state:  $c = 28.30$  kPa,  $\varphi = 17.20^\circ$ ,  $\gamma = 20.10$  kN/m<sup>3</sup>; under saturated state:  $c = 27.35$  kPa,  $\varphi = 14.60^\circ$ ,  $\gamma = 20.20$  kN/m<sup>3</sup>.

3. The failure mechanism and stability of the landslide are analyzed by engineering geology

analysis, limit equilibrium method and finite element method. When the deep landslide is under the three conditions (dead weight, dead weight + rainstorm, dead weight + earthquake), the plastic zone mainly appears in the middle and trailing edge of the slope, the plastic zone doesn't

**Fig. 7** Numerical simulation results of plastic zone for B–B' profile deep landslide. **a** Dead weight. **b** Dead weight + rainstorm. **c** Dead weight + earthquake



go through the slope, so the overall slope is stable. However, when the shallow landslide is in the state of rainstorm and earthquake, the plastic zone almost completely cut through the slope, it indicates that the shallow landslide is under the situation of understable–basically stable. The calculation results and the limit equilibrium

analysis results are basically consistent. The results obtained by the two methods show that when Wanjia middle school slope is in the state of rainstorm and earthquake, shallow landslides are very likely to occur. So the monitoring and prevention of the slope should be paid more attention during a rainstorm and earthquake.

4. It is suggested that the shallow landslide should be managed by some engineering measures, such as retaining engineering and drainage engineering. Moreover, the dangerous rocks in the mountain should be cleared up in time.

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