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A Coupled Logarithmic Damage and Plastic Model to Numerical Simulation of Rocks Failure Mechanism

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ABSTRACT: The rock materials surrounding the underground excavations typically demonstrate nonlinear mechanical response under high stress states. The dominant causes of irreversible behavior are plastic flow and damage process. The plastic flow is controlled by the presence of local shear stresses which cause dislocation to some preferential elements due to existing defects. During this process, the net number of bonds remains practically unchanged. The main cause of irreversible changes in quasi-brittle materials such as rock is the damage process occurring within the material.

In this paper, a coupled logarithmic damage and plastic model was used to simulate irreversible deformations and stiffness degradation of rock materials under loading. In this model, damage evolution and plastic flow rules were formulated in the framework of irreversible thermodynamics principles. To take into account the stiffness degradation and softening in post-peak region, logarithmic damage variable was implemented. Also, a plastic model with Drucker-Pruger yield function was used to model plastic strains. Then, an algorithm was proposed to calculate the numerical steps based on the proposed coupled plastic and damage constitutive model. The developed model was programmed in VC^{++} environment. Then, it was used as a separate and new constitutive model in DEM environment code (UDEC). Finally, the experimental oolitic limestone rock behavior was simulated based on the developed model. The irreversible strains, softening and stiffness degradation were reproduced in the numerical results. Furthermore, the confinement pressure dependency of rock behavior was simulated in according to experimental observations.

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1- Introduction

Due to increasing human needs to rock excavations, the analysis of stress and strain surrounding rock mass and stability evaluation of these excavations are essential. Rocks surrounding excavations under induced stresses have non elastic, non-linear mechanical behavior within the elastic stiffness degradation and unrecoverable plastic strains. In this regard, the inelasticity associated with most of the brittle solids, during external loadings, is the result of two kinds of irreversible changes: micro-cracking (damage process) and inelastic flow. These two kinds of irreversible phenomena, which may be assumed to occur in coupled or uncoupled forms, lead to the degradation of elastic property of the material and the development of moderate to large permanent deformations at the macro-scale level, respectively. The strain softening and elastic stiffness degradation on macro-scale are due to the damage process including nucleation, growth and propagation of micro-cracks on micro-scale of rocks, while the plastic strains are due to the plastic flow in undamaged parts and mismatch of micro-cracks faces under unloading. The most of experimental observations in the past few years have shown that the use of plasticity theories is appropriate to model the deformation component caused by inelastic flow, whereas the use of damage mechanics theories to model the nucleation and propagation of micro-cracks is clearly evident in the literature. Therefore, these two mechanisms –microcracking and inelastic flow– are to be addressed properly through the use of combined damage and plasticity theories, while developing constitutive models for brittle solids. Many researchers (Dragon and Mrotz [1], Jefferson [2], Salari et al. [3], Simo and Ju [4], Voyiadjis et al. [5], Yazdani and Karnawat [6], Shao et al. [7], Chiarellia et al. [8] and Kamal et al. [9]) have adopted combined damage-plasticity approach in the constitutive modeling of brittle solids such as concrete and rocks.

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2- Methodology

By using of logarithmic damage model proposed by Carol et al. [10], the elastic stiffness degradation and strain softening on post-peak region can be considered simultaneously. The damage law was formulated in terms of the so-called logarithmic damage variable and its associated thermodynamic force, which is physically meaningful and corresponds to the density of energy stored in the deformation of the damaged material. In this regard, to simulate of rock behavior, the logarithmic damage model has been implemented in the laboratory and field scales data [11, 12]. In this paper, the logarithmic damage model was coupled with plasticity theory. Therefore, stiffness degradation and irreversible strain can be taken into account simultaneously especially on post-peak region of rock behavior. In this investigation, to take into account the elastic stiffness degradation, strain softening and irreversible strains at the same time especially on post-peak region, the coupled elastoplastic-logarithmic damage model has been proposed. The proposed coupled elastoplastic-logarithmic damage model has been formulated in the framework of continuum thermodynamics by using of the internal variables. In this regard, a Drucker– Prager yield function has been applied for plastic loading of the material and a non-associated flow rule has been employed to control inelastic dilatancy.

Although, the plastic models have usually been implemented in geomechanics numerical software in order to non-linear analysis of rock excavations, to take into account the damage process and plastic flow simultaneously, the combined implementation of damage mechanics and plasticity is essential. In this study, the proposed coupled elastoplastic-logarithmic damage model has been programmed and implemented into a commercial software to simulate the oolithic limestone rock, finally, a number of load histories are examined to investigate the performance of the model.

3- Results and Discussion

In this investigation, to simulate the behavior of the rock, the coupled elastoplastic-logarithmic damage model programmed and implemented in a commercial software environment. In order to numerical simulation, the behavior of an oolitic limestone with Uniaxial compressive strength (UCS) equal to 68 MPa reported by Brady & Brown [13] has been selected as a basis of modeling. The complete stress-strain curve of oolitic limestone simulated with the coupled elastoplastic-logarithmic damage model under UCS test conditions has been illustrated in Figure 1.

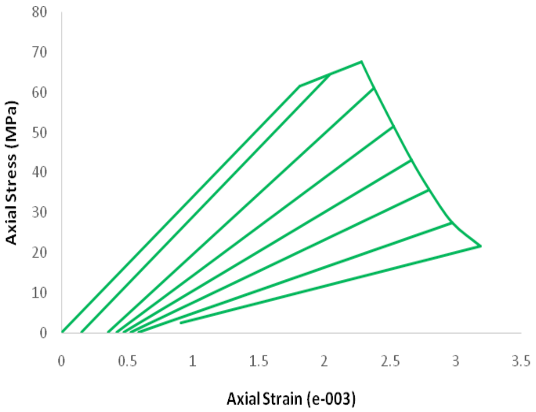

Figure 1. The complete stress-strain curve of oolitic limestone simulated with the coupled elastoplastic-logarithmic damage model

According to Figure 1, if the developed coupled elastoplastic-logarithmic damage model has been applied, in addition to the stiffness degradation and softening behavior, the irreversible strains due to the plastic flow will simultaneously occur.

According to the simulation results, three distinctive regions can be observed. In the first phase OA, the material behavior remains linear elastic. Hence neither plastic flow nor damage evolution occur in this phase. The slopes of the axial stress–strain curves are the same as the Young modulus. As can be seen in the Figure 1, after the yield stress (point A), the behavior of oolitic limestone changes from elastic to plastic hardening immediately. The phase AB corresponds to hardening behavior before peak strength as a result of plasticity. This process continues until the maximum point (peak strength). In the third phase BC, the damage evolution law also is activated. In other words, after this point (B), in addition to softening behavior, according to the cycles of unloading and reloading, the plastic flow and stiffness degradation occur simultaneously. Finally, softening behavior, stiffness degradation and irreversible strains after peak strength because of simultaneous plastic flow and damage evolution can be seen in Figure 1.

4- Conclusions

The proposed coupled elastoplastic-logarithmic damage model has been formulated within the framework of the principles and laws of irreversible thermodynamics. In the developed model, it is assumed that no damage evolution and stiffness degradation will occur before the maximum strength (pre-peak). In other words, the strain energy caused by the loading is stored in these type of materials as much as possible. Finally, due to sudden release of this energy, rock is immediately fractured. In addition to the small number of input parameters, the simplicity in the determination of them is another characteristic of the proposed model. In this regard, all parameters used in the proposed model are calculated by standard experiments.

The numerical simulation based on coupled elastoplastic-logarithmic damage model in experimental scale, shows both of the simulated behavior of rock sample such as irreversible strain resulting from plastic flow and stiffness degradation due to damage evolution. Using the logarithmic variable damage, the thermodynamic force associated with damage gets a certain physical meaning. In other words, to simulate the softening behavior of rocks after the maximum strength (post peak), the definition of model and yield damage function based on the thermodynamic force associated with logarithmic damage is necessary.

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