Research on deformed slope parameters inversion based on equivalent conversion of soil pressure and application

Shengjie Di¹,²*, Heng Zhōu¹,², Ying Zhang¹,² and Peng Huang¹,²
¹Northwest Engineering Corporation Limited, Power China, Xi’an, Shanxi, 710065, China
²High Slope and Geological Hazard Research & Management branch, National Energy and Hydropower Engineering Technology R&D Center, Xi’an, Shanxi, 710065, China

*Corresponding author’s e-mail: 14276804@qq.com

Abstract. In this paper, a structural surface parameter inversion method for equivalent conversion of soil pressure is proposed. It can avoid the adverse effects of low overburden parameters, most dangerous sliding surface and relatively concentrated deformation limited to the overburden location. On this basis, we obtain the real inverse shear strength parameters of the deformation control structural surface. It can provide a reliable basis for evaluating the whole stability and protecting design of deformed slope. This paper analyzes and compares two kinds of supporting schemes for the deformed slope. The stability meets the requirements. In the actual situation, the design schemes can be selected according to the execution conditions, excavation and support sequence, and economic conditions.

1. Introduction
The deformed slope studied is 200m high, its top part is steep and the bottom part is slow. As for the deformed slope concerned, the upper edge of the deformed slope has appeared tensile crack and opening crack, and the investigation reveals that there is a deep sliding surface of the fracture zone, which deforms into unstable mass. Due to the backpressure effect of loosen deposited mass, the deformation is in a stable state temporarily. Considering the harm and influence on the permanent building and site at the foot of slope, it needs to be permanently treated. Now, for complex engineering problems, numerical analysis method has become one of the main irreplaceable methods[1-3]. The key technologies to be considered in stability assessment are as follows:

1. The deformed slope is in a critical stable state within the range of reasonable physical and mechanical parameters of rock, structural plane and overburden due to the anti-pressure action of loose accumulation overburden. Because the overburden parameters of loosen deposited mass are low, the overburden parameters can only be obtained through the inversion of slope parameters, but the structural surface parameters of deformation slope that are concerned cannot be obtained;

2. According to the requirements, the overburden should be removed at the later stage. On this basis, the deformable slope should be cut down as much as possible, and the economical and reasonable excavation load reduction and support reinforcement should be carried out. At this time, the structural surface parameters, especially the shear strength parameters, are the key factors to control the excavation and support, and determine the safety and rationality of the supporting measures.
According to the qualitative evaluation of deformation slope stability, it is shown that the fracture and tensile opening of structural plane are in a critical state. Therefore, the inversion of control parameters of structural plane for deformation slope should reflect the following aspects: Firstly, it is necessary to consider the back pressure boundary condition of overburden under the action of gravity. Secondly, it is necessary to reflect the freedom constraints and coordinate deformation conditions of deformable bodies when the overburden is assumed to exist. Thirdly, the shear action of overburden is not considered when inversion of structural surface parameters of deformed slope. Fourth, it is necessary to consider the effect of avoiding concentrated deformation of overburden, and the law of displacement and velocity development trend of deformation slope along the control structure plane should be reflected and simulated according to the actual judgment. The inversion of structural surface parameters under the above four conditions is of practical significance.

2. Calculation and estimation methods
Considering the discontinuities of slope, such as faults, joints and weak interlayers, and considering the anisotropy and discontinuity of rock and soil media, the discrete element method was adopted for this analysis and UDEC program was used for calculation. The discrete element model of slope is shown in the figure 1. Molar coulomb model was used for rock mass and deformed slope mass, and coulomb slip calculation was used for structural plane.

Figure 1. Discrete element numerical model and material partition

The active earth pressure under the dead weight of overburden is calculated. The whole model was simulated by calculating the field stress, and the earth pressure action of the overburden was obtained and shown in figure 2. The calculated results are compared and analyzed, and the soil pressure is reasonably selected and accurately applied to the rock mass boundary of the model. On this basis, the overall stability and factor of safety using strength reduction method of the deformation slope is calculated and analyzed.

The safety factor \( F \) of deformed slope is defined according to the equations:

\[
\begin{align*}
\sigma_{trial} & = \frac{1}{F_{trial}} c \\
\phi_{trial} & = \arctan \left( \frac{1}{F_{trial}} \tan \phi \right)
\end{align*}
\]

A series of calculations are made using trial values of the factor \( F_{trial} \) to reduce the cohesion, \( c_{trial} \), and friction angle, \( \phi_{trial} \), until the deformed slope failure occurs. And if the deformed slope is initially
unstable, the initial shear strength parameters $c$ and $\phi$ will be increased until the limiting condition is found. The following information is displayed during the solution process[4-6]: 1. Number of calculation steps completed to determine a given value of factor, as a percentage of Nr. 2. Number of completed solution cycles (i.e., tests for equilibrium or nonequilibrium). 3. Operation currently being performed. 4. Current bracketing values of factor. The factor of safety solution stops when the difference between the upper- and lower-bracket values becomes smaller than 0.005.

Figure 2. Initial field stress simulation to assess overburden soil pressure of loosen deposited mass

3. Calculation analysis and scheme comparison

In order to obtain the equivalent inversion parameters of the deformed loose structural surface, an inverse method of the shear strength parameters of the deformed structural surface with equivalent earth pressure replacement is proposed. In this way, the physical model of the overburden is removed and the overall original stress field is retained. Considering the vertical gravity and lateral earth pressure coefficient of the overburden, the uniform earth pressure is replaced, which serves as the initial condition for the inversion of the parameters of the critical slip surface of the deformation slope, and the shear strength parameters of the loose surface are obtained on this basis. The calculation method avoids the adverse effects of low overburden parameters and the most dangerous slip surface limited to the overburden position. Using this method, Initial parameters and inversion parameters are shown in Table 1.

Covering layer stability and the relatively concentrated deformation is shown in figure 3. This will affect the analysis and evaluation of structural plane slip.

Table 1. Initial parameters and inversion parameters

| Geologic types               | Trial parameters | Inversion parameters |
|------------------------------|------------------|----------------------|
|                              | unit weight kN/m3| cohesion (kPa) | friction angle $^\circ$ | unit weight kN/m3| cohesion (kPa) | friction angle $^\circ$ |
| Critical slip surface        | ——              | 0                  | 15–21                      | ——              | 0                  | 17.5               |
| Anti-sliding segment         | ——              | 100–150            | 25–30                      | ——              | 150               | 28.8               |
| Group structural planes      | ——              | 100–200            | 21.8–24.2                  | ——              | 200               | 24.2               |
| Level III rock mass          | 28              | 300                | 35                          | 28              | 300               | 35                 |
| Weak rock mass               | 28              | 200–300            | 28.8                        | 28              | 200               | 28.8               |
| Loosen deposited mass        | 21.5            | 0                  | 21.8                        | ——              | ——                | ——                 |

Deformation and displacement vectors of the deformed slope mass and critical surface under equivalent earth pressure and the dangerous position are shown in figure 4 and figure 5.
They both show that the potential sliding surfaces move backward to avoid the support structures. The cable and anchor pile are adopted in the case, and treatment design scheme I of cutting slope and supporting for deformed slope is shown in figure 6, and treatment design scheme II of excavation and supporting is shown in figure 7. Reinforcement of cable and anchor pile are adopted in the case, and construction progress is stimulated. As can be seen from figures, displacement and maximum shear strain contour are consistent with the actual judgment. They both show that the potential sliding surfaces move backward to avoid the support structures. The safety factor meets the code requirements in each working condition. Calculation results of safety
factor for the deformed slope are listed in table 2. The control condition is natural and the safety factor is 1.25 for the design scheme 2 and 1.26 for the design scheme 1.

| calculation conditions | design scheme I | design scheme II | control standards |
|------------------------|-----------------|-----------------|------------------|
| Natural state          | 1.26            | 1.25            | 1.25             |
| Rainstorm state        | 1.22            | 1.21            | 1.15             |
| Earthquake state       | 1.23            | 1.22            | 1.05             |

4. Appendices
The stability and the results meet designers’ requirements. In the actual situation, the design schemes can be selected according to the execution conditions, excavation and support sequence, and economic conditions. The results from numerical calculation analysis show that this method is effective and practical value for engineering application. Analysis methods and engineering design cases can provide useful references for engineers.

Acknowledgments
This work was financially supported by the major science and technology project of Northwest Engineering Corporation Limited, Power China. In the meantime, we express thanks to our colleagues for their help and technical support.
References

[1] Di, S.J., Xu, W.Y., Ning, Y. (2011) Macro-mechanical properties of columnar jointed basaltic rock mass. J. CENT. SOUTH UNIV. T., 18:2143-2149.

[2] Xu, W.Y., Di, S.J., Zheng, W.T. (2011) Safety performance analysis of rock wedges under left skewback of upstream dam line in Baihetan Hydropower Station. Chin. J. Rock Mech. Eng., 30:910-916.

[3] Cundall, P. A., and R. D. Hart. (1992) Numerical Modeling of Discontinua. Engr. Comp., 9:101-113.

[4] Fu, W., and Y. Liao. (2009) Non-linear shear strength reduction technique in slope stability calculation. Computers and Geotechnics, 37: 288-298.

[5] Dawson, E. M., Roth, W. H. and Drescher, A. (1999) Slope Stability Analysis by Strength Reduction. Géotechnique, 49: 835-840.

[6] Michalowski, R. (2002) Stability Charts for Uniform Slopes. J. Geotech. Geoenviron. Eng., 128: 351-355.