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特　集

# Slope Stability Analysis Considering Sliding Effect of Upper Body

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Owing to the human engineering activities, the phenomenon that new landslide happen on the upper part of the old sliding body can be found everywhere. This kind of slope consisting of two sliding bodies, which are upper body and lower body, is named as double-sliding-body slope. Its stability is usually analyzed according to two slopes. However, the effect of new landslide movement on the stability of entire slope system is not taken into account. In this paper, sliding effect of upper body is analyzed, and the formula considering sliding effect of upper body is derived based on Sarma method for analysis of entire slope. Theoretical analysis and a case history indicate that the spasmodic motion of upper body has bad effect on the lower body stability; Sliding along the top face of lower body, the effect on the lower body is disadvantageous during starting instant. Nevertheless, the bad effect will disappear and transform as the advantageous effect as descending of the slope gradient and sliding acceleration. For the slope controlling, the sliding effect of upper body should be considered in the stability analysis of double-sliding-body slope, thus it will help us recognizing and mastering or forecasting the evaluative trend of double-siding-body slope. Further reliable scientific basis can be provided in order to make effective controlling measures.

Keywords : Double-sliding-body slope, Upper body, Lower body, Sliding effect, Sarma method

## 1　INTRODUCTION

Old sliding bodies can be found everywhere [1,2]. On the upper part of the old sliding body, New landslide happen commonly, such as Baiyian landslides in Three Gorges Reservoir area[3,4], Dijiapo Slope in Baoji City[5] and Linjiaya Landslide in Xi'ning City[6]. Will the new landslide movement induce the reactivation of old sliding body or the part of old sliding body? Sometimes, sliding does not start in total sliding range but expand in its plane scope. The start of different parts could exist time difference. The expansion in slope surface is obvious, but we don't know or notice whether the expansion exist in depth range. This is because the expansion is invisible in depth range, maybe due to the very short interval time between new sliding body's movement and induced sliding body's reactivation. However, in mechanics terms, the new landslide must has effect on stability of the lower part of the old sliding body. There are many case histories during Wenchuan Earthquake in 2008[7]. In order to prevent and reduce disaster effectively, correctly recognizing its influence law is very important.

This kind of slope in which a new sliding body exist on the upper part of the old sliding body is called double-sliding-body slope. Namely, double-sliding-

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body slope comprises two superimposed sliding bodies. The new sliding body is named as upper body and the body below upper body is called lower body. Both of them have their own sliding face or potential sliding face.

A double-sliding physical model for accumulation soil slope is established by He Keqiang in 1992(8). In this model, the first sliding face is the interface between accumulation soil and bedrock, and the sliding face located inside accumulation soil is the second sliding face, and the activities of double-sliding body can be induced each other. The generation condition of the second sliding face is established based on the limit equilibrium theory. According to this theory, The movement in Jiangjiapo region of Xintan landslide belongs to double-layer sliding(8). A new method considering interlayer interactions for analysis of multi-layers landslides was put forward by Yao Tao in 2005(9). In 1995, on the base of his tens years' research on slope, Hu Guangtao summed up a series of the dynamic law on development, sliding, disunity, running, inactivity, perish and renewal of sliding body during the slope formation and evolutionary process (10).

In this paper, based on Sarma method, the formula for the stability analysis is derived considering sliding effect of upper body. Selecting Linjiaya double-sliding landslide as an example, the sliding effect law of upper body is analyzed.

## 2 SLIDING EFFECT OF UPPER BODY

There are three stages during a slope movement, such as start, running and stagnation. The sliding of the upper body will have effect on stability of lower body during the two earlier stages.

### 2．1 Starting instant of upper body

At starting instant of upper body sliding, its effect on lower body can be expressed by two forces; one is the normal component of upper body's weight acted on top face of the lower body, and the other is one paralleling to the sliding face of upper body which is equal to dynamic shear strength in size. Because of the different peak-residual strength fall or superposition of seismic motion on the sliding face, the force acted on lower body obviously varies in size at the starting instant of upper body sliding. At the same time, starting velocity of upper body sliding also varies widely(7,10,11). For simplicity, the paralleling force is assumed to be equal to peak-shear strength on sliding face, or dynamic peak-shear strength under earthquake situation.

### 2．2 Running of upper body

There are two basic forms of upper body movement, i.e., the along-slope sliding and spasmodic motion.

(1) Along-slope sliding. Supposing the top-face of lower body is relatively flat, the sliding of upper body is shown as along-slope sliding. According to equivalent static analytical method, the forces acted on the lower body by the upper body include both normal component $N_s$ of upper body's weight and sliding friction force $f$ . Sliding friction force $f$ can be represented by following formula

$$f = N_S \cdot \tan \varphi_d$$

where $\varphi_d$ is a kinetic friction angle related to sliding velocity.

(2) Spasmodic motion. The spasmodic motion of the upper body happens when top-face is obviously irregular. Meanwhile, the force acted on the lower body will exist only when both bodies collided. Tremendous impulse is produced while the upper body collides with lower body. The impulsive force can be represented, based on the principle of energy conservation:

$$F \cdot t = m \cdot V \quad \text{or} \quad F = m \cdot V / t$$

where $F$ is the impulsive force acted on the lower body, $t$ is the collusion time, $m$ is the mass of upper body, $V$ is the colliding velocity of upper body, which can be calculated by the formula in literature (10).

## 3 SARMA FORMULA CONSIDERING SLIDING EFFECT OF UPPER BODY

Above analyses indicate that a set of force will acts on the lower body due to sliding of the upper body. Generally, it can be shown by normal force and shear force which are perpendicular and parallel to top face of lower body, respectively. Supposing that the parallel force is denoted by $F$ and the perpendicular force is denoted by $N_s$ , $F_i$ and $N_{si}$ are used to denote the corresponding forces on the $i$th slice of the lower body.

Mechanical and geometric models for the $i$th slice are shown in Fig.1 and Fig.2, respectively. According to the basic principle of Sarma method(11), the following mathematical formula can be derived.

$$K_C = \frac{E_1 e_2 e_3 \cdots e_n + a_2 e_3 e_4 \cdots e_n + \cdots\cdots + a_{n-1} e_n + a_n - E_{n+1}}{p_1 e_2 e_3 \cdots e_n + p_2 e_3 e_4 \cdots e_n + \cdots\cdots + p_{n-1} e_n + p_n}$$

$$\begin{aligned} a_i = Q_i[ & W_i \sin(\varphi_{Bi} - \alpha_i) + R_i \cos\varphi_{Bi} + \\ & S_{i+1}\sin(\varphi_{Bi} - \alpha_i - \delta_{i+1}) - S_i \sin(\varphi_{Bi} - \alpha_i - \delta_i) \\ & - F_i \cos(\varphi_{Bi} - \alpha_i + \beta_i) + N_{Si}\sin(\varphi_{Bi} - \alpha_i + \beta_i)] \end{aligned}$$

$$e_i = Q_i\left[\sec\varphi_{Si}\cos(\varphi_{Bi} - \alpha_i + \varphi_{Si} - \delta_i)\right]$$

$$Q_i = \cos\varphi_{Si+1}\sec(\varphi_{Bi} - \alpha_i + \varphi_{Si+1} - \delta_{i+1})$$

$$S_i = C_{Si} - PW_i \tan\varphi_{Si}$$

$$S_{i+1} = C_{Si+1} - PW_{i+1}\tan\varphi_{Si+1}$$

$$R_i = C_{Bi} b_i \sec\alpha_i - U_i \tan\varphi_{Bi}$$

$$p_i = Q_i W_i \sin(\theta - \varphi_{Bi} + \alpha_i)$$

where $\varphi_{Bi}, C_{Bi}, \varphi_{Si}, C_{Si}$ are internal friction angle, cohesive strength on base and side of *i*th slice respect- tively. $PW_i$ and $PW_{i+1}$ are forces due to water pressure on the slice sides. $U_i$ is uplift force due to water pressure on the slice base. $W_i$ is weight of the *i*th slice.

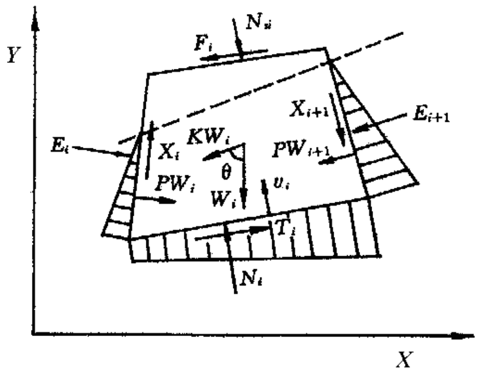


Fig. 1. The mechanical model of *i*th slice

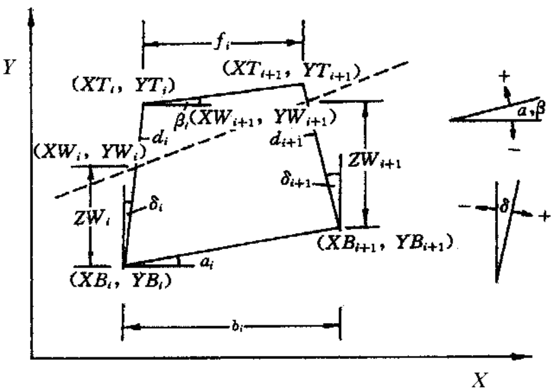


Fig. 2. The geometric model of *i*th slice

## 4 CASE HISTORY

Linjiaya landslide is developing in the quaternary eluvium and talus. There are gravel-bearing gypsum and clay in its upper, and mixture of clay with gypsum in the lower part. The sliding bed is mainly composed of the tertiary mudstone, sandstone and gypsum. The quaternary talus and diluvium are in front edge of it, and the sliding zone is constituted by clay. The exploration shows that the groundwater mainly comes from infiltration of atmospheric water. Due to soluble salt in the sliding body, the water will make the soil strength fall rapidly. It is worth noting that a new small landslide $I_n$ occurs in its posterior border. Obviously, this landslide system belongs to double-sliding-slope. We use $I_n$ and I to denote upper and lower body respectively. A computing section of the slope is shown in Fig.3. Four conditions are considered in their stability analysis:

1. natural state.
2. natural state + earthquake.
3. saturated.
4. saturated state + earthquake.

The soil parameters are shown in the Table 1. Analysis result from traditional Sarma method (Table 2) indicates that the upper body is more unstable than the lower body. Because being influenced easily by environment, it is quite possible to slide firstly. We show a strong interest in the following problems: will the upper body's sliding lead to the lower body's sliding? How much effect on the stability of the lower body?

The testing data of sliding soil show that the soil strength is obviously different between in dry and saturation state, besides the ratio of the peak strength to the residual strength is higher. Due to high gradient of the upper body and larger environmental impact, on the base of the study of Professor Hu Guangtao(10), the upper body will start and run at high speed once sliding. Because the top-face gradient varies slowly on the lower body, we deem that the potential sliding form of the upper body is along-slope sliding or small skip movement. To the Linjiaya landslide, we infer that the upper body will cause the greatest effective on the stability of the lower body in the starting instant of the upper body. Table 2 shows the stability factor of the entire slope at the start sliding of the upper body, which is deduced from the writer's software and the static soil strength instead of dynamic strength. At the starting instant of the upper body, the stability factor of the entire slope is clearly fall and lower about 10-15% than the result from the traditional Sarma method.

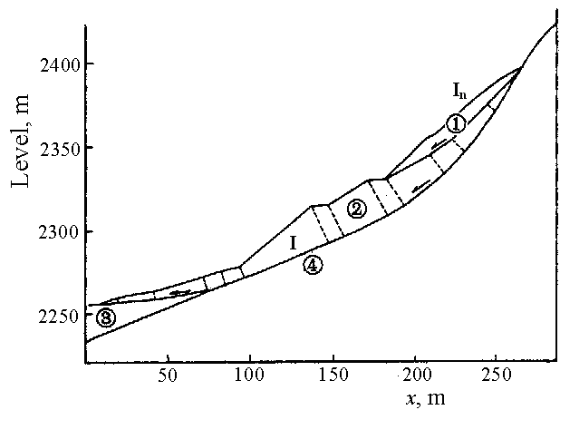


Fig. 3. The computing profile and sliced lower body of Linjiaya landslide
① mixture of gravel-bearing gypsum with clay; ② clay and gypsum; ③ talus and proluvium; ④ mudstone, sandstone and gypsum; $I_n$,I denoted upper and lower body respectively.

## 5 DISCUSSION

The process of the landslide is divided into the following three stages: the start, the running and the stagnation. If stoping on the lower body, upper body may play a role of giving a press to the foot of lower

Table 1. The parameters for computing stability of Linjiaya landslide

| Sliding body name and state | | Sliding body | | | Sliding face | |
|---|---|---|---|---|---|---|
| | | c/kPa | φ/(°) | γ (kN·m$^{-3}$) | c/kPa | φ/(°) |
| I | natural | 45.0 | 38.0 | 20.7 | 34.0 | 22.2 |
| | saturated | 40.0 | 30.0 | 21.0 | 27.8 | 18.0 |
| $I_n$ | natural | 35.0 | 25.0 | 20.0 | 33.5 | 19.67 |
| | saturated | 30.0 | 20.0 | 20.5 | 26.2 | 14.08 |

Table 2. The computing results of Linjiaya landslide stability

| scheme | Upper body | Lower body | Sarma method | method in this paper |
|---|---|---|---|---|
| 1. natural | 1.028 | 1.227 | 1.106 | (1.106) |
| 2. Natural + earthquake | 0.850 | 1.020 | 0.971 | 0.843 |
| 3. saturated | 0.732 | 0.975 | 0.875 | 0.759 |
| 4. Saturated+earthquake | 0.607 | 0.809 | 0.722 | 0.667 |

body or inducing a slip of lower body, otherwise has no effect. Slope stability at the third stage, which belongs to the static problem, is not discussed in this paper.

For Lijiaya slope, the relations between the safety factor of the lower body and horizontal distance of upper body sliding are shown in Fig. 4. For a landslide controlling and treatment, its minimum stability factor should be pay more attention to. At computing, we presume that the lower body does not move and the upper body sliding on top-face of the lower body at constant speed. The computing safety factor of the lower body is also one of entire slope system under this condition, which is taken as the vertical axis in Fig. 4. In Fig. 4, the level dotted by lines mark the safety factors of the lower body of Linjiaya slope in condition of no upper body. From the figure, we know that the sliding effect is different in the different scheme at different sliding stage: the upper body has the most effect on the landslide system at the start instant, but disadvantageous effect may be changed into beneficial effects during the running stage, finally the effect vanish due to the upper body out of the lower body. The effect of upper body is related to the grading angle of top-face of the lower body.

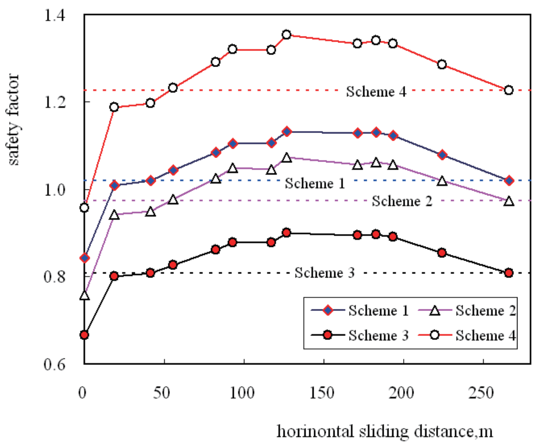


Fig. 4. The sliding effect of the upper body

Enlarging thickness (weight) of the upper body will make the sliding effect more evident. Figure 5 show the curves of safety factor corresponding 5 times or 10 times of the upper body's weight. It can be seen that the safety factor curves are stretched far from factor line of the lower body. The stability of the entire slope system is descending with the upper mass's scale enlarging at the starting instant.

It is known above that the effect of the upper body on the lower body is denoted by nomal force and tangential force during sliding on the top-face of the lower body. As the top face dip is the same as slope, the normal force is beneficial to the entire slope, yet the tangential force is unfavorable. While the effect of the tangential force is more unfavorable than that of the normal force, the security of the entire slope system will go down. Lijiaya landslide is just the case. For the skip movement, there is only one force acted on the lower body. If the sliding face dip of the lower body is the same as force direction, it will make the entire slope's stability factor descend.

To sum up, the sliding effect of the upper body is very complex, its effect on the stability of the entire slope should be analyzed with method in this paper.

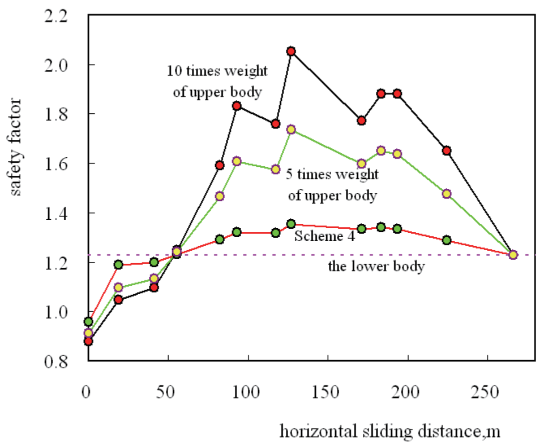


Fig. 5. The upper body's scale effect on sliding effect

It is only through analysis that the characteristics and trend of entire slope can be better understood, and that the better prevention and countermeasure can be made.

## 6 CONCLUSIONS

Double-sliding-body slope (system) is common in nature, and its stability analysis is a barely noticeable problem. The sliding effect of the upper body is analyzed in this paper, and stability analysis formula considering the sliding effect of upper body is derived in the base of Sarma method. Theoretical analysis and computing examples show that the upper sliding body's skip movement is an unfavorable effect on the stability of the lower body, but it is disadvantage at the starting instant and early stage during along-slope sliding. Accompanied with the gradient falling and the accelerated sliding, the unfavorable effect gradually vanish and change into the favorable effect. From the view of landslide prevention and controlling, the sliding effect of the upper body should be considered for stability analysis. Thus is helpful to understand and forecast the development trend of the double-sliding-body slope (system), also provide reliable scientific basis for make effective method of prevention and controlling.

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