APPLICATION OF UBIQUITOUS JOINT MODEL IN NUMERICAL MODELING OF HILLTOP MINES IN JAPAN

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Abstract Numerical modeling of three cases (Fuka Mine，Okayama；Shouda Mine，Okayama；Tokiwa Mine，Fukushima) of mining in Japan using FLAC (fast Lagrangian analysis of continua) is introduced to evaluate the stability of hilltop excavation. Ubiquitous joint model is adopted to account for the presence of weak planes，such as weathering joints，bedding planes，in FLAC Mohr-Coulomb model. By studying the distribution of stress，displacement and safety factor，the stability of excavation can be evaluated and new suggestions based on the numerical modeling process can be presented. Further consideration and methodology of the numerical modeling method are also discussed.

Key words mining engineering，hilltop mine，FLAC，ubiquitous joint model，numerical analysis

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1 INTRODUCTION

In order to carry out prediction calculation of mechanical behavior of rock mass containing discontinuities induced by artificial disturbance such as mining，a lot of numerical methods have been developed. As stated by Uno et al (2002)[1]，the methods can be classified roughly into three categories. The first one is to model the rock mass which contains many unspecific discontinuities by replacing it with an equivalent continuum. The second one is to model all of the discontinuities of rock mass，in which specific joints exist distinctly. The third one is to analyze formation of shear band as the result of successive development of micro-fractures and accumulation of those，which depends on heterogeneity of rock mass. These numerical methods have been rapidly developed since the decade of 1960 when FEM analyses were introduced into rock engineering and computer came into wide use.

In the case studies reported here，the numerical modeling adopted by the authors corresponds to the first category，that is，the rock mass contains ubiquitous joints along a specified direction，and numerical calculations for all of the three cases were carried out by using the code FLAC (fast Lagrangian analysis of continua). FLAC is an improved explicit finite difference method that was originally developed by Cundall & Board (1988)[2]. It has been improved and established by the employees of ITASCA Consulting Group，Inc.，and it is commercially provided over the

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world as a powerful microcomputer program for modeling soil，rock and structural behavior.

The stability evaluation was carried out for underground caverns at several stages of geometrical conditions in underground mining progress，for each of three limestone mines，taking strata boundaries and original rock stress into consideration. The original horizontal stresses have been actually measured along a vertical drilling hole by hydraulic fracturing technique developed by Dowa Engineering Co. Ltd..

2　UBIQUITOUS JOINT MODEL

Ubiquitous joint model is adopted here to account for the presence of weak planes，such as weathering joints，bedding planes，in FLAC Mohr-Coulomb model. Yielding may occur either in the solid or along the weak planes，depending on the stress state，the orientation of the weak planes and the material properties of the solid and weak planes[2]. Fig.1 illustrates the weak plane existing in a Mohr-Coulomb model and the global (x-y) and local (x'-y') coordinate frames.

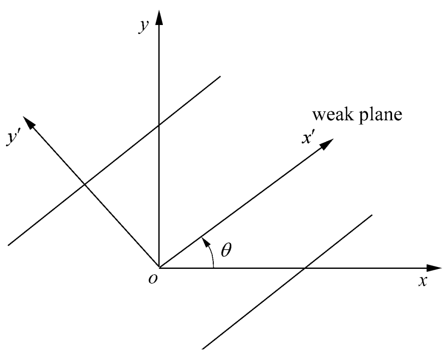

Fig.1　A weak plane oriented at an angle θ to the global reference frame

These global stresses are resolved into local components using the expressions：

$$\left.\begin{aligned}\sigma'_{11} &= \sigma_{11}\cos^2\theta + 2\sigma_{12}\sin\theta\cos\theta + \sigma_{22}\sin^2\theta \\ \sigma'_{22} &= \sigma_{11}\sin^2\theta - 2\sigma_{12}\sin\theta\cos\theta + \sigma_{22}\cos^2\theta \\ \sigma'_{33} &= \sigma_{33} \\ \sigma'_{12} &= -(\sigma_{11}-\sigma_{12})\sin\theta\cos\theta + \sigma_{12}(\cos^2\theta - \sin^2\theta)\end{aligned}\right\} \quad (1)$$

where θ is the joint angle (measured counterclockwise from the x-global axis). The local failure envelope is defined as follows：

$$\left.\begin{aligned}f^{\mathrm{s}} &= -\tau - \sigma'_{22}\tan\phi_{\mathrm{j}} + c_{\mathrm{j}} \\ f^{\mathrm{t}} &= \sigma^{\mathrm{t}}_{\mathrm{j}} - \sigma'_{22}\end{aligned}\right\} \quad (2)$$

where ϕ_{j}，c_{j} and $\sigma^{\mathrm{t}}_{\mathrm{j}}$ are the friction angle，cohesion and tensile strength of the weak plane，respectively，and $\tau = |\sigma'_{12}|$. If the local stresses violate the weak plane composite yield criterion，corrections must be applied to the components σ_{ij} to give the new stress state. Here，a function $h(\sigma'_{12},\ \tau) = 0$ is used，which may be represented by the diagonal between the representation of $f^{\mathrm{s}} = 0$ and $f^{\mathrm{t}} = 0$ in the $(\sigma'_{12},\ \tau)$ plane (see Fig.2). This function has the form：

$$h = \tau - \tau^{\mathrm{p}}_{\mathrm{j}} - \alpha^{\mathrm{p}}_{\mathrm{j}}(\sigma'_{22} - \sigma^{\mathrm{t}}_{\mathrm{j}}) \quad (3)$$

where $\tau^{\mathrm{p}}_{\mathrm{j}}$ and $\alpha^{\mathrm{p}}_{\mathrm{j}}$ are constants defined as

$$\left.\begin{aligned}\tau^{\mathrm{p}}_{\mathrm{j}} &= c_{\mathrm{j}} - \tan\phi_{\mathrm{j}}\sigma^{\mathrm{t}}_{\mathrm{j}} \\ \alpha^{\mathrm{p}}_{\mathrm{j}} &= \sqrt{1+\tan\phi^2_{\mathrm{j}}} - \tan\phi_{\mathrm{j}}\end{aligned}\right\} \quad (4)$$

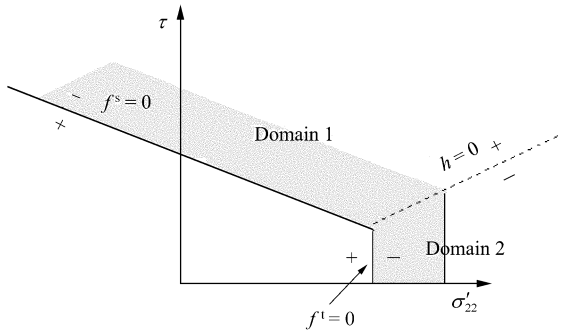

Fig.2　Domains used in the definition of the weak plane flow rule in ubiquitous joint model

The stress state violating the local failure criterion is represented by a point in the $(\sigma'_{22},\ \tau)$ plane located either in domain 1 or 2，corresponding to positive or negative domain of h = 0，respectively. If in domain 1，shear failure takes place on the weak plane，while in domain 2 weak plane，tensile failure is declared. New stresses are evaluated by adding relevant plastic corrections to σ_{ij}.

The numerical modeling produces insights into the ubiquitous joint system under practical geometries and given boundary conditions.

3　CASE MODELING

Three cases of numerical modeling in different locations in Japan are studied.

3.1 Shouda Mine in Okayama Prefecture

Shouda Mine lies in Niimi City，Okayama prefecture with abundant limestone of good quality. A bird′s eye view of the mine is shown in Fig.3.

Fig.3　Shouda Mine with abundant limestone

The mine consists of three different kinds of rocks：crystalline limestone，hornfels and tonalite，and a fault zone at the direction of N42°W84°N is considered. Distribution of the three kinds of rocks and their properties are shown，respectively，in Fig.4 and Table 1. To account for the presence of discontinuities and heterogeneities in rock mass，the laboratory-measured properties should not be used directly in the modeling. Bieniawski (1978)[2] developed an empirical relation for the modulus of deformation，based upon field test results at sites throughout the world. For rocks with a rating higher than 55，the test data can be approximately fit to

$$E_{\mathrm{m}} = 2RMR - 100 \tag{5}$$

The unit of E_{m} is GPa. For the material properties of the joints，their cohesion and tensile strength are taken as half of the surrounding rocks and the internal friction angle as 20°，since most jointed rocks have

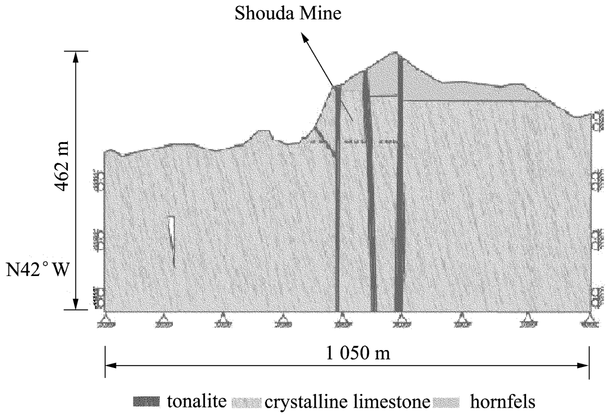

Fig.4　Geometry model of Shouda Mine

friction angle higher than 20°[3].

The excavation of Shouda Mine starts from the level 285 m and reaches level of 382.5 m with intervals of 3 m each step，which amounts to 26 steps. The boundary of the final excavated stage is shown in Fig.5，where the void parts mean final caverns excavated.

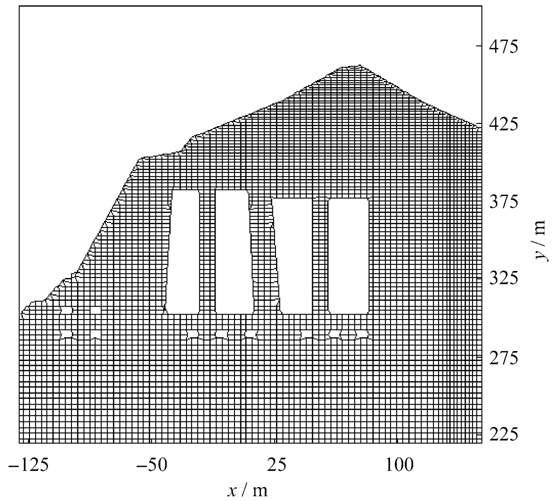

Fig.5　Grid plot of the final stage of Shouda Mine

Since FLAC is a two-dimensional explicit finite difference program，a plane strain condition assumption was made provided that the geometry of excavation

Table 1　Material properties for the lithologic units in numerical modeling of Shouda Mine

Media	Density / kN • m^{-3}	Young′s modulus/GPa	Poisson′s ratio	Cohesion/MPa	Internal friction angle /(°)	Tensile strength /MPa
Ore (crystalline limestone)	26.87	16.1	0.28	6.3	31.1	1.5
Hornfels	28.34	41.2	0.27	19.7	27.5	6.1
Tonalite	25.22	39.8	0.23	30.0	30.4	7.9
Joints				3.1	20.0	0.8

plane and the loading conditions are uniform over a comparatively long distance in the perpendicular direction.

Two models with different numbers of elements, 90 000 and 37 500 elements, were run on trial. It has been found out that these two models provided nearly the same result about the distribution of initial stress. Thus the fewer elements model was selected in the simulation.

The boundary condition is established with x direction fixed at both sides and x, y direction both fixed at the bottom as shown in Fig.4.

The initial vertical stress is assigned linearly according to the mass-density of the materials. As for the estimation of in-situ horizontal stress, the data obtained by hydraulic fracturing method are assigned to the numerical model from the depth of 158 to 258 m (Fig.6). The hydraulic fracturing method has the advantage over other stress measuring methods in that it can be used at considerably greater depths from a point of access (Y. Mizuta, 1996)[4]. The data shown in Fig.6 are adopted in the numerical modeling to improve the accuracy.

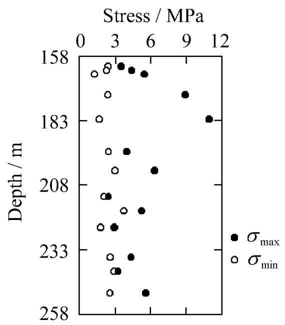

Fig.6 Values of horizontal principal stresses

After studying the principal stress and safety factor distribution in each step during the simulation, a final elevation of 370.5 m can be reached stably instead of 380 m preplanned. Note that a failure mechanism is indicated only when there is a contiguous line of active zones that joins two surfaces, which does not exist in further study of plastic indicator plots for Shouda Mine.

The safety factor of weak plane by shear failure is calculated as follows:

$$F_s = \frac{C_j + |\sigma| \tan\phi_j}{|\tau|} \tag{6}$$

where C_j and ϕ_j are the cohesion and angle of internal friction of the weak plane, while the safety factor of weak plane by tension failure is calculated as follows:

$$F_s = \frac{S_j^t}{|\sigma|} \tag{7}$$

where S_j^t is the tensile strength of the weak plane.

A plot of safety factor contour at elevation of 334.5 m is shown in Fig.7, which is the stage that yielding starts along the joints.

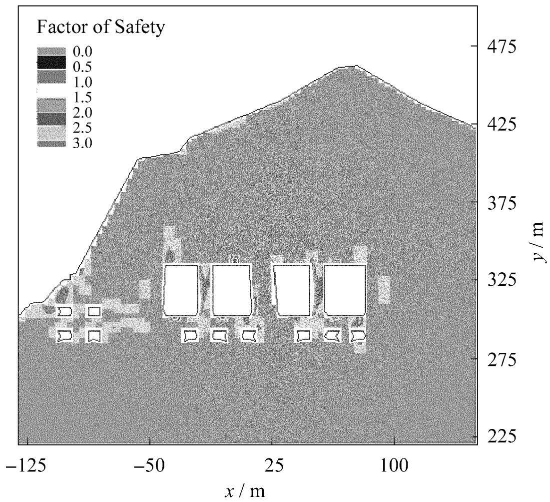

Fig.7 Safety factor contour at elevation of 334.5 m

3.2 Tokiwa Mine in Fukushima Prefecture

Tokiwa Mine lies in Tokiwa Town, Fukushima Prefecture. An ichnography view of the mine is shown in Fig.8. The mine consists of crystalline limestone surrounded by granite, whose material properties used in numerical modeling are shown in Table 2. Since the plane strain assumption of the modeling assumes the ore pillar to be elongated rectangular one, the abatement of material properties of the ore pillar is necessary and it is decided by the area ratio of the ore pillar and caverns.

The prospector plans to take 20 steps to excavate all crystalline limestone from elevation of 360 m to elevation of 465 m. The finite difference grid for Tokiwa Mine is illustrated in Fig.9, where the geological boundary shows the crystalline limestone surrounded by granite.

Table 2　Material properties for the lithologic units in numerical modeling of Tokiwa Mine

Media	Density / kN • m^{-3}	Young′s modulus / GPa	Poisson′s ratio	Cohesion/MPa	Internal friction angle / (°)	Tensile strength / MPa
Ore (crystalline limestone)	26.95	33.0	0.23	6.0	30.9	1.5
Granite	26.93	38.9	0.30	27.5	33.2	5.7
Ore pillar	26.95	10.8	0.23	1.9	30.9	0.5
Joints				3.0	20.0	0.8

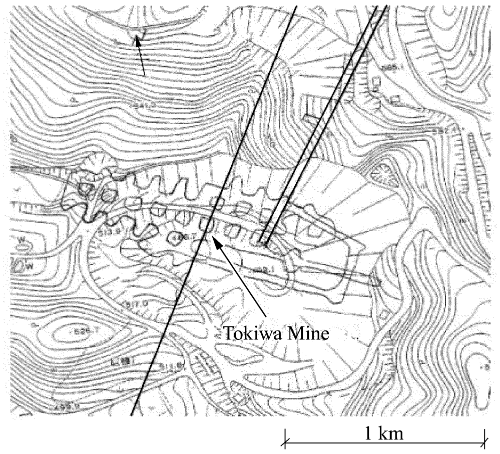

Fig.8　Topographic map of Tokiwa Mine

Hydraulic fracturing technique is applied here to determine the in-situ horizontal principal stresses from the third layer of the excavation at the elevation of 435 m to the bottom at the elevation of 352 m (see Fig.9).

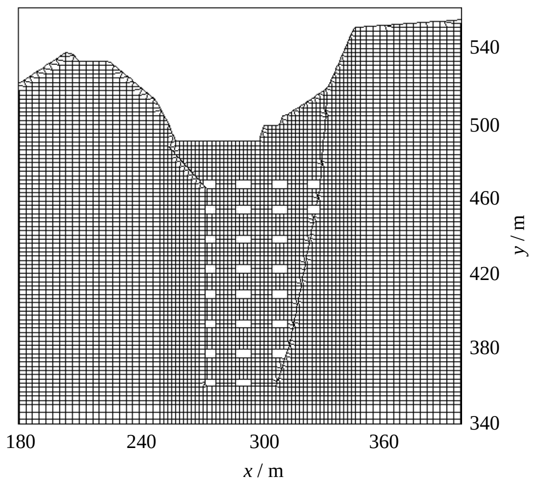

Fig.9　Finite difference grid of Tokiwa Mine

The numerical analysis shows that the mining is safe until the final two stages in which tension yielding occurs at some stress concentration part，and more attention should be paid to the top right part.

3.3　Fuka Mine in Okayama Prefecture

Fuka Mine in Okayama Prefecture consists of white marble exploited by room and pillar method. The north bed consists of 5 stages and each stage has been assigned different strength property in the numerical modeling due to the scale effect.

A weak plane at the direction of N2°W65°N is considered and both Mohr-Coulomb and Ubiquitous-Joint model are applied to evaluate the stability of excavation.

Fig.10 shows the major principal stress contour after five stages excavation. After studying the principal stress and safety factor，the result shows that a wider low safety factor area between 1.75 and 2 exists in ubiquitous joint model than in Mohr-Coulomb model. The induced stress during mining process is much lower than the rock strength or the joint strength and the final mining stage remains stable.

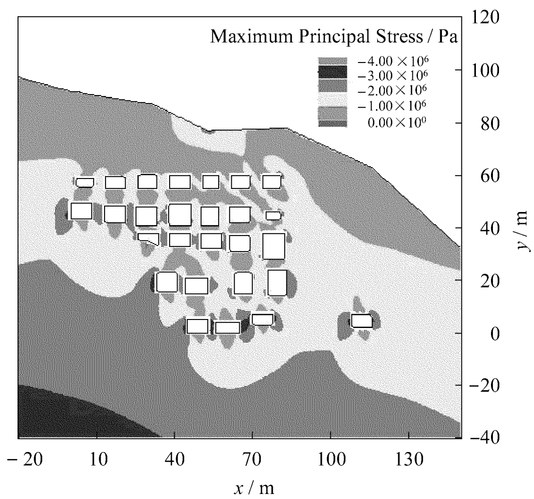

Fig.10　The major principal stress contour of Fuka Mine

4　FURTHER DISCUSSIONS

As introduced above，the explicit finite difference formulation of the code makes FLAC ideally suited for modeling geomechanical problems that consist of several stages，such as sequential excavation，backfilling and loading.

The formulation can accommodate large displacements and strains and non-linear material behavior，even if yield or failure occurs over a large area or total collapse occurs. For this reason a harmonized excavation method can be considered to improve the stress distribution during the excavation by alteration of the original excavation sequence，which in Shouda Mine，Okayama is shown in Figure 11.

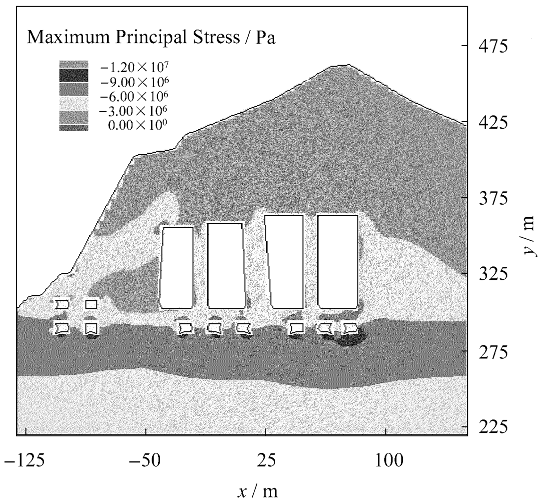

Fig.11 The major principal stress contour of Shouda Mine

It can be seen from the drawing that by excavating the right side earlier there is no tension occurred during the excavation，therefore tensile failure is avoided.

5 CONCLUSIONS

(1) A simple，generic numerical model is always more effective，especially when the harmonized excavation method is considered，and provides more conclusive results than trying to model the practical geometry exactly.

(2) The relative differences in material properties between different lithologies are more important than the exact values themselves，which means that it is the differences between different materials affect the stress distribution the most and so alter the results.

(3) The ubiquitous joint model is appropriate for application on hillside mines with weak plane and provides reasonable results.

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