Back-analysis of initial stress fields in underground powerhouse using deformation data observed in field

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Abstract

Based on in-situ observed deformation data in underground powerhouse constructions and the response surface approach, back analysis procedure for estimating geotechnical parameters of rock mass is proposed. The relationship between unknown geotechnical parameters of rock mass and deformations of some observing point is approached by the response surface procedure. The excavation process is divided into 13 operation steps for simulation of the stress redistribution due to excavation. The variations of the stress sate and deformation field in the rock mass due to the excavation is simulated through a finite element analysis. By defining objective function for back analysis procedure to make the difference between computed deformations and observed ones minimize, the inverse problem of parameter identification is changed into optimization problem. By using optimization algorithm, the stress ratio and elastic modulus are determined. The practical application results show that the forecasted deformations by finite element method agree well with observed ones in-situ. The effectiveness of proposed back analysis procedure for estimating geotechnical parameters of rock mass is validated.

Keywords: back analysis procedure, geotechnical parameters of rock mass, response surface approach, in-situ observed deformation data, underground powerhouse construction, stress ratio, elastic modulus.

Introduction

Rock layer is composed of rock block, joint, fracture, fault and porosity. In ideal condition, rock at depth is only subjected to stress resulting from the weight of the overlying strata, and the stress ratio, ratio between horizontal and vertical stresses, is only related to Poisson ratio. Because of the influence of structural movement of the earth's crust, there exists drape, fracture and dislocation in rock mass, and the initial stress field in rock mass is changed. The stress ratio is not satisfied to classical elastic theory. In some sites, the horizontal stress is larger than vertical stress. So, how to estimate stress field in rock mass has increase intensive interests both from the point of engineering application and from scientific investigation. Cai developed a novel method to back-calculate rock mass strength parameters from acoustic emission monitoring data in combination with FEM stress analysis[Cai M., Morioka H., Kaiser P.K., 2007]. Loui examined the existing roadway support systems in seven underground manganese mines through numerical modelling employing theoretically derived in situ stresses to see whether such an approach is reasonable in a practical mining situation[Loui J.P., Jhanwar J.C., Sheorey P.R., 2007]. Kruschwitz evaluated the successful and reliable application of the complex resistivity method for the detection, specification and monitoring of the excavation damaged zone[Kruschwitz S., Yaramanci U., 2004]. Martino conducted extensive rock mechanics research, including work to understand the character and extent of excavation damage. Martino pointed out that damage exists around underground openings and that the damage develops from the energy imparted to the rock by the excavation method and by redistribution of the in situ stress field around the excavated openings[Martino J.B., Chandler N.A.,2004]. Kontogianni thought this induced deformation is not due to effects such as nearby excavations, changes in the hydrological conditions, etc., and to tertiary creep; its distribution along the tunnel axis seems to depend on the potential of host sections to accommodate additional stresses from neighboring deformation source sections, and it may lead to a progressive, domino-type failure[Kontogianni V.A., Stiros S.C.,2004]. Ishida pointed out that a conventional elastic theory predicts that the maximum compression occurs just behind a stress relaxed region, and gradually decreases as a function of the distance from the chamber wall; thus, this theory cannot be applied to the stress redistribution of a heterogeneous jointed rock mass [Ishida T., Uchita Y., 2000].Hatzor performed some numerical stress analysis and revealed that in the case of very large span openings, tensile fracture of intact rock may be responsible for instabilities, which may lead to global failure [Hatzor Y.H., Talesnick M., Tsesarsky M., 2002]. Farias used numerical analyses with the finite element method to simulate the full 3-D stages that characterize an NATM tunnel excavation. Some relevant techniques for settlement control were investigated and their relative importance was state based on the numerical results [Farias M. M.de, Moraes Junior A.H., Assis A.P. de, 2004].Based on field investigations, Sapigni used two numerical models (FEM and DEM codes) to investigate the overall stability of the excavation and to predict the expected deformation caused by each excavation phase. The measurements of actual deformations, by multi-base extensometer data, are reasonably close to those predicted through the numerical approaches[Sapigni M., Barbera G.La, Ghirotti M., 2003].Cai used a coupled numerical method to study AE at the Kannagawa underground powerhouse cavern in Japan. Two codes, Fast Lagrangian Analysis of Continua, a finite difference code and Particle Flow Code, a distinct element code, are coupled[Cai M., Kaiser P.K., Morioka H., Minami M., 2007]. The aim of the paper is to propose a back analysis procedure for estimating geotechnical parameters of rock mass, and validate the effectiveness of proposed parameter estimation procedure through comparing field observed deformations with those predicted by numerical approaches.

Numerical simulations for excavation process of underground powerhouse

The Baishan hydropower station was constructed on the second Songhua River in the Jilin Province, northeast China, between 1975 and 1983. The concrete gravity arch dam is 149.5m high, and 676.5 m long, as shown in Figure 1. The power plant has an installed capacity of 1700MW. In order to increase the generating ability of the Baishan hydropower station, the pumped storage power station with an output of 300MW was constructed. The underground powerhouse of the pumped storage power station is located in the left bank of river. The underground powerhouses of the first and the second periods of power stations are located in the right and left banks of river, respectively, as shown in Figure 1.

Figure 1. Baishan Hydropower station.

The powerhouse cavern is located approximately 120m below ground surface, as shown in Figure 2. The underground cavern's dimensions are 24.5m wide, 50m high and 69m long, as shown in Figure 3. It was excavated by dividing 6 operation layers. In order to monitor the rock displacement and rock stress during excavation period, the rock displacement and the stress of rock anchor were measured. Continuous displacement monitoring on the cavern support helped designers to evaluate the support appropriateness. The finite element method is well suited to solving problems involving heterogeneous or non-linear material properties, since each element explicitly models the response of its contained material. However, finite elements are not well suited to modelling infinite boundaries, such as occur in underground excavation problems. One technique for handling infinite boundaries is to discretize beyond the zone of influence of the excavation and to apply appropriate boundary conditions to the outer edges. Another approach has been to develop elements for which one edge extends to infinity i.e. so-called 'infinity' finite elements. In practice, efficient pre- and post-processors allow the user to perform parametric analyses and assess the influence of approximated far-field boundary conditions.

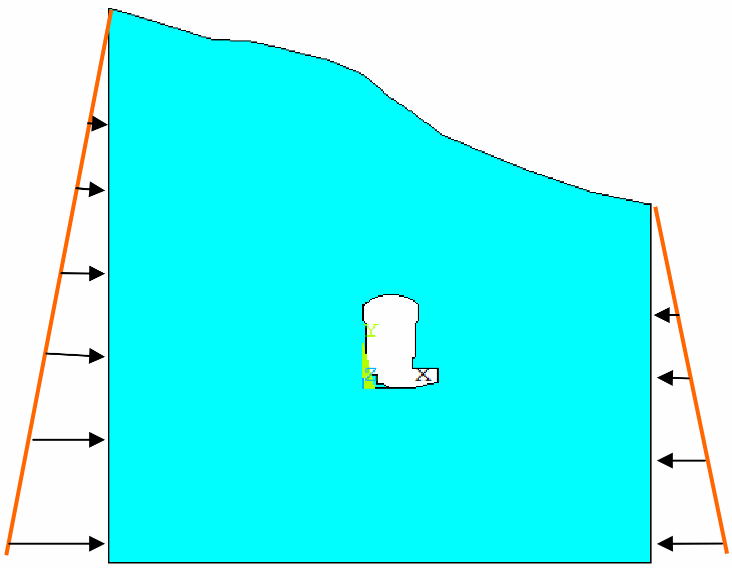

Figure 2. FEM model of underground powerhouse and rock mass

Based on elastic theory, classical formula for calculating initial ground stresses in underground rock mass can be expressed as follows:

$$\sigma_v = \rho g h \tag{1}$$

$$\sigma_h = k\sigma_v \tag{2}$$

$$k = \frac{\mu}{1-\mu} \tag{3}$$

Where σ_v is vertical stress, σ_h is horizontal stress, μ Poisson ratio, *h* is depth, *k* is stress ratio. Most in-situ observation results reveal that the horizontal stress calculated by above equations is not reasonable.

During the construction of the underground powerhouse of the first period (on the right bank of river) of power station, geotechnical parameters in underground powerhouse on right bank of river were measured in-situ, and listed in Table 1. These data supply references for estimating geotechnical parameters of rock mass in underground powerhouse on left bank of river.

Table 1: Geotechnical parameters measured in-situ in underground powerhouse on right bank of river

Parameters	E/GPa	μ	σ_v/MPa	σ_h/MPa	k
No.1	54.1	0.19	14.60	14.06	0.96
No.2	57.0	0.13	7.47	9.45	1.26
No.3	62.0	0.13	7.52	11.35	1.50

In order to simulate the excavation process of cavern, the initial horizontal stress in rock mass is supposed to linear distribution with depth, as shown in Figure2. On the left boundary of FEM model, the horizontal load is defined as:

$$\sigma_{hl} = k_e \rho g z_l \tag{4}$$

Where z_l is the depth from ground surface corresponding to left boundary of FEM model. k_e is the identified stress ratio and will be determined by back analysis procedure. On the right boundary of FEM model, the horizontal load is defined as:

$$\sigma_{hr} = k_e \rho g z_r \tag{5}$$

Where z_r is the depth from ground surface corresponding to right boundary of FEM model.

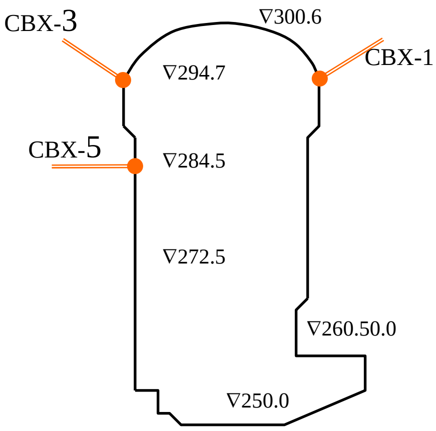

Figure 3. Displacement measuring profile.

The excavation process is divided into six operation steps for simulation of the stress and deformation redistributions due to excavation, as shown in Figure 5. The variations due to the excavation of the stress sate and deformation field in the rock mass can be evaluated through a finite element analysis.

In-situ monitoring during the excavation and at longer intervals after the underground cavern is completed should be regarded as an integral part of the design not only for checking the structural safety and the applied design model but also for verifying the basic conception of the response of the rock mass to tunnelling and the effectiveness of the structural support. In order to monitor the displacements of powerhouse caver during excavation process, the three sliding micrometers were installed as shown in Figure 3. Figure 4 shows sequences for cavern excavation. Table 2 lists scheduling for cavern excavation operation. ST denotes starting time. ET denotes ending time. Subareas of cavern excavation for FEM simulation is depicted in Figure 5.

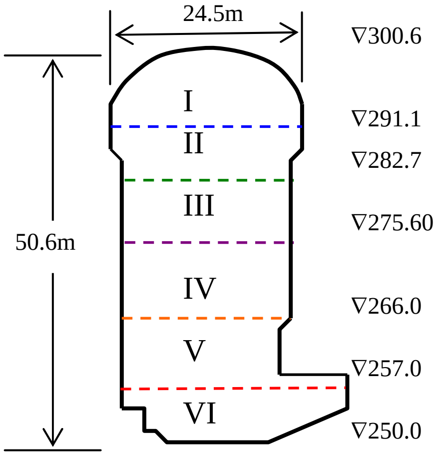

Figure 4. Sequences for cavern excavation

Table 2. Scheduling for cavern excavation operation

No.	I	II	III	IV	V	VI
ST ET	03-04-01 03-08-16	13-08-17 13-11-26	03-11-27 03-12-23	03-12-28 04-01-13	04-01-14 04-02-11	04-02-14 04-03-11

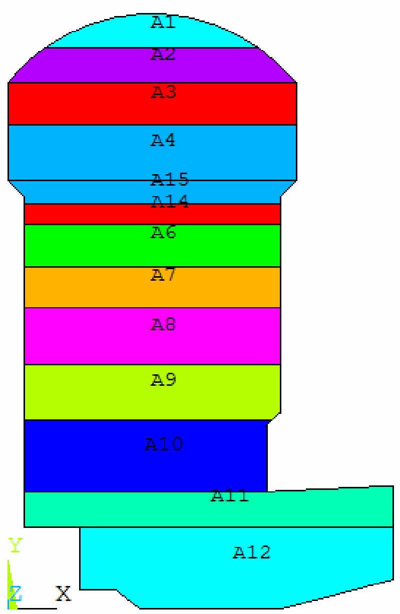

Figure 5. Subareas of cavern excavation for FEM simulation

According to Figure 4 and Table 2, subregions of cavern excavation for FEM simulation are divided into 13 parts, as shown in Figure5.

Response surface procedures for back analysis of geotechnical parameters

Based on the response surface method, the relationship between unknown geotechnical parameters of rock mass and displacement of some observing point is approached as:

$$s_k(\bar{x}) = a + \sum_{i=1}^{2} b_i \bar{x}_i + \sum_{i=1}^{2} c_i \bar{x}_i^2 \quad (6)$$

Where $s_k(\bar{x})$ is displacement of some observing point k, a, b_i ,and c_i are unknown coefficients, $\bar{x}$ is unknown geotechnical parameter vector after dimensionless procedure.

$$\bar{x} = \{\bar{x}_1, \bar{x}_2\}^T = \{\bar{E}, \bar{k}\}^T \quad (7)$$

$$\bar{E} = \frac{E}{E_I} \quad (8)$$

$$\bar{k} = \frac{k}{k_I} \quad (9)$$

Where E_I and k_I denote initial evaluating values of geotechnical parameter according to prior to information induced from observed data in-situ in underground powerhouse of right bank of dam, E_I=40MPa, k_I=1.0.

Taking the first observing point as an example, the right items of following equations can be calculated using finite element method under the given parameter combinations .

$$s_1^1(\bar{x}) = s(\bar{E}, \bar{k}) \quad (10)$$

$$s_1^2(\bar{x}) = s(\bar{E} + \Delta E, \bar{k}) \quad (11)$$

$$s_1^3(\bar{x}) = s(\bar{E} - \Delta E, \bar{k}) \quad (12)$$

$$s_1^4(\bar{x}) = s(\bar{E}, \bar{k} + \Delta k) \quad (13)$$

$$s_1^5(\bar{x}) = s(\bar{E}, \bar{k} - \Delta k) \quad (14)$$

Where ΔE is increment of elastic modulus after dimensionless, ΔE=0.2. Δk is increment of stress ratio, Δk =0.2. s_1^i denotes computed displacement of the first observing point under i-the parameter combination, which is computed by using finite element method. There exist 5 unknown coefficients and 5 equations. So, the 5 unknown coefficients in response surface functions about first observing point are determined by solving linear equation set with Excel software. The unknown coefficients in response surface functions for other observing point may be deduced by analogy. There are 3 observing points located on the surface of the cavern, as shown in Figure 3. The 8 excavation steps for every observing point are simulated using FEM. So, total 24 series of response surface functions will be determined. And 120 coefficients of response surface function are calculated.

Estimating Geotechnical parameters of rock mass using optimization algorithm

The objective function of estimating geotechnical parameters of rock mass is defined as Root Mean Square（RMS）:

$$\min J = \sqrt{\frac{1}{N*M} \sum_{k=1}^{k=N*M} (s_k(\bar{x}) - s_k^m)^2} \quad (15)$$

Where J is objective function, s_k^m is the observed displacement for the-k observing point, N is the number of observing point, k=3, M is the observing time for every point, M=8. In order to estimate geotechnical parameter vector x, some methods based on the gradient present convergence rates of first order are commonly used. Newton's methods guarantee convergence rates of second order; however, they present the inconvenience of calculating the Hessian and its inverse. The Gauss-Newton method is used as a way to achieve convergence rates closed to second order with lower computation efforts when compared to Newton's methods. According to observed deformations induced from cavern excavation and response surface functions, the geotechnical parameters of rock mass are identified, as listed in Table 3.

Table 3. Identified geotechnical parameters of rock mass

Geotechnical parameters	*E*/GPa	*k*
Initial estimated value	40.0	1.0
Estimated value by back analysis	56.0	1.2

The deformations of different observing point induced from cavern excavation are further simulated by using identified geotechnical parameters of rock mass. Comparisons between observed and forecasted deformations in different excavation step for 3 observing point are shown in Figure 6, 7 and 8.

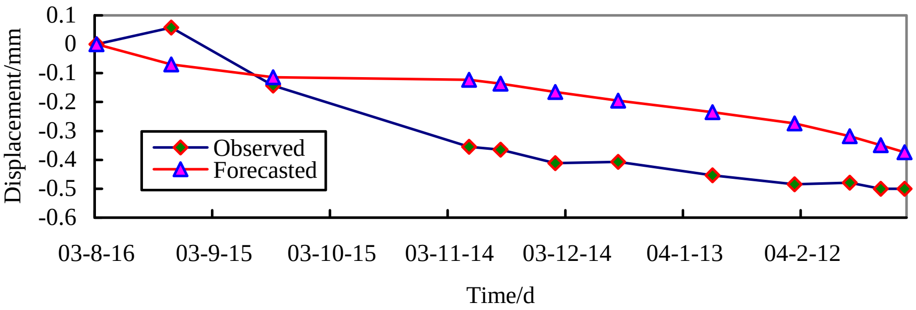

Figure 6. Comparison between observed and forecasted deformations in different excavation step for CBX-1

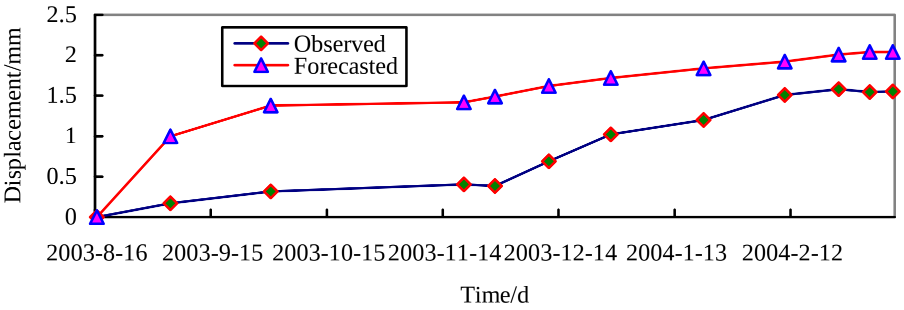

Figure 7. Comparison between observed deformations and forecasted ones in different excavation step for CBX-3

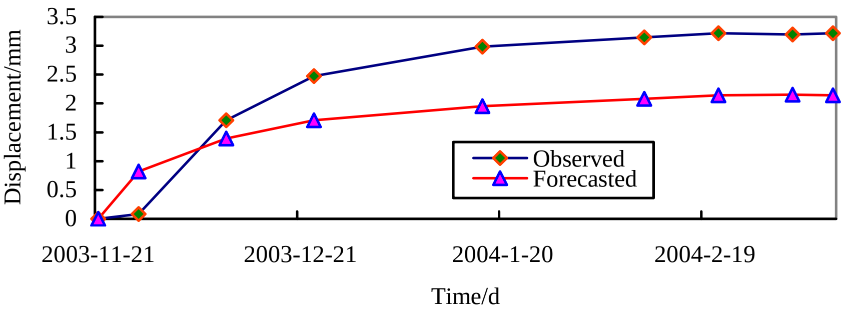

Figure 8. Comparison between observed and forecasted deformations in different excavation step for CBX-5

Conclusions

The back analysis procedure for estimating geotechnical parameters in rock mass is presented to demonstrate how the response surface method, finite element method and optimization algorithm should be used as the tools to understand ground stress field and mechanical parameters in rock mass. The observed deformation data of cavern during excavation process supply foundations for solving inverse problem of parameter identification. The effectiveness of proposed inversion procedure is validated by comparing the difference between predicted deformations and observed values in situ.

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