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A dynamic material model for rock materials under conditions of high confining pressures and high strain rates

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ABSTRACT

A dynamic material model is presented to characterize the mechanical behavior of rock materials under high confining pressures and high strain rates. The yield surface is defined based on the extended Drucker–Prager strength criterion and the Johnson–Cook material model. Two internal damage variables are introduced to represent, respectively, the tensile and compressive damage of rock materials. The proposed dynamic material model of rocks is incorporated into the nonlinear dynamic analysis code LS-DYNA through a user-defined material interface. Its reliability and accuracy are verified by the simulation of various basic experiments with different loading conditions. The present rock model is also applied to simulate the penetration of granite target plate by hard projectile. The typical damage and failure on the granite targets predicated by the proposed dynamic material model of rocks agree well with the experimental results. It demonstrates that the proposed model is capable of capturing the failure of rock materials.

1. Introduction

Rock is a commonly used material in civil engineering construction. Many civil structures are built with rocks, so it is necessary to study the mechanical behavior of rocks. The behavior of rock under different conditions can be complicated. Various models have been used for the constitutive modeling of rock materials, including the elastic, von-Mises, Mohr–Coulomb, Drucker–Prager and Hoek–Brown models, etc. In the field of numerical modeling, constitutive models for rock play an important role in rock mechanics and rock engineering [1]. Rock mechanics has been developed for over half a century, and the influence of static stress is considered in the traditional criterion of rock strength. Only a few researchers have investigated the effects of high confining pressures and high strain rates on rock strength. The compressive strength of brittle rock is strengthened with the increase of lateral confining pressure [2]. The strain softening phenomenon is most obvious in an unconfined condition, while it is weakened by the increase of confining pressures. The transition from brittle to ductile is observed in some rocks [3]. A number of elastoplastic constitutive models have been developed to describe the mechanical behavior of rock-like materials under confining pressures [2,4–9].

In practical engineering, the failure of rock is related to not only the stress state that is applied to rock, but also the level of loading rates. The dynamic mechanical property of rock in these conditions is very different from that exhibited in static conditions. Previous research indicates that the mechanical behavior of rocks is obviously affected by strain-rate; that is, the rock strength increases with strain rate. Zhang and Zhao [10] described this development in detail using dynamic testing techniques to investigate the dynamic mechanical behavior of rock material. A few investigators have found that the DIF (dynamic increase factor) of rock increases with strain rates (Klepaczko [11], Lajtai et al. [12], Cho et al. [13], Qi et al. [14], Cadoni [15], Liang et al. [16], Liu et al. [17]). According to the experimental results of Liu et al. [17], in the condition of a uniform confining pressure, the dynamic compressive strength of amphibolites depends on the strain rate, and the strain rate effect can be expressed by linear approximations. The relationship between the dynamic increase factor and the logarithm of the strain rate is approximately linear. According to the rate-dependent constitutive equation of rock, Rouabi et al. [18] applied the rate-dependent plasticity theory to simulate the behavior of quasi-brittle materials under compression loading, such as fragmentation in blasting. Saksala [19,20] presented a damage-viscoplastic model for the numerical simulation of brittle fracture in heterogeneous rocks under low-velocity impact loading. The process of flow and fracture of rock is very complex due to the combined influences of pressure, temperature and strain-rate at great depths. High confining pressure and temperature were taken into account in the proposed model for lithospheric strength [5]. Wei

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and Zang [21] presented an empirical formula for the fracture strength of some typical rocks in the lithosphere, and included the combined influence of the confining pressure, the size of the rock samples, the temperature and the strain rate in their formula. However, they pointed out that the strain rate in the experiment was in the range of 10^{-7} s^{-1} to 10^{-2} s^{-1}. Whether the formula can be extrapolated to a low strain rate or a high strain rate needs further study [21].

Generally, the constitutive models applied by previous research are mostly considered to be one of the factors of confining pressure or strain rate effect. Few studies have taken into account the combined effect of both of these factors in examining the constitutive relationship of the material. The constitutive models for rocks accounting for the extreme loading conditions are limited, while the models for metals and concrete have been widely used in the same condition. The most well-known and commonly used constitutive model for metallic materials is the Johnson–Cook model [22]. The Holmquist–Johnson–Cook (HJC) model [23], Continuous Surface Cap (CSC) model [24], Karagozian and Case Concrete (KCC) model [25] and Riedel–Thoma–Hiermaier model (RHT) model [26] are widely applied to simulate concrete material [27]. The CSC, KCC and RHT models require many parameters, some of which are difficult to determine by a simple material test. The HJC model considers most of the important material parameters of concrete, including the influence of hydrostatic pressure, strain rate and compressive damage [23]. It has been widely applied in numerical simulations of the dynamic response of concrete structures, because it provides a compromise between conciseness and accuracy for practical engineering computations. However, the tensile damage of concrete and the influence of the third deviatoric stress on material strength are not involved in the HJC model.

Shi and Sun [28] pointed out that a reliable computational material model of concrete-like materials should include features such as the combined hardening of the strain rate and pressure, the different hardening coefficients for the strain rate enhancement of tensile and compressive strength, and the damage evolution. In conclusion, based on the Johnson–Cook material model and the extended Drucker–Prager strength criterion, a new rock material model accounting for the effects of high confining pressures and high strain rates is presented in this work. The temperature effect in rock is considered less significant, excepting the high temperature condition, and is not taken into account in this study. The proposed constitutive model is programmed in FORTRAN and implemented in LS-DYNA through the user subroutine UMAT. The proposed dynamic damage model is applied to simulate rock behavior under different loading conditions. Comparisons between the present numerical predictions and experimental results reported in the literatures are presented. Finally, an example for the application of the present rock material model to typical engineering problems is illustrated by the simulation of the ballistic test of ogive-nose projectile striking at granite target, in which the predicted tensile failure agrees well with the experimental results.

2. A new dynamic material model for rocks subjected to high pressure and high strain rate

To obtain a reliable prediction of rock behavior under dynamic loading, a proper constitutive model that can reflect the characteristics of rock subjected to high confining pressures and high strain rates is important. The main characteristics of the present rock model are: (1) the involvement of confining pressure nonlinear hardening, the strain rate hardening effect, and the strain softening effects resulting from the plastic deformation described by effective plastic strain and plastic volumetric strain for rock compressive strength; (2) the influence of the third deviatoric stress invariant is introduced; (3) two internal damage variables are introduced to represent the tensile and compressive damage, respectively; and (4) the non-associative plastic flow rule is used to describe the plastic deformation.

The new material model of rocks is an elastoplastic model coupled with isotropic damage, where the response is separated into hydrostatic and deviatoric contributions [29]. The Cauchy stress tensor σ_{ij} is decomposed into deviatoric and hydrostatic parts:

$$\sigma_{ij} = s_{ij} - p\delta_{ij} \tag{1}$$

where s_{ij} is the stress deviator, $p = -\sigma_{kk}/3$ is the hydrostatic stress, and δ_{ij} is the Kronecker delta.

2.1. Yield criterion

As discussed in the introduction, the Mohr–Coulomb and Hoek–Brown models are accurate for rocks, but the non-smoothness of their loading surface causes many difficulties for application in the numerical simulation of rocks under severe loading conditions. The failure surface should be dependent on the third invariant of the deviatoric part of the stress tensor. The ultimate compressive strength for a given pressure can be much greater than the ultimate tensile strength. The classic Drucker–Prager model and HJC model both assume a circle in the deviatoric plane and, therefore, no dependence on the third invariant of the deviatoric part of the stress tensor. The capacity of rock subjected to tension loading is overestimated in the above two models. The major drawback of the HJC model is that it cannot capture the brittle failure of rock and concrete.

In the framework of the Johnson–Cook material model [22], based on the extended Drucker–Prager strength criterion, the yield surface can be expressed as a function of hydrostatic pressure, strain rate and damage. The specific expression is of the form:

$$\frac{\tau}{f_c} = \left[A(1-D) + B(p^*)^N\right]\left[1 + C\ln(\dot{\varepsilon}^*)\right] \tag{2}$$

where τ is the equivalent stress, f_c is the quasi-static uniaxial compressive strength, D is the compressive damage parameter, $p^* = p/f_c$ is the normalized pressure (p is the actual pressure), and $\dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0$ is the dimensionless strain rate. Additionally A, B, N, and C denote the material parameter, where A is the normalized cohesive strength, B is the normalized pressure hardening coefficient, N is the pressure hardening exponent, and C is the strain rate coefficient.

The equivalent stress used in the extended Drucker–Prager strength criterion can be adopted for rock, in order to account for the difference of the compressive strength and tensile strength of rock and to meanwhile also make the resulting loading surface smooth. The equivalent stress τ is of the form:

$$\tau = \frac{1}{2}\sigma_{eq}\left[1 + \frac{1}{K_s} - \left(1 - \frac{1}{K_s}\right)\left(\frac{r}{\sigma_{eq}}\right)^3\right] \tag{3}$$

in which $\sigma_{eq} = \sqrt{3J_2} = \sqrt{\frac{3}{2}s_{ij}s_{ij}}$, $r^3 = \frac{9}{2}s_{ij}s_{jk}s_{kj} = \frac{27}{2}J_3$, s_{ij} is the stress deviator, and J_2 and J_3 are the 2nd and 3rd invariants of the deviatoric stress tensor. The deviatoric stress measure τ accounts for different responses under tension and compression through the parameter K_s. It varies within the range of $0.778 \le K_s \le 1.0$ to ensure the convexity of the yield surface. When $K_s = 1$, the yield surface in the deviatoric plane does not depend on the third deviatoric stress invariant, and therefore, the original Drucker–Prager model is recovered [30]. The loading surface given by Eqs. (2) and (3) is depicted in Fig. 1.

By substituting Eq. (3) into Eq. (2), the yielding surface of rocks is expressed as: