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Numerical modeling and experimentation of dynamic Brazilian disc test on Kuru granite

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ABSTRACT

A simulation method consisting of a constitutive model, originally developed for numerical modeling of percussive drilling, based on viscoplasticity and damage mechanics and a FEM based numerical technique for simulating the dynamic Brazilian disc test using the Split Hopkinson pressure bar apparatus is presented. The model incorporates the strain rate-dependency via linear viscoplastic hardening/softening laws both in tension and compression. Dynamic Brazilian disc tests were performed on Kuru granite. A linear dependency between the loading rates and the indirect tensile strength of Kuru granite discs was observed in the range from 5 to 20 m/s of impact velocity, corresponding to the sample strain rates from 6.7 to 30 s^{-1}. The experimental results were simulated under the plane stress assumption in order to determine the viscosity parameters, i.e., to find the correct values for the viscosity moduli in tension and compression with which the experimental dynamic (indirect) tensile strength and the compressive contact force levels were matched. Despite the continuum assumption of the modeling approach, the diametrical splitting failure mode of the discs was predicted with a reasonable accuracy. Finally, the plane stress assumption was validated by carrying out a genuine 3D simulation.

1. Introduction

Material behavior under dynamic loading depends on the applied loading rate such that higher loading rates – generally – result in higher peak strengths before failure. This loading rate hardening effect is particularly pronounced with brittle materials such as rocks. Therefore, a numerical model for rock should accommodate the loading rate dependency even at relatively low loading rate regimes involved, e.g., in percussive rock drilling.

The background of the present study is in numerical modeling of percussive drilling [2,3]. Therein, a viscoplastic-damage model for rock originally developed in [1] was applied for the description of rock behavior under the dynamic bit-rock interaction in percussive drilling. The model accommodates the strain-rate effects via viscoplastic softening/hardening laws for the tensile strength and the cohesion of the material. However, in those studies the values of the viscosity moduli were chosen more or less randomly, i.e., without an experimental basis. Therefore, suitable dynamic experiments are needed for a determination of the viscosity moduli in order to correctly predict the dynamic tensile and compressive strengths of rock.

In percussive drilling the typical piston impact velocity ranges from 5 to 10 m/s. This impact velocity is easily produced with the Split Hopkinson pressure bar apparatus (SHPB). Moreover, it is a suitable experimental setup due to its similarities with percussive drilling. As for the specific experiment, the dynamic Brazilian disc (BD) test for measurement of the indirect tensile strength was chosen since the direct dynamic tensile test is more challenging to perform in practice. In addition, the tensile fracture is the major failure mode involved in the bit-rock fracture mechanisms [2,3]. Finally, since the Brazilian test is a compressive test, it also provides means to calibrate, to some extent, the softening/hardening law in compression. Nevertheless, the Brazilian disc test is a uniaxial test while the rock just beneath the buttons of the drill bit is under tri-axial compression. However, the tri-axial effects, i.e., the confining pressure effect, on the dynamic uniaxial compressive strength of the rock can be taken into account by a tri-axial strength (yield) criterion, such as the Mohr–Coulomb and Hoek–Brown criteria [4].

In the experimental part of this work, quasi-static Brazilian disc tests are first conducted with a servo-hydraulic testing machine to find the static reference value for the tensile strength of Kuru granite. Then, the dynamic Brazilian disc tests using the SHPB device are performed at four different impact velocities, 5, 10, 15 and 20 m/s, in order to provide experimental data on the dynamic tensile strengths and failure modes of Kuru granite. This data is used for the

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adjustment of the viscosity moduli of the present constitutive model. For this end, this paper presents and implements a numerical model based on FEM for simulating the dynamic Brazilian disk test. The simulations are carried out under the plane stress assumption. Finally, a simulation in genuine 3D case is carried out in order to validate the plane stress assumption.

Other numerical studies, based on FEM with a continuum damage and/or plasticity models, on dynamic material properties using the Brazilian disc test are those presented, e.g., by Zhou and Hao [5] (using AUTODYN hydrocode), Dong et al. [6], and Zhu and Tang [7]. Cohesive elements theory has been used by Yu et al. [8] in a numerical study of advanced ceramics. Finally, the experimental and numerical studies by Brara et al. [9] on direct tensile test of concrete using discrete element method (DEM) and by Mahabadi et al. [10] using combined FEM/DEM approach are noticed. Especially, the latter authors obtained realistic failure patterns in their simulation of dynamic Brazilian disc test on Barre granite. Their model, however, does not accommodate loading rate effects explicitly as the model presented in this work does.

2. Experimental setup and results

2.1. Principle of the SHPB device with the BD sample

The SHPB apparatus is a widely used experimental setup for dynamic testing of various materials. For rock testing it has been used, e.g., [11–15]. A schematic illustration of the SHPB setup with a BD sample is shown in Fig. 1.

The striker bar impacts the free end of the incident bar generating a compressive stress pulse (incident pulse), which travels through the incident bar and the BD sample causing its diametrical splitting. The incident, transmitted and reflected pulse strains, ε_i, ε_t, ε_r, respectively, are measured as a function of time using the strain gages indicated in Fig. 1. Moreover, a disc shaped pulse shaper of relatively soft material (copper and rubber) is used to improve the dynamic equilibrium, i.e., $P_1 = P_2$, by increasing the rise time of the incident stress pulse. For other pulse shaping techniques, see [16–18]. The dynamic forces acting on both sides of the BD sample are calculated from the measured and dispersion corrected strains as [12]

$$P_1 = A_b E_b(\varepsilon_i + \varepsilon_r), \quad P_2 = A_b E_b \varepsilon_t \tag{1}$$

where A_b and E_b are the cross-sectional area and the Young's modulus of the bars, respectively. The indirect tensile strength is calculated based on the linear elasticity solution (for the transversal stress) of the problem of a cylindrical disc under diametrical compression. At the center of the disc this solution reads [19]

$$\sigma_T = 2P/\pi LD \tag{2}$$

where P is the force acting on the sample with length (thickness) L and diameter D. In fact, being a 2D solution, Eq. (2) is incorrect for discs with high thickness. A 3D corrected version for it was derived by Yu et al. [20]. With Eq. (2), it can be written as: $\sigma_T^{3D} = (0.2621k+1)\sigma_T$ with k being the thickness/diameter ratio of the disc. With the present BD dimensions, the correction factor is 1.103. Thus, use of Eq. (2) results in 10% error. However, the simulations are carried out in 2D (plane stress) case in order to save computational time. Therefore, in this paper Eq. (2) is used for calculating the indirect tensile stress.

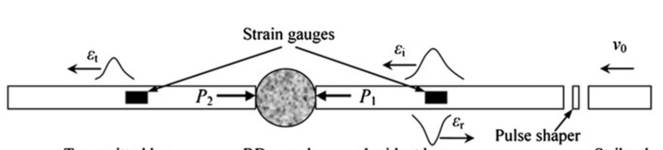

Fig. 1. Schematic picture of the SHPB setup with Brazilian disc sample.

2.2. Low loading rate BD tests with servo-hydraulic testing machine

The static tensile strength of Kuru granite was needed for the calibration of the rate-dependent hardening/softening law of the present constitutive model (see Section 3.1). In order to determine the quasi-static (indirect) tensile strength, BD tests were conducted using Instron 8800 servo-hydraulic materials testing machine. The disc diameter and thickness used in the tests were 40.8 and 16 mm, respectively. The quasi-static indirect tensile strength, f_{t0}, for Kuru granite was found to be approximately 13 MPa. Hence, this value will be used in the simulations (see Eq. (4)).

2.3. Dynamic BD tests with SHPB apparatus

The impact velocities of the piston in percussive rock drilling range from 5 to 10 m/s. However, in order to cover a slightly wider spectrum of loading rates, an experimental program with four tentative striker bar velocities 5, 10, 15 and 20 m/s was decided to be carried out. Five Brazilian disc tests were carried out for each loading rate. The lengths of the bars in the SHPB setup were $L_i = L_t = 1.2$ m and $L_{sb} = 0.4$ m (striker bar). The diameter of the high strength steel bars was 22 mm and a rubber pulse shaper was used in the tests. The sample dimensions, target and measured striker bar velocities in each test are given in Table 1.

The experimental incident stress pulses, after conversion from voltage, for Tests 1, 6, 11, and 16 and the loading configuration are shown in Fig. 2. During the tests, the BD samples were placed between the bars on a support made of soft tissue towels, i.e., no feed was exerted on the sample in order to hold it against gravity.

The pulses in Fig. 2 are not plotted in real time scale but as shifted to the origin. Fig. 3 shows the loads (shifted to the origin in time) imparted on the BD sample, i.e., the end forces P_1 and P_2 calculated from the measured signals with Eq. (2), from Tests 1, 6, 11, and 16.

Clear secondary peaks can be observed in the curves for P_1 in Fig. 3. These peaks are related to the gradually – along with the failure process – increasing contact area (impedance) between the disc and the incident bar. As the impedance increases due to fractures and crushing, the reflecting part of the incident pulse increases as well. Consequently, since P_1 is calculated based on a sum of the incident and reflected pulses, the result is what is seen

Table 1
BD sample dimensions and striker bar velocities in tests.

Test no.	D [mm]	L [mm]	Set v_0 [m/s]	True v_0 [m/s]
1	40.77	15.98	5	6.05
2	40.79	15.99	5	6.02
3	40.78	15.97	5	6.04
4	40.79	15.93	5	5.59
5	40.77	16.1	5	6.13
6	40.74	15.93	10	10.52
7	40.82	16.1	10	10.6
8	40.82	16.09	10	10.8
9	40.75	16.11	10	10.74
10	40.79	15.85	10	–
11	40.8	16.06	15	13.25
12	40.76	16.02	15	14.08
13	40.82	16.05	15	14.24
14	40.74	16.23	15	14.38
15	40.74	16.02	15	14.25
16	40.75	16.06	20	19
17	40.84	16.13	20	19
18	40.83	16.03	20	19
19	40.78	15.96	20	19.14
20	40.76	16.07	20	18.97