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Numerical scheme for elastoplastic parameter identification and finite element analysis of wall-slope of the Fushun West Open Pit Mine

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Abstract The elasto brittle plastic finite element analysis has been taken on the prediction for the deformation of the northwall of an open pit of Fushun, China. Numerical simulation has been made on the reinforcement measures of the slope structure. Using parameter identification techniques and connecting with elasto brittle plastic finite element program, the displacement back analysis has been made on the material parameters of the rockslope. The equivalent parameter values of the real slope structure have been obtained. The process of the rapid increment of the slope's deformation caused by open mining during 1987～1990 has been reappeared through the numerical simulation.

Keywords rockslope, parameter identification, displacement back analysis, elasto brittle plasticity, open-pit mining

Introduction

The first Fushun Oil Refinery, which is 2 000 m long (from the east to the west) and 600 m wide (from the north to the south), was founded in 1928. The south of the factory is Fushun West Open-Pit, the east and west are two coalmines respectively. The Fushun West Open-Pit was founded in 1914. Now its depth has reached 245～306 m and it is estimated that the designed excavation depth (D - bound) is 327～459 m. The horizontal distance between the north bound and the south bound in the open-pit is 800 m in the west and 420 m in the east. Shengli Coal Mine, which was founded in 1907 and closed in1987, is located to the east of the factory. Its'excavation has affected the ground-surface of the First Oil Refinery. The deep well mine, which was exploited in 1952 and closed in 1964, has affected the ground-surface of the First Oil Refinery on its deformation to some extent. Especially since the year of 1984, the deformation of the wall of open pit and the ground of the factory were increased rapidly. Some installations in the workshops were severely damaged, which seriously interfered the safe production of the oil refinery, made the factory suffer heavy economic losses and bad social influence. In 1987, the National Planning Committee of China trade the harness policy as the "double preserving" of both the factory and the open pit. A series of investigations were done by each invade quarters.

In this paper, the W200- section of the northwall of the open pit is chosen as the analysis object. Using parameter identification techniques and connecting with elasto-brittle-plastic finite element program, the displacement back analysis has been made on the material parameters of the rock-slope, the equivalent parameter values of the real rockmass of the slope have been obtained. On the basis of the above works, calculation has been made on the possible deformation caused by further excavation.

1 Elasto-brittle-plastic finite element computation on northwall of the open pit

Because of the complexity of the rock-slope structure and its composition, it is impossible to determine exactly the detailed structure of the rockmass and the property parameter of various kinds of materials. Therefore under the given condition we have to combine experience and theory and according to the geological data we construct a simplified structure model for the rock-slope. Owing to the variety of rockmass, complicated distribution and damages to different extent, this paper adopts the techniques of parameter identification. The property parameters of the rockmass are obtained inversely from the observed data of displacement. Since displacement value of subsidence of ground is the mainly factor which affects the stability of the ground, the computation takes the measured data on the spot of the subsiding displacement as the reference for the displacement back analysis. The constructed rock-slope model is called the imitation of real sinking rock-slope to predict possible sinking deformation of the rock-slope for its similarity between the sinking deformation of the model and the real rock-slope.

1.1 The computational model of the rock slope

1.1.1 Geological model

Exhaustive investigation with inquiries the geological engineers of the open-pit on its deep geologic structure has been made in order to obtain the most similar model. For the same purpose many technical data concerning the project also had been looked up. The simplified model used in this paper not only considers the structure of different rock layers but also the effect of broken layers and synclinal fold and the effect of empty area of underground excavation.

1.1.2 Model of mechanics

(1) Constitutive model. In plasticity, softening means reduction of strength (stress- or load-carrying capacity) due to inelastic deformation processes. The essential feature of softening is that an external agency apt to impose an infinitesimal configuration change while preserving equilibrium, performs negative second-order work for some deformation path. In other terms, softening in the local behavior is a manifestation of instability. After the plastic yield, the change of strength of rocklike material will be in the state of strain softening. In this paper the elasto- brittle- plastic constitutive model is adopted to describe stress-strain relationship. The model will adopt initial strength to make the judgement of stress state for the stress points which have not been yielded, further details can be found in references [1～3].

(2) Type of yield criterion and elements. In the computation the structure has been considered as an elasto brittle plastic jointed rockmass and the continuous part of the structure is discretized with 8-node quadrilateral iso-parametrc element. The 6-node elastic-plastic joint element is adopted for the discretization of joint surface in the computation. The yield criterions for both the 8-node isoparametric element and 6-node jointed element are Mohr-Coulomb type. The yielding function of 8-node element is expressed by the principal stress form:

$$f(\sigma_1, \sigma_2, \sigma_3) = [(\sigma_1 - \sigma_3) + (\sigma_1 + \sigma_3)\sin \phi]/2 - \cos \phi = 0,$$

where, σ_1, σ_2, σ_3 are principal stresses; c and ϕ are cohesive strength and friction angle respectively.

The yield criterion of 6 - node joint element is expressed as

$$f(\sigma) = (\tau_{xy}^2 + a^2 c^2)^{\frac{1}{2}} + \mu\sigma_y - c = 0,$$

where, $a^2 = 0$ is a disturbance parameter which can make the yield surface with odd points be smooth; μ is internal friction coefficient; τ_{xy} and σ_y are shearing stress component and normal stress component of the joint element respectively.

(3) Type of constraint boundary condition. The computed section is taken from real structure. The bottom of the structure will displace little, two directional restraint x, y is be adopted. Computing the initial crustal

stress field, the restrained x - direction and free y - direction is taken as the boundary condition of both sides. When calculating the excavated displacement field, the far end will be affected a little, in fact, the far end can be y - direction restraint without displacement. So that two-dimensional restraint will be taken. The sides of near end will be affected by excavation and unloading, so that it will still be x uni-dimensional restraint, shown in Fig. 1.

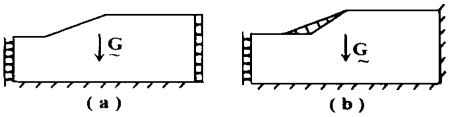

Fig. 1 Displacement boundary conditions assumed for the computation

(a) Initial geo-stress field;

(b) Displacement filed due to excavation

1.2 The solution scheme and finite element discretization

In this calculation, the elastic-brittle- plastic constitutive integration scheme and the numerical simulation scheme for excavation proposed by Shen et al [4,5] are adopted. The finite element mesh is shown in Fig. 2. 302 elements have been used for the discretization of the section W200, including 81 joint elements with 6 nodes and 221 isoparametric elements with 8 nodes. For the comparison with measured data, the whole excavation was divided into three periods; the end of 1979～1987 was the first period. The end of 1987～the end of 1990 was the second period. The end of 1990～2014 will be the third period, at that time, the excavation of D - bound will be finished. Consulting the fairly complete observed data of sinking-displacement at the second excavating period the inverse calculation for the parameter of rockmass is conducted.

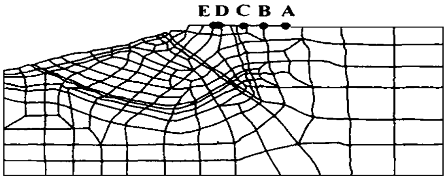

Fig. 2 A cross section of the northwall of the open pit

1.3 Elasto-brittle-plastic displacement back analysis for the property parameter of rockmass

The geological condition of the north wall of the open-pit is complex. It is difficult to make the practical measurement for material parameter. The existing part of data can't meet the requirement for calculation. Besides, owing to the different geological condition, the data at geological design handbook also can't be taken in discriminatly as the chosen value of material parameter. Therefore, the elasto brittle plastic displacement back analysis for the property parameter of each kind of rockmass has been carried out. There are dozens of materiel parameters to be identified, the calculation will be rather massive, if all of the identification be conducted with regularized least square iterative method. The displacement values are not very sensitive to all of the material parameters. For the sake of the calculation efficiency, the displacement back analysis for the material parameter is divided into two stages in this paper. The first stage is that a rough back analysis of the unknown material parameters is carried out by trial method. Firstly, on the basis of existing data and the method from experience and analogy, the rough scope of material parameter can be estimated. Then the trial calculation can be made with 20 groups of different material parameters. The calculated result from a certain group parameter which is most closed to the practical deformation trend can be taken as the result of the back analysis. The second stage is that the displacement back analysis has been conducted with regularized least square iterative method and elasto brittle plastic finite element program. The correct selection of the objective parameter (i. e. requited parameter for identification) will be the foundation of successful calculation. With faulty selection of parameter, the displacement at measuring points may not be sensitive to this parameter. Then no convergensive result can be achieved. The successful selection of objective parameter is taken on the foundation of survey of current deformation state of structure, empiric judgement and analysis, and the as detailed as possible understanding to geological situation.

On the basis of above analysis, the residual strength coefficients of each kind of rockmass from the top of underground excavated region to surface as principal objective parameters for displacement back analysis.

1.3.1 Direct method (trial calculation) for back analysis on the material property parameters

(1) The selection of initial value consults the value of mechanical parameters recommend by some engineering handbooks and the practically measured values of parameter of rockmass. After more than 20 times of trial computation to the direct problem the adopted material parameters of each rockmasses are listed in Table 1.

Table 1 The material parameters

No. of material	E/ GPa	ν	ρ/ 10^3kg·m^{-3}	c/ MPa	ϕ/ (°)	β
1	2.60	0.15	2.6	5.00	40.0	0.5
2	1.20	0.20	2.4	0.60	23.0	0.3
3	1.00	0.20	2.4	0.90	25.0	0.3
4	1.50	0.15	2.4	3.00	34.0	0.4
5	1.20	0.15	1.3	2.70	34.0	0.3
6	0.80	0.20	1.5	0.40	28.0	0.3
7	2.50	0.15	2.6	2.50	34.0	0.5
8	2.40	0.23	2.9	1.89	36.0	0.3
9	0.90	0.30	1.4	0.40	20.0	0.3
10	0.90	0.30	1.4	0.40	20.0	0.3
11	0.60	0.30	1.4	0.08	23.0	0.5
12	0.80	0.30	1.4	0.05	25.0	0.5
13	0.15	0.20	2.4	0.05	10.0	0.4
14	0.20	0.15	2.4	0.05	10.0	0.4
15	0.55	0.20	2.4	0.05	10.0	0.3
16	0.50	0.20	2.4	0.05	10.0	0.3
17	1.20	0.15	2.4	0.80	21.0	0.4
18	0.80	0.15	1.8	1.00	23.0	0.5

(2) The comparison between the numerical result of deformation corresponding to the excavation period of 1987～1990 obtained from direct computation with the parameters listed in Table 1 and the measured data are shown in Fig. 3. The deformation tendencies of the two are the same but the values are quite different.

1.3.2 Displacement back analysis of the material property with regularized least square method

Taking the residual strength coefficient β_2 of the cretaceous rockmass (material 2), β_3 of the chlorite rockmass (material 3) and β_{19} of damaged region (material 19) over the underground excavation region, the modulus E_{16} of broken cretaceous (material 16) as the objective variables. In the computation, taking $\beta_3 = \beta_{19} = x_1$, $\beta_2 = \beta_{16} = x_2$, $E_{16} = x_3$.

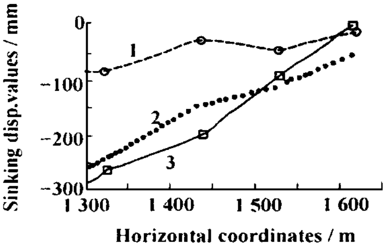

Fig. 3 The convergence of the objective value during inverse iteration

(1) Firstly, the value of diagonal component of the regularization matrix R is obtained through large number of trial calculation. The value of diagonal component of R corresponding to three unknowns have been taken as 0.04, 0.04, 0.02 respectively in the process of inverse computation, the fluctuation of β is rather small thus convergence is favored.

(2) Secondly, the selection of the step length of the difference is carried out. Substituting derivative with

finite difference means substituting tangent direction with secant direction. In theory the less the step length of the difference, the nearer for secant direction to tangent direction is. But in the process of elasto-brittle-plastic finite element analysis for large scale slope of rockmass, there exists certain tolerable error in calculation, too small the step length of the difference will cause the error to exert more effect on the declining direction of objective function. Sometimes, it will even make objective function not decline. After many times of calculation the results show that taking 0.1 as the step length of the difference is suitable.

(3) The convergence criterion. In this paper, the double convergence criterion from the convergence of objective variable and the decline of objective function are taken as convergence standard in the process of calculation. The convergence tolerable error of objective variables is set at 2%, the convergence tolerance for objective functional is also 2%. If it can meet the above two conditions simultaneously, convergence can be confirmed.

Fig. 3 and Table 2 show the convergence situation of objective functional. Fig. 4 shows the comparison curve from the numerical results of subsidence displacement at observation points caused by open mining and the real measured value in 1987～1990.

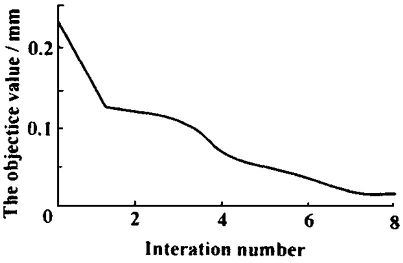

Fig. 4 The displacement comparison

Table 2 The convergence of the unknown parameters during computation

Items	$x_1(\beta_1)$	$x_2(\beta_3)$	$x_3(E_{16})$/MPa	$\lVert x^r - x^{r-1} \rVert / \lVert x^{r-1} \rVert$	T / T_0
Initial value	0.500	0.500	600		
Lower bound	0.150	0.150	300		
Upper bound	0.900	0.900	1 500		
Iter. No. $r=1$	0.511	0.480	766	27.670	53.45
$r=2$	0.514	0.428	753	1.737	49.45
$r=3$	0.511	0.351	900	19.540	43.11
$r=4$	0.514	0.296	714	20.620	25.79
$r=5$	0.518	0.296	907	27.060	19.40
$r=6$	0.505	0.268	812	10.540	12.94
$r=7$	0.504	0.262	832	2.519	5.32
$r=8$	0.510	0.260	866	1.010	5.23

T ——Objective function.

In this research, different calculations have been carried out. The result shows that the value of residual strength coefficients of collapse region over the underground excavated region and the chlorite away from it a little distance has a controlling effect on surface deformation.

1.4 Finite element calculation

Taking the above results of back-analysis as input parameters, the numerical simulation on the excavation of the slope in 1987～1989 has been made. The deformed mesh is shown in Fig. 5. Along with the excavation process, the plastic region over the empty excavated region will spread continuously and develop upwards, until reaching chlorite stratum, only 50 m from the surface. It indicates that the open mining causes the reactiveness of

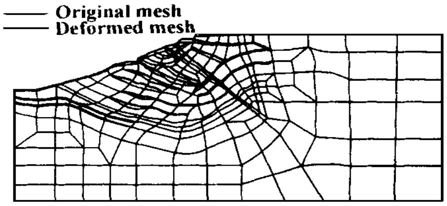

Fig. 5 The deformation caused by excavation during the period of 1987～1990

old collapse region over underground excavation region.

2 Numerical estimation of deformation slope and the effects of reinforcement measures[6]

2.1 Numerical estimation of deformation of northwall and ground surface saused by the excavation of D-bound

On the basis of above functional equivalent model for rockslope deformation, after the first two periods of **excavation, the numerical simulation of the third** excavation period has been made. It is the excavation of slope designed finial bound. The excavation was divided into 13 increment steps. The distribution of plastic regions is shown in Fig. 6. Fig. 6 shows that when excavation reaching D - bound, the ruptured region of rockmass has developed from south of fault F_{1A} to north of it. In addition, the ground-surface to the north of the fault subsided remarkably. It indicates that along with the progress of open mining deformation of the slope will increase rapidly and the ground of the oil refinery will also subside further, and will exert fairly serious unfavorable effect on the region to the north of the fault (At present the subsidence is not serious thus it does not cause grave damage.

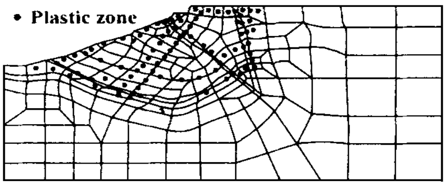

Fig. 6 The plastic region caused by the excavation of the D - bound

2.2 Numerical simulation of the reinforcement measures

In order to protect the facilities of the oil refinery and the safety of the slope, while in progress of open mining. The reinforcement measures should be taken to control the deformation of the slope to guarantee safe production of the oil refinery and west open-pit. The current reinforcement measure is mainly cramming with mortar-injection to the cracks centralized at the fault zone and over the empty excavated region. The mortar is composed of cement and coal ash with changeable proportion. The effect is reduce the space of cracks, increase the shear strength c and ϕ of the structure. In the condition of filling the fault zone, the Young's modulus E can be also increased. According to the experimental data and practical experience, the estimated increment is about 50 % of matrix's strength closing to it. Accordingly, in this computation it is increased the residual strength coefficient of material at existing cement mortar filling zone (it is mainly chlorite and cretaceous rock layer) to **0.5.** The shear strength of weak sandwich being increased to 50 % of its adjoin matrix. At the fault zone, the filling mortar is mainly composed of high content coal ash, the corresponding simulation is the increase of elastic modulus in the computation.

After taking the reinforcement measures, when the excavation reached the designed finial bound, the corresponding deformation reduced obviously. Fig. 7 shows the comparison of subsiding value of ground surface caused by excavation before/after the reinforcement measures and the effectiveness of the reinforcement measures.

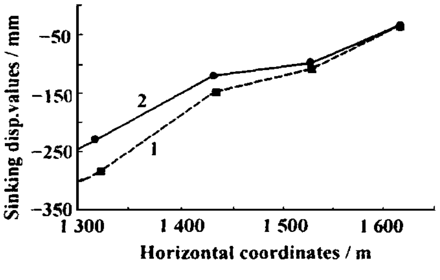

Fig. 7 The comparison of subsiding value

3 Conclusions

(1) Combining systematic method with solid mechanics, by means of systematic parameter identification techniques, and with the elasto-brittle-plastic finite element program, the regularized least-square algorithm has been proposed for the elasto-plastic identification problem. It was found an useful technique in the geotechnical engineering. With this technique, the displacement back anal-

ysis to the property parameter of material at slope rockmass has been made, and obtained the geomechanical model of real slope rockmass with rather high accuracy, and every material property parameter of it.

(2) The numerical simulation of elasto-brittle-plastic finite element analysis for the deformation of ground surface of the oil refinery and the slope caused by the open mining during the end of 1987～the end of 1990 has been made with the above model and parameters. The numerical simulation has reappeared the fading away of self-supporting system over the underground excavation region caused by open mining the reactivates of old collapsed region. Comparing with the practical measured value, the numerical result of surface subsidization deformation has the identical tendency as a whole, the quantity being also very closed.

(3) The result of finite element analysis also indicates that the existence of F_{1A}fault and its non-tensional intensifies ground surface deformation over F_{1A} fault zone and the zone to the south of it, thus causing the facilities at that zone to have been damaged seriously. On the other hand, however, it protects the ground surface to the north of F_{1A} fault from serious deformation, causing a great quantity of important facilities avoid serous damage.

(4) Through the numerical simulation of rockslope under the condition of further construction, the estimation has been made on the deformation of slope and ground surface possible caused by finial bound opening. The results of estimation indicate that D-bound open mining will cause further subsiding of the ground surface of the oil refinery, and the region to the north of F_{1A} fault will also subside to rather large extent. Therefore, in case of no measure to be adopted the caused consequence will be serious. After adopting the enforcement measures, the ground surface deformation has reduced obviously. On the condition of adopting relevant reinforcement measures and improving the techniques of construction, the finial goal can be achieved, that is the safety in production of both the oil refinery and the open pit can be ensured.

(5) By way of analyzing the effectiveness of reinforcement measures, it can be concluded that the reinforcement of the northwall should be made by filling cement mortar to the collapse region over empty excavated region, increasing its ability in compressive resistance and shearing strength as main measures. Simultaneously, making the mortar filling solidifying and anchorage at the weak sandwich around the unstable rock mass of the core of synclinal of slope and mortar filling to the two fault zones as subsidiary, in which the reinforcement of F_{1A} fault should be mainly mortar filling, thus increasing ability of supporting and compressive resistance of the lower part of fault in time. The increasing of tensile strength at F_{1A} fault zone will lead to deformation of the northward stable rock body by southward displacement of the rockmass at south part of the fault. So it is harmful, and attention should be paid.

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