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Numerical simulation of an excavation disturbed zone around a tunnel in brittle rock

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The micromechanics-based damage model proposed by Golshani et al. (2005) is extended so that time-dependent behavior of brittle material can be taken into account, with special attention to the numerical analysis of an excavation damage zone (EDZ) around a tunnel, which is a major concern in assessing the safety of underground repositories. The present model is capable of reproducing the three characteristic stages of creep behavior (i.e., primary, secondary and tertiary creep) commonly observed in laboratory creep tests. Using the present model, sub-critical microcrack growth parameters (i.e. n and A) can be determined for Inada granite by fitting the numerical results of elapse time to failure versus the creep stress ratio curve with the experimental data under both dry and wet conditions. It is found that moisture has a significant influence on the parameter A rather than the parameter n. Use of the extended model makes it possible to analyze not only the extension of microcrack length, but also the development of the excavation damage zone (EDZ) around tunnels as a function of time. The disturbed zones mainly develop in the sidewalls of the tunnel in the case that the vertical stress is larger than the horizontal stress.

Keywords: Time-dependent behavior, Brittle material, Creep failure, Numerical Simulation

1. Introduction

The use of underground facilities such as waste reservoirs and power station caverns is increasing. However, excavation of such spaces results in a change in stress distribution; the changes alter the mechanical properties of rock mass such as strength, deformability and the hydraulic conductivities, and hence influence contaminant pathways.

Depending on mechanical host rock properties, the stress redistribution may lead to the development of a plastic zone around the space, termed as the excavation disturbed zone (EDZ). The hydro-mechanical behavior of EDZ around underground repositories is a major concern in assessing the safety of these geotechnical barriers. For example, EDZ, which is commonly associated with increased permeability, constitutes a potential risk to the effectiveness of isolating high-level nuclear waste from the environment.

Crystalline rocks such as granite fail as a result of initiation and growth of microcracks (e.g. Kranz 1979). When a tunnel is excavated in a crystalline rock at great depth, say 1,000m, microcracking may occur around the excavation by two mechanisms; (i) stress-induced microcracking (short term) and (ii) time-dependent microcracking (long term), both of which are no doubt related to the formation of EDZ around the tunnel. Stress-induced microcracking occurs when the stress in

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the vicinity of a microcrack is large enough that the stress intensity factor K_I surpasses the fracture toughness K_{IC} . On the other hand, time-dependent microcracking occurs under a constant loading. Importantly, time-dependent microcracking, called sub-critical crack growth, can take place even if the stress intensity factor K_I at the microcrack tip is below the fracture toughness K_{IC} .

In the past, EDZ was studied by various means, particularly in the field. For example, Meglis et al. (2001) measured ultrasonic wave velocities within a 1m deep shell around one quadrant of the Mine-By tunnel at Canada's Underground Research Laboratory during excavation. Their measurements suggested that damage growth is most concentrated in the material immediately adjacent to the tunnel, extending more deeply into the rock in the side walls. Martino and Chandler (2004) studied EDZ at the Underground Research Laboratory (URL) in the Lac du Bonnet granite batholith in southern Manitoba, Canada. They measured the properties of the damage zone surrounding the excavation, and found that the *in situ* stress, the tunnel shape and its orientation relative to the maximum stress, excavation method, changes in pore pressure, and the creation of nearby excavations all affect the development of EDZ.

Unfortunately, however, it must be realized that such experimental approaches, in spite of their great importance, cannot be effectively used to predict future behavior of EDZ, which might result in tunnels collapsing. In order to overcome this difficulty, some numerical models have been developed by numerous authors. Hommand-Etienne et al. (1998), for example, proposed a model for numerically analyzing the damage zone around an underground opening excavated in brittle rocks, and found that the highly damaged zones are formed in association with the zones of highly compressive stress. Fakhimi et al, (2002) simulated a biaxial test on a rectangular prism of the Berea sandstone containing a circular opening, and observed that the damage zone started to develop from the side walls of the opening where the compressive stresses were large. Chen et al. (2004) studied the numerically time-dependent behavior of rock around underground excavations in the Shanxai Yellow River Diversion Project. They concluded that the damage zone in the vicinity of side walls is larger than in that of the roof and floor. They successfully investigated how deformation accumulates around a tunnel over time. However, they did not discuss how microcracks grow as a function of time around the excavation. In all honesty, there is very little knowledge on the actual time-dependent development of EDZ arising from stress-induced and time-dependent microcracking in the surrounding rock environment. Considering underground storage of hazardous waste, sufficient knowledge on this issue is crucial because contaminants may migrate through a network of thus induced microcracks.

In this paper, the micromechanics-based continuum damage model, which was originally proposed by Golshani et al (2005) for the analysis of stress-induced (short term) microcracking in brittle rocks, is first extended so that time-dependent microcracking can also be incorporated in the numerical analyses of time-dependent development of EDZ.　Subsequently, the proposed model is applied to the creep tests on Inada granite to assess whether creep behaviors are successfully simulated, and to confirm that the parameters for describing sub-critical microcrack growth can be experimentally determined. Finally, the developed model is applied to simulate the time-dependent development of EDZ around a circular tunnel in terms of the model parameters for Inada granite.

2. Time-dependent behaviors around a circular tunnel with special interest in development of EDZ

A rectangular region $(500mm \times 500mm)$ with a circular tunnel of 160 mm in diameter was analyzed by means of FEM in order to show the time-dependent development of the Excavation Disturbed Zone (EDZ).

The number of finite element meshes and nodes are 290 and 168 are shown in Fig. 1. All the parameters in the governing equations are selected as those for dry Inada granite (i.e., $n = 50$ and $A = 2.0 \times 10^{-23}$). The rectangular

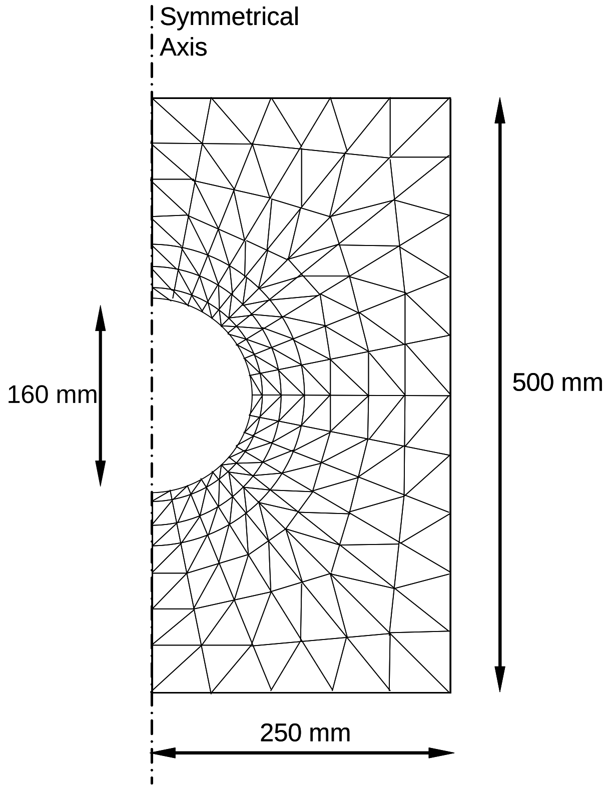

Fig. 2 Finite element mesh

region was subjected, on a tentative basis, to the far field stresses of $\sigma_{11} = 10$ MPa and $\sigma_{22} = 70$ MPa under planned stress conditions.

Figs 2 (a) to (h) show the time-dependent development of EDZ around the circular tunnel by illustrating microcrack length over eight different time steps. The following observations are worth noting:

1) Disturbed zones are mainly developed in the vicinity of the sidewalls of the tunnel in the case that the vertical stress σ_{22} is larger than the horizontal stress σ_{11}. Fakhimi et al. (2001) obtained a similar result in the analysis of stress-induced damage zones around a circular tunnel. Meglis et al. (2001) also reported a similar trend in a real tunnel by constructing a two-dimensional tomographic image of wave velocity.
2) Microcracks continue to grow all the time, particularly in the vicinity immediately adjacent to the tunnel wall, until failure finally takes place. Here, "failure" means that microcracks tend to grow without a limit so that no convergence is attained in the iterative calculation.

3. Concluding remarks

The micromechanics-based damage model proposed by Golshani et al. (2005) was extended so that time-dependent behaviors of brittle material could be taken into account, with special interest in the numerical analysis of the Excavation Damage Zone (EDZ) around a tunnel. Using Inada granite, we carried out creep tests in a triaxial vessel under a confining pressure with the following two objectives; i.e. to see how the damage growth model can predict the time-dependent behaviors of brittle materials like Inada granite, and to determine the model parameters involved in the model. The conclusions are summarized, as follows:

1) The sub-critical microcrack growth parameters (i.e. *n* and *A*) can be determined for Inada granite by fitting the numerical results of elapsed time to failure versus creep stress ratio curve with the experimental data under both dry and wet conditions. The results agree with the fact that the presence of moisture reduces creep failure times. It is found that the moisture condition significantly influences the parameter A rather than the parameter *n*.
2) Use of the extended model makes it possible to analyze not only the extension of microcrack length, but also the development of EDZ around tunnels as a function of time. The disturbed zones are mainly developed in the sidewalls of the tunnel in the case that the vertical stress σ_{22} is larger than the horizontal stress σ_{11}. Microcracks continue to grow continuously, particularly in the vicinity immediately adjacent to the tunnel walls, until failure takes place.

4. References

1) Chen, W. Z., Zhu, W. S. and Shao, J.F. (2004): Damage coupled time-dependent model of a jointed rock mass and application to large underground cavern excavation, *Int. J. Rock Mech. Min. Sci.*, 41, pp. 669-677

2) Fakhimi, A., carvalho, F., Ishida and T., Labuz, J. F. (2002): Simulation of failure around a circular opening in rock, *Int. J. Rock Mech. Min. Sci.*, 39, pp. 507-515

3) Golshani, A., Okui, Yoshiaki, Oda, Masanobu and Takemura, Takato (2005): A micromechanical model for brittle failure of rock and its relation to crack growth observed in triaxial comopression tests of granite, *Mechanics of Materials* (under publishing).

4) Hommand-Etienne, F., Hoxha, D. and Shao, J.F. (1998): A continuum damage constitutive law for brittle rocks, *Computer and Geotechnics*, 22 (2), pp. 135-151.

5) Kranz, R. L. (1979): Crack growth and development during creep of Barre granite, *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, 16, pp. 23-35.

. 1413-1426.

7) Meglis, L. L., Chow, T. and Young, R. P. (2001): Assessing microcrack damage around a tunnel at the underground research laboratory using ultrasonic velocity tomography, 38th Rock Mechanics Symposium, DC Rocks, Washington D.C., U.S.A., July 7-10, pp. 919-925.

8) Meglis, L. L., Chow, T. and Young, R. P. (2001): Assessing microcrack damage around a tunnel at the underground research laboratory using ultrasonic velocity tomography, 38th Rock Mechanics Symposium, DC Rocks, Washington D.C., U.S.A., July 7-10, pp. 919-925.

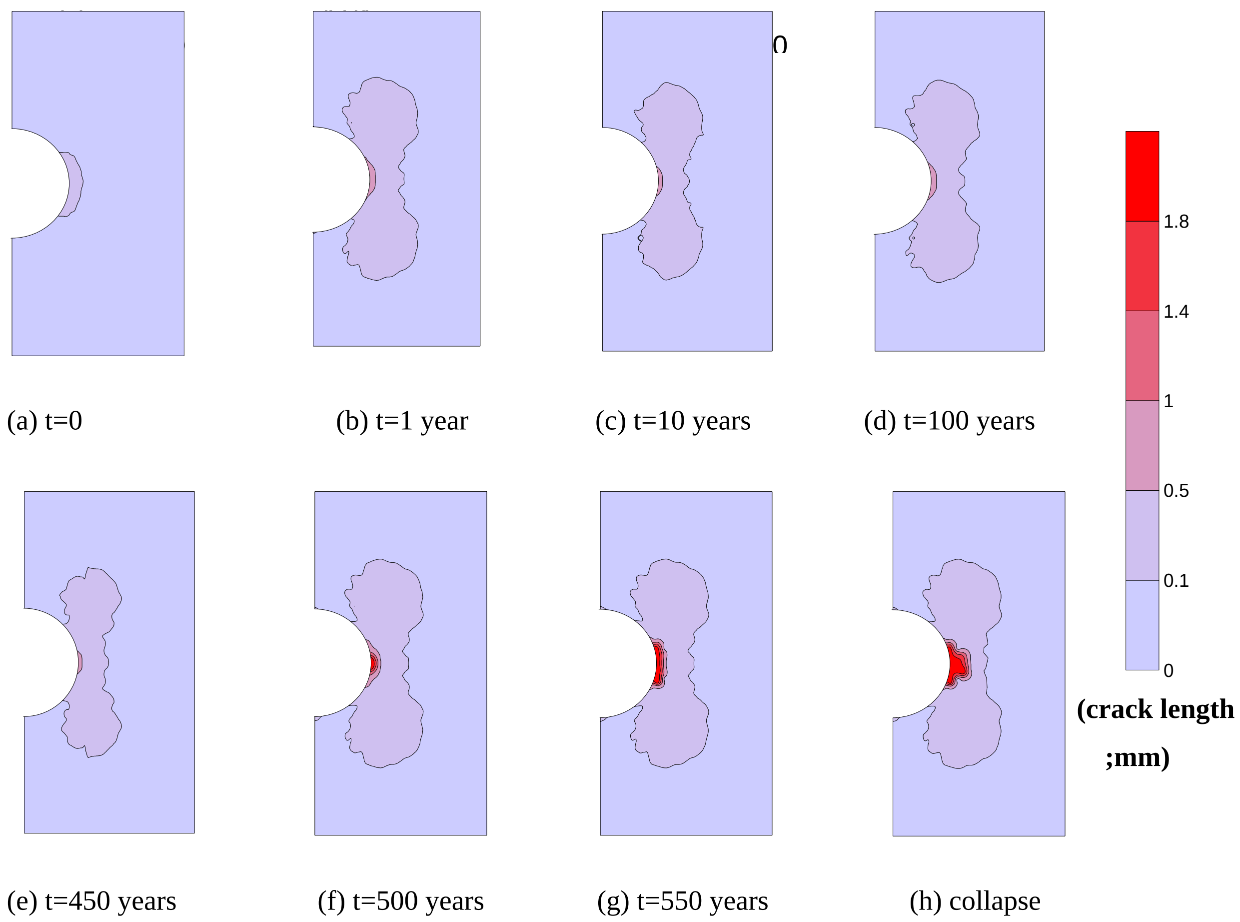

Fig. 2 Progressive development of excavation disturbed zone (EDZ)