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Testing and numerical simulation of a medium strength rock material under unconfined compression loading

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ABSTRACT

This study aims to numerically and experimentally investigate the response of a medium strength rock material under unconfined compression loading up to failure. The unconfined compressive strength (UCS) is one of the most important parameters in characterising rock material behaviour. Hence the UCS is crucial in understanding the failure mechanism of fractured rocks. An effective approach to determine the UCS and to investigate the behaviours of rock materials under unconfined compression is essential in the majority of research fields of rock mechanics. The experimental configuration for the unconfined compression test, suggested by the protocols of the ASTM standard, has some limitations which affect the accuracy in determination of the real UCS. Among several alternative configurations proposed, the Mogi's configuration seems to be the most appropriate one. Therefore, the ASTM and Mogi's configurations were used to perform the tests on a medium strength rock material, i.e. Pietra Serena sandstone. The results using two configurations were discussed in terms of the differences. The tests were also replicated in LS-DYNA using a finite element method (FEM) coupled smooth particle hydrodynamics (SPH) technique. This technique is employed in this study due to its capabilities to cope with large deformation issues related to the rocks. An advanced material model, called the Karagozian and Case Concrete (KCC) model, is implemented in the numerical simulations. The KCC model consists of three independent fixed failure surfaces and it can consider the damage accumulation based on the current state of stress among these failure surfaces. An equation-of-state (EOS) is used in conjunction with KCC material model for decoupling the volumetric and deviatoric responses. The numerical and experimental results were finally compared with the focus on the stress–strain diagram and the failure patterns. The comparison shows that the numerical results are in good agreement with the experimental results.

1. Introduction

This article presents experimental and numerical investigations in the rock mechanics domain with a focus on the oil and gas requirements. Comprehensive knowledge about the mechanical behaviours of rock materials in sub-aqueously deep well drilling applications is mandatory (Pepper, 1954; Lacy and Lacy, 1992; Brady and Brown, 2013). The mechanical behaviour of rock at material scale is generally controlled by the geometric arrangements of the mineral particles and voids in combination with the microcracks. However, the microflaws often significantly influence the rock mechanical behaviours (Åkesson et al., 2004; Szwedzicki, 2007; Basu et al., 2009). The failure modes of brittle crystalline rock materials under compression loading are rather complex and difficult to be predicted (Santarelli and Brown, 1989). This complexity originates from different sequential processes, which are discussed in this paper for the case of uniaxial compression loading (Martin, 1993; Malvar and Crawford, 1998; Li et al., 2003; Jaeger et al., 2007). Therefore, investigation on the failure mode of the rock material, a medium strength rock material (i.e. unconfined compressive strength (UCS) in the range of 40–80 MPa (Attewell and Farmer, 1976)) can advance our understanding and facilitate the future design in this domain.

The UCS is one of the most significant parameters to characterise the rock materials and it plays an important role in predicting the boreability of the material (Kahraman, 2001; Ceryan et al., 2013; Nazir et al., 2013). Boreability is used widely in analysis, design and classification of rock materials and is

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expressed by the maximum principal stress that the material can sustain under uniaxial compression. Due to this, a precise approach for UCS measurement is necessary in most fields of rock mechanics. Basically, a cylindrical specimen loaded by two compressive platens in parallel to its main axis is considered conventionally as the configuration of unconfined compression test. This conventional test suggested by the standard ASTM D7012-04 (2004) has its drawback, mainly due to the radial shear stressed generated at the contact interface when applying a compressive load. The undesired radial stresses appear due to different elastic properties of the steel of the testing machine platen and the rock specimen. Mogi (1966, 2007) suggested another arrangement to design the specimen in order to address this problem. The experimental and numerical analyses in this context show that the Mogi's suggested method can measure the UCS more precisely. The experimental results reveal that the variability of the results obtained by Mogi's configuration is much lower than that of conventional configuration. Later, numerical simulations also confirm it when stress concentration is considered at the rock-steel (of compressive platen) interface using conventional configuration (Mogi, 2007).

An alternative to expensive field testing is available due to the rapid development of numerical analysis technology in conjunction with advanced computer facility. Several numerical methods have been recently employed (Kochavi et al., 2009; Anghileri et al., 2011; Jaime, 2011; Wu and Crawford, 2015; Zhao et al., 2016) for simulating the mechanical behaviours of quasi-brittle materials, e.g. concrete and sandstones. The finite element method (FEM) is the most commonly used numerical technique in the research fields as well as in industrial applications. The implementation of the FEM for solving the solid mechanics problems, which are analysed in the continuum domain, is still one of the most accurate numerical simulation techniques. The presence of highly distorted solid elements in the numerical modelling of fractured rock is often encountered, which is one of the main drawbacks of Lagrangian FEM. The smooth particles hydrodynamics (SPH) is a mesh-less Lagrangian method which can discretise a system as a number of particles (or "mesh-points") carrying the field variables. The capability of the SPH method to cope with high distortion has been proved as the nodal connectivity is not fixed in this method (Anghileri et al., 2011; Olleak and El-Hofy, 2015; Bresciani et al., 2016). However, the performance of the FEM in terms of accuracy and time consumption is generally higher than that when the SPH particles are used. Therefore, inspired by the study of Bresciani et al. (2016), an approach was implemented to take advantage of both the FEM and the SPH methods in exploiting the finite element software.

Exploitation of efficient and realistic constitutive models has become one of the essential tools in structural analyses. A material model, called Karagozian and Case Concrete (KCC) model, was used in this study. The KCC model was developed by Malvar et al. (1994, 1996, 1997, 2000). Finally, the results of the numerical models were compared with the experimental data.

2. Experimental programme

The unconfined compression test is conventionally performed by applying axial load to a cylindrical specimen with a specific length to diameter ratio. Various arrangements have been developed to perform the unconfined compression tests as indicated in Fig. 1. The short cylindrical specimen represented as type 1 is in direct contact with the compressive platens, which is a configuration suggested by the ASTM standard. The different mechanical behaviours of the rock specimen and the steel of compressive platens result in radial shear stresses at their interfaces, which is a focus in this context. The two configurations represented as types 2 and 3 were developed to overcome the shortcomings of the type 1.

In the configuration type 2, various types of lubricants were basically applied at the interfaces to eliminate the friction forces. Due to the frictionless boundaries, it may seem that this configuration is a preferred one. The sample end conditions are principally plan, and the stress state will not vary throughout the specimen and the deformation can be considered homogeneous. However, during the testing, a number of vertical cracks propagate starting from the outer surfaces of the rock, which is induced by the intrusion of soft lubricator into the specimen (Mogi, 2007). Therefore, the idea of using lubrication to produce frictionless boundaries is not practical.

The dog-bone specimen, represented as type 3, was suggested by Brace et al. (1966) to avoid extending the effect of a mismatch at the ends of the specimen into the region of the specimen where fracture occurs. The Brace specimen is however unsuitable for performing the unconfined compression test mainly due to two drawbacks: difficult fabrication procedure and presence of bending stresses. Therefore, Mogi (2007) proposed another configuration, represented as type 4, to overcome the shortcomings existing in the other configurations. The merits and drawbacks of the Mogi's configuration will be discussed in Section 2.2.

The merits and drawbacks of the configurations types 1–4 under uniaxial compression conditions are summarised in Table 1. The

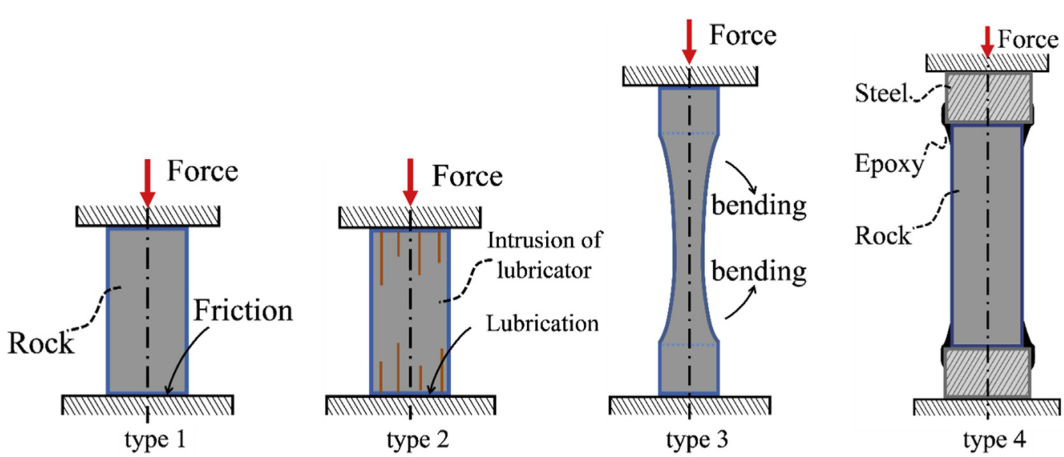

Fig. 1. Various configurations of rock specimens under uniaxial compression (Mogi, 2007).