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Shearing Rate Effect on Residual Strength of Slip Soils and Its Impact on Deformation Characteristics of Landslides

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ABSTRACT

Due to the earthquake or rainfall, the shearing rates of sliding zone can be orders of magnitude higher than those during general condition. The response of residual strength of slip soils is noticeable with the corresponding shearing rate. Using ring-shear testing on reconstituted soil samples from Sanjiaotan landslide in a wide range from 0.2 mm/min to 20 mm/min, this paper examines the influence of shearing rates on the residual strength of slip soils. And the impact of shearing rate effect on the deformation characteristics of landslides is revealed by $FLAC^{3D}$. The results show that the residual strength of Sanjiaotan slip soils is positively dependent on the shearing rates and the internal friction angle has a linear relation with the shearing rates. The shearing rate effect on residual strength of slip soils has an important influence on the deformation characteristic of landslides, which may provide an explanation for the landslides with step-like deformation.

KEYWORDS: slip soils; residual strength; shearing rate effect; deformation characteristics

INTRODUCTION

Residual strength of slip soils is extremely important from the viewpoint of evolution and stability of reactivated landslides [1]. Based on geotechnical mechanics theory, residual strength of slip soils is a kind of dynamic parameter and changes with the deformation process of landslides. If residual strength is considered as a static parameter, the stability analysis or repair of landslides must be inaccurate. Specifically, residual strength of slip soils changes with the variation of shearing rates of sliding zone [2]. And the change restricts conversely the variation of shearing rates of sliding zone. The shearing rates of sliding zone are expected to be very low, whilst during dynamic events such as the earthquake or rainfall the shearing rates can be orders of magnitude higher than those during general conditions [3]. The response of residual strength of slip soils is extremely obvious, which may be enough to change the stability of landslides. Thus, the study of shearing rate effect on residual strength of slip soils has a certain engineering significance.

Lemos et al [4] concluded that there are three types of variation of residual strength with an increase of shearing rates: (a) the residual strength can increase (positive rate effect), (b) decrease (negative rate effect), and (c) does not change (neutral rate effect). Many studies (for example, Tika et al [5], Wang et al [6] and Bhat et al [7]) also recognized shearing rate effect on residual strength of soils is noticeable. Binod et al [8] reported that shearing rate effect on residual strength can be attributed to changes in the effective normal stress that are caused by development of shear-induced pore water pressures. However, Tika [9] found that shearing rate effect on residual strength depends upon the shear mode (sliding, transitional and turbulent). Saito [10] and Bhat [11] also agreed with Tika [9]. Khosravi et al [12] concluded the variation of residual strength does not represent real behavior of the slickensided surface, but rather a “machine effect” that is attributed to load redistribution between the two proving rings. Wu et al [13] reported that if the motion of materials in sliding zone can be described as a kind of two-phase flow motion, the liquid-phase pressure changes as the shearing rate changes and the pressure will affect the contact stress between the solid-phase particles. As a result, the shear strength will be changed. Wang et al [14] found that the residual strength of a rainfall-triggered landslide is positively dependent on the shearing rates, which may provide an explanation for the continuous accelerating-decelerating process of the landsliding. Obviously, the previous studies focus on the experiment and mechanism of shearing rate effect on residual strength of soils. There has been a lack of studies about the impact of shearing rate effect on the deformation characteristics of landslides.

In this study, various shearing rates from 0.2 mm/min to 20 mm/min are performed to clarify the shearing rate effect on the residual strength of slip soils from Sanjiaotan landslide that occurred at Chungking, China. The impact of shearing rate effect on the deformation characteristics of the landslide is revealed by $FLAC^{3D}$, which may provide an explanation for the landslides with step-like deformation.

TEST SAMPLE

Soil samples used for the laboratory tests were collected from the back edge of Sanjiaotan landslide in which the sliding surface was exposed. The landslide is located in the right bank of the Qijia River which is the branch of Yangtze River. **Figure 1** is a longitudinal section of Sanjiaotan landslide. The sliding mass consists of gravel soil with average thickness of 12 m. The sliding surface which is the contact surface between gravel soil and bedrock, consists of silty clay with little gravel. The bedrock in the landslide area is calcareous shale, shale and limestone of the higher Jurassic Ziliujing formation (J_{1-2z}). Based on the field investigation and processing data, the landslide has begun to move since 1982. A crack with 150 m long and 2 m wide appeared at this time. For nearly

30 years, multiple sliding were triggered by rainfall and excavation at the toe. Every time, the landslide restored to steady state operation with its gravity. The step-like deformation came up repeatedly. The deformation characteristics of the landslide is common in Three Gorges Reservoir area.

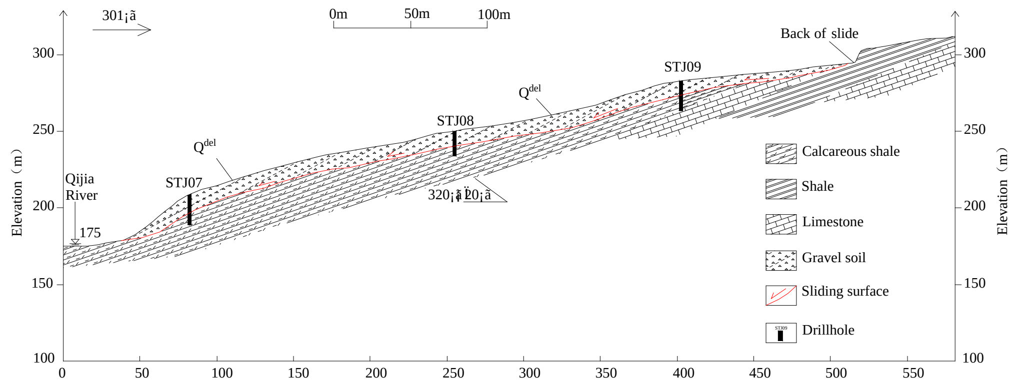

Figure 1: Longitudinal section of Sanjiaotan landslide(unit: m)

The samples are yellow and have dense structure as shown in **Figure 2**. To clarify the basic properties of samples, grain size analyses, Atterberg limit measurements were conducted on them. **Figure 3** depicts the grain size distribution of samples. It is clear that the samples have more silt and clay particles and the content of coarse particles (grain size > 2 mm) is less than 10%. Especially, the content of clay particles is vital to the engineering properties of soils. **Table 1** shows the physical properties of soil samples. The samples are plastic in the state of natural, which can be attributed to the low permeability.

Figure 2: Images of soil samples

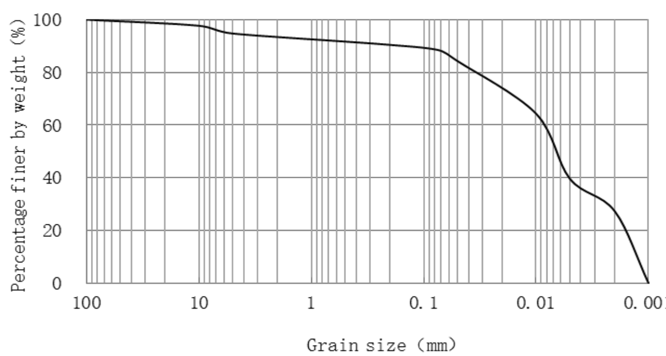

Figure 3: Grain size distribution curves of samples

Table 1: Physical properties of soil samples used

Soli density（g/cm^3）	Density index	Natural water content（%）	Plastic limit（%）	Liquid limit（%）	Plasticity index	Liquidity index
2.00	2.73	16.41	15.19	24.82	9.63	0.13

LABORATORY TESTING

Test Apparatus

The tests were performed in the DTA-138 ring shear apparatus designed by Seiken Inc, as shown in **Figure 4**. In this apparatus, the specimen container has inner and outer diameters of approximately 100 mm and 150 mm, respectively, an average specimen thickness of 20 mm, and a ring area of shear plane of 98.16 cm^2. The apparatus can supply the maximum of normal stress and shear stress of 1 MPa and 1.5 MPa, respectively. The maximal axial displacement is 20 mm. Shearing rate controlled by a high-precision machine is from 0.00055 mm/min (angular velocity: 0.0005 °/min) to 109 mm/min (angular velocity: 100 °/min) with changing linearly or jumpily. All parameters of apparatus meet the needs of tests.

An annular specimen is ruptured on a plane of relative rotary motion while being confined laterally between pairs of lower and upper confining rings. The lower half of apparatus below the plane of failure is made to rotate, while the upper part is not movables during the tests. A normal stress is applied directly above the apparatus to the annular specimen through the upper ring. Shear stress, normal stress, shear displacement, and pore water pressure are monitored and recorded automatically. Especially, this apparatus has a special structure to prevent soils and water leakage during long displacement.

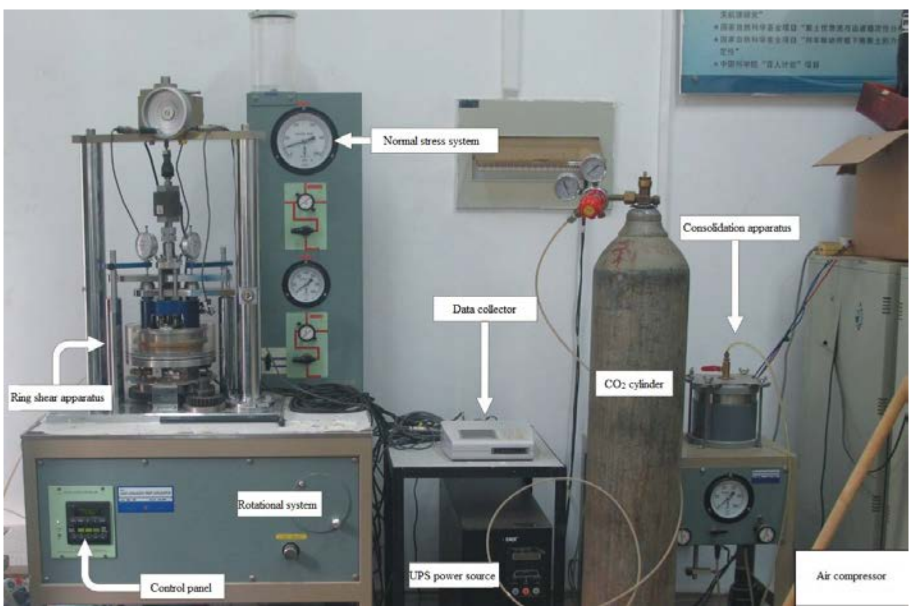

Figure 4: System of DTA-138 ring shear apparatus

Test Procedure

Previous theory and test results indicate that residual strength is independent of stress history and initial structure of soils [15]. Thus, residual strength of soils can be obtained by using ring-shear testing on reconstituted samples as same as undisturbed samples. There are three basic stages in the ring shear tests: (a) Reconstituted samples preparation: The fresh samples were dried by a oven. The temperature of 105 ℃ in the oven kept no less than 24 hours. The dry samples passing through 2 mm sieve were taken and mixed with distill water to attain the state of natural water content (16.41%).

The samples were then poured into the specimen mold for the consolidation. (b) Primary consolidation stage: The samples were consolidated at different effective normal stresses ranging from 100 to 400 kPa. The end of primary consolidation was confirmed from the data logger graph where a long straight line without the variation of sample height indicated that the consolidation was over. Then, the samples were ready for the shearing. (c) Shearing stage: After the end of the primary consolidation, shearing was begun. The types of shearing methods, including pre-shearing and multi-stage shearing, were conducted to investigate the residual strength of samples. During the shearing, the effective normal stress was the same as the consolidation pressure, giving the value of OCR of 1. The tests were performed under drained conditions.

It is clear that various shearing rates have impact on residual strength of soils only in a certain range [16]. Selecting appropriate shearing rates is essential to reflect the impact of shearing rate effect on residual strength of slip soils. Skempton [13] reported that residual strength of soils is almost constant in a range from 0.002mm/min to 0.01 mm/min in conventional tests. Many researchers (Bhat et al [7], Bhat et al [11], and Chen [18]) also found that residual strength of soils is negligible before a shearing rate of 0.2 mm/min. Moreover, Hu [19] concluded that a large shearing rate causes the effect of leaking and soil-compacting, resulting in a noticeable difference of residual strength. He suggested a shearing rate range from 0.2 mm/min to 20 mm/min. Based on the previous achievements, the ring shear tests were performed at four shearing rates (0.2, 2.0, 10 and 20 mm/min). Particularly, the process of shearing consists of pre-shearing and multi-stage shearing. Firstly, pre-shearing with a shearing rate of 2.0mm/min was completed to obtain residual strength quickly. Secondly, multi-stage shearing was performed at four shearing rates (0.2, 2.0, 10 and 20 mm/min) in a row. Every stage shearing needs to reach at residual. Undoubtedly, the above process is more consistent with the fact of sliding.

TEST RESULTS

Figure 5 shows the relationships between shear stress and shear displacement at different normal stresses. Due to the long shear displacement and drained conditions, the excess pore water pressure becomes more stable and nearly dissipates. The maximum value of steady pressure is only 5.4 kPa. It is pointed out that the peak strength of samples is not obvious, which is common in the ring shear tests of reconstituted samples. The residual strength of samples is positively dependent on the shearing rates. And the variation of residual strength becomes more obvious with the increasement of normal stress. This phenomenon may be induced by the interparticle friction, which is positively related with the normal stress. The mechanism of shearing rate effect on residual strength can be attributed to the shear mode varying with the shearing rates and causing the internal frictional angle of soils to change [20]. It will be validated in the following section.

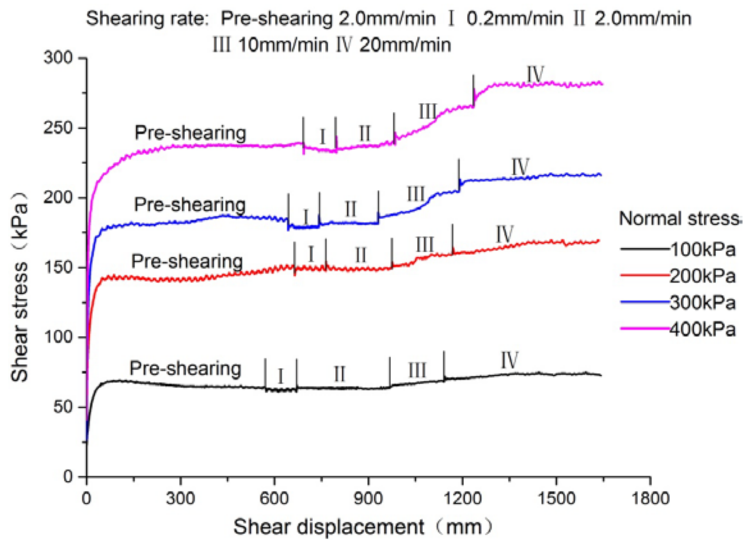

Figure 5: Relationships between shear stress and shear displacement

The particles almost orientate in the direction of shearing due to the long shear displacement. The residual cohesion c_r reduces obviously and hardly makes a contribution to the residual strength. Many studies (for example, Wu et al [16], Lu [21] and Tiwari et al [22]) recognized that c_r is equal to zero at residual. Hence, the study of shearing rate effect on residual strength of slip soils, actually discusses the variation of residual angle of internal friction with various shearing rates. **Figure 6** shows the relationships between shear strength and effective normal stress. The internal friction angle increases 4.65° in a range from 0.2 mm/min to 20 mm/min. The growth rate of 14.65% approximately has a great influence on the landslide.

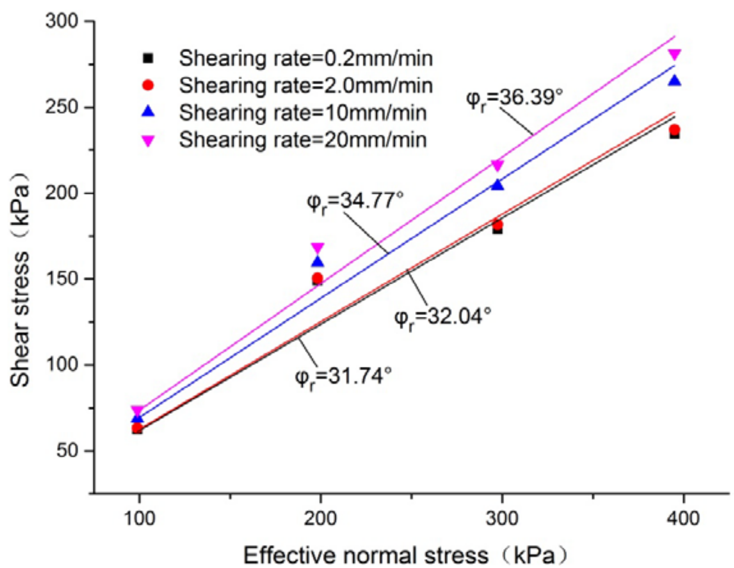

Figure 6: Relationships between shear strength and effective normal stress

Figure 7 depicts the relationship between internal friction angle and shearing rate. It is observed that the internal friction angle has a linear relation with the shearing rate and the fitting degree is great. This result agrees with the previous results ([11], [23]). The residual strength of slip soils can display different types and violent degree of shearing rate effect, accompanying the slope of line. The slope of Sanjiaotan slip soils is 0.24, ten times larger than the slope of kaolin clay, but close to the slope of mudstone. This phenomenon may be attributed to the grain size distribution of samples, which consist of silt and sand particles (grain size from 0.075 mm to 2 mm) except clay particles.

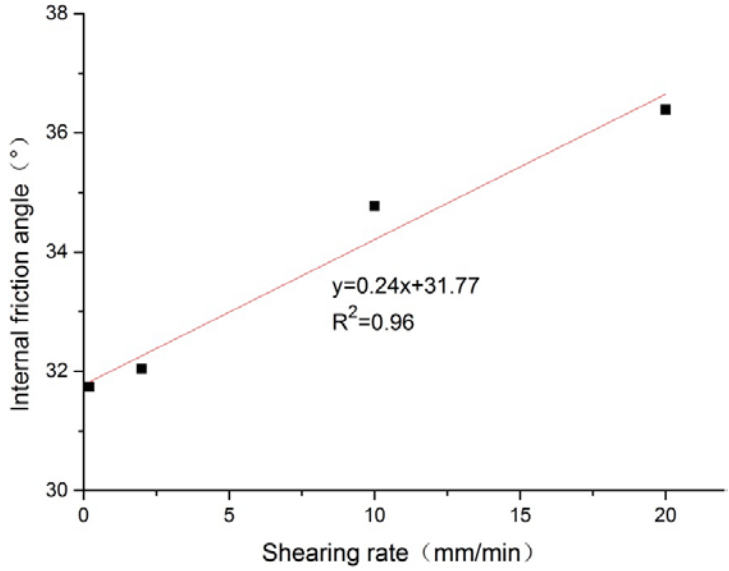

Figure 7: Relationship between internal friction angle and shearing rate

There are three types of shearing rate effect on residual strength of soils: (a) positive rate effect, (b) negative rate effect, and (c) neutral rate effect. **Figure 8** is the simple sketch of positive, negative and neutral rate effect. Which shearing rate effect on residual strength of slip soils is dependent on the physical properties of soils. For instance, Miao [24] concluded that residual strength of slip soils has a positive rate effect with higher clay content and a negative rate effect with lower clay content. Meanwhile, Tika [5] reported that residual strength of slip soils may have a positive rate effect with higher clay content due to a change in shear mode in the sliding zone (The particles in the sliding zone almost orientate in the direction of shearing. However, the particles with increasing the shear rates will lose their alignment and turbulent shearing will become dominant, resulting in increasement of residual strength). Obviously, **Figure 7** indicates that the residual strength of Sanjiaotan slip soils has a positive rate effect, corresponding to the higher clay content of soils.

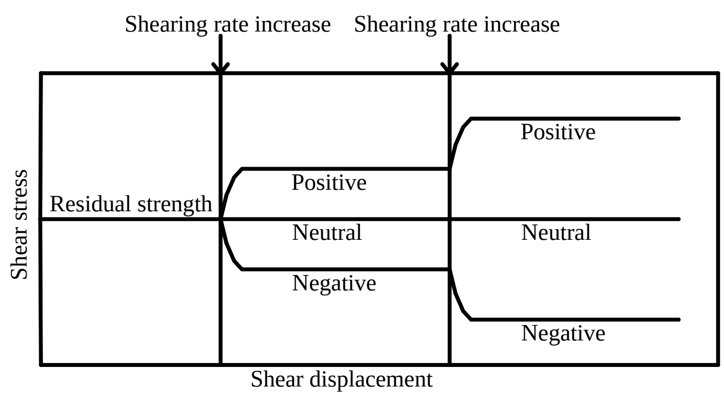

Figure 8: Simple sketch of positive, negative and neutral rate effect

Due to the positive rate effect, the residual strength of slip soils increases linearly with increasing the shearing rates. This kind of landslides needs continuous external forces to move and commonly shows continuous walking-stopping process during and after external forces. The stability of landslide is supposed to be controlled by that deformation characteristic. But multiple deformation and strong external forces can make them disasters. For example, the residual strength of Xiangshanlu slip soils has a positive rate effect [24], but the landslide was triggered by the rainfall in 2008, resulting in destroying some infrastructures and seven houses. In this paper, the central section of Sanjiaotan landslide appeared a large number of cracks and the front section collapsed, resulting in moving five families. There is a lack of recognition about the deformation characteristic of landslides affected by positive rate effect. Taking Sanjiaotan landslide as an example, the impact of shearing rate effect on the deformation characteristic of the landslide is revealed by $FLAC^{3D}$ in the following section.

IMPACT OF SHEARING RATE EFFECT ON THE DEFORMATION CHARACTERISTIC OF LANDSLIDES

In order to explore the impact of shearing rate effect on the deformation characteristic of landslides, the process of Sanjiaotan landslide was simulated by $FLAC^{3D}$. Mohr-Coulomb criteria was used in the simulation and the slip soils was regarded as low-intensity unit.

Based on the above results, the residual strength of slip soils is a timeliness parameter with the shearing rates changing. Specifically, c_r is equal to zero and φ_r is the function of shearing rates. Internal friction angle φ_r will be changed every ten time-steps with the average shearing rate of sliding zone units. The changing is performed by Fish language programming, in accordance with **Figure 7**. Physico-mechanical parameters of sliding mass, sliding zone and sliding bed were confirmed by laboratory tests, as shown in **Table 2**.

Table 2: Physico-mechanical parameters of sliding mass, sliding zone and sliding bed

Location	Density (kg/m^3)	Bulk modulus (kPa)	Shear modulus (kPa)	Internal frictional angle (°)	Cohesion (kPa)	Tensile strength (kPa)
sliding mass	2061	1.85E+5	1.45E+5	32	35	0.1
sliding zone	2000	1.89E+4	9.77E+3	φ_r	0	0.1
sliding bed	3360	4.44E+6	3.33E+6	40	1000	4000

Figure 9 shows the relationships between horizontal displacement of monitoring sites and time-step. The monitoring sites in the simulation coincide with the surface coordinates of drillholes (as shown in **Figure 1**), named after SJT07, SJT08 and SJT09, respectively. It is observed that the landslide gradually stabilized after the short sliding, due to the positive rate effect on the residual strength of slip soils. However, a landslide in reality is an open system. The process from walking to stopping will appear repeatedly with external forces, resulting in the step-like deformation. Meanwhile, the horizontal displacements of three monitoring sites hardly changed after six thousand time-steps. It suggests that the landslide restored to steady state operation and the positive rate effect disappeared.

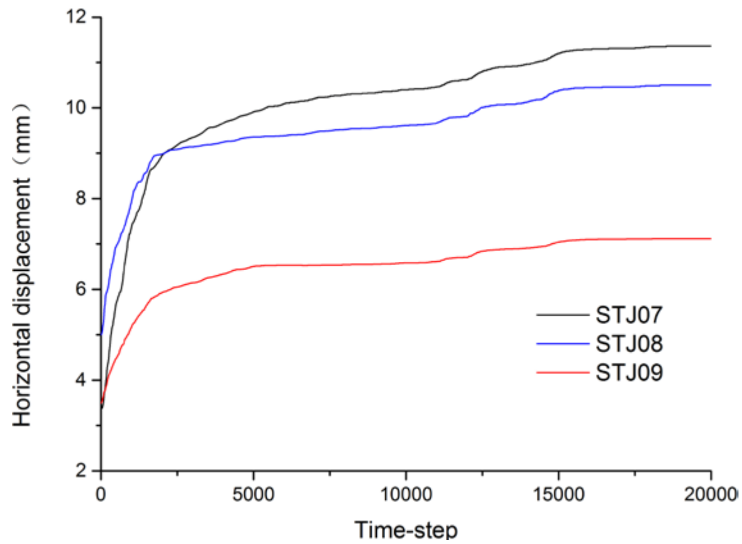

Figure 9: Relationships between horizontal displacement of monitoring sites and time-step

Figure 10 shows the relationship between internal friction angle and time-step. It is clear that the residual strength of slip soils presents extreme fluctuation in the shearing. And the fluctuation results from the interaction between the shearing rates and residual shear strength. The impact of positive rate effect on the deformation characteristic of landslide is recognized from the point of kinesiology in the following: (a) When the landslide began to slide with external forces, it got initial acceleration with the energy releasing. The shearing rate of sliding zone increased rapidly. And the residual strength of slip soils increased because of the positive rate effect, resulting in reducing the acceleration of landslide. (b) When the acceleration was equal to zero, the shearing rate was maximum and so was the corresponding residual strength. (c) Due to the positive rate effect, the residual strength was greater than the sliding force of slip soils and negative acceleration appeared. The residual strength decreased gradually with the shearing rate until the negative acceleration was equal to zero. The above stages worked repeatedly. Finally, the landslide restored to steady state operation because the energy has been dissipated.

As mentioned above, the residual strength of slip soils presents extreme fluctuation in the shearing due to the positive rate effect. The landslide restores to steady state operation because the energy has been dissipated. With external forces, the walking-stopping process of landslide appears repeatedly. The simulation reveals that shearing rate effect on residual strength of slip soils has an important influence on the deformation characteristic of landslides, which may provide an explanation for the landslides with step-like deformation.

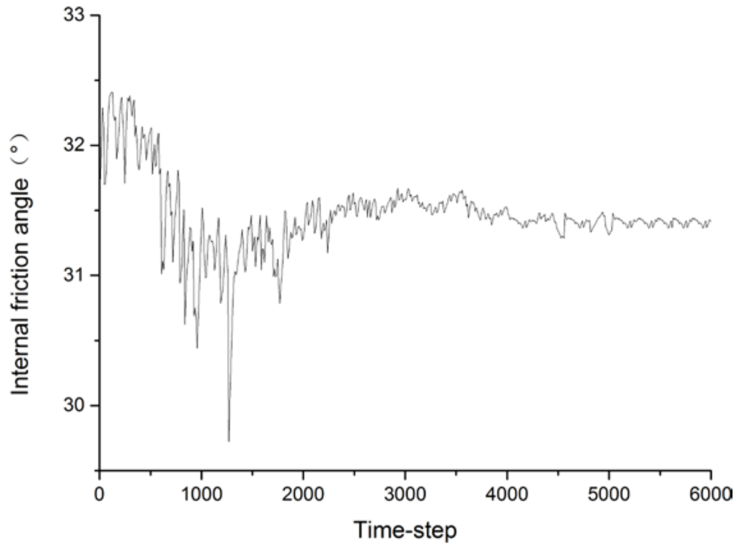

Figure 10: Relationship between internal friction angle and time-step

CONCLUSIONS

The following conclusions were obtained based on the study:

(1) The residual strength of Sanjiaotan slip soils is positively dependent on the shearing rates.

(2) The internal friction angle has a linear relation with the shearing rates and increases 4.65° in a range from 0.2 mm/min to 20 mm/min, with the growth rate of 14.65% approximately.

(3) Shearing rate effect on residual strength of slip soils has an important influence on the deformation characteristic of landslides. The increase of residual strength with the shearing rates may be the key reason for the deformation characteristic of Sanjiaotan landslide with step-like deformation.

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