Effect of strength decrease of rock on the displacement of Tangjiashan Landslide in 2008 Wenchuan Earthquake, China

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ABSTRACT

The sliding mass of Tangjiashan Landslide in 2008 Wenchuan Earthquake moved more than 350 m (toe part) horizontally. Based on the field investigation, peak and residual strength of rock (strictly, rock discontinuities) were evaluated. Then, the displacement was calculated using extended Newmark and Janbu method (extended NJ method). In order to give a rapid evaluation of displacement in field, more attention was paid on the effect of strength decrease of rock during sliding. The result shows that if the strength did not decrease largely after a short displacement, the displacement would be much less than the actual displacement during the earthquake. In addition, the sliding duration was significantly affected by the minimum value of displacement for the residual state.

Keywords: extended Newmark and Janbu method, earthquake-induced slope failure, strength decrease, dip slope

1 INTRODUCTION

On 12 May in 2008, the catastrophic 2008 Wenchuan earthquake (Ms 8.0) triggered many landslides. As a typical dip slope failure, Tangjiashan Landslide (Fig. 1), located in the upstream section of the Jian River in Beichuan County, has a displacement of over 350m (toe part) with a volume of 2.04 × 10^7 m^3.

Many researches were preformed (e.g., Schuster and Costa 1986; Jibson, 2007; Cheng et al. 2007; Deng et al., 2010) to interpret the mechanism of large displacement of landslides. Among them, the effect of rainfall has been emphasized in some researches (e.g., Deng et al., 2011). However, the shocked area in 2008 Wenchuan Earthquake had very limited rainfall within two weeks before the earthquake (e.g., 2mm/day; WUI, 2008), therefore, rainfall effects are possibly not a main reason for the large displacement of landslide in this earthquake.

In this study, based on the field observation results and the relevant laboratory test results, the effect of strength decrease of rock during sliding on the large displacement of Tangjiashan Landslide was evaluated by using extended Newmark and Janbu method (extended NJ method) (Deng et al., 2010; 2011).

2 FIELD INVESTIGATION AND STRENGTH OF GEOMATERIAL ON SLIDING BAND

The landslide was about 150 km from the epicenter and 5km from Yingxiu-Beichuan Fault, located in the upstream section of the Jian River in Beichuan county, Sichuan Province. The slope profiles (Hu et al., 2009) relevant to this study including the topography and the geological formation were determined by summarizing the information of the photography, the core drill and the relevant laboratory tests in the previous and the authors’ investigations. Several observation results are important for the displacement calculation:

1) The cross section and the geomaterial in each layer were shown in Fig. 2. The sliding plane was very planar with an inclination of about 40°. The horizontal displacement was over 350m at the toe and induced a barrier lake. From top to bottom of the barrier dam, the sliding mass had three clear layers:
(i) The top layer was fragmented rocks with soils; (ii) The middle layer was boulders and blocks; (iii) The bottom layer was non-completely disintegrated siltstone strata which was slightly weathered or unweathered. Beneath the bottom layer of the sliding mass, there was a sandy gravel band.

As for the new section of sliding plane (N1 and N2 in Fig. 2), the sliding band was possibly the mixture of the crushed rock and the original river sediments as the angular gravel can be observed while D50 is about 1mm. This sandy gravel band indicated that the rocks in the vicinity of the sliding plane was completely disintegrated and served as a sliding band. The riverbed, which was the siltstone of Qingping Formation of Cambrain system, was found beneath the sandy gravel band.

![Fig. 2. Sliding mass and the cross section (based on Hu et al., 2009)](image)

2) By performing physical property test on 6 samples from the bottom layer, the physical and mechanical parameters of sandy gravel in the sliding band were evaluated as: Dry density $\rho_d = 167$–206 g/cm³, Water content $W = 3.1\%$–14.1%, $c = 13$–27 kPa and $\phi = 27^\circ$–$32^\circ$ (Hu et al., 2009). Other properties of siltstone strata relevant to the slope stability, such as bedding fault, were not evaluated in detail due to their complication.

3) Strength parameters in the displacement calculation were empirically determined based on the relevant test results or set as trial values.

In the displacement calculation, it is necessary to determine the residual strength (Skempton, 1985) of rock (strictly, rock discontinuities). As schematically shown in Fig. 3, after a small displacement from the original state along the path $\overline{OB}$, the material reaches the peak state with strength parameters $c$ and $\phi$. Then, the peak strength decreases from state C and reaches the residual strength at state D ($\delta = \delta_0$) with parameters of $c_r$ and $\phi_r$. Here, $\delta_0$ is defined as the minimum value of displacement for the residual state.

By assuming the shear stress increases along $\overline{DA}$ not $\overline{OB}$ for simplicity, the stress-strain relation can be uniquely determined by six parameters: $c$, $\phi$, $c_r$, $\phi_r$, $\delta_p$, and $\delta_0$.

The values of $c$ and $\phi$ of siltstone strata were determined (Table 1) by referring to the proposed strength parameters by Hu et al. (2009) ($c = 150$–250 kPa and $\phi = 36^\circ$–$38^\circ$). $c_r$ is set to be zero by considering that the adhesion of crushed siltstone strata has possibly dropped to zero. As $\delta_p$ was only 6mm in the previous simple shear test on a similar soft rock sample (Deng et al., 2011), it was set to be 1 cm in this study. Due to lack of relevant test data, $\delta_0$ cannot be accurately determined in this study, and thus four different values of $\delta_0$ were considered in calculations: $\delta_0 = 0.5$, 1, 1.4m or 105m (i.e. strength does not decrease during sliding). It is difficult to directly determine $\phi_r$ by laboratory test on the natural strata. As a substituted method, $\phi_r$ may be determined by using the crushed natural strata, e.g., material in the sandy gravel band in spite that river sediments were mixed in. Therefore, based on the direct shear test results on the samples from the sandy gravel band (Hu et al., 2009), $\phi_r$ of the siltstone strata was set to be $25^\circ$ which was slightly lower than the values of $\phi$ ($=27^\circ$–$30^\circ$) considering $\delta_0$ listed in Table 1 are much larger than the shear displacement in direct shear tests (maximum value, 6mm).

As for the sandy gravel in the left side section of sliding plane which consists of part N1 and part N2 (Fig. 2b), it is assumed the sandy gravel has reached residual state when it reaches the left side section. Their parameters of residual strength were evaluated as listed in Table 1.

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**Table 1. Parameters used in the displacement calculation**

|                   | Wet density, $\rho$ (g/cm³) | Peak strength, c (kPa) | Residual strength parameters, $c_r$ (kPa) | $\phi_r$ (°) | $\delta_p$ (m) | $\delta_0$ (m) |
|-------------------|-----------------------------|------------------------|--------------------------------------------|--------------|----------------|----------------|
| Siltstone strata  | 2                           | 200                    | 0                                          | 25           | 0.01           | 0.5, 1, 1.4m   |
| Sandy gravel on N1 | 2                           | -                      | 0                                          | 10           | -              | -              |
| Sandy gravel on N2 | 2                           | -                      | 0                                          | 25           | -              | -              |

![Fig. 3 Simplified shear testing result of rock discontinuities](image)
3 DISPLACEMENT CALCULATION

A rapid evaluation of displacement was performed by using the aforementioned strength property parameters.

As the sliding direction is almost northward, the input ground acceleration was a negative NS component of strong motion record (Fig. 4a) at Wolong Station (Fig. 1), which is located 20 km away from the epicenter. The effects of possible amplification of the seismic response of the slope were not considered in this study due to the limitation in detailed geological survey at this area. The time interval of the acceleration was 0.005 second.

The initial cross-section was set as shown in Fig. 2; the width of each slice was about 10m; the strength parameters of rock and gravel and the densities were set as those listed in Table 1.

The calculation was executed by using extended Newmark and Janbu method (Deng et al., 2010). This method employs the Newmark’s sliding block analysis (Newmark, 1965) in which the yield seismic coefficient (or critical seismic acceleration coefficient) $K_y$ to yield $F_s=1.0$ is computed by using the Janbu method (Janbu, 1957), while considering the effects of irregular geometry of the sliding plane and change of the apparent friction angle mobilized on the sliding plane. Refer to Deng et al. (2010) for the details of the $K_y$ calculation procedure.

The calculation results are shown in Figs. 4 and 5. Fig. 4a shows the history of $K_y g$. Based on the Newmark’s sliding block analysis with the calculated $K_y g$, the relative velocity of the sliding slope was calculated as shown in Fig. 4b. Subsequently, the relative displacement was calculated by integrating the relative velocity between the sliding slope and the bedrock as shown in Fig. 4c. Fig. 5 shows a typical displacement calculation result. The calculation results can be summarized as follows:

1) $K_y$ decreases with the decrease in strength of material on the sliding plane, while it increases due to the change of sliding plane geometry. In the case $\delta_0=0.5$m in Fig. 4a, $K_y g$ decreases very significantly due to the decrease in strength of rock. It even decreased temporarily to a value below zero (-237gal at $t=32.425s$), so a very large velocity (20m/s, Fig. 4b) and a very large displacement (286m, Fig. 4c) are yielded due to the negative $K_y$. While $K_y g$ finally increased to be positive (337 gal at $t=54.315s$, Fig. 4a) in the subsequent stage of sliding due to the change of the geometry of the sliding plane. In the case $\delta_0=105$m in Fig. 4a, $K_y$ decreases very little because the strength of rock is virtually constant during sliding.

The effect of negative $K_y$ on the velocity and the displacements implies that the countermeasure to avoid a long run-out slope failure is to guarantee a positive $K_y$ value.
2) The effect of $\delta_0$ is very significant not only on the ultimate residual displacement but also on the sliding duration. The effect on the ultimate residual displacement can be shown by comparing the case $\delta_0=0.5$m to the case $\delta_0=1.4$m in Fig. 10. The residual displacement $\delta_{\text{res}}$ is 286m with $\delta_0=0.5$m. However, the $\delta_{\text{res}}$ value is only 0.45m if $\delta_0=1.4$m (Fig. 4c). The reason for this large difference can be explained by the effect of $\delta_0$ on $K_y$; for case $\delta_0=0.5$m, as the strength of rock decrease very significantly with displacement, so $K_y$ decrease to be negative very soon (Fig. 4a), thus a large displacement can be expected; however, for case $\delta_0=1.4$m, a negative $K_y$ was not induced by the earthquake force (Fig. 4a), so the sliding velocity cannot be accelerated by the gravity, and the displacement is very limited. This calculation results indicate that, if the strength of rock decrease gently with displacement (i.e., $\delta_0=1.4$m) the damming will not occur, i.e., the strength of geomaterial (e.g., siltstone with joint) on the sliding plane in Tangjiashan Landslide possibly decreased significantly with displacement during sliding.

It is interesting to compare the $K_y$'g history of $\delta_0=0.5$m to that of $\delta_0=1.0$m. The calculated ultimate residual displacements in the two cases are similar (Fig. 4c), however, the sliding duration in case $\delta_0=1$m is 20s longer than that in case $\delta_0=0.5$m. The large displacement in the case $\delta_0=1.0$m is induced by the ground motion after t = 50s (Fig. 4c). However, the sliding has stopped at t = 55s in the case $\delta_0=0.5$m (Fig. 4b). This implies $\delta_0$ can significantly affect the sliding process even if the ultimate residual displacements are similar.

3) The calculated residual displacements can explain the damming phenomenon, while smaller than the actual displacement. The residual displacement estimated at the site is about 350m at the toe part. On the other hand, the $\delta_{\text{res}}$ values evaluated in this study are smaller than the value at the toe part: if $\delta_0=0.5$m, the $\delta_{\text{res}}$ value is 286m (Figs. 4c & 5). The underestimation in the displacement is possibly due to the other factors which can accelerate the sliding, such as the effect of vertical component of the ground motion, the effects of possible amplification of the seismic response of the slope, the negative shear rate effects and aerodynamic effects (Cheng et al., 2007).

4 CONCLUSIONS

In this study, the effect of strength decrease of rock (strictly, rock discontinuities) during sliding was emphasized. In the calculation, the strength parameters of siltstone in the vicinity of sliding plane was soundly determined based on the relevant laboratory test or set as trial values. The analysis results can be summarized as follows:

1) In the calculation with extended Newmark and Janbu method, it is the strength decrease of rock during sliding which induces the temporarily negative yield seismic coefficient $K_y$. Due to the temporarily negative yield seismic coefficient $K_y$, the large residual displacement of the rock slope occurred. In addition, the sliding duration was significantly affected by the minimum value of displacement for the residual state.

2) As the negative $K_y$ always accompanies with an accelerated sliding velocity, it is essential to guarantee $K_y$ always keeps positive to avoid a long run-out slope failure which may induce a barrier dam. Further researches on such countermeasure are needed.

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