Computers and Geotechnics 71 (2016) 237–246

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Influence of material heterogeneity on failure intensity in unstable rock failure

Amin Manouchehrian [a,b], Ming Cai [a,b,c,*]

[a] Bharti School of Engineering, Laurentian University, 935 Ramsey Lake Road, Sudbury P3E 2C6, Canada
[b] MIRARCO, Laurentian University, 935 Ramsey Lake Road, Sudbury P3E 2C6, Canada
[c] State Key Laboratory for GeoMechanics and Deep Underground Engineering, D11 Xueyuan Road, Haidian District, Beijing 100083, China

ARTICLE INFO

Article history:
Received 1 May 2015
Received in revised form 28 September 2015
Accepted 11 October 2015

Keywords:
Numerical simulation
Heterogeneity
Unstable rock failure
Tensile failure
Confinement

ABSTRACT

Unstable failure of brittle rocks is a hazardous problem in deep mining and tunneling projects. Failure of brittle rocks around excavation boundaries is dominated by tensile fracturing. Homogeneous models cannot capture this rock failure mechanism while heterogeneous models are proven capable of capturing it. A question that may arise is how a change in failure mechanism influences the failure intensity. In this paper, an explicit FEM tool (Abaqus) is employed to simulate failure of homogeneous and heterogeneous rocks. Material heterogeneity is introduced into Abaqus models using Python scripts and the simulation results demonstrate that heterogeneous models can capture splitting rock failure. The effect of material heterogeneity on rock failure intensity in unconfined and confined compression tests is investigated. The simulation results from both types of models show that rock failure is more violent when the loading system is softer and the confinement is lower. However, it is observed that when two materials have the same peak strength, the heterogeneous model has more released energy than the homogeneous model due to the difference in the failure mode. The tensile splitting failure mode of the heterogeneous model releases more energy than the shear failure mode of the homogeneous model. This can be an important point to be considered for rockburst support design. Furthermore, the simulation results show that for two models with similar material composition, the strength of the more heterogeneous model is lower than the less heterogeneous model; as a result, the failure of the more heterogeneous model will be less violent if it fails in an unstable fashion, and this is in good agreement with field observation results.

1. Introduction

When rock failure occurs, broken pieces of rock can be spalled (stable failure) or ejected violently (unstable failure). Unstable rock failure is accompanied by a sudden release of energy and rapid ejection of broken rocks. Case histories in underground construction have documented many violent rock failures (rockbursts) [1–5]. In some cases, these violent unstable rock failures have resulted in loss of life and total collapses of entire mine panels [6,7]. Violent rock failure can occur locally which may not affect the general stability of a mine but it poses a great threat to workers nearby. Modern mining operations take available measures to reduce the likelihood of unstable rock failures but a complete elimination of rockburst is difficult in practice due to the uncertainty in parameters such as rock stress, strength, and stiffness [8]. Over the past several decades, researchers have employed various analytical, numerical, experimental, and statistical approaches to study different aspects of unstable rock failure, such as why it happens, how it happens, and how violent it would be. Despite of these efforts, the exact conditions of rockburst occurrence are still unknown. Hence, more studies are needed to understand the mechanism of rockburst so as to control and mitigate its risk.

Studies have demonstrated that numerical methods can be used to simulate rock failure [9–16]. Continuum (e.g. FEM and FDM) and discontinuum (e.g. DEM) methods have been used to model rock failure. Many numerical models consider a continuous, isotropic, homogeneous, and linearly elastic medium in simulation. Despite of these simplifications, these models are useful for solving some geomechanical problems. In homogeneous models, it is implicitly assumed that shear failure is the dominant failure mechanism [17,18]. When the major failure mode is tensile splitting, a homogeneous model cannot produce realistic results even if it properly reflects the prescribed mechanical properties such as peak

* Corresponding author at: MIRARCO, Laurentian University, 935 Ramsey Lake Road, Sudbury P3E 2C6, Canada. Tel.: +1 705 675 1151.

E-mail addresses: amin.manouchehrian@gmail.com (A. Manouchehrian), mcai@laurentian.ca (M. Cai).

http://dx.doi.org/10.1016/j.compgeo.2015.10.004
0266-352X/

strength. Hajiabdolmajid et al. [19] showed that traditional homogeneous models were not capable of simulating failure zone around excavations. They developed a cohesion weakening and frictional strengthening (CWFS) model to capture the failure zone around AECL's Mine-by tunnel in Lac du Bonnet granite. In their model, the failure zone was captured as shear failure zone. Despite of the capability of this model for simulating the damage zone around the tunnel, it was not capable of capturing the gradual tensile failure process. Hence, homogeneous models may not be suitable for rock failure process analysis (stable and/or unstable) around excavation boundaries where failure predominantly occurs in tensile splitting.

Heterogeneity is a characteristic of rocks and rock-like materials such as concrete, which makes this group of materials behave differently from others. Heterogeneity affects rock behavior under mechanical loads. The key function of heterogeneity is the formation of local stress concentration inside the body which leads to local tensile stresses even if the whole rock is under compression [20–22]. From previous studies it is understood that the process of crack development is initiated due to tensile micro-cracking. Shear failure becomes dominant in a later deformation stage when sufficient numbers of tensile fractures have been generated [23–29]. Hence, to capture tensile splitting failure of rocks, material heterogeneity needs to be introduced into the models.

Over the years efforts have been made to develop numerical codes that can consider discontinuity, heterogeneity, anisotropy, and non-elasticity of rocks. Advanced numerical tools such as Particle Flow Code (PFC), Rock Failure Process Analysis (RFPA), Universal Distinct Element Code (UDEC), Elasto-Plastic Cellular Automaton (EPCA), and ELFEN have been developed for simulating rocks as heterogeneous media. Application of these numerical tools demonstrated that consideration of rock heterogeneity is essential in simulating rock failure processes [30–39]. In addition, some advanced numerical tools have been utilized to study unstable rock failure. For example, Chen et al. [40] developed a double rock sample model to study unstable rock failure using RFPA. They simulated progressive rock failure and calculated the number of seismic events due to failure. A sudden drop or quiescence of microseismic events was used to identify unstable rock failure. In another numerical study using RFPA, Sun et al. [41] simulated unstable rock failure in circular tunnels under unloading conditions. They showed that the stability of the surface rocks and the beddings in the rocks affect rock failure and concluded that installation of rockbolts could prevent unstable rock failure. Kias and Ozbay [16] used a hybrid DEM–FDM modeling approach using PFC and FLAC to analyze unstable failure of coal pillars. They used the work performed by damping in PFC as an indicator of unstable failure. Gu and Ozbay [42] studied the failure stability of rock and rock discontinuities in coal mines. They used UDEC models to consider failure stability of both rock discontinuities in slip and coal in compression and showed that the post-failure characteristic of the discontinuity and the loading stiffness of the surrounding rock could affect the slip failure mode at an existing rock discontinuity. They concluded that unstable rock failure might happen when an unstable slip failure happened at the coal-rock interfaces. The above mentioned examples showed the suitability of heterogeneous models to simulate rock failure. However, previous studies did not focus on the effect of heterogeneity on unstable rock failure.

In this study, simulation results of unstable rock failure of heterogeneous rocks under unconfined and confined conditions using an Abaqus^{2D} explicit code are presented. Introduction of heterogeneity using Python scripting into Abaqus models is explained in Section 2. In the developed heterogeneous models, mechanical properties of Young's modulus (E), cohesion (c), and friction angle (φ), which follow normal distribution functions, are set randomly in each element. A parametric study is conducted to understand the effect of each parameter's heterogeneity on the mechanical behavior of rocks. Effect of Loading System Stiffness (LSS) and confinement on failure intensity is investigated. A comparison of results between the homogeneous and the heterogeneous models is presented in Section 3.

2. Abaqus models for rock failure simulation

Abaqus is a FEM-based numerical tool developed by Dassault Systems (3DS). Application of Abaqus has resulted in very realistic simulation of many complicated problems [43–46]. Abaqus has a broad application in automobile, aerospace, and industrial products. This numerical tool is equipped with implicit and explicit solvers, making it applicable to solving a large variety of physical and engineering problems.

Despite of Abaqus's capability for simulating physical problems, its application in the geomechanical field is limited. A key characteristic of geomaterials is material heterogeneity, which cannot be readily modeled in Abaqus. Fortunately, Abaqus provides windows for adding and improving its capability using scripting. Hence, for modeling rock-like materials, it is possible to introduce material heterogeneity into the models to produce more realistic results. In this section, a simulation of rock failure processes in compression using homogeneous material models is presented first, followed by an introduction of material heterogeneity into Abaqus models and a simulation of rock failure processes in compression using heterogeneous material models.

2.1. Compression test simulation using homogenous models

This study investigates the effect of material heterogeneity on unstable rock failure. For this purpose, the tested mechanical properties of T_{2b} marble (Table 1) are used as the base case. T_{2b} marble is the host rock of the diversion tunnels at the Jinping II Hydropower Station in China, which have experienced violent rock failures during construction [47].

To investigate the failure mechanism of rocks in homogeneous models, unconfined and confined compression tests were simulated using Abaqus^{2D}. A homogeneous elasto-plastic Mohr–Coulomb strain-softening model was used to model the strength behavior of the T_{2b} marble. Table 2 presents the adjusted parameters for defining the strain-softening behavior of the rock in the homogeneous model. A rectangular specimen with a height of 250 mm and a width of 100 mm was used for the simulation. In the unconfined compression test simulation, one end of the specimen was fixed in the maximum stress direction and the other direction was free (roller constraint) and a constant velocity of 0.03 m/s was applied directly to the other end to load the specimen. The same end boundary conditions were applied to the specimens in the confined compression test simulation and the confinements applied were 5, 10, 20, and 40 MPa. In the unconfined and confined

Table 1
Physical and mechanical properties of the T_{2b} marble [47].

Parameter	Test value
Density, ρ (kg/m^3)	2780
Young's modulus, E (GPa)	55
Poisson's ratio, ν	0.27
Uniaxial compressive strength, UCS (MPa)	110.7*
Cohesion, c (MPa)	32.6
Friction angle, φ (°)	29.0
Post-peak modulus, E_{pp} (GPa)	150**

* UCS of the T_{2b} marble was reported between 100 and 160 MPa in [47]. This value was calculated according to $UCS = \frac{2c \cdot \cos\varphi}{(1-\sin\varphi)}$ for the present study.
** Post-peak modulus (K_{pp}) of the T_{2b} marble is extracted by digitizing curves presented in [47].