Mechanism on progressive failure of a faulted rock slope due to slip-weakening

ZHANG Junfeng, XU Yongjun, QI Tao & LI Zhengguo

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China
Correspondence should be addressed to Zhang Junfeng (email: zhangjf@imech.ac.cn)

Received July 1, 2004

Abstract Slip-weakening is one of the characteristics of geological materials under certain loadings. Non-uniform rock structure may exist in the vicinity of the slip surface for a rock slope. Some portion of the slip surface may be penetrated but the other not. For the latter case, the crack or the fault surface will undergo shear deformation before it becomes a successive surface under a certain loading. As the slipped portion advances, slip-weakening occurs over a distance behind the crack tip. In the weakening zone, the shear strength will decrease from its peak value to residual friction level. The stress will redistribute along the surface of crack and in the weakening zone. Thus the changed local stress concentration leads the crack to extend and the ratio of penetration of the slip surface to increase. From the view of large-scale for the whole slip surface, the shear strength will decrease due to the damage of interior rock structure, and the faulted rock behaves as a softening material. Such a kind of mechanism performs in a large number of practical landslides in the zones experienced strong earthquakes. It should be noted that the mechanism mentioned above is different from that of the breakage of structural clay, in which the geological material is regarded as a medium containing structural lumps and structural bands. In this paper, the softening behavior of a faulted rock should be regarded as a comprehensive result of the whole complicated process including slip-weakening, redistribution of stress, extension of crack tip, and the penetration of the slip surface. This process is accompanied by progressive failure and abrupt structural damage. The size of slip-weakening zone is related to the undergoing strain. Once the relative slide is initiated (local or integrated), the effect of slip-weakening will behave in a certain length behind the crack tip until the formation of the whole slip surface.

Keywords: faulted rock slope, slip-weakening, progressive failure.

DOI: 10.1360/04zze5

1 Introduction

The damage or failure of faulted rock slope is a quite difficult problem in geotechnical engineering, and attention has been drawn from researchers for a long time. Apart from the toppling damage of steep slopes, most of the failure pattern of faulted rock slopes is shear-typed. The failure process of such a slope includes: initiation and development of a single micro-crack, breakthrough of two or more cracks, formation of failure zones, and even shear damage in large scale. In general, a crushed shear band will be formed in such a kind of failure process[1]. Under static loadings such as gravity or engineering building, the rock material within a certain zone behind the tip of a crack/fault will behave strain-softening property due to the action of stress erosion or chemical erosion. Similarly, slip-weakening as a characteristic will occur in the vicinity of the tip of crack/fault under seismic loadings due to cyclic fatigue or slide relatively. In such a case, stick slipping will occur on the crack surfaces.

From the viewpoint of microscope, the slip-weakening characteristic of rock materials can be used to explore the initiation and extension of micro-cracks. From the angle of local region, combining the shear failure pattern, slip-weakening may be considered as strain-softening. After the failure of this local region, which may be the result of extension of one main crack or integration of many micro-cracks, the stress field will be redistributed, and rock material in the adjacent region along a certain direction will exhibit slip-weakening property. Such a new local region should be located behind the new tip of main crack or at a zone with rock material undergoing larger shear strain. This kind of failure for a faulted rock slope performs as a progressive pattern, and results in a shear band, i.e. the slip surface of the slope.

By using the slip-weakening characteristic, the mechanism of progressive failure for a kind of faulted rock slope is analyzed in terms of local strain softening method in this paper.

2 Failure mechanism of a faulted rock slope due to slip-weakening

The results of geological survey showed that faults, cracks or joints exist abundantly in rock slopes or stack layers. Some cracks are connected but others not. For rock material with a crack under shear stress, slip-weakening phenomena will occur in the region behind the crack tip before extension of the crack[2]. The characteristic of slip-weakening for faulted rocks is quite different from the structural damage of natural clays, nor the shear dilation of rock-soil material.

Studying the damage of natural clays, Shen and his colleagues[3−6] proposed structural damage models based on the survey to natural clays and laboratory experiments. For the constitutive model of natural structural clays, because the distribution of cementation action is non-uniform, the geological material is conceptualized as binary structural bodies consisting of bonded blocks and weakened bonds, in which the strong cemented zones are bonded blocks and the others are weakened bonds. In the damage process of a structural geological material, cementational force decreases progressively and frictional force takes effect simultaneously. It can also be considered that the banded blocks become failure progressively and the weakened bonds extend at the same time. The behavior of such kinds of geological materials performs as strain softening in macro-scale.

Then, the damage process of a structural geological material can be divided into three stages: 1) the structure of soil becomes damaged; 2) the weakened bonds form progressively and the shear strength of material in the bonds decreases; and 3) the slide is initiated.

As to the property of shear dilation for the geological material, though it indeed occurs in the process of frictional sliding as indicated in ref. [7], the further study also showed that shear dilation is the direct result of the initiation, opening, and extension of micro-cracks. Seemingly, both shear dilation and slip-weakening exhibit that the shear strength decreases from a peak value to a residual one after sliding, but the essential difference of them is the specific zones. The softening zone induced by shear dilation generally means a small region in the vicinity of the contact surfaces, including existing crack and new-developed micro-cracks before and after damage. However, the slip-weakening zone is behind the crack tip within a certain size, which is determined by the original size of the crack, the characteristic of the interface, the state of stress and local stress concentration, and slipped displacement (or shear strain). Fig. 1 illustrates the slip-weakening zone in a faulted rock after a certain relative displacement, in which τ is shear stress, and u is the relative displacement of two surfaces of crack.

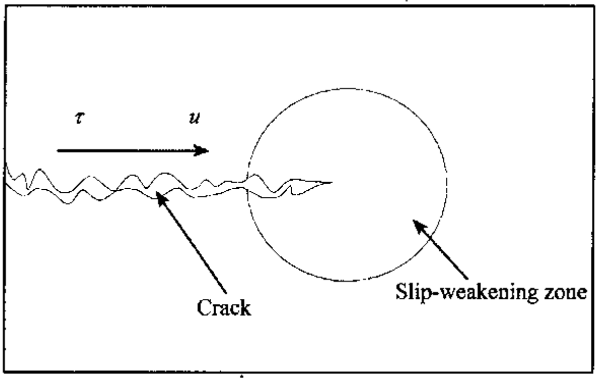


Fig. 1. Schematic diagram of slip-weakening zone in a faulted rock under shear force.

For a faulted rock slope under a certain loading, the inner stress behind the crack tip is redistributed due to slip-weakening, and the concentration of stress is intensified. So the crack develops further along a certain direction, the structure of rock soil becomes damaged, and at last, the whole slip surface is breakthrough and landslide occurs. Hence, slip-weakening is one of the reasons causing landslide for some faulted rock slopes.

It should be noted that, for the above-mentioned type of landslide, the formation of slip surface is different from that of the geological shear faultage, which may cause strong earthquake in a large scale. The precondition for the former is that the slope will slide as a whole but not initiate yet, the local rock structure is still integrated, and the whole slip surface is still not penetrated. The result of slip-weakening leads the shear strength to decrease in the vicinity of the crack tip, the stress state to redistribute, the stress concentration to intensify, and the original crack to extend or new micro-cracks to develop. At last, the whole slip surface becomes progressively breakthrough and landslide occurs.

3 Slip-weakening zone and the shear strength

3.1 Range of slip-weakening zone

Palmer and Rice[8] assumed that the shear strength is in linear relation with slipping displacement, and they gave out the mathematical expression of the size of weakening zone behind the tip of crack as follows:

$$R=\frac{\pi G\delta^*}{4(1-\nu)(\tau_c-\tau_f)}, \tag{1}$$

in which G is shear modulus, ν the Poisson's ratio, δ^* the relative slipping displacement, and τ_c, τ_f the peak of shear strength and residual shear strength respectively.

A similar result was given in ref. [2], in which the size of weakening zone is expressed as

$$R=\frac{3\zeta G\delta^*}{4(1-\nu)(\tau_c-\tau_f)}, \tag{2}$$

where the value of parameter ζ in most cases: $\zeta = 1 \pm 0.11$.

3.2 Shear strength in the slip-weakening zone

In general, the relation between the weakening shear strength and slipping displacement in slip-weakening zone is obtained from laboratory test. Sometimes a simplified model can be introduced to describe the above relation [2, 9]. Just like in ref. [2], the linear relationship is employed, i.e.

$$\frac{\tau-\tau_f}{\tau-\tau_f}=1-\frac{w}{w_c}, \tag{3}$$

in which τ is shear strength while the slipping displacement is u, $w_c = \delta^*/2$ the largest weakening displacement before damage, w the weakening displacement, and its series expression is

$$aw_n(u)=a_n R^{n+3/2}u^{n+3/2}, \qquad n=1,2,\cdots \tag{4}$$

in which a_n is a constant with dimension $[L]^{1-n-3/2}$.

Fig. 2 shows the $\tau - w$ curve having been given in ref. [2] according to a triaxial test result for a granite

4 Numerical simulation for progressive failure of a faulted rock slope

According to the analysis above, a numerical simulation for the progressive failure

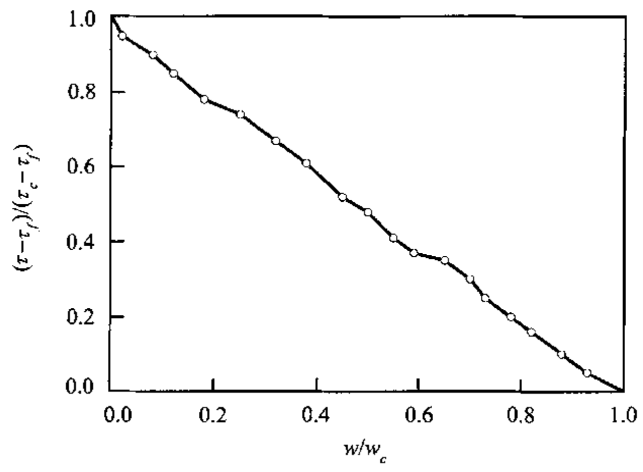


Fig. 2. Shear strength τ versus slip displacement w of a triaxially tested granite specimen.

progress of a faulted rock slope is carried out by using the finite difference method. To achieve this computing work, a commercial program called FLAC^{3D} is employed here. During the process, the selection of slip-weakening zone and its direction is controlled by the inner language. A schematic diagram of a faulted rock slope with slope gradient 2:1 is shown in Fig. 3. The parameters used in the simulating analysis are: density of rock material γ=2.6 kN/m^3, Young's modulus 2.57×10^3 MPa, and Poisson's ratio 0.28. Elasto-plastic model is taken as the constitutive relation for the rock material, and Mohr-Coulomb model is also employed as failure criterion. In the slip-weakening zone, the rock material behaves in macro-scale as a strain softening one. The initial cohesive coefficient is c = 140 kPa and inner frictional angle is φ=45°. For the model bedrock, we take it as an elastic material with high Young's modulus. The limit difference meshes used for computation are shown in Fig. 4.

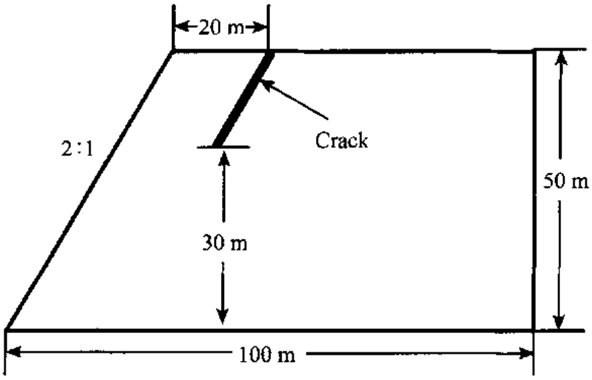


Fig. 3. Schematic diagram of a faulted rock slope.

4.1 Determination of slip-weakening zone and its developing direction

According to the description in sections 1 and 2 above and the weakening zone shown in Fig. 1, the primary analysis indicates that the strain and the ratio of strain in the vicinity of the crack tip are larger than that in the other part, that means concentration exists there. Taking the crack tip as the center of a circle, we select the radius for the circle which includes the adjacent four meshes (note: only the four meshes) as shown in Fig. 5. Then these four meshes are assumed to be the slip-weakening zone. According to the computed strain field and the maximum strain increment, the second center of weakening zone can be determined. Analogically, the rest can be done in order until the weakening zone reaches the boundary of the slope, which indicates that the slip surface becomes breakthrough completely. Such a method also can be regarded as an application of the theory of strain localization.

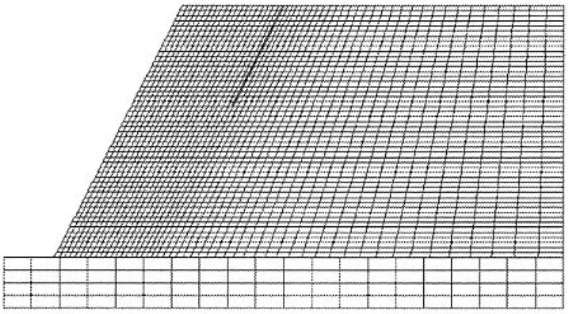


Fig. 4. Mesh for computation with $\mathrm{FLAC^{3D}}$.

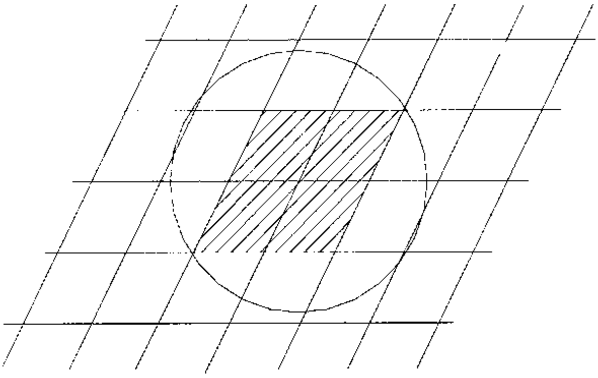


Fig. 5. Models for determination of slip-weakening zone.

Generally, the four cases may occur while one selects the developing direction of the weakening zone: two in-order types (see Fig. 6(a) and (b)) and two deviation types (see Fig. 6(c) and (d)). No matter which type we met, the developing direction should be determined based on that of the maximum strain, and the center of new weakening zone should be aimed at the closest node.

4.2 Simulating results of progressive failure for a faulted rock slope

The strain-softening curve of the rock material in slip-weakening zone is shown in Fig. 7. It should be noted that, in ref. [2], a linear relation between shear stress and strain

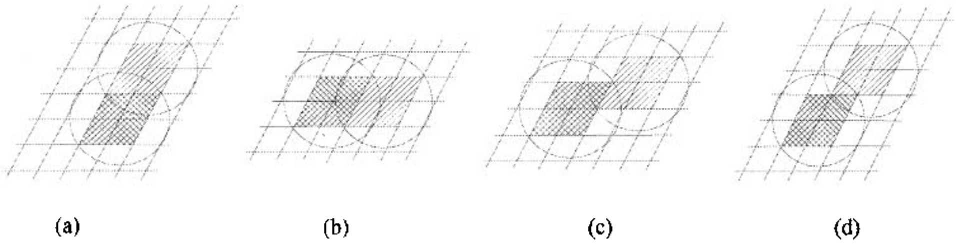


Fig. 6. Determination for the developing trend of slip-weakening zone.

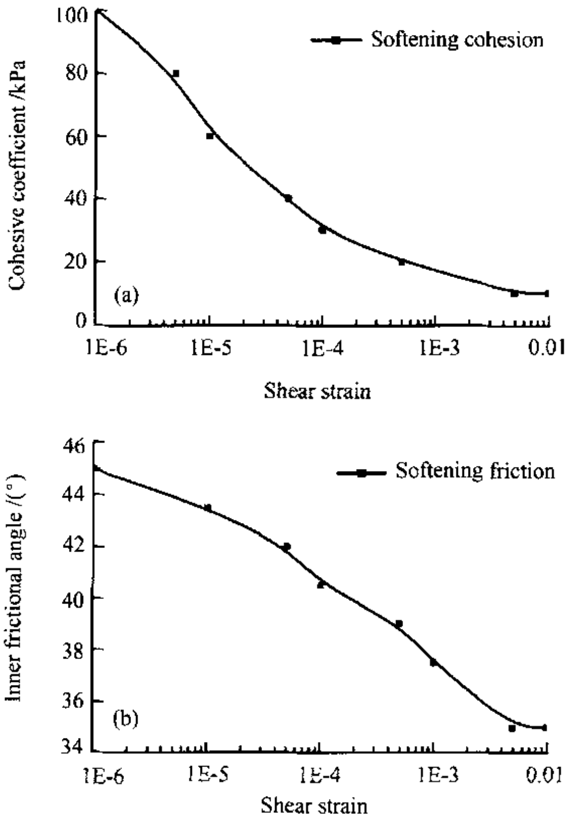
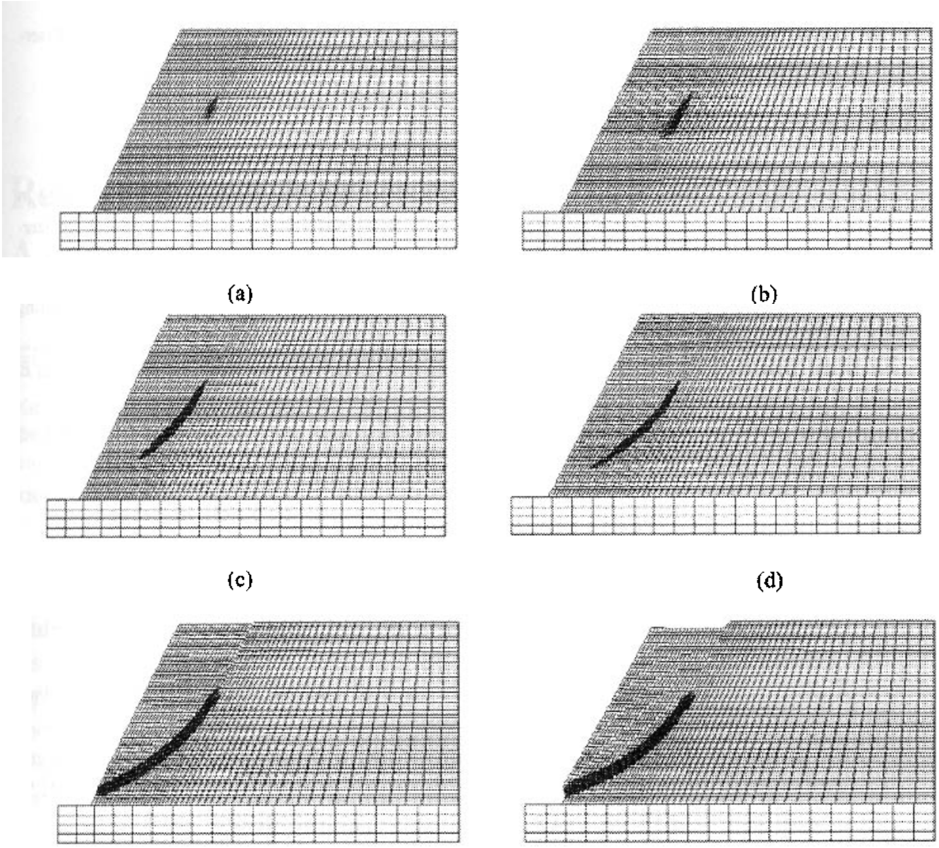


Fig. 7. (a) Cohesive constant versus shear strain; (b) friction angle versus shear strain.

is taken. The linear relation is also mentioned and experimentally testified in refs. [9—11]. Fig. 8(a) illustrates the initial distribution of shear strain increment in the weakening zone of the tip of crack. Fig. 8(b)—(f) show the evolution of the strain increment field in the whole failure process of the formation of slip surface.

From Fig. 8 we can get the failure process of the faulted rock slope. Slip-weakening occurs in the vicinity of the tip of crack due to stress concentration (Fig. 8(a)). The shear strength decreases in the weakening zone (strain-softening), and the local failure result leads the slide to develop progressively. In Fig. 8, the local failure zone has evolved into a failure band. Thus, we can focus on studying the failure band instead of the extension of



(a) (b)

(c) (d)

(e) (f)

Fig. 8. Progressive failure process of a faulted rock slope.

micro-cracks. Fig. 8(f) shows the further slide after the breakthrough of the crack (i.e. the formation of the slip surface).

5 Concluding remarks

Slip-weakening is one of the properties of intact or faulted rock. Under a certain loading, especially, strong seismic loadings, the shear strength decreases and the stress is redistributed due to a relative slide in the vicinity of the tip of crack in a slope. The high stress concentration there leads the crack to extend, and the slip surface to become breakthrough, then the whole slope to become damage. Hence, slip-weakening is one of the mechanisms of landslide or toppling for rock slopes, especially for faulted rock slopes. The similar mechanism may adapt for the stack layers. So further study needs to be done for slip-weakening. Exploration for the determination of weakening zone and its developing trend can let the formation process of progressive failure and breakthrough be more clarified.

Acknowledgements The authors wish to thank all their colleagues in the Institute of Mechanics, CAS, for their valuable discussion on various parts of the work described in the paper. This work was supported by the National Natural Science Foundation of China (Grant No. 10372104), the Special Funds for the Major State Basic Research Project (Grant No. 2002CB412706), the Knowledge Innovation Project of the Chinese Academy of Sciences (Grant

No. KJCX2-SW-L1-2), the Special Research Project for Landslide and Bank-collapse in The Three Gorges Reservoir Areas (Grant No. 4-5).

References

1. Atkinson, B. K., Fracture Mechanics of Rock, London: Academic Press Limited, 1987.
2. He Changrong, Slip-weakening constitutive relation and the structure in the vicinity of a shear crack tip, in Mechanics Problems in Geodynamics Part I (eds. Wang Ren, Keiiti Aki), Birkhäuser Verlag, Basel, Switzerland: PAGEOPH, 1995, 145(3/4): 747—757.
3. Shen Zhujiang, An elasto-plastic damage model for cemented clays, Chinese Journal of Geotechnical Engineering (in Chinese), 1993, 15(3): 21—28.
4. He Kaisheng, Shen Zhujiang, Elasto-viscoplastic damage model for structural clays, Hydro-science and Engineering (in Chinese), 2002, 4: 7—13.
5. Shen Zhujiang, Breakage mechanics for geological materials: an ideal brittle-elasto-plastic-model, Chinese Journal of Geotechnical Engineering (in Chinese), 2003, 25(3): 253—257.
6. He Kaisheng, Shen Zhujiang, Investigation on structural properties of natural sedimental clays, Journal of Southeast University (Natural Science Edition) (in Chinese), 2002, 32(5): 7—13.
7. Teufel, L. W., Pore volume changes during frictional sliding of simulated faults, in Geophysical Monograph, 24, Mechanical Behavior of Crustal Rocks, the Handin Volume (eds. Cater, N. L., Friedman, M. et al.), Washington D.C.: American Geophysical Union, 1981, 135—145.
8. Palmer, A. C., Rice, J. R., The growth of slip surface in the progressive failure of over-consolidated clay, Proc. Roy. Soc. Lond., 1973, A332: 527—548.
9. Wang Xuebin, Pan Yishan, Ren Weijie, Instability criterion of shear failure for rock specimen based on gradient-dependent plasticity, Chinese Journal of Rock Mechanics and Engineering (in Chinese), 2003, 22(5): 747—750.
10. Wang Xuebin, Pan Yishan, Ma Jin, Analysis of strain and strain rate in shear band and its instability based on energy criterion, Engineering Mechanics (in Chinese), 2003, 20(2): 111—115.
11. Wang Xuebin, Pan Yishan, Ma Jin, A theoretical study on ductile shearing bands based upon strain gradient plasticity theory, Engineering Mechanics (in Chinese), 2002, 8(1): 79—86.