Analysis of the post-earthquake stability and research on deformation and failure mechanism of the talus slope located in front of the dam of Zipingpu hydraulic project

LANG Jing-xuan(1), HU Xie-wen(1,2), WU Jian-li(1) and DIAO Ren-hui(1)

(1) Engineering Laboratory combined with national and local of spatial information technology of high speed railway operation safety, Southwest Jiaotong university, Sichuan Chengdu 610031, China
(2) Key Laboratory of Ministry of education of traffic tunnel, Southwest Jiaotong university, Sichuan Chengdu 610031, China

Abstract

In order to figure out the influence on the talus slope located at left riverbank in front of the dam of Zipingpu hydraulic under the "5.12"Wenchun earthquake, the stability of the talus slope under different conditions is calculated based on field investigation. The results show that the talus slope is generally stable under various conditions, while only the front part of Dengzhan plateau collapsed under the earthquake. The research of its deformation characteristics show that, the deformation and failure mode of the talus slope is in the charge of the micro-landform, and earthquake-induced slope failures usually take place on where the slope is deep and where the deep part joins the gentle part.

Key words: talus slope, stability analysis, deformation and failure mechanism, Wenchuan earthquake

1. Introduction

A large amount of avalanches and landslides was triggered by the earthquake occurred in 2008 in Wenchuan with a *Ms*=8.0(Huang Runqiu,2009). The Zipingpu hydraulic project which located about 17km away from the earthquake epicenter suffered a intensity of Ⅸ~Ⅹ(Zheng Sheng'an et al, 2008), a large old landslide on its left bank maintained stable while only where on the slope the steep part joints the gentle's slumped. So it is of great importance to find out the deformation and failure performance of the older landslide and analyze its stability and mechanism under severe earthquakes.

The Zipingpu hydraulic project locates on the upstream of Minjiang River, 67km northwest of Chengdu, Sichuan. It mainly provides us with agricultural irrigation and water supply, it also has the function of power generation, flood control, environmental protection and tourism, what's more, it is the water source of the city of Dujiangyan and Chengdu(Zheng Shengan et al, 2008). 618m upstream of the dam on the left bank locates a large older landslide, it has a total capacity of 35 million m^3 ~ 45 million m^3, whose stability after the earthquake directly influences the normal operation of the dam project. Therefore, find out the deformation and failure performance and use the Limit equilibrium theory to analyze the deformation characteristics and stability of the older landslide is of universal significance on investigation of older landslide, engineering control and other aspects of theory and practice.

2. The basic characteristics of the older landslide

2.1 Terrain features and engineering partition

The older landslide locates within the dam of Shakin to the Maxi of the reservoir(that is at the left bank in front of the dam) , its upstream boundary reaches to the Tang Jialin gully and Peaches plateau, while the downstream boundary reaches to Jiajia gully, the scarp is near the watershed with a elevation up to 1300m, its toe reaches to the Minjiang River. The older landslide has a longitudinal length of 1600m, a width of 300 ~ 870m, and a horizontal distribution area of approximately 1.0km^2 in the main study area.

Fig.1 Location of the study area(from Google Earth)

The frontier of the talus slope is relatively narrow, while widened as go into the back of the slope, it is as a whole like a round chair. Several plateaus on different elevations and slopes that connect them constitute the older landslide. The plateaus mainly consist the Guanyin plateau(elevation of 1110 ~ 1150m), Baimiaozi(elevation of 1000 ~ 1040m), Dengzhan plateau(elevation of 960m) and Hudou plateau(elevation of 800 ~ 820m), the terrain of the talus slope is relatively moderate, usually 20 ~ 30 °, while the peripheral bedrock up to 40 °.

The talus slope according to its origin, composition characteristics and engineering significance could be divided into two parts: zone Ⅰ is constructed by several bedrock falling bodies, it contains the Mid-Devonian (D_2) dolomite and dolomitic limestone, which constitutes disconnected buttes, and zone Ⅰ is not directly related to the project. Zone Ⅱ is bounded to Tangjialin gully and can be divided to zone Ⅱ-1 and zone Ⅱ-2.

Zone Ⅱ–1: locates in the vicinity of the Baimiaozi and Peaches plateau, the upstream of the Tangjialin gully. Almost there is no change to the boundary conditions after water impoundment. Tangjialin gully is deeply cut, the rockmass along the Minjiang River(ie, the Dengzhan Plateau direction) in the area has no free suface, and would not probably collapse.

Zone Ⅱ–2: locates in the vicinity of the Dengzhan and Hudou plateau, the downstream of the Tangjialin gully. The maximum thickness of the talus slope here is about 128.0m, the total volume is (2.5 ~ 3.0) × 10^{7}m^3, and the front edge of Dengzhan plateau has crept several times, so it is more likely to deform after the earthquake.

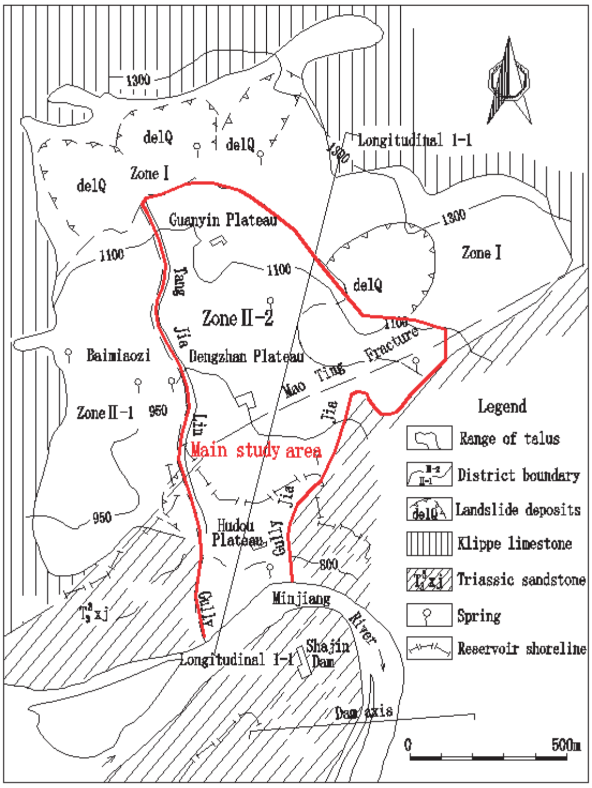

Fig.2 Geological zonation of talus slope (Yang Jian et al,2006)

Outcrops and pit holes by exploration revealed that the talus slope is mainly piled up by gravel and clay. Block gravel mainly composed of limestone and dolomitic limestone, with a small amount of fine sandstone and diabase can be divided into 7 layers according to its obvious vertical zonation, from the new to the old respectively: Q⑦(gravel containing clay), Q⑥ (clay containing gravel), Q⑤ (gravel containing clay), Q④(gravel containing clay), Q③ (gravel), Q② (gravel containing clay), Q① (clay containing gravel). The bedrock below has a morphology of steep-to-slow shape on downslope direction (similar to the surface shape of the slope) with a tendency out of the slope, and in the longitudinal view the interface between rock bed and overlying talus at both ends is steep while the middle is relief, inclination angle could up to 13.5° ~ 16°, with a minimum of 5.5°~ 6°, the surface of rupture on the back edge of the Dengzhan plateau is 42 °.

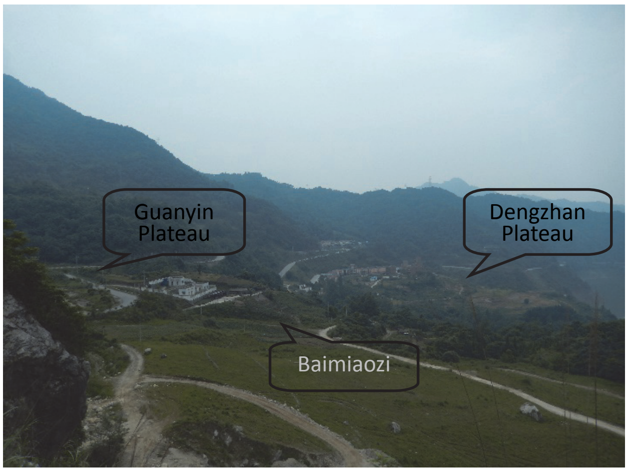

Fig.3 Landform characteristics of the II zone of the talus slope

The layer Q①, mainly contains fine particles mixed with the coarse particles started from interface between rock bed and overlying talus under the front part of Dengzhan plateau, extended to the front edge of Hudou plateau. The layer which is weak, of low shear strength, coupled with the extremely weak permeability, is the key layer affecting the stability of the talus slope(Xu Xiangtao et al, 2008).

2.2 Deformation and failure of the older landslide after the earthquake

The analysis and calculation of the stability of the talus slope on the left bank of Dengzhan Plateau after impoundment shows that the stability of the whole slope is stable, yet only the front shallow part of the slope is of poor stability, so before impoundment the front edge of the slope was heaped. The ballast body has a length of about 470m and width of 330m at the bottom and 60m at the top respectively, what's more, on the elevation of 845m, 815m and 790m three platforms with a gradient of 1:3.0 between them was set(Wang Jialin et al, 2009).

Though suffered from the "5.12" Wenchuan earthquake in 2008, the whole talus slope did not slide, yet only four small-scale collapses and two surface deformations appeared under the road on elevation of 890m on the front edge of the Dengzhan Plateau. The small-scale collapses are less than 30m high; while the surface deformations located downstream outside the road, the visible length of the fracture is about 30m, the maximum width is about 50cm with a dislocation about 20cm and a depth of about 1m.

Fig.4 Fissure on the surface in the vicinity of 890m elevation

Besides the pavement was damaged by there three shear failure on the road on elevation of 950m and 980m. There was no deformation phenomenon on other parts, the overall talus slope is stable.

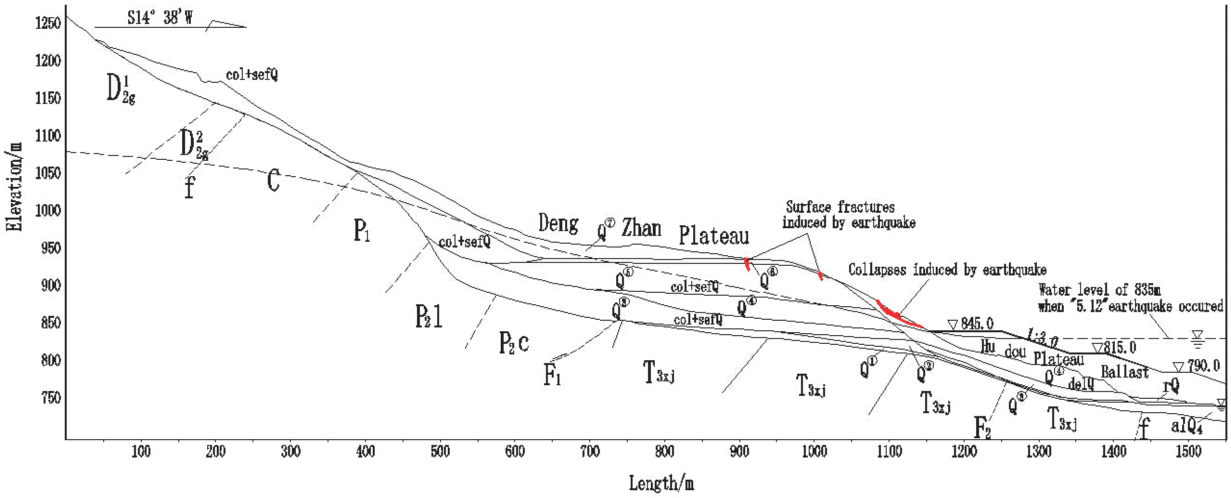

Fig.5 Longitudinal cross-section 1-1 of the talus slope

3. Analysis of the stability

3.1 Selection of calculation condition and parameters of rockmass

When "5.12" earthquake occurred, the water level in Zipingpu reservoir is approximately 835m, after the earthquake the main water kept a normal level of 877m and probably drop from 877m to 872m. Calculation using Limit equilibrium includes three kinds of conditions:1) water level of 835m when earthquake occurred; 2) the normal water level of 877m; 3)the normal water level of 877m plunge 5m. Each condition includes three states: 1) natural state; 2)earthquake; 3) continuous rainfall (full of water).

The field actually suffered from a basic intensity of Ⅸ, equivalent to a level acceleration of 392gal when "5.12" earthquake occurred; while after the earthquake the intensity dropped to Ⅷ, and acceleration to 185gal. According to relevant regulations, The composite effect factor of the earthquake is 0.25. Learn from experiment results, physical and mechanical parameters of the soil was obtained through sample testing(Table 1).

Table1 Physical-mechanical parameters of the talus slope

Soil type in slide zone	Physical Properties		Strength	
	Natural density,γ (kN/m^3)	Saturation density,γ (kN/m^3)	C（kpa）	φ(°)
Soil	24	24.3	20	31
Soft slide zone	22	22.4	10	16
Ballast		20	50	27

3.2 Analysis of limit equilibrium

Limit equilibrium(Zheng Yingren et al, 2009; Hu Xiewen et al,2009; Yan Zhixin et al, 2010), based on static equilibrium theory of force acted on slide body or block, is to evaluate the stability of the slope through analyzing stress conditions under various failure modes and relationship between stabilizing force and sliding force(Kang Yaming et al, 2006).

According to the deformation and failure modes of talus slope, potential mainscarp and toe of surface of fracture generally appear in where the steep side joins the gentle, therefore a total of 18 potential surfaces of rupture was found in calculation of stability using search method of arcuate surface of rupture(Fig.4).

Table2 Stability calculation results of the talus slope under the 835m water lever with its front loaded when the earthquake occurred.

Section number	Potential slide surface	Stability factor		
		Normal	Normal +earthquake(Ⅸ)	Normal +earthquake (Ⅷ)
1-1'	CI	1.537	1.084	1.286
	BI	1.442	1.031	1.216
	AI	1.429	1.015	1.201
	CH	2.181	1.373	1.710
	BH	1.976	1.282	1.577
	AH	1.909	1.240	1.524
	CG	2.199	1.457	1.776
	BG	1.958	1.328	1.603
	AG	1.878	1.268	1.533
	CF	1.648	1.227	1.421
	BF	1.544	1.149	1.331
	AF	1.516	1.106	1.292
	CE	1.458	1.150	1.297
	BE	1.609	1.209	1.395
	AE	1.561	1.132	1.327
	CD	1.214	0.975	1.091
	BD	2.421	1.741	2.047
	AD	1.839	1.289	1.533

Because the groundwater in slope body is rich and shallow and the stability coefficient of each potential surface of rupture is essentially the same in rainstorm and natural state, so the rainstorm state was excluded from the analysis. The calculation results are shown in Table2~3. In the typical1-1 'profile, because of the ballast on the front edge, all potential surfaces of rupture are stable in natural state under different water levels(835m,877m and plunge 5m) .

Under the Intensity=Ⅸ in "5.12" earthquake, in addition to the stability of potential surface of rupture CD in the slope is poor, its stability coefficients in different water levels were 0.975, 0.974 and 0.913, the stability coefficients of the whole slope (along the interface between the rock bed and overlying soil AI) were 1.015, 1.058 and 1.045, also in less stable to basic stable state. While the rest of the potential surfaces of rupture cutting through the overlying soil are in stable state. The calculation results are consistent with the actual situation of deformation and failure after the earthquake.

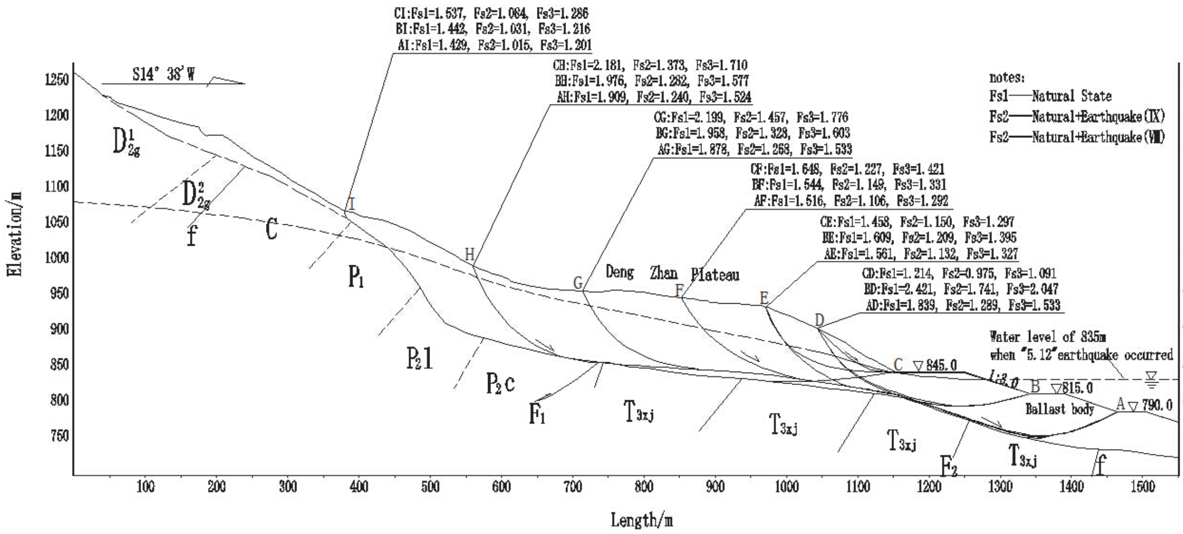

Fig.6 Schematic diagram of calculation cross-section 1-1 of the talus slope under the 835m water level when the earthquake occurred.

Table3 Stability calculation results of the talus slope under the 877m water lever and a rapid drawdown of 5m with its front loaded.

Section number	Potential slide surface	Stability factor of the water level of 877m			Stability factor of the water level of 877m plunged 5m		
		Normal	Normal +earthquake(Ⅸ)	Normal +earthquake (Ⅷ)	Normal	Normal +earthquake(Ⅸ)	Normal +earthquake (Ⅷ)
1-1'	CI	1.540	1.083	1.286	1.531	1.079	1.281
	BI	1.520	1.072	1.272	1.492	1.057	1.252
	AI	1.513	1.058	1.260	1.488	1.045	1.242
	CH	2.047	1.314	1.623	2.021	1.303	1.607
	BH	1.945	1.269	1.557	1.939	1.266	1.553
	AH	1.902	1.238	1.520	1.897	1.236	1.517
	CG	2.037	1.379	1.665	2.006	1.365	1.645
	BG	1.921	1.312	1.579	1.914	1.309	1.574
	AG	1.873	1.268	1.531	1.867	1.266	1.528
	CF	1.623	1.209	1.400	1.592	1.192	1.377
	BF	1.614	1.190	1.385	1.607	1.186	1.380
	AF	1.601	1.155	1.357	1.596	1.152	1.353
	CE	1.432	1.134	1.277	1.336	1.069	1.198
	BE	1.839	1.344	1.570	1.797	1.320	1.539
	AE	1.776	1.249	1.484	1.746	1.233	1.462
	CD	1.197	0.974	1.083	1.113	0.913	1.011
	BD	3.181	2.128	2.583	3.036	2.057	2.483
	AD	2.315	1.520	1.859	2.248	1.487	1.814

Table 3 shows that, before the earthquake, each potential surfaces of rapture in the talus slope kept stable under different water levels, which illustrates that underground water plays a less important role in various factors that influence the stability of the slope. Strong earthquake affects the front edge of the Dengzhan Plateau severely, results in collapse and deformation by reducing its stability; but the whole terrain and the interface between rock bed and overlying soil are generally gentle, though dislocation might appear along the interface between the rock bed and overlying soil, the short duration of vibration and the resistance from the gentle interface made the whole slope stable. The results from the analysis point out that the whole talus slope kept stable though suffered from the "5.12" earthquake, while only the front edge where the steep part joints the gentle's(part of CD) of Dengzhan Plateau collapsed. This phenomenon has a close relation to the micro-terrain, especially the gradient of the slope. The angle of the talus slope and interface between rock bed and overlying soil are generally about 20°and 13° respectively, while the deformation part is 30～40°. This is because the protrusion and gradient transition part of the slope has an amplification of seismic waves on vertical and free face(Xu Guangxing et al, 2008), which made the slope suffered more intense vibration damage.

Fig.7 Collapse deformation on the front of the Dengzhan plateau after the earthquake

4. Reactivation mechanism under the earthquake

The evolution of the talus slope is a long term progressive failure process, usually it can be divided into four stages(Xu Xiangtao et al, 2008): creep stage, pressing stage, sliding stage and stable stage. After the "5.12" Wenchuan earthquake, there is no significant deformation on the entire talus slope, the calculation of stability also shows that, the whole slope kept stable, yet only the front edge of Dengzhan Plateau is unstable, which resulted in some small scale collapse. Through its long-term adjustment and releasing, stress redistribution in the talus slope has been completed at this time, the stress tends to form the original stress field in vertical and horizontal direction. Rock and soil are compacted and terrain becomes flat(Zhang Zhuoyuan et al, 1994), the slope is in a very stable state, External factors (rainfall, earthquakes, etc.) has little effect on its stability(Qin Siqing et al, 2005).

The front edge of Dengzhan Plateau is relatively steep, which results in the concentration of stress in the vicinity of the free surface, so a tension area was formed in the shoulder of the slope, where deformation and failure are easily to generate because of the maximum stress difference or the maximum shear stress here. In addition, seismic wave will produce instant tension stress(Zhang Zhuoyuan et al, 1994), so the shoulder of the slope will probably generate relative large displacement or collapse, while those gentle slope will keep stable or only generate small displacement.

Tens of thousands of landslides and avalanches, etc. were induced by "5.12" Wenchuan earthquake in 2008, Huang Runqiu analyzed the regulation of the distribution of the hazards and pointed out that most of the hazards were originated on the slope angle of 20～50°, and the maximum density of the hazard appeared on slopes steeper than 40°(Huang Runqiu et al, 2008). Several typical large landslides were initiated by this earthquake, for example, the original slope inclination of Daguangbao landslide is 55～60°(Huang Runqiu et al, 2008), slope inclination of Donghekou landslide is 70～80°, and that of Tangjiashan landslide is 40°,etc.

In the contrast, all of the older landslides in the seismic region have not been reactivated, e.g. Malingyan landslide in Tangjiashan dammed lake, Qingtushan landslide in Wenchuan County and the Zipingpu talus slope discussed in this paper.

This phenomenon indicates that the materials made up the older landslides have already been failed, the energy has been released, the slope has become gentle. The Zipingpu talus slope is not steeper than 20° , while the interface between the rock bed and overlying soil is not steeper than 13°, which made the reactivation impossible and only collapsed on where the steep part changes into the gentle's.

5. Conclusion

Study of the stability of the Zipingpu talus slope affected by earthquake under various conditions shows that:

(1)In natural and rainfall states, each potential sliding surface kept stable under different water levels before the earthquake, which illustrates that rainfall and groundwater are less important to the stability of the talus slope.

(2)The whole talus slope also kept stable though suffered from the earthquake with Intensity=Ⅸ, yet only four small-scale collapses and surface fractures occurred on the front edge of Dengzhan Plateau.

(3)The deformation and failure mode of the slope is controlled by micro terrain(Gan Jianjun, 2014). The average inclination of the Zipingpu talus slope and the interface between bedrock and overlying soil is gentle, which is not susceptible to failure caused by earthquake; but the front part of Dengzhan Plateau where collapsed is steep, which has a amplification for seismic wave because of the concentration of stress or the area of tension stress in the vicinity of the free surface, which resulted the failure by the earthquake.

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