International Journal of Rock Mechanics & Mining Sciences 48 (2011) 535–545

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Dynamic validation of a discrete element code in modeling rock fragmentation

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ARTICLE INFO

Article history:
Received 7 January 2010
Received in revised form
6 December 2010
Accepted 9 February 2011
Available online 21 April 2011

Keywords:
Model validation
Discrete element model
Dynamic compression test
SHPB test
Strain rate dependence
Fragmentation size distribution

ABSTRACT

A discrete element code has been developed to simulate dynamic behavior of rock materials, particularly rock fragmentation upon impact in rock-fall analysis. Dynamic compression tests at a lower strain rate regime ($\dot{\varepsilon} < 0.2\,\mathrm{s}^{-1}$) and Split Hopkinson Pressure Bar tests at a higher strain rate regime ($\dot{\varepsilon} > 10.0\,\mathrm{s}^{-1}$) have been performed to validate the discrete element code. The dynamic strength and fragment size distribution of the tested granite showed clear strain rate dependence; the dynamic strength of granite increases with strain rate and a higher strain rate loading tends to produce more fragments. It has been found that the developed discrete element code can reasonably simulate the dynamic behavior in terms of strain rate dependent dynamic strength but not fragment size distribution. The strain rate dependent dynamic strength of granite can be explained as an inertial effect, in which material inertia inhibits crack propagations. The experimental fragment size distribution can be well represented by a two-parameter Weibull distribution.

1. Introduction

The motivation for this study came from an investigation of rock fragmentation upon impact in rock-fall analysis. Although rock fragmentation is frequently observed during rock-fall events, because of its complexity, it is usually not accounted for in the design of defense structures against rock-fall events. Impact rock fragmentation is still the most complicated and poorly understood aspect in rock-fall analysis. Very few contributions have been made so far [1–3]. By using a discrete element code developed by the authors [4], the controlling factors that affect rock impact fragmentation during rock-fall analysis have been investigated. The present paper presents the validation of the code developed for dynamic modeling.

In order to fully investigate the mechanisms of rock fragmentation upon impact in rock-fall analysis, the dynamic behavior of rock materials under impact loading is of great concern. One of the main features of dynamic behavior of rock materials is the loading rate dependent dynamic strength, which a model must reproduce. The understanding of this rate effect has been the purpose of many experimental works, as well as of numerical models.

The strain rate for rock-falls ranges from about 0.5 to several hundred s^{-1}, but this is probably only for the case of rock block impacting against hard rock (hard impacts). For rock-falls onto a soft ground, most of the kinetic energy dissipates via the ground by creating a plastic zone and by wave scattering, which extend the impact duration. Hence, the loading and the loading rate applied to rock blocks are very low for rock-falls onto soft grounds. Moreover, for rock-fall impact, the loading rate mentioned here only refers to the impact zone, which accounts for a very small portion of the rock block. The remaining major portion of the rock block is subjected to very low strain rates, but it is the locally highly strain rate loaded zone that initiates cracks and drives the propagation of cracks to create the general fragmentation process.

Various experimental devices have been used to explore a wide range of strain rates [3,5,6–8]. Compression tests have been performed, from static loading up to strain rates of $10^{-1}\,\mathrm{s}^{-1}$, with a hydraulic servo-controlled testing machine. With Drop Weight Impact tests, rates of $10^{1}\,\mathrm{s}^{-1}$ may be reached, but the energy transmitted to the specimen is limited by the size of the device. Higher strain rates as large as $10^{2}\,\mathrm{s}^{-1}$ can be obtained with a Split Hopkinson Pressure Bar (SHPB) test, which has now become very popular.

As shown in Fig. 1, a large number of experimental results on concrete were compiled in [9,10] in terms of the dynamic strength over static strength ratio. These results show that at relatively low strain rates, the strength increment with strain rate

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doi:10.1016/j.ijrmms.2011.02.003

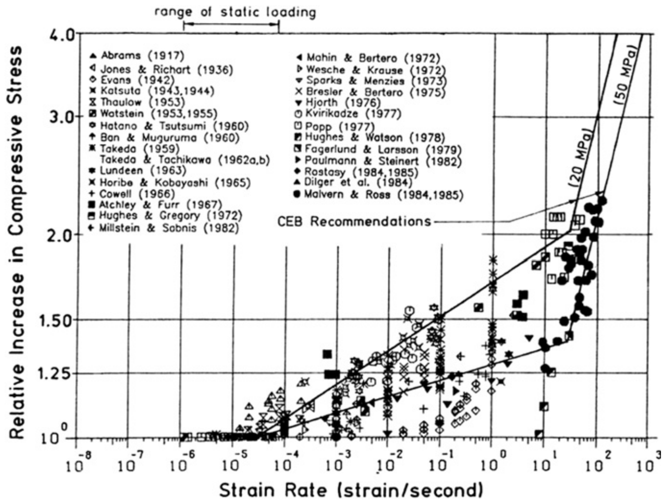

Fig. 1. Strain rate effect on dynamic uniaxial compressive strength of concrete (after [9,10]).

is less prominent than that at higher strain rates, where a sharp rise occurs at around a strain rate of 30 s^{-1}.

The work presented in the paper is purpose to validate a discrete element code developed by authors in modeling dynamic behavior of rock materials, particularly rock fragmentation upon impact in rock-fall analysis, using experimental results of dynamic compression and SHPB tests on granite at different strain rate regimes. The model was first calibrated under quasi-static condition using the results of static triaxial tests to obtain micro-model parameters. These identified model parameters were then applied in modeling dynamic problems while using "zero" numerical damping instead of a high numerical damping used in quasi-static model. Strain rate dependent dynamic strength and fragment size distributions were investigated and compared against the experimental observations. It has demonstrated that the developed discrete element code can reasonably simulate the experimental dynamic behavior in terms of strain rate dependent dynamic strength over the entire range of strain rates, but not the fragment size distribution, especially at a lower strain rate due to the model resolution (the smallest particle size). The dynamic strength can be reliably simulated by using micro-parameters identified based on static triaxial tests. The strain rate dependent dynamic strength of granite can be explained as an effect of material inertia that inhibits crack propagation.

2. Discrete element model

A 3D DEM code was developed [11–13] to simulate rock behavior, in which rock material is modeled as an assembly of spherical particles. DEM can be generally viewed [14] as a method that allows for finite displacements and rotations of discrete bodies, and updates contacts automatically as the calculation progresses. DEM adopts an explicit time integration scheme and can easily model the material failure process under different stress conditions by simulating contact failures at the micro-level, i.e. between spheres. As a consequence, the method has the advantage of modeling materials' failure behavior and dynamic processes (e.g., wave propagation, wave-crack interaction) without implementing complex continuum constitutive relations. When modeling the behavior of intact rock, the particles used in the model are bonded to each other with a specific strength and do not represent the actual material particle size. The initial model is setup by using the packing assembly (which is randomly distributed) and considering the initial state as "zero stress" state. This is achieved by introducing an "equilibrium distance" [5], D_{eq}, at each contact, which is equal to the distance between the centers of the two contacting spheres at the end of the packing (releases the lock-in stress). A factor of interaction range, which is defined as the ratio of the maximum distance of center-to-center interaction over the summation of the two contacting spherical radii, is introduced into the model to simulate materials other than simple granular materials, in particular those, which involve a matrix [5]. A factor of interaction range of 1.1 was used in this study, which means that two spheres are considered as a potential contact pair for interaction only if the center-to-center distance is smaller than 1.1 times the summation of the two spherical radii.

In DEM, the model parameters (micro-parameters), including deformability and strength, cannot be directly derived from measurable material properties (macro-properties). Deformability parameters include particle Young's modulus, E_c, and the ratio of normal stiffness, K_n, to shear stiffness, K_s at the contact point. Strength parameters include the contact tensile strength, T, cohesion, c, and friction angle, φ, for shear components. It requires extensive calibration work to identify these micro-parameters to reproduce specified material behavior. Calibration algorithms based on sensitivity analysis and optimization process have been developed to identify the micro-parameters that govern the deformability and strength at the contact between any two particles that make up the simulated rock block. This extremely important issue is outside the scope of this paper, and the reader is referred to papers [12,13] for details on the parameter identification algorithm that allows the micro-parameters to be identified based on conventional triaxial tests.

In DEM modeling, specimens are prepared by random sphere packing [12,13,15]. Different packing realizations have different internal structures even if the same number of particles is the same. These internal packing structures can affect the macroscopic behavior of packing assemblies. Strictly speaking, in DEM modeling, every packing specimen must be calibrated to match the desired properties before using it in actual simulations, and different packing realizations should have different micro-model parameters to match specific material properties. However, the authors have observed that, when the parameter identification algorithm in [12,13] is adopted to determine the micro-parameters, beyond a critical value of number of spheres different packing assemblies give similar simulated macroscopic behavior. The samples used in this study have a number of spheres much greater than this critical value.

The developed discrete element code has been successfully calibrated to model rock material in quasi-static loading regime: the model was calibrated to match material's deformability properties and strength envelopes using the results of a set of quasi-static triaxial tests on granite rock samples [13]. In order to ensure that the calibrated DEM model can also be used to model the dynamic behavior of rocks, dynamic tests using both a compression-testing machine at low strain rates and a Split Hopkinson Pressure Bar (SHPB) apparatus at higher strain rates were performed to validate the code in a relative large range of dynamic regime.

3. Dynamic tests

In order to validate the DEM code, two types of dynamic tests on granite were carried out at different strain rates, namely dynamic compression and SHPB tests. The material used in the tests was the same as the one used in triaxial tests to calibrate the quasi-static model. Strain rates performed in dynamic compression tests were relatively low from 5.0×10^{-6} (typical of