IOP Conf. Series: Earth and Environmental Science **64** (2017) 012014 doi:10.1088/1755-1315/64/1/012014

Stability analysis and optimum reinforcement design for an intense weathered rock slope

Kuan Qi[1], Zhuoying Tan[1, 2,*] and Wen Li

[1]School of Civil & Environmental Engineering, University of Science and Technology Beijing, Beijing, China
[2]Key Laboratory of Ministry of Education of China for Efficient Mining and Safety of Metal Mines, University of Science and Technology Beijing, Beijing, China

*Corresponding author e-mail: markzhy_tan@163.com

Abstract. In view of the complex structural characters of Chengmenshan copper mine slope, the slope stability should be analyzed and additional reinforcement measures need to be considered to ensure mining safety. In this paper, the slope model was built and its stability was analyzed by numerical simulation method under nature and dynamic loading state. After that the design of orthogonal experiment was discussed for the key factors which influence the reinforcement effect of anchors with SPSS software, and the primary and secondary relation of factors and the optimal combination were obtained using the range analysis method. Finally, the slope stability with optimal reinforcement measure was tested. The results show that the safety factor of slope under nature state is low and it is in the critical instability condition. Under dynamic loading state, the failure probability of slope increases from 0 to 18% as the seismic magnitude varies from 6 to 8. Primary and secondary sequence of factors that influence the anchor reinforcement effect is the bonding length, anchor installing angle, anchor length at 3rd bench, anchor length at 2nd bench and anchor length at 1st bench .The safety factor of slope reinforced with anchors is larger than 1.1, which could ensure the safety and stability of the slope.

1. Introduction

The main task of slope stability analysis is to calculate the safety factor, to evaluate the condition of slope at present and the probable change and development trends in the future, which can be used as the technical foundation of slope renovation engineering [1]. Slope is one of the main dangerous structures in open-pit mine, geological disasters such as landslide and collapse are often occurred, which seriously threaten the safety of workers and engineering equipments and affect the normal production of mine [2]. Therefore, effectively analyzing of the slope stability in open-pit mines and proposing scientific reinforcement techniques are the technical problems that should be urgently solved at present. At present, numerous scholars have done investigations on slope stability, and kinematics, limit equilibrium and numerical modelling techniques are commonly used methods for rock slope stability analysis [3]. Meanwhile, numerical modelling techniques are much more suitable for estimating the failure dimensions of complex rock slope [4].

IOP Conf. Series: Earth and Environmental Science **64** (2017) 012014 doi:10.1088/1755-1315/64/1/012014

Chengmenshan is a multi-metal open-pit mine. The dominated ore elements of ores are copper and sulphur. The rock physics mechanics property of the slope in the mining boundary is weak, weathering and the soil erosion are mightiness. The stability of the slope is directly affected by the fault distribution. The engineering geology group of the slope is granodiorite-porphyry [5].Because of the strong weathering, the top of the slope shows granular structure. The potential or progressive failure pattern of the slope is circular failure. Based on detail data of the engineering geological exploration, a numerical simulation model of slopes was established and the slope stability was analyzed with the numerical method under nature and dynamic loading state. According to orthogonal design, anchor reinforcement scheme was determined and the priority of each factor for the stability of open mining slope was obtained through range analysis method. Finally, the slope safety stability with optimal reinforcement measure was tested.

2. Slope model and rock mass parameter definition

The open-pit mine slope model was built based on the previous geological survey, and shown in Fig. 1. The stratums were partioned and assigned physical-mechanics parameters [5] according to Table 1.

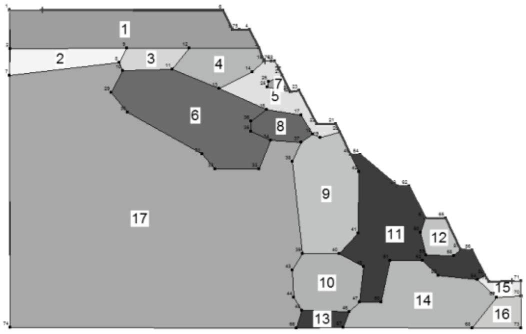

Figure 1. Slope model of open-pit mine.

Table 1. Rockmass physical-mechanics parameters of slope.

Rock region and description		Rock mass physical-mechanics parameter				
Region	Rock description	Density γ/KN/m^3	Cohesion c/KPa	Internal friction angle Φ/°	Elasticity modulus E/GPa	Poisson ratio μ
1	surface soil	27.4	80	25	0.0002	0.33
2	Sludgy loam	26.46	27	15.3	0.0002	0.33
3	dacite	24.5	239.3	15.7	18.7	0.29
4	granodiorite-porphyry (intense weathered)	24.6	316	13.1	20.7	0.27
5	limonite	37.34	241.4	13.6	26.8	0.24
6	limestone (intense weathered)	26.1	212.2	7.7	10	0.28
7	breccia	28.8	78	26.2	23.7	0.25
8	quartz-porphyry	24.5	976.6	18.4	18.7	0.29
9	skarn	33.12	836.3	14.8	32.9	0.25
10	magnetite	33.7	1002.8	19.1	31.5	0.23
11	pyrite	33.7	1002.8	19.1	31.5	0.23
12	limestone (weathered)	26.1	704.6	11.6	14.9	0.28
13	granodiorite-porphyry	24.6	969	18.2	28.7	0.27
14	quartz-porphyry (intense weathered)	24.5	325	13.2	10	0.29

3. Stability analysis of mine slope

The key factors that influence the stability of slope mainly include slope shape, geo-stress, underwater, engineering geology, earthquake and blasting vibration [6]. As drainage works have been done around the mining boundary before mining, the influence of water was not considered in the analysis of slope stability [7]. The safety conditions of slope under static and dynamic loading were carried out in this article.

3.1. Rock sample preparation

The stability analysis results of slope under static condition are shown in Table 2. And the critical sliding surface of slope is shown in Fig. 2.

Table 2. Safety factors of slope under natural condition.

	Stability analysis method			
	Ordinary	Bishop	Janbu	M-Price
Safety factor	1.001	1.031	0.97	1.038

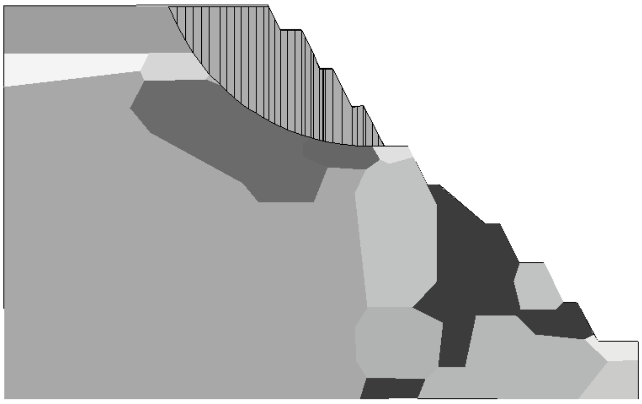

Figure 2. Critical sliding surface of slope.

The data in Table 2 show that safety factors of slope under static loading are all lower than 1.10 which is the required minimum value according to the national regulation. The critical sliding surface occurs at the upper four benches from the Fig. 2. So, reinforcement measurements should be taken to the unstable benches in order to improve its stability and ensure the safety of slope.

3.2. Stability analysis of slope under dynamic loading

The influence of dynamic loading is very important to structures which may cause serious damages or destructions [8]. So the stability of slope under dynamic loading should be analyzed and the possible damage should be evaluated.

3.2.1 Quasi-static method. By using quasi-static method, a seismic inertia force is imported into the analysis of slope stability. Due to its simplicity and applicability, quasi-static method is widely used in the stability analysis of slope, a larger amount of engineering experiences have accumulated and the method has been written into some related regulations about slope stability analysis[9]. Safety factors of slope under different seismic intensities are listed in Table 3.

Table 3. Safety factors of slope under different seismic intensities.

Safety factor		Stability analysis method			
		Ordinary	Bishop	Janbu	M-Price
Seismic intensity	6	0.920	0.947	0.877	0.958
	7	0.849	0.875	0.797	0.888
	8	0.75	0.756	0.721	0.769

According to the results of slope stability analysis using quasi-static method, safety factors of slope under different seismic intensities are all lower than 1.As the deficiencies of quasi-static method's assumptions, H. B. Seed once put it: even though the safety factor of slope is less than 1 for the moment, global instability will not always happen to the slope, and just a certain permanent deformation will occur [9].

3.2.2 Time-history method. During the period of earthquake, the minimum safety factor of slope under seismic loading only occurs at a certain moment, which is not suitable to evaluate the seismic stability of slope. The probability of occurrence that safety factor is lower than 1 during the seismic loading is considered to be a good index to evaluate the stability of slope under seismic loading [10].

The acceleration time-history curves of different seismic intensities are shown in Fig. 3, and the time-history curves of safety factors were obtained after loading seismic acceleration curves onto the slope, and shown in Fig. 4.

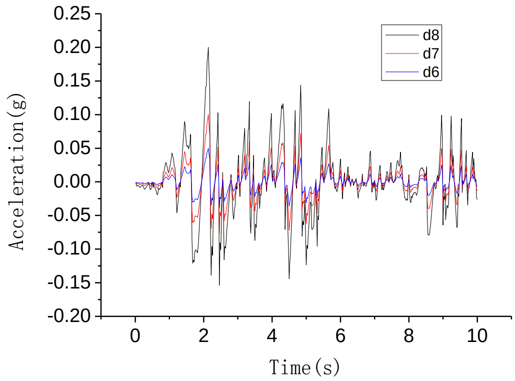

Figure 3. Acceleration time-history curves of different seismic waves.

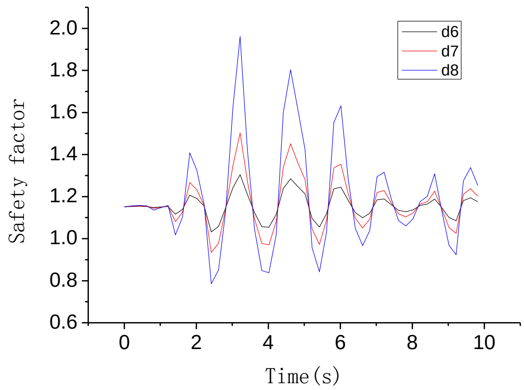

Figure 4. Safety factor time-history curves of slope under different seismic intensities.

From Fig.4 it appears that slope safety factor changes along with the changes of loading stress waveforms. The initial, minimum and maximum value of the safety factors and failure probabilities [11] are shown in Table 4.It can be seen from these data that under different seismic intensities, safety factors of slope fluctuate near the initial value and the range increases as the seismic intensity increases, meanwhile, the failure probability also increases. There is an 18% probability of slope instability when the seismic intensity is 8.

Table 4. Safety factors and failure probabilities of slope under different seismic intensities.

Seismic intensity	Safety factor			Probability of instability
	initial	minimum	maximum	
6	1.152	1.032	1.304	0
7	1.152	0.934	1.502	10%
8	1.152	0.785	2.156	18%

4. Acoustoelastic theory of rock based on continuous medium hypothesis

Based on the analysis above, some measures should be taken to reinforce the slope to improve its stability.

4.1. Optimum scheme of anchor reinforcement

According to the position of the critical sliding surface of slope (as shown in Fig.2), anchors are arranged in three benches (Fig.5), three anchors in 1stand 2nd bench and two in 3rd bench, the spacing is 5m, 3m and 5m. The parameters of anchor are as follows: elastic modulus E=201Gpa, Poisson's ratio μ=0.26, diameter d=0.1m, cohesion (tangential and normal) C=0.18GN/m, angle of internal friction φ=29°, stiffness (tangential and normal) $K=1GN/m^2$.

The reinforcement effect mainly depends on anchor length, length of anchorage segment and anchorage direction. Based on these factors, SPSS was used to design orthogonal experiments to calculate and analyze the slope stability [12].The results are shown in Table 5.

Table 5. Orthogonal experiment schemes and results of anchors reinforcement.

Test number	Influencing factor					Safety factor			
	Anchor length of first bench A/m	Anchor length of second bench B/m	Anchor length of third bench C/m	Length of anchorage segment D/m	Anchorage direction E/ °	Ordinary	Bishop	Janbu	M-Price
1	40	35	20	8	40	1.198	1.242	1.142	1.247
2	40	40	25	10	45	1.189	1.231	1.138	1.236
3	40	45	30	12	50	1.198	1.242	1.142	1.247
4	40	50	35	14	55	1.2	1.244	1.149	1.233
5	45	35	25	12	55	1.165	1.208	1.112	1.213
6	45	40	20	14	50	1.229	1.277	1.088	1.272
7	45	45	35	8	45	1.148	1.187	1.102	1.193
8	45	50	30	10	40	1.221	1.263	1.167	1.268
9	50	35	30	14	45	1.232	1.281	1.096	1.275
10	50	40	35	12	40	1.243	1.292	1.106	1.287
11	50	45	20	10	55	1.136	1.176	1.087	1.182
12	50	50	25	8	50	1.128	1.167	1.081	1.173
13	55	35	35	10	50	1.162	1.204	1.111	1.209
14	55	40	30	8	55	1.108	1.146	1.063	1.152
15	55	45	25	14	40	1.242	1.291	1.104	1.285
16	55	50	20	12	45	1.235	1.284	1.098	1.278

Results of orthogonal experiment were analyzed by using range analysis method. Firstly, the algebraic sum of the indexes K(i), average value k(i) and range R of all factors and levels were calculated. According to the range(R), the influence order of the parameters was determined. Finally the optimal combination was determined by the principle of maximum safety factor. The results of different analysis methods are shown in Table 6-9.

IOP Conf. Series: Earth and Environmental Science **64** (2017) 012014 doi:10.1088/1755-1315/64/1/012014

Table 6. Test results of Ordinary method.

Index	Result				
	A	B	C	D	E
*K*1	4.785	4.757	4.798	4.582	4.904
*K*2	4.763	4.769	4.724	4.708	4.804
*K*3	4.739	4.724	4.759	4.841	4.717
*K*4	4.747	4.784	4.753	4.903	4.609
*k*1	1.19625	1.18925	1.1995	1.1455	1.226
*k*2	1.19075	1.19225	1.181	1.177	1.201
*k*3	1.18475	1.181	1.18975	1.21025	1.17925
*k*4	1.18675	1.196	1.18825	1.22575	1.15225
Range *R*	0.0115	0.015	0.0185	0.08025	0.07375
Primary and secondary order	D>E>C>B>A				
Optimal combination	A1B4C1D4E1				

Table 7. Test results of Bishop Method.

Index	Result				
	A	B	C	D	E
*K*1	4.959	4.935	4.979	4.742	5.088
*K*2	4.935	4.946	4.897	4.874	4.983
*K*3	4.916	4.896	4.932	5.026	4.89
*K*4	4.925	4.958	4.927	5.093	4.774
*k*1	1.23975	1.23375	1.24475	1.1855	1.272
*k*2	1.23375	1.2365	1.22425	1.2185	1.24575
*k*3	1.229	1.224	1.233	1.2565	1.2225
*k*4	1.23125	1.2395	1.23175	1.27325	1.1935
Range *R*	0.01075	0.0155	0.0205	0.08775	0.0785
Primary and secondary order	D>E>C>B>A				
Optimal combination	A1B4C1D4E1				

Table 8. Test results of Janbu method.

Index	Result				
	A	B	C	D	E
*K*1	4.571	4.461	4.415	4.388	4.519
*K*2	4.469	4.395	4.435	4.503	4.434
*K*3	4.37	4.435	4.468	4.458	4.422
*K*4	4.376	4.495	4.468	4.437	4.411
*k*1	1.14275	1.11525	1.10375	1.097	1.12975
*k*2	1.11725	1.09875	1.10875	1.12575	1.1085
*k*3	1.0925	1.10875	1.117	1.1145	1.1055
*k*4	1.094	1.12375	1.117	1.10925	1.10275
Range *R*	0.05025	0.025	0.01325	0.02875	0.027
Primary and secondary order	A>D>E>B>C				
Optimal combination	A1B4C3(4)D2E1				

Table 9. Test results of M-Price method.

Index	Result				
	A	B	C	D	E
*K*1	4.963	4.944	4.979	4.765	5.087
*K*2	4.946	4.947	4.907	4.895	4.982
*K*3	4.917	4.907	4.942	5.025	4.901
*K*4	4.924	4.952	4.922	5.065	4.78
*k*1	1.24075	1.236	1.24475	1.19125	1.27175
*k*2	1.2365	1.23675	1.22675	1.22375	1.2455
*k*3	1.22925	1.22675	1.2355	1.25625	1.22525
*k*4	1.231	1.238	1.2305	1.26625	1.195
Range *R*	0.0115	0.01125	0.018	0.075	0.07675
Primary and secondary order	E>D>C>A>B				
Optimal combination	A1B4C1D4E1				

The primary and secondary order of factors that affect the reinforcement effect obtained from the above analysis method is as follows: Ordinary method, D>E>C>B>A; Bishop Method, D>E>C>B>A; Janbu method, A>D>E>B>C; M-Price method, E>D>C>A>B. From the above results we can see that the important order differs across these methods. The results from these four analyses suggested that the most reasonable order is the bonding length, anchor installing angle, anchor length at 3rd bench, anchor length at 2nd bench, anchor length at 1st bench. Finally, A1B4C1D4E1 was taken as the optimized combination. The result is as follows: anchor length at 1st bench is 40m, anchor length at 2nd bench is 50m, anchor length at 3rd bench is 20m, bonding length is 14m and anchor installing angle is 40 °.

4.2. Checking calculation of slope stability after reinforcement

The slope was reinforced by the arrangement which determined by the orthogonal experiment (Fig.5) and the stability was calculated and checked. The slope safety factors are shown in Table10 and the critical sliding surface is shown in Fig. 6.

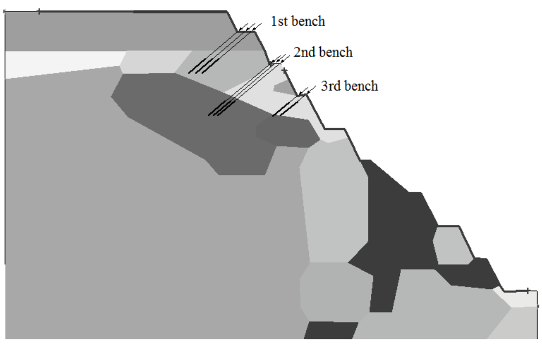

Figure 5. Arrangement diagram of anchors reinforcement.

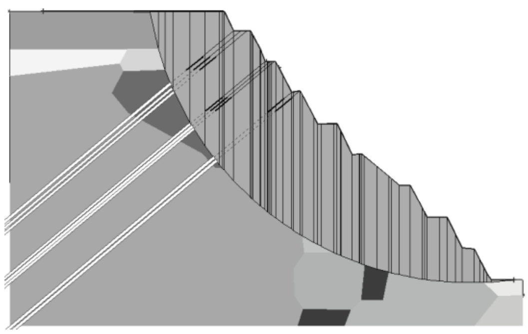

Figure 6. Critical sliding surface of slope with anchors reinforcement.

Table 10. Safety factor of slope with anchor reinforcement.

Stability analysis method	Safety factor		
	Before reinforcement	After reinforcement	Increment
Ordinary	1.001	1.242	24.1%
Bishop	1.031	1.291	25.2%
Janbu	0.97	1.104	13.8%
M-Price	1.038	1.285	23.8%

As seen from the table, the safety factors are all above 1.1 after reinforcement, which could meet the demands of security and stability. By comparison with natural state, the safety factor increases 13.8%~25.2%.Anchor reinforcement plays a decisive role in the stability of the slope.

5. Conclusions

The slope is in a state of critical instability and the safety factor is low in nature condition. Under dynamic loads, the probability of slope instability increases from 0 to 18% as the seismic intensity varies from 6 to 8.

The primary and secondary order of factors that affect the reinforcement effect is the bonding length, anchor installing angle, anchor length at 3rd bench, anchor length at 2nd bench, anchor length at 1st bench. The optimum anchor reinforcement scheme: anchor length at 1st bench is 40m, anchor length at 2nd bench is 50m, anchor length at 3rd bench is 20m, bonding length is 14m and anchor installing angle is 40°.

The safety factors are all above 1.1 after reinforcement, which could meet the demands of security and stability.

Acknowledgments
This work was financially supported by National Natural Science Foundation of China (51174013, 51574015).

References

[1] Ma Jianxun, Lai Zhisheng, CaiQing'e, et al, 3D FEM Analysis of Slope Stability Based on Strength Reduction Method, J. Chinese Journal of Rock Mechanics and Engineering. 2004, 23(16): 2690-2693.

[2] VermaDhananjai, Thareja Rahul, KaintholaAshutosh, et al, Evaluation of open pit mine slope stability analysis, J. International Journal of Earth Sciences and Engineering. 2011, 4(4): 590-600.

[3] ZulfuGurocak, SelcukAlemdag, Musharraf M. Zaman, Rock slope stability and excavatability assessment of rocks at the Kapikaya dam site, Turkey, J. Engineering Geology. 2008, 96(1): 17-27.

[4] Changqing Qi, Jimin Wu, Jin Liu, et al, Assessment of complex rock slope stability at Xiari, southwestern China, J. Bulletin of Engineering Geology and the Environment. 2016, 75(2): 537-550.

[5] Tan Zhuoying, Zhong Wen, Hu Tianshou, et al, Engineering Case Study of Weak Interfaces Detection by EH-4 for Highly Weathered Rock Slope, J. Metal Mine. 2013, (10): 84-87.

[6] ChenPeng, XuBohou, Reliability Analysis of Slope Stability Based on Factors Sensitivity, J. China Journal of Highway and Transport, 2012, 25(4): 42-48.

[7] GeWeixiang, Stability Analysis of the Lake Mud Slope of Chengmenshan Copper Mine, J. Metal Mine. 2002, (8): 24-25.

[8] TolonMert, Ural Derin N, Slope stability during earthquakes: A neural network application, J. International Review on Computers and Software. 2010, 5(4): 454-459.

[9] LiHaibo, Xiao Keqiang, Liu Yaqun, Factor of Safety Analysis of Bedding Rock Slope Under Seismic Load, J. Chinese Journal of Rock Mechanics and Engineering. 2007, 26(12): 2385-

IOP Conf. Series: Earth and Environmental Science **64** (2017) 012014 doi:10.1088/1755-1315/64/1/012014

2394.
[10] Liang Li, Yu Wang, Zijun Cao, Probabilistic slope stability analysis by risk aggregation, J. Engineering Geology. 2014, 176: 57-65.
[11] Griffiths D. V., Fenton Gordon A, Probabilistic slope stability analysis by finite elements, J. Journal of Geotechnical and Geoenvironmental Engineering. 2004, 130(5): 507-518.
[12] JiangZhaorong, Wang Lehua. The affecting factors of slope stability based on orthogonal design[C]. 4th International Conference on Manufacturing Science and Engineering, ICMSE 2013, Dalian China, 756-759.