Journal of Applied Sciences

ISSN 1812-5654

science alert

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 13 (21): 4371-4378, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.4371.4378

Failure Modes and Stability of Rock Mass Slope Containing Multi-weak Interlayer

[1]Liu Jie-Qun, [2]Chen Lu-Wang and [3]Liu Jin-Long
[1]Department of Computer Science and Technology, Key Laboratory of Network and Intelligent Information Processing, Hefei University, 230601, Hefei, China
[2]School of Resource and Environmental Engineering, Hefei University of Technology, 230009, Hefei, China
[3]Department of Civil Engineering, Hefei University, 230601, Hefei, China

Abstract: The phenomena of rock mass slope with multi-weak interlayer can be found in real engineering frequently. It is worthy to study the influence of multi-weak interlayer on failure of rock mass slope. Based on the shear strength reduction finite element method, stability and failure surface of rock mass slope with different parameters had been studied, the failure mechanism of rock mass slope containing multi-weak interlayer has been analyzed. It can be found that the stability of consequent rock slope decreased first and increased later with increasing of rock stratum inclination which got its minimal value at 30° of rock stratum inclination. The stability of anti-dip rock slope fluctuated with increasing of rock stratum inclination which got its maximal value at 135° of rock stratum inclination. Whether consequent rock slope or anti-dip rock slope, the stability of slope decreased with angle of slope increased. Although, the stability of rock slope reduced or weakened by multi-weak interlayer, the failure and stability is controlled by parameters of rock mass mostly.

Key words: Rock mass slope, multi-weak interlayer, stability, fractured surface, finite element methods

INTRODUCTION

In the road engineering, railway engineering, mining engineering and hydraulic engineering, it can be found rock mass slope with multi-weak interlayer frequently which influenced and controlled the failure and stability of engineering construction (Wang *et al*., 1995; Huang and Xu, 2008).

Such as at June 5, 2009, more than 700×10^4 m^3 rock and soil slipped at Jiweishan rockslide in Wulong, Chongqing which made 74 people died (Yin, 2010), as showed in Fig. 1. According to the geologic investigation later, the rock of Jiweishan is a typical monoclinal structure, the rock stratum inclination is 20~35°, towards north- northwest. There are carbon and bituminite shale bands continuous distributed in limestone which acting as the multi-weak interlayer of slope and is the latent failure surface of rock mass slope (Xu *et al*., 2009).

At September, 5, 2004, a big landslide more than 2500×10^4 m^3 slipped induced by rainstorm at Tiantai village of Xuanhan, Sichuang which destroyed 2983 buildings and 1097 acres farm field, more than 1255 people were hit by the natural adversity. The landslide belongs to consequent rock slope which slide surface composited with sandstone, with rock stratum inclination of 5~7°, as showed in Fig. 2 (Yin, 2008).

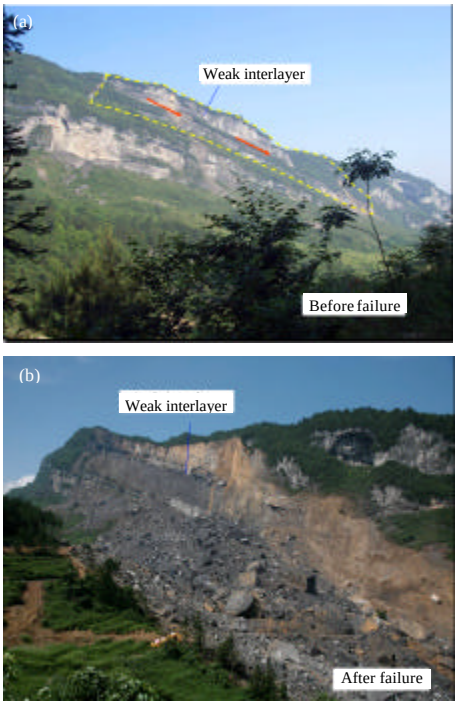

Fig. 1(a-b): Jiweishan landslide in Wulong, Chongqing (a) Before failure and (b) After failure

Corresponding Author: Liu Jin-Long, Department of Civil Engineering, Hefei University, 230601, Hefei, China

At southwestern high mountain canyon of China, some anti-dip rock slope could also be destroyed as bending, overturning and slipping. Such at river beach of jinping, middle course of Yalongjiang, Sichuang, there is large-scale bending deformation happened along more than 10 km river embankment, as showed in Fig. 2 and 3 big landslides developed at each left and right bank (Huang, 2007; Chongqing 136 Geological Mineral Resource Co. Ltd., 2008).

In a certain degree, the rigid limiting equilibrium method and similar experiments could be used to study stability of layered slope. Based on elastic plane theory, Liu and Zhou (2002) had studied failure mechanism of consequent rock slope with small rock stratum inclination.

Fig. 2: Interbedded sandstone and mudstone at the base of the sliding mass

Zhu *et al.* (2004) got the theoretical formula of buckling failure curve of rock mass with special mathematic functions and the position and length of the failure surface of consequent rock slope had been studied. Chen *et al.* (2007) established a geomechanical model based on the analysis of engineering geology and theory of similarity and studied on distortion and breakage mechanism of inverve-dip layered slops rock mass (Lu *et al.*, 2006; Chen *et al.*, 2007). Based on experiment of basal contact friction with physical simulation methods, Feng *et al.* (2004) studied the deformation of different phases and the final failure mechanism of low-angle bedded high slope, whether trends outside or inside.

With the development of cheaper personal computer, Finite Element Method (FEM) has been increasingly used in slope stability analysis. Many researchers' work has showed that the finite element method with shear strength reduction technique is a reliable and robust approach to evaluate slope stability. Comparing to the limiting equilibrium method, there is no factitious assumption in shear strength reduction FEM, the failure surface and safety factor could be searched automatically with FEM and the process of failure occurred and plastic zone developed could also be demoed with FEM. Therefore, the application of FEM in slope stability analysis has been rapidly developed recently (Matsui and San, 1992; Ugai and Leshchinsky, 1995; Dawson *et al.*, 1999; Griffiths and Lane, 1999; Luan *et al.*, 2003).

Based on shear strength reduction FEM, the stability and failure surface of layered rock mass slope with different rock stratum inclination, slope angle, distance of

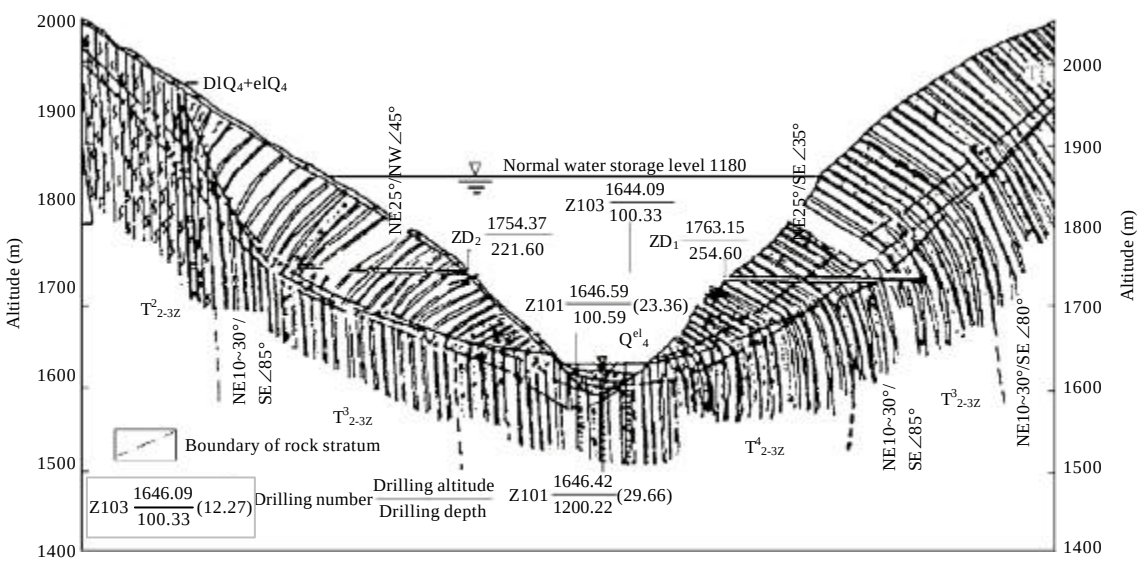

Fig. 3: Engineering geological profile of hydrologic station site in Yalong river (unite: m)

structural surface and parameters of rock had been studied in this article, the failure mechanism of rock mass slope containing multi-weak interlayer has been analyzed.

FEM MODEL OF CALCULATION

Now a typical model of layered rock mass slope is to be analyzed, the slope angle marked as β(.), the rock stratum inclination marked as θ(.), the distance of structural surface marked as h (m), as showed in Fig. 4. Rock mass and weak interlayer were simulated with solid element with different parameters. This problem can be treated as plane strain model, both rock mass and weak interlayer could be simulated with Mohr-Coulomb failure criterion. The parameters of each layer are showed in Table 1.

The domain of FEM model should be large enough to eliminate the influence of boundary. The vertical settlement and lateral displacement fixed at bottom of model and lateral displacement fixed at both sides of model. The mesh of FEM is divided by 15 nodes triangle elements, as showed in Fig. 5 with β = 45° and θ = 60°.

The stability of rock mass slope is to be studied with shear strength reduction of FEM that is, the intensive parameters c, ϕ of each layers soil should be reduced by coefficient F_{tiral} simultaneously:

$$c_r = \frac{c}{F_{trial}},\ \phi_r = \arctan\left(\frac{\tan\phi}{F_{trial}}\right) \quad (1)$$

where, c_r, ϕ_r is reduced cohesive strength and internal friction angle, respectively. The model analyzed by FEM with reduced parameters, if the slope arriving limiting equilibrium state judged by some criterion (Liu *et al*., 2005), the safety factor of slope equal the value of coefficient F_{trial}. Otherwise, the model should be recalculated with new reduced parameters until slope arriving limiting equilibrium state. Lots of researches indicated that it is reliably and feasibly to analyze stability of slope with shear strength reduction of FEM.

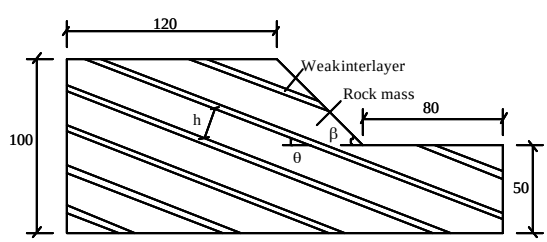

Fig. 4: Numerical analysis model (unit: m)

RESULTS OF FEM CALCULATION

Influence of rock stratum inclination on stability of slope: The relationship between rock stratum inclination and deformation or failure of slope is showed in Fig. 6, with the condition of slope angle β = 45°, distance of structural surface h = 20.0 m and thickness of weak interlayer d = 3.0 m. The corresponding safety factor and position of failure surface is showed in Fig. 7 and 8, respectively.

It can be found from those figures showed above:

- Slip deformation mainly occurred by gravity in level layered rock mass slope (θ = 0°) and deformation at top of slope is bigger and earlier than that of waist or toe of slope. Cracks happened at top of slope by level tension stress which belongs to press-cut failure, as showed in Fig. 6a
- Consequent rock slope is a slope with rock stratum inclination 0°<θ<90° which stability controlled by strike of rock stratum, included angle of rock stratum, relationship between slope angle and rock stratum inclination, dimorphism and strength of structural surface and so on

  When rock stratum inclination little than slope angle (θ<β), slope destroyed by shear along structural surface, with steps of faulted between interlayers, creep deformation along structural surface and sheared along weak interlayer, such as showed in Fig. 6b

  When rock stratum inclination equal slope angle (θ = β), as showed in Fig. 6c, slope destroyed along weak interlayer, cracks emerged at posterior margin of slope and sheared by compression at anterior border of slope

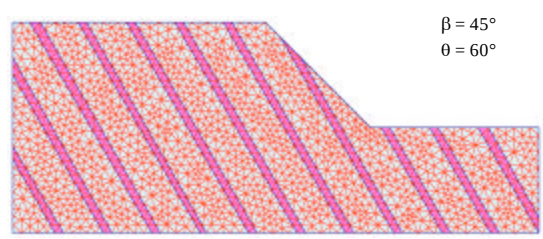

Fig. 5: Mesh of FEM (elements: 3033)

Table 1: Parameters of each layer

Soil layers	Gravity (kN m^{-3})	Cohesive strength c (kpa)	Internal friction angle φ (.)	Deformation modulus E_0 (MPa)	Poisson's ratio
Rock mass	25.0	106.0	36.0	3450	0.28
Weak interlayer	20.0	49.0	28.0	1450	0.31

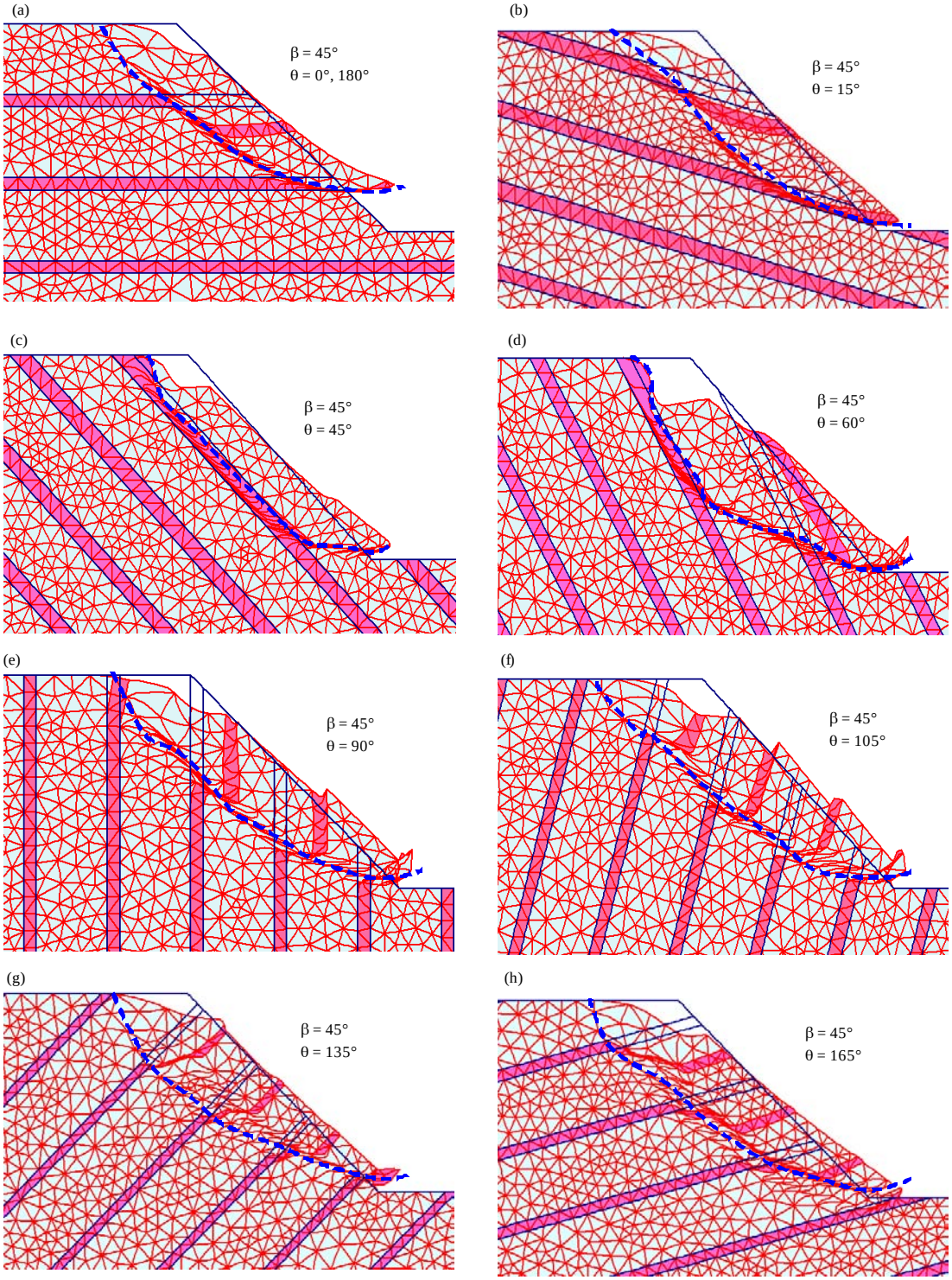

Fig. 6(a-h): Deformation of slope containing multi-weak interlayers (a) θ = 0°, 180°, (b) θ = 15°, (c) θ = 45°, (d) θ = 60°, (e) θ = 90°, (f) θ = 105°, (g) θ = 135° and (h) θ = 165°

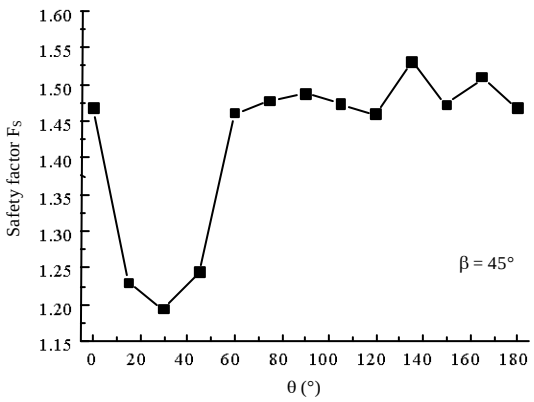

Fig. 7: Relationship between safety factor of slope and rock stratum inclination

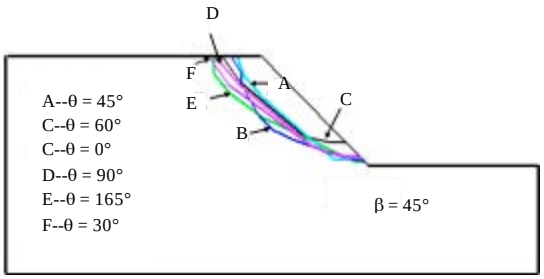

Fig. 8: Position of failure surfaces of slope containing multi-weak interlayers

When rock stratum inclination bigger than slope angle (θ>β), as showed in Fig. 6(d), not only slope destroyed along weak interlayer at middle position of slope, but also bending deformation or burst deformation happened at toe of slope, with steps of relaxed by unloading, drawing breakage, expanded by compression and collapsing with whole (Luan *et al*., 2003)

- Vertical layered rock mass slope (θ = 90°) would be collapsed or ripped by gravity, as showed in Fig. 6e. Bending deformation or burst deformation happened towards surface of slope and cracks emerged at posterior margin of slope which belongs to flexing-collapsing failure
- Anti-dip rock slope (90°<θ<180°) would be collapsed or ripped by moment of gravity towards outside of slope, followed with local glide and local crack, emerged with disturbed belts by gravity. Slope ruptured when main stress and shear stress bigger than strength of extension of structural surface, as showed in Fig. 6f~h
- The stability of consequent rock slope (0°<θ<90°) decreased first and increased later with increasing of rock stratum inclination which got its minimal value at 30° of rock stratum inclination, as showed in Fig. 7. When 0°<θ<60°, the curve of stability is symmetrical distribution at θ = 30°. The stability of anti-dip rock slope (90°<θ<180°) fluctuated with increasing of rock stratum inclination which got its maximal value at 135° of rock stratum inclination. The stability of anti-dip rock slope is obviously bigger than that of consequent rock slope, with the same other conditions. Therefore, stability of rock mass slope is distinctly influenced by rock stratum inclination
- The position of failure surface of interlayer slope is greatly influenced by rock stratum inclination, as showed in Fig. 8 which controlled by thickness of rock mass, rock stratum inclination, strength of structural surface and so on

Influence of slope angle on stability of slope: Slope angle is a key influence factor during design of excavation and supporting of slope. The influence of slope angle on failure mechanism and stability of slope is showed in Fig. 9, where consequent rock slope with θ = 45°, anti-dip rock slope with θ = 150°.

It can be found from Fig. 9:

- To the consequent rock slope, as showed in Fig. 9a and b, slope would be destroyed with model of slippage-flexing by gravity at β = 30°. While at β = 60°, slope destroyed along weak interlayer by gravity, almost no flexing happened at toe of slope
- To the anti-dip rock slope, as showed in Fig. 9c and d, slope destroyed with the model of overturning by gravity. When slope angle increased, slope would be overturned by gravity more easily

Therefore, there is big influence on failure mechanism of slope with different slope angle.

The influence of slope angle on stability of rock mass slope is showed in Fig. 10. It can be found whether consequent rock slope or anti-dip rock slope, safety factor of slope would be decreased with slope angle increased. Therefore, a reasonable and economic slope angle should be designed in excavation of slope with weak interlayer in real engineering.

Influence of distance of structural surface on stability of slope: With the condition of β = 45° and θ = 135°, the influence of distance of structural surface h on failure mechanism and stability of multi-weak interlayer slope is showed in Fig. 11 and 12, respectively.

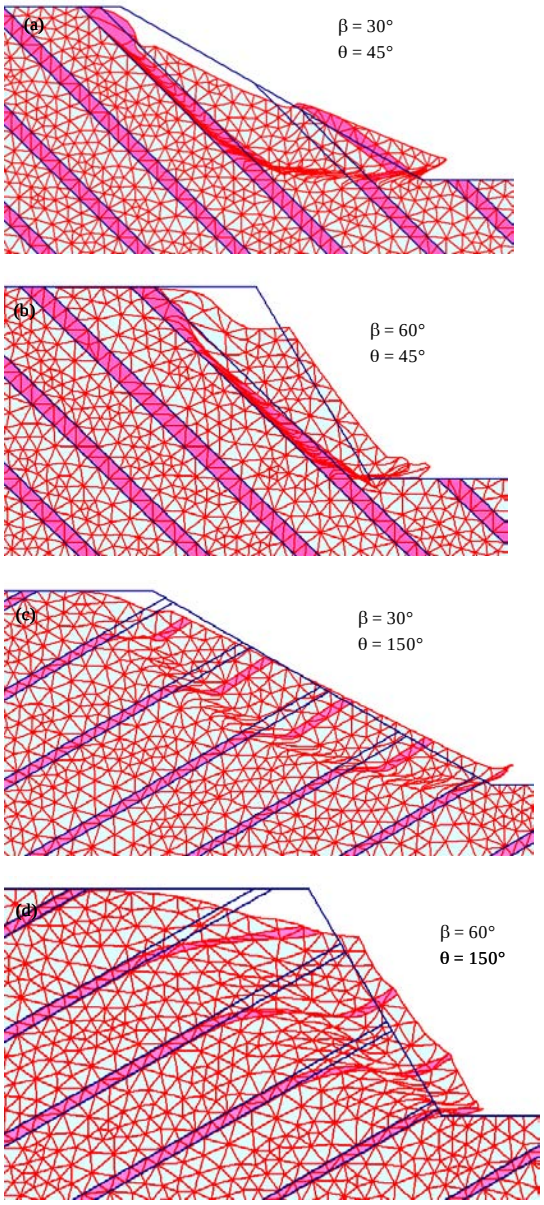

Fig. 9(a-d): Deformation damage characteristics and critical failure surface with different slope angles (a) β = 30°, θ = 45°, (b) β = 60°, θ = 45°, (c) β = 30°, θ = 150° and (d) β = 60°, θ = 150°

The deformation and stability of multi-weak interlayer slope is depended on the distance or number of structural surface. Strength of rock decreased badly by weak interlayer with small value of distance of structural surface. When the distance of structural surface

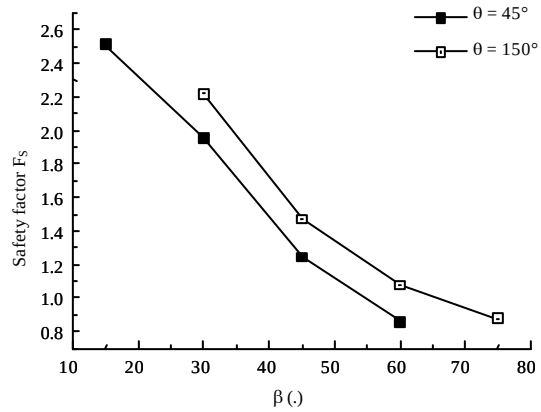

Fig. 10: Relationship between safety factor of slope and slope angle

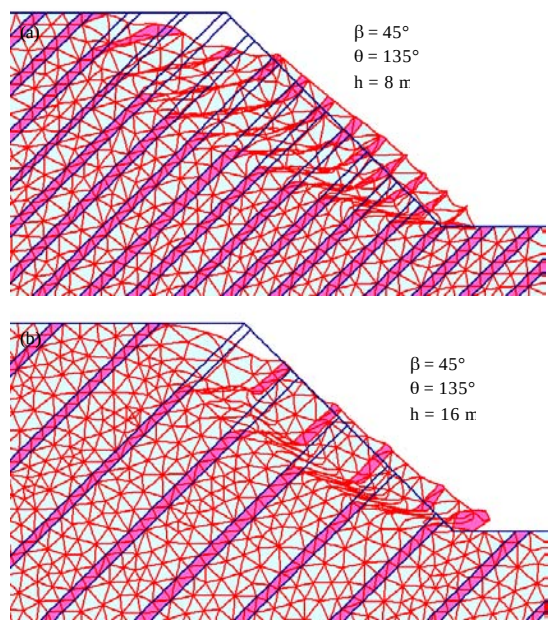

Fig. 11(a-b): Deformation and critical failure surface of slope with different distance of structural surface (a) h = 8 m and (b) h = 16 m

increased, the number of structural surface in a fixed scope decreased, so the equivalent strength of whole slope increased and the stability of slope enhanced.

Influence of parameters of rock and structural surface on stability of slope: In a certain degree, there is big difference between parameters of rock mass and weak interlayer, so it is need to evaluate the influence of parameter of rock mass and weak interlayer on stability of multi-weak interlayer slope.

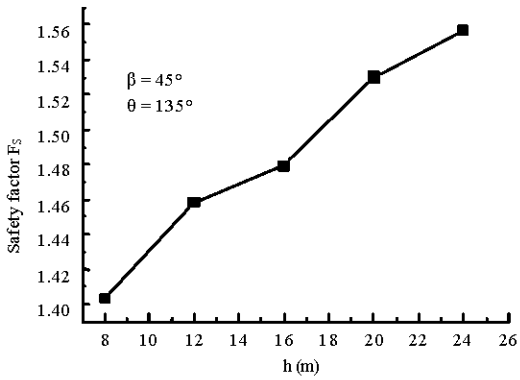

Fig. 12: Relationship between safety factor of slope and distance of structural surface

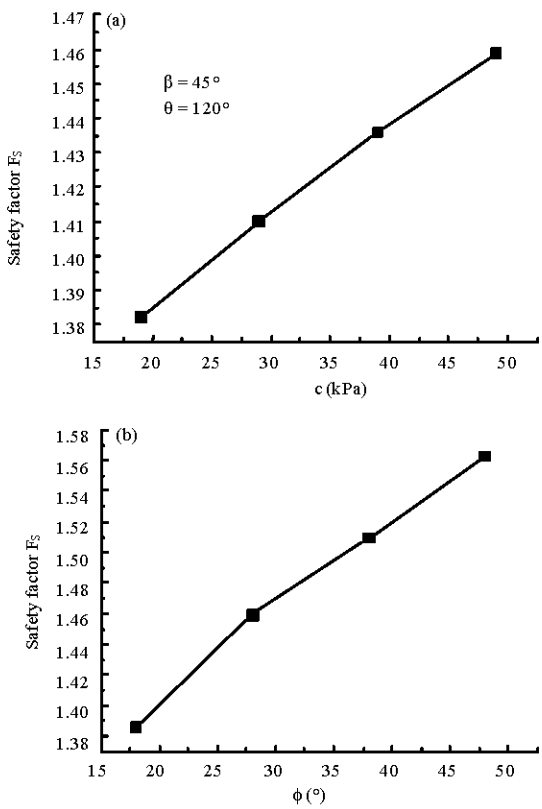

Fig. 13(a-b): Influence of parameter of weak interlayer on stability of slope (a) Influence of cohesive strength and (b) Influence of inner friction angle

With the condition of β = 45° and θ = 120°, the relationship between stability of slope and parameter of weak interlayer and rock mass are showed in Fig. 13 and 14, where only the studied parameter changed

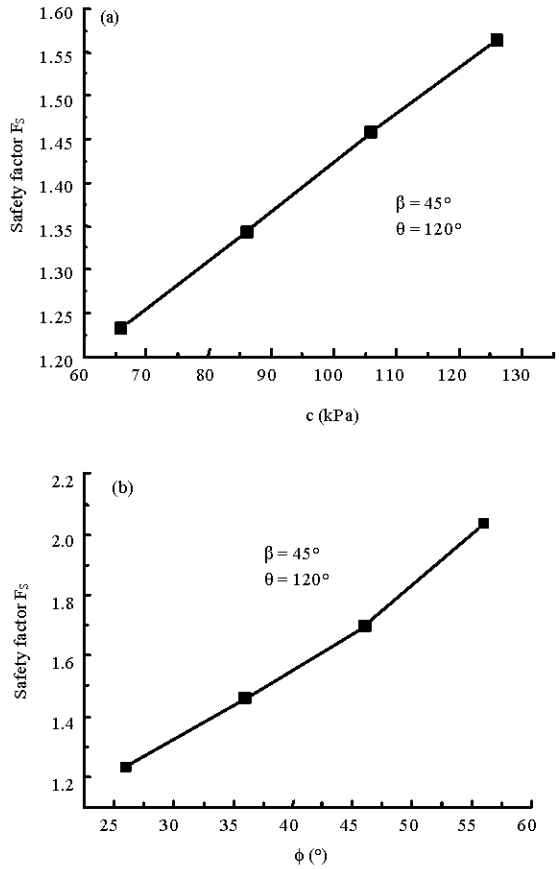

Fig. 14(a-b): Influence of parameter of rock mass on stability of slope (a) Influence of cohesive strength and (b) Influence of inner friction angle

and other parameters unchanged. It can be found that the stability of slope enhanced with the value of cohesive strength or inner friction angle of weak interlayer or rock mass increased.

During further contrastingly study, it can be found the stability of slope enhanced 0.00257 when cohesive strength of weak interlayer increased 1 kpa while the stability of slope enhanced 0.00568 when cohesive strength of rock mass increased 1 kpa. On the same way, the stability of slope enhanced 0.0059 when inner friction angle of weak interlayer increased 1° while the stability of slope enhanced 0.02638 when inner friction angle of rock mass increased 1°. It seems the parameter of rock mass is more important than that of weak interlayer. That is, although the stability reduced by weak interlayer, the stability of slope with multi-weak interlayer mainly be controlled by parameters of rock mass.

CONCLUSION

- To the consequent rock slope, slope would be destroyed by shear along structural surface, cracks emerged at posterior margin of slope and bending deformation or burst deformation happened at toe of slope. While anti-dip rock slope would be collapsed or ripped by moment of gravity towards outside of slope, followed with local glide and local crack and disturbed belts emerged
- The stability of consequent rock slope decreased first and increased later with increasing of rock stratum inclination which got its minimal value at 30° of rock stratum inclination. The stability of anti-dip rock slope fluctuated with increasing of rock stratum inclination which got its maximal value at 135° of rock stratum inclination. The stability of anti-dip rock slope is obviously bigger than that of consequent rock slope, with the same other conditions
- Whether consequent rock slope or anti-dip rock slope, safety factor of slope would be decreased with slope angle increased
- When the distance of structural surface increased, the number of structural surface in a fixed scope decreased, so the equivalent strength of whole slope increased and the stability of slope enhanced
- The stability of slope enhanced with the value of cohesive strength or inner friction angle of weak interlayer or rock mass increased. Although the stability of slope with multi-weak interlayer reduced by weak interlayer which mainly be controlled by parameters of rock mass

ACKNOWLEDGMENT

This research was funded by National Science Foundation of China (41306088) and Anhui Provincial Natural Science Foundation (1208085QE89).

REFERENCES

Chen, C.X., P.L. Huang and Z.M. Lu, 2007. Study on correlation between stability of consequent rock slope and obliquity of rock layer by simulation experiment. Rock Soil Mech., 28: 476-481.

Chongqing 136 Geological Mineral Resource Co. Ltd., 2008. Report on geo-hazards risk assessment in mining mountain of Gonghe factory in Wulong country. Chongqing City.

Dawson, E.M., W.H. Roth and A. Drescher, 1999. Slope stability analysis by strength reduction. Geotechnique, 49: 835-840.

Feng, W.K., Y.C. Shi and H.J. Chai, 2004. Study of mechanism of deformation failure of a low-angle bedded high slope with physical simulation method. China J. Highway Transport, 17: 32-36.

Griffiths, D.V. and P.A. Lane, 1999. Slope stability analysis by finite elements. Geotechnique, 49: 387-403.

Huang, R., 2007. Large-scale landslides and their sliding mechanism in China since the 20th century. Chin. J. Rock Mech. Eng., 26: 433-454.

Huang, R. and Q. Xu, 2008. The catastrophic landslides in China. Science Press, Beijing.

Liu, X.L. and D.P. Zhou, 2002. Stability analysis of layered dip rocky slopes with elastic plane theory. Rock Soil Mech., 23: 162-165.

Liu, J.L., M.T. Luan and S.F. Zhao, 2005. Discussion on criteria for evaluating stability of slope in elastioplastic FEM based on shear strength reduction technique. Rock Soil Mech., 26: 1345-1348.

Lu, Z.M., C.X. Chen and B.C. Zuo, 2006. Experimentation research on factors influencing stability of anti-dip layered slope. Rock Soil Mech., 27: 629-632.

Luan, M.T., Y.J. Wu and T.K. Nian, 2003. A criterion for evaluating slope stability based on development of plastic zone by shear strength reduction FEM. J. Disaster Prevention Mitigation Eng., 23: 1-8.

Matsui, T. and K.C. San, 1992. Finite element slope stability analysis by shear strength reduction technique. Soils Foundations JSSMFE, 32: 59-70.

Ugai, K. and D. Leshchinsky, 1995. Three-dimensional limit equilibrium and finite element analysis. Soils Foundations, 35: 1-7.

Wang, S., R. Huang and Y. Li, 1995. Key Engineering geology problems and research on jinping hydropower station in yalongjiang river. Chengdu University of Science and Technology Press, Chengdu.

Xu. Q., R. Huang, Y. Yin, S. Hou, X. Dong, X. Fan and M. Tang, 2009. The jiweishan landslide of June 5, 2009 in Wulong, Chongqing: Characteristics and failure mechanism. J. Eng. Geol., 178: 433-444.

Yin, Y., 2008. Typical Landslides in China. China Land Press, Beijing, pp: 4-8.

Yin, Y., 2010. Mechanism of apparent dip slide of inclined bedding rockslide-a case study of Jiweishan rockslide in Wulong, Chongqing. Chin. J. Rock Mech. Eng., 29: 217-226.

Zhu, H.Y., M.L. Ma and Y.Q. Shang, 2004. Analysis of buckling failure of consequent rock slope. J. Zhejiang Univ., 38: 1144-1149.