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Technical Note

Analysis of Shiobara Powerhouse Cavern Using Equivalent Continuum Approach

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Introduction

Underground excavations in rock are used in various fields of engineering to serve many purposes like mining, transportation and carriage of power cables. The stress state in rocks gets altered due to the excavation and the stresses are redistributed around the created open void. To estimate the stresses and ground movement around these excavations, detailed analysis of the excavations is required. Analysis of these excavations is not very easy considering the inherent discontinuities that are common features of surrounding rocks. The strength of composite rock mass is not as frequently investigated as the strength of intact rocks. Some of the earlier researchers tried to estimate the strength of rock mass by applying scale effect to the strength of small size samples tested in laboratory, e.g. Hoek and Brown (1980), Krauland et al. (1989). However, it was reported that the strength of large scale rock mass is very small in magnitude compared to the small scale sample taken from the same rock mass due to the increased number of discontinuities in rock mass from small scale joints to larger faults. Thus the reasonable estimate of the strength of jointed rock mass can only be obtained from numerical modeling. In the numerical modeling also the explicit inclusion of all the joint sets present in the rock mass becomes impractical many times because it requires detailed and careful exploration of the orientation, location and strength of all the joint sets.

The difficulties associated with explicitly describing rock mass strength based on the actual mechanisms of failure has lead to the

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development of equivalent continuum approach in which the rock mass is treated as a continuum with equivalent strength derived from empirical relations. Some equivalent continuum models were developed to simulate the jointed rock mass by Singh (1973a, 1973b), Zienkiewicz et al. (1977), Gerrard (1982), Kawamoto et al. (1988), Cai and Horii (1992), Oda et al. (1993) and Yoshida and Horii (1998). Some researchers have developed empirical relations to estimate the equivalent material properties of the jointed rock mass from the geometrical and mechanical properties of discontinuities. These equations can be incorporated in other constitutive models for effective simulation of jointed rock masses, e.g. Wei and Hudson (1986) Barton and Bandis (1990), Ramamurthy (1994), Hoek and Brown (1997), Sridevi and Sitharam (2000) and Sitharam et al. (2001a). Most of these models were developed based on laboratory triaxial testing of small jointed rock samples and few of them were verified against field test data of rock masses. The equations based on joint factor to estimate the equivalent elastic modulus for jointed rock mass proposed by Ramamurthy (1994) and Sitharam et al. (2001a) from extensive laboratory testing of intact and jointed rock specimens are very simple and practical among all the models stated above. These equations require the estimation of two simple joint parameters, namely the number of joints in the rock per meter depth and the inclination of most critical joint set. Detailed description of these equations and design tables for estimating the joint strength parameter from the unconfined compressive strength of the intact rock and joint inclination parameter from the orientation of the joint are given by Ramamurthy (1994) and Sitharam et al. (2001a). These equations were successfully used by Sitharam et al. (2001b) to predict the failure behaviour of Kiirunavaara mine in Sweden and also by Varadarajan et al. (2001) to analyse a powerhouse cavern in Himalayas. In both these cases, the surrounding rock mass consisted of different joint sets.

In the present study, the equivalent continuum equations developed by Ramamurthy (1994) incorporated in a commercial explicit finite difference code Fast Lagrangian Analysis of Continua [FLAC] is used for the analysis of a cavern in jointed rock mass for the Shiobara power station in Japan. The complete field information along with instrumented data of displacements was available for this case for analysis and comparison with the numerical model. Earlier, Sitharam et al. (2001a) performed finite element analysis of the same cavern using the equivalent continuum model to predict the displacements after complete excavation. The time history of displacements with the progress of excavations is not compared with field data in their analysis and also the stress distribution around the cavern is not reported. In this study, the equivalent continuum model is implemented in the commercial finite difference code FLAC making the simulation of stage excavation easy and thus permitting the comparison of time history of displacements obtained from numerical analysis at each stage of excavation with the available field

TABLE 1 : Properties of Intact Rock for Shiobara Powerhouse Cavern

Uniaxial compressive strength (MPa)	83.3
Young's modulus (Mpa)	42100
Poisson's ratio	0.38
Cohesion (MPa)	1
Angle of internal friction (degrees)	45

instrumentation data. The predicted stress distribution and plastic strains around the cavern are also presented in this study.

Description of Shiobara Powerhouse Cavern, Japan

Shiobara power station in Japan constructed by the Tokyo Electric Company is a large pumped storage power station with a maximum output of 900 MW. The construction involved the excavation of a large cavern. The rock mass surrounding the cavern was characterized mainly as rhyolite consisting of platy and columnar joints. The cavern was located at a depth of 200 m below the ground level. The cavern measured 28 m in width, 51 m in height and 161 m in length. The amount of jointed rock mass excavated due to opening of the cavern was estimated to about 190000 m^3 of rock mass. The three in-situ principal stresses were recorded as 5.0, 3.9 and 2.8 MPa. The properties of intact rock are presented in Table 1. The dip angle and the average spacing of the three dominant joints present in the surrounding rock of the Shiobara power cavern and the computed jointed factor for different joint sets are given in Table 2.

The joint factor for the above problem has been estimated as follows. Joint frequency value J_n is estimated as the number of joints per meter depth in the surrounding rock. The value of joint inclination parameter (n) and the

TABLE 2 : Properties of Joint Sets for Shiobara Powerhouse Cavern

Joint set	Dip angle	Spacing	Joint frequency (J_n)	Joint inclination parameter(n) (n)	Joint strength parameter (r)	Joint factor (J_f) $J_n/(n \times r)$
I	60R	30 cm	17	0.46	0.9	41
II	60L	100 cm	5	0.46	0.9	12
III	30L	100 cm	5	0.05	0.9	111

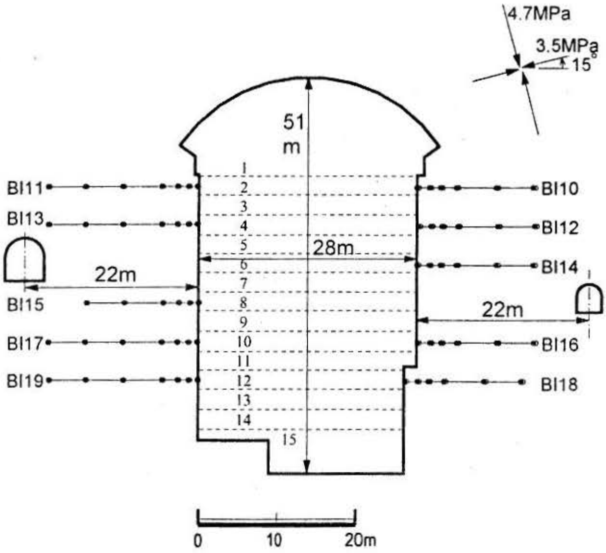

FIGURE 1 : Cross Section and Locations of MPBX for the Cavern at Shiobara Power Station

joint strength parameter (r) are determined from the inclination of joint and the uniaxial compressive strength of the rock respectively as described by Ramamurthy (1994) and Sitharam et al. (2001a).

Multi-point bore hole extensometer (MPBX) data were available at several locations along different measurement lines BI10 to BI19 (Fig.1) around the cavern. The cavern is excavated in 15 stages. The cross-section of the cavern along with the sequence of excavation is as shown in Fig.1. The measurement lines along which the field displacements are available are also shown in Fig.1. The displacement measurements along all these measurement lines are available with different stages of excavation of the cavern (Horii et al., 1999).

Equivalent Continuum Model

In this paper, an equivalent continuum equations developed by Ramamurthy (1994) is used for the analysis of the Shiobara power cavern in Japan. In this model, the rock mass properties are represented by a set of empirical relations, which express the elastic modulus of the jointed rock mass as a function of joint factor and the elastic modulus of the intact rock. Extensive laboratory testing of intact and jointed specimens of different grades of plaster of Paris, sandstone and granite revealed that the properties of rock joint can be integrated into a single entity called Joint factor (Arora, 1987; Yaji, 1984 and Roy, 1993) given by the following equation.

$$J_r = \frac{J_n}{n\,r} \tag{1}$$

where J_n = number of joints per meter depth,

n = inclination parameter depending on the orientation of the joint β,

r = roughness or joint strength parameter depending on the joint condition.

The values of 'n' are for various orientation angles and the joint strength parameter 'r' for various uniaxial compressive strengths of intact rock are presented by Ramamurthy (1994) and Sitharam et al. (2001a). Empirical equations were developed from regression analysis of experimental data to estimate the strength and elastic modulus of the jointed rock mass from the joint factor and confining pressure. These relations are obtained from the analysis of experimental data of Roy (1993), Arora (1987), Yaji (1984), Brown and Trollope (1970) and Einstein and Hirschfield (1973). These relations were validated by Sitharam et al. (2001a) against experimental results and also with the results from explicit modeling and the results indicated that the equations work well for jointed rock masses with different joint fabric and joint orientation. In the present study, these equations are incorporated in FLAC by writing a special FISH function as described in the next section.

Numerical Model

In the present study the explicit two-dimensional finite difference program FLAC version 3.3 (Cundall, 1976; Itasca, 1995), has been used for the analysis. This program which can simulate the behavior of structures built of soil, rock, or other materials subjected to static, dynamic, and thermally induced loads, has gained widespread use in geomechanics society in recent times. FLAC is based upon a "Lagrangian" scheme that is well suited for large deflections and has been used primarily for analysis and design in mine engineering and underground construction. This program uses an explicit time-marching scheme to find the solution for a problem. The explicit time-marching solution of the full equations of motion, including inertial terms, permits the analysis of progressive failure and collapse. Modeled materials respond to applied forces or boundary restraints according to prescribed linear or non-linear stress/strain laws and undergo plastic flow when a limiting yield condition is reached. The equations of motion are solved to derive new velocities and displacements from stresses and forces. Velocities are then used to calculate strain rates, from which new stresses can be found through a constitutive equation. The advantage of using this explicit formulation is that the numerical scheme stays stable even when the physical system being modeled is unstable. This is particularly advantageous when modeling non-linear, large-strain behaviour of rock masses. A FISH function is written in FLAC to determine the elastic modulus of the jointed rock with the statistical relations proposed by Ramamurthy (1994).

The FISH function obtains the value of modulus ratio E_r for the rock mass, which is the ratio of elastic modulus of the jointed rock (E_j) to the elastic modulus of the intact rock (E_i) at zero confining pressure given the value of joint factor J_f using the following equation.

$$E_r = \frac{E_j(\sigma_3 = 0)}{E_i(\sigma_3 = 0)} = \exp\left(-1.15 \times 10^{-2} J_f\right) \tag{2}$$

The elastic modulus of the jointed rock at zero confining pressure E_j ($\sigma_3 = 0$) is then obtained by multiplying E_r with the elastic modulus of the intact rock (E_i). The compressive strength ratio σ_{cr}, which is the ratio of uniaxial compressive strength of the jointed rock (σ_{cj}) to the uniaxial compressive strength of the intact rock (σ_{ci}). is then obtained as

$$\sigma_{cr} = \frac{\sigma_{cj}}{\sigma_{ci}} = \exp\left(-0.008\, J_f\right) \tag{3}$$

Then the elastic modulus of the jointed rock at the confining pressure of σ_3, which is the measured minor principal stress in the field is calculated as

$$E_j(\sigma_3) = \frac{E_j(\sigma_3 = 0)}{1 - \exp\left[-0.1\left(\frac{\sigma_{cj}}{\sigma_3}\right)\right]} \tag{4}$$

The constitutive behaviour of the rock mass is represented with confining stress dependant nonlinear hyperbolic relation proposed by Duncan and Chang (1970) with Mohr-Coulomb failure criterion in the numerical analysis. In this model, the elastic behavior of the soil is defined by the bulk and shear modulus, and the soil strength is defined by the angle of friction and cohesion.

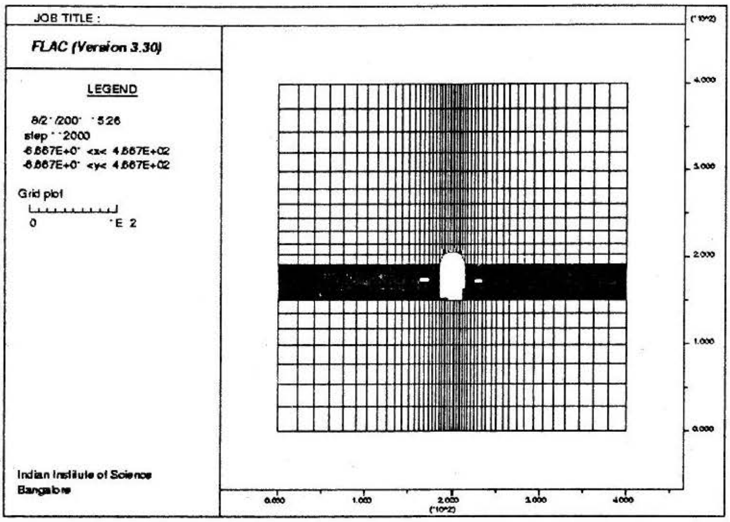

FIGURE 2 : Finite Difference Grid Used for the Analysis of Cavern

Analysis

The total size of the numerical model used for the analysis of the cavern is 200 m × 200 m. Figure 2 shows the finite difference grid after the cavern is completely excavated. The problem was analyzed for the initial stresses existing in the surrounding rock and the overburden stress due to the weight of the rock above the cavern. Sequential excavation was simulated in the analysis with exact representation of all the 15 stages of excavation in the field. This is achieved by representing the excavated material in each step using 'null' model that is available in FLAC. The FISH function for joint factor model is called at each iterative step in the numerical analysis. Equilibrium is defined in the analysis as the state in which the out-of-balance force is less than 100 N. In all the cases, the model is run for each excavation step and solved for equilibrium before proceeding to the next excavation step.

Horii et al. (1999) observed that the critical joint set that influence the behaviour of cavern is varying with the location under consideration, resulting in anti-symmetry in deformations. They have mentioned that the joint set I, which has smaller spacing is critical for the right side of the cavern, where as for the left side the joint set III with an inclination angle of 30° is critical. In the present analysis, the influence of two different joint sets is simulated by taking a J_f value of 41 for the left portion of the cavern starting from the axis of the cavern and a J_f value of 111 for the right

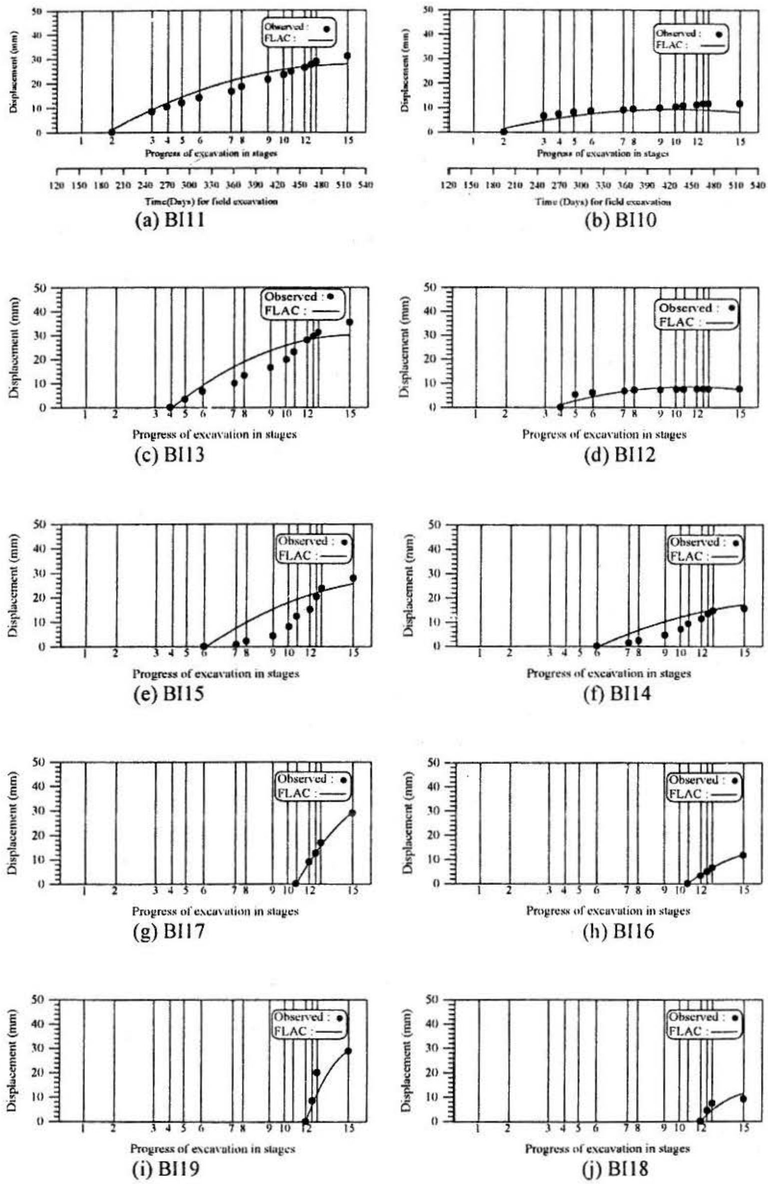

FIGURE 3 : Comparison of Observed and Predicted Displacements near the Cavern Wall at Different Levels with the Progress of Excavation

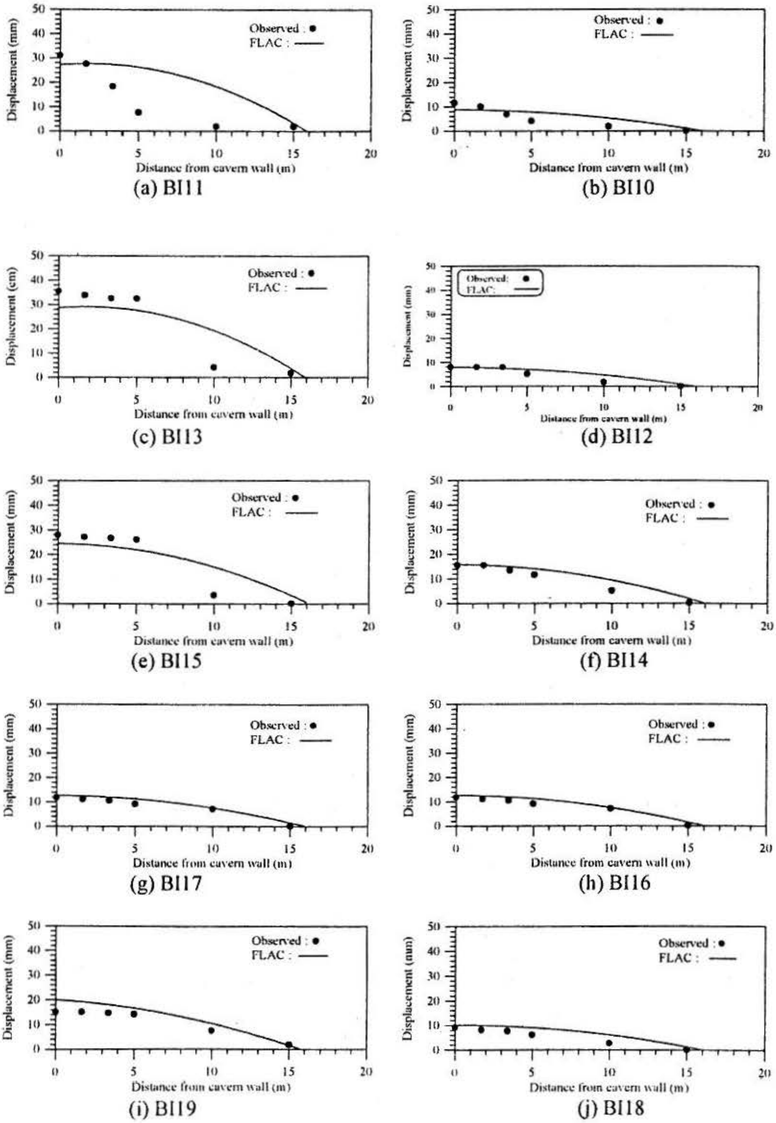

FIGURE 4 : Comparison of Observed and Predicted Displacements along Different Measurement Lines at the Completion of Whole Excavation

portion of the grid. For this purpose, a special FISH function is written to incorporate the joint factor as a built-in property of the rock, thus allowing for the variation of J_f with distance and direction.

Results and Discussion

The variation of relative displacement at the cavern wall at the end of different excavation steps with progress of cavern excavation is compared with the time-displacement measurements along each measurement line given by Horii et al. (1999 and 2000). The relative displacement versus stages of excavation along the measurement lines BI10 to BI19 is shown in Fig.3 along with the measured values. As the time taken for different excavations was different, a second x-axis showing the time in days is presented for first two graphs showing displacements along measurement lines BI10 and BI11. From the above figure, it is found that the equivalent model is capable of predicting the observed behaviour of the cavern. The model is also suitable to simulate the progressive excavation and anti-symmetry in displacements due to anisotropy in the variation of joint factor. The variation of relative displacement along different measurement lines with distance at the end of the completion of the whole excavation is shown in Fig.4. The numerical results matched very well with the field measurements as observed from the figure. The anti-symmetry in displacements with the cavern sliding more towards the left side is captured well by the numerical model. Also the displacement is almost constant near the cavern wall (about 30 mm on the left side and 10 mm on the right side) in the numerical model, matching well with the field measurements.

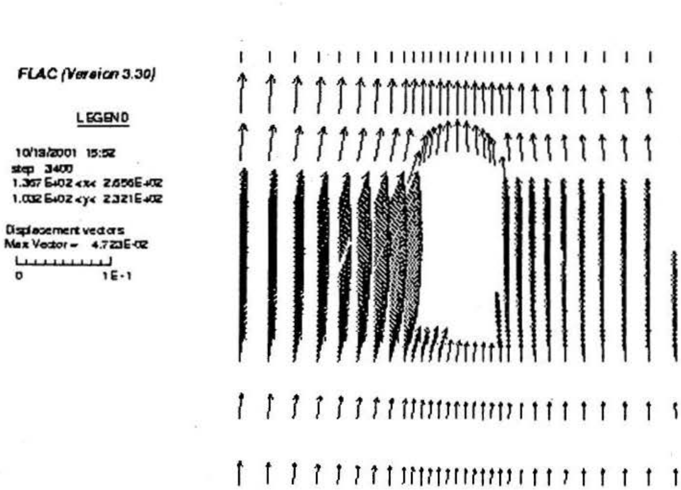

FIGURE 5 : Displacement Vectors Around the Opening Showing the Deformed Shape of the Cavern

The displacement vectors showing the deformed shape of the excavation is shown in Fig.5. The tunnel portion of the grid is several times zoomed in these figures to clearly visualize the deformations in the vicinity of the cavern. From this figure, the ground movement at any location around the excavation, apart from the places where the MPBX records are available, can be found.

Conclusions

The equivalent continuum equations used in the present study are very simple because they require only the elastic modulus and uniaxial compressive strength of the intact rock along with the joint factor to model the complete behaviour of the jointed rock mass. In the present study the above model is incorporated in a commercial explicit finite difference code FLAC, thus developing a numerical tool for easy and faster application of equivalent continuum approach based on joint factor for problems involving jointed rocks. The efficiency of this tool is verified by analyzing a field case of powerhouse cavern in Japan using this model. The deformations around the cavern were compared with the available field data. The anti-symmetry in deformations around the cavern is captured well by the numerical model and the predicted deformations at various locations around the cavern matched very well with the instrumentation data available from field studies. Apart from the locations where the extensometers were fixed to record the deformations in field, the deformations at any location around the cavern can be obtained from the numerical analysis. The approximations involved in developing the equivalent continuum equations from regression analysis of experimental data are concealed by the large scale of rock masses involved, thus permitting the successful prediction of the field behaviour using the model. Present study emphasizes this fact and recommends a simple model for field problems involving jointed rocks.

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Notations

E_i	=	elastic modulus of the intact rock
E_j	=	elastic modulus of the jointed rock
E_r	=	modulus ratio
J_f	=	joint factor
J_n	=	joint frequency
n	=	joint inclination parameter
r	=	joint strength parameter
β	=	inclination of joint with the direction of major principal stress
σ_{ci}	=	uniaxial compressive strength of the intact rock
σ_{cj}	=	uniaxial compressive strength of the jointed rock
σ_3	=	confining pressure