III－391 Numerical Analysis of Deformation Behavior of Jointed Rock Masses under Loading-Unloading Conditions

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1. Introduction

Rock masses are characterized by the existence of distributed joints. The mechanical properties of jointed rock masses are strongly dependent on the property and geometry of joints. Test results both in-situ and in the laboratory have shown that the deformation behavior of jointed rock masses is strongly non-linear, showing irrecoverable deformation upon unloading and hysterisis during repeated loading.

In the present study, the mechanical behavior of joints described by a hyperbolic model is implemented into a continuum model of jointed rock masses in an attempt to predict the mechanical behavior of rock masses under loading-unloading conditions.

2. A Constitutive Model of Highly Jointed Rock Masses

A constitutive model of jointed rock masses, which reflects the size, density, orientation and their mechanical property as well as the effects of joint interaction and connection, is proposed by Cai and Horii(1992). The incremental constitutive relation is formulated by taking the volume average of stress and strain inside a representative volume element(RVE) as

$$\Delta\bar{\varepsilon}_{ij} = C^{R}_{ijkl}\Delta\bar{\sigma}_{kl} + \frac{1}{2V}\sum_{k}\int_{S^J_k}(\Delta[u_i]n_j + \Delta[u_j]n_i)_k dS \,, \qquad (1)$$

where C^{R}_{ijkl} is the compliance tensor of the intact rock,S^J_k is the surface of joint k, n_i is the unit normal vector of the joint surface, and $\Delta[u_i]$ is the incremental displacement jump across the joint surface. The average incremental displacement jumps over the joint are related to the average incremental stresses over the joint through a constitutive law of joints. With the introduction of the joint stress concentration tensor(JSCT), the increment of the traction on the joints is expressed in terms of the increment of the average stress and the complete incremental constitutive relation is obtained. The concept of system stiffness is introduced and a simple homogenization method is used to evaluate the JSCT. For details, see Cai & Horii(1992).

The formulation of the constitutive model of jointed rock masses is general and any kind of joint constitutive model can be used. Since the mechanical behavior of joints is very complex, a simple method of modelling, which is similar to the famous Duncan-Chang modelling method(1970), has been proposed by Bandis et. al.(1983) based on their experimental data. The hyperbolic model describes well the normal and shear behaviors observed by many investigators(Bandis et. al., 1983; Hungr & Coates, 1978; Sekine et. al., 1982; see Fig.1). The following joint hyperbolic model is used in the present study

$$\begin{pmatrix}\Delta\sigma\\ \Delta\tau\end{pmatrix} = \begin{bmatrix}K_n(\sigma) & 0\\ 0 & K_s(\sigma,\tau)\end{bmatrix}\begin{pmatrix}\Delta v\\ \Delta u\end{pmatrix}, \qquad (2)$$

where $K_n(\sigma)$ and $K_s(\sigma,\tau)$ are the tangential normal and tangential shear stiffness of the joint, respectively, and σ, τ are the stresses acting on the joint. Both loading and unloading curves of a joint under normal load are described well by hyperbolas, and the tangential normal stiffness is defined as

$$K_n = K_{ni}\left[1 - \frac{\sigma}{(V_m-\Sigma V_i)K_{ni} - \sigma}\right]^{-2} \qquad (3)$$

for a closing joint(loading) ,

$$K_n = K^{(M)}_{ni}\left[1 - \frac{\sigma}{(V_m-\Sigma V_i)(1-\eta_M)K^{(M)}_{ni} - \sigma}\right]^{-2} \qquad (4)$$

for an opening joint(unloading) ,

where V_m is the maximum closure of the joint, K_{ni} is the initial normal stiffness, ΣV_i is the displacement corresponding to the complete unloading state, M is the number of loading loops, and η_M is the ratio of the irrecoverable displacement to the total one in each loop. The loading curve of a joint under shear load is described by a hyperbola while the unloading curve is best described by a straight line. Similar to the Duncan-Chang model, the joint tangential shear stiffness before peak shear strength is defined as

$$K_s = K_j(-\sigma)^{n_j}\left[1 - \frac{\tau R_f}{\tau_p}\right]^2 \quad loading \,, \qquad (5)$$

$$K_s = \frac{-\sigma\tan\phi_r}{0.3u_p} \quad unloading, \qquad (6)$$

where K_j is the stiffness number, n_j is the stiffness exponent, R_f is the failure ratio($=\tau/\tau_{ult}$), τ_p is the peak shear strength, ϕ_r is the residual frictional angle and u_p

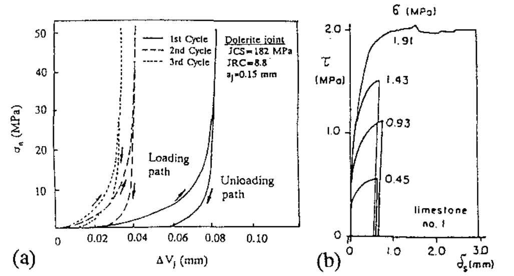

Fig.1 Stress-displacement relation of joints. (a) Normal stress vs closure curve(after Bandis et. al.,1983; (b) Shear stress vs shear displacement curves(after Hungr & Coates, 1978)

is the peak shear displacement of the joint. The unloading shear stiffness is assumed to be the shear elastic stiffness given by Barton's model(Barton et. al., 1985). This hyperbolic model of joints is characterized by the facts that the non-linear behavior is described by hyperbolas, the inelastic response is considered by incorporating different stiffness upon loading and unloading process and all the parameters can be obtained from the test data of joints in laboratory.

3. Numerical Examples

The joint hyperbolic model is implemented into a two dimensional FEM program based on the framework of the jointed rock mass model described above. In order to illustrate the mathematical formulation discussed in the present study, results of some numerical analysis are shown as examples. The stress-strain relations of a jointed rock mass with two sets of cut-through joints are shown in Fig.2. σ_2 is kept constant while σ_1 is increased or decreased. The model predicts the nonlinear and inelastic deformation of jointed rock masses, which is qualitatively in agreement with the stress-strain curves of loading-unloading tests on rock masses (see, e.g., Sekine et. al., 1982).

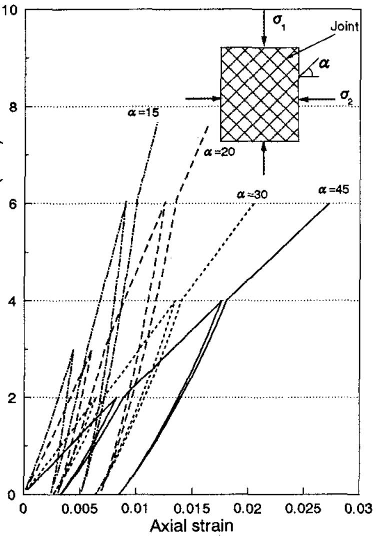

Fig.2 Stress-strain relations of a jointed rock mass with two sets of joints

The result of a simulation of a plate-loading test is shown in Fig.3(b). Two sets of joints exist in the rock mass as is shown in Fig.3(a), one set being cut-through while the other is non-persistent. The predicted curve agrees fairly well qualitatively with the test one except that the hysterisis upon unloading-reloading is not predicted. Non-linear and inelastic responses observed in the plate loading test are captured in the present computation.

4. Conclusion

When dealing with the mechanical property of rock masses, particular attention should be paid to the unloading phase, especially in the tunnelling and underground space engineering practice. In the present study, the joint hyperbolic model is implemented into the constitutive model of jointed rock mass and numerical results obtained are in agreement with experimental data showing the characteristic features of the non-linear and inelastic deformation behavior of jointed rock masses under loading-unloading conditions. In order to predict the hysterisis shown upon the unloading-reloading process, extension of the present study which includes other deformation mechanisms such as the growth of joints and fracture of the intact rock is necessary.

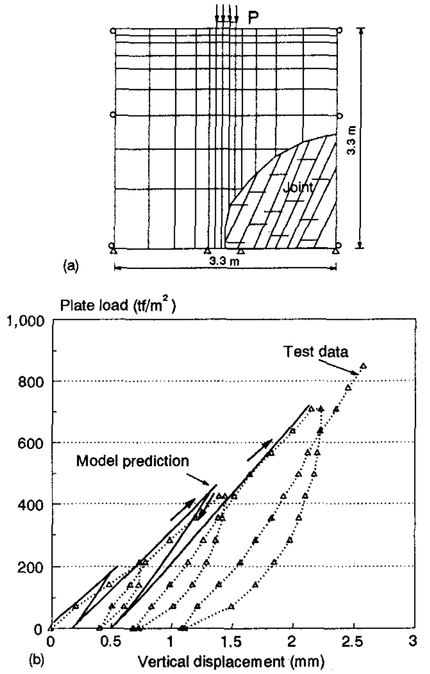

Fig.3 (a) FEM mesh; (b) Vertical load density vs vertical displacement curves at the plate center

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