BEM Analysis and Monitoring of Unstable Slope During Reinforcement

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Abstract: Taking the excavation and reinforcement of an unstable slope as an example, the slope stability is analyzed firstly in this paper by the Boundary Element Method, the changing response of stresses, displacements and safety factor of the slope was known. Secondly, the deformation laws were given based on the in-situ monitoring, and the slide duration (if not reinforced) was forecasted by Golden Section Principle. The forecasted result was used to guide the correct reinforcement.

Keywords: slope, reinforcement, monitor and forecast, BEM, Golden Section

1 Introduction

Geheyen Hydraulic Power Station is a water conservation structure which the installed capacity is 1,200,000Kw. An artificial steep shale slope is excavated where it is in the bottom of a natural slope for the need of factory foundation and sump construction. The height of slope is 50m, the slope angle is 50 degrees and the angle of its bench up to 70 degrees (Fig1) which exceeds the stable standard for shale rocks. So tensile crack is formed in the crest of berm (Fig 2) during excavation, and the rate of crack propagation becomes worse. So the concrete retaining wall would be adopted to reinforce the unstable slope. For the purpose of demonstrating the feasibility of reinforcing scheme, the slope stability is analyzed firstly in this paper by Boundary Element Method. The changing laws of stresses, displacements and safety factor of slope were known with the construction of the retaining wall. Secondly, the deformation and stability tendency are monitored and forecasted by Golden Section Principle (Zhang Zuojuan, 1988) and is used to guide the correct reinforcement.

2 The BEM stability analysis of slope

Considering the material difference between shale slope and concrete wall, the Displacement Discontinuity Method (DDM) of boundary element is used to
calculate the stresses, displacements and yield zones in different stage of retaining wall construction using the interaction model. At the same time, the slope stability factor based on above DDM analysis data combining with Limit Equilibrium Method is given.

Fig.1 The profile of slope  Fig.2 Distribution of slope crack

2.1 Criterion and safety factor formula

The calculation model is shown in Fig.3, the Mohr-Coulomb rule is used to determine the rock and concrete strength

\[ \tau = \sigma \tan \phi + c \] (1)

If the maximum and minimum stresses \( \sigma_1 \) and \( \sigma_3 \) are used for above formula, it becomes:

\[ \sigma_1 = \frac{1 - \sin \phi}{\sin \phi} \frac{2 \cos \phi}{1 + \sin \phi} \frac{\sigma_1 - \sigma_3}{2} C \] (2)

where \( \sigma_1, \sigma_3 \) are the maximum and minimum stresses;

\( C, \phi \) are the cohesion and friction angle.

The conventional limit equilibrium analysis method of slope stability factor does not consider the stress-strain relation. This paper computes the slope stability factor using the calculated stresses by above DDM.

If \( \sigma_1, \sigma_3 \) are the maximum and minimum stresses of point i in slide surface (see Fig.3), then the minimum safety factor of point i can be determined:
\[
F_{\text{min}}' = \frac{2C + \tan \phi \left(\left(\sigma_i + \sigma_j\right) - \left(\sigma_i - \sigma_j\right) \sin \phi\right)}{\left(\sigma_i - \sigma_j\right) \cos \phi}
\]  

(3)

The overall stability factor of possible slide surface is given by length weighted method:

\[
F_{\text{min}} = \frac{\sum F_{\text{min}}' \Delta L_i}{L}
\]

(4)

where, \( L \) is the total length of slide surface;
\( L_i \) is the length of \( i \)th slide surface;

The slide surface location is determined by simplified Bishop method (Bishop, 1988), considering the fact of vertical tensile crack in the top of slope. The slide surface form is composed of the upper vertical crack and lower circular (Fig3). In the BEM analysis process, the slide surface is treated with a discontinuity plane (see Fig3).

2.2 Analysis of Results
The results showed that large tensile stresses existed at the top, and the shear stresses at the bottom before wall is constructed. With the construction of wall, the tensile stresses become small, and they changes to a state of compressive stress. The shear stresses also diminish. In other words, the state of stresses in the slope is improved obviously.

Otherwise, according to the combination of BEM with the limit equilibrium method, the safety factor in different stage of construction is given in table 1.

<table>
<thead>
<tr>
<th>Altitude of construction (m)</th>
<th>60</th>
<th>54.7</th>
<th>51.0</th>
<th>48.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{\text{min}} )</td>
<td>1.56</td>
<td>1.27</td>
<td>1.10</td>
<td>0.93</td>
</tr>
</tbody>
</table>
The calculated results showed that the slope and retaining wall were in a state of limit equilibrium (safety factor \( F_{\text{min}} = 1.1 \)) when retaining wall was constructed to a height of 51 m; the stability of slope was assured when a height of 54.7 m (\( F_{\text{min}} = 1.27 \)).

So the retaining wall must be constructed to the height of 51.0-54.7 m before slide occurs. The allowed time of construction may be determined by the deformation forecast method based on in-situ monitoring.

3 Monitoring forecast and feedback during construction of retaining wall

3.1 Monitoring method of slope
Based on the above analysis and prediction, the possibility of loss of slope stability is encountered, the multiple-borehole displacement gauge serves to survey the deformation of inner slope in the altitude of 78-60 m. The remote-controlling crack gauge, more stable and reliable for operation is installed to keep informed time to time on the crack's development in 78 plat, and some simple survey points are installed on the potential sliding body.

3.2 Slope deformation law analysis
Fig4-Fig5 show the displacement-time in different depth and crack width-time changes. It shows that the deformation of slope may be divided into three stages which respond to different stages of construction. In addition, the deformation survey is in accordance with the results of above stability analysis. Firstly, the change of deformation is in a normal developing progress (stable and linear stage) until the excavation is down to the level of 54.7 m (safety factor \( F_{\text{min}} = 1.27 \)). As the level of 48.7 m is approached, the slope deformation becomes larger. In the state of unstable and nonlinear behaviour, tensile cracks appear in the slope benches and their width develops with a velocity of 1 mm/day (\( F_{\text{min}} = 0.93 \)). All the above verify that the state of slope stability gets worse with excavation's progress. But when the concrete wall is poured in time, the deformation attains a stage in which it becomes stationary.

3.3 Slide time forecasting by Golden Section Principle
Zhang Zhuoyuan (1988) advanced the Golden Section Principle method of slide time forecasting based on the study of many examples of loss of rock engineering. He discovered that the deformation-time curve of rock mass may be divided into two stages of stable-linear and unstable-nonlinear. The time \( T_1 \) of linear stage and the time \( T_2 \) of nonlinear stage have the following relation:

\[
T_2 = 0.618T_1
\]  \( (5) \)
So if $T_1$ is known, then $T_2$ can be forecasted, and the possible slide time can be forecasted before slide occurs. According to the information of monitoring deformation in situ, the Golden Section Principle is adopted to forecast the time $T_2$

![Displacement-time curve](image1)  ![Crack width-time curve](image2)

Fig4 Displacement-time curve  Fig5 Crack width-time curve

of nonlinear stage deformation. According to the forecast results, the retaining wall must be constructed to a height of 51-54.7m. Otherwise, grey united GM(1,1) and Verhulst is used to forecast the tendency of deformation and sliding time of slope. The results are also immediately used to guide the correct construction. Subsequently the reinforcement of slope is done successfully.

4 Conclusions

The use of BEM for calculation of interaction between slope and retaining wall has the advantages of less data preparation, simple boundary discretization and good accuracy compared to the FEM.

The combination of numerical stresses with limit equilibrium method overcomes the disadvantages of a single method.

The forecast method of Golden Section Principle and Grey theory is suited for the guiding of safe construction.

Under the direction of monitoring-forecasting feedback, the quick reinforcement for unstable slope is possible and safe.

References

