Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 797–806

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Fracturing process and effect of fracturing degree on wave velocity of a crystalline rock

Charalampos Saroglou*, Vasileios Kallimogiannis

Department of Geotechnical Engineering, School of Civil Engineering, National Technical University of Athens, Athens, Greece

ARTICLE INFO

Article history:
Received 27 November 2016
Received in revised form
30 January 2017
Accepted 5 March 2017
Available online 18 July 2017

Keywords:
Wave velocity
Fracturing
Crack initiation
Damage
Granite

ABSTRACT

The present paper investigates the effect of fracturing degree on P- and S-wave velocities in rock. The deformation of intact brittle rocks under loading conditions is characterized by a microcracking procedure, which occurs due to flaws in their microscopic structure and propagates through the intact rock, leading to shear fracture. This fracturing process is of fundamental significance as it affects the mechanical properties of the rock and hence the wave velocities. In order to determine the fracture mechanism and the effect of fracturing degree, samples were loaded at certain percentages of peak strength and ultrasonic wave velocity was recorded after every test. The fracturing degree was recorded on the outer surface of the sample and quantified by the use of the indices P_{10} (traces of joints/m), P_{20} (traces of joints/m^2) and P_{21} (length of fractures/m^2). It was concluded that the wave velocity decreases exponentially with increasing fracturing degree. Additionally, the fracturing degree is described adequately with the proposed indices. Finally, other parameters concerning the fracture characteristics, rock type and scale influence were found to contribute to the velocity decay and need to be investigated further.

1. Introduction

The effect of fracturing on mechanical properties of rock can be investigated by recording the change of P- and S-wave velocities due to the presence of microcracks. Wave velocities are related to the dynamic parameters of the rock and are also used as a quality index of rocks. Limited research on the effect of fracturing degree on the wave velocity is available and mostly concerns studies in the field in terms of wave velocity of rock masses.

In the present study, fractures were induced in the samples with staged loading. The findings from the present study cannot be directly used in field as the effect of the scale is important and further research is required for this purpose. Granite was tested, as its behavior is brittle and its microcracking process is well documented in existing literature (e.g. Lac du Bonnet granite in Canada). The tested rocks are sampled from a granite intrusion in Greece.

2. Literature review

2.1. Fracture initiation and propagation

According to Brace (1964) and Bieniawksi (1967), the progressive failure of intact rock is characterized by a fracturing procedure, consisting of the following stages: (a) crack closure, (b) linear elastic deformation, (c) crack initiation and stable crack growth, (d) crack damage and unstable crack growth, and finally (e) failure.

Griffith (1924) suggested that crack initiation occurs at the tips of microscopic pre-existing flaws (elliptical cracks) of intact rock when the tensile strength is exceeded. According to Hoek and Martin (2014), Griffith theory is significant in understanding brittle fracture process but its practical value is limited due to the fact that Griffith's crack is a deficient model of the crack network, which originates and propagates through the intact rock.

According to Martin (1993), crack initiation and damage thresholds are dependent on rock properties and not on loading conditions. A thorough review of the available methods for determining crack initiation in low-porosity rocks during compression tests was presented by Nicksiar and Martin (2012). Furthermore, Martin and Nicksiar (2014) used a discrete element numerical approach for these rocks and suggested that the ratio of crack

---

* Corresponding author.
E-mail address: saroglou@central.ntua.gr (C. Saroglou).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2017.03.012

initiation stress to peak strength is usually constant (approximately 0.45 ± 0.05).

Acoustic emission (AE) is widely used to investigate the fracturing process and detect the crack initiation and damage thresholds. Eberhardt (1998) studied the fracturing process of Lac du Bonnet granite thoroughly and detected the microcracking stages by using stress–strain data and AE tests in uniaxial compression. Eberhardt et al. (1997) suggested that AE should be used qualitatively when identifying crack initiation and damage thresholds. Scholz (1968) and Boyce et al. (1981) correlated the number of AE events with the applied stress.

More recently, Zhao et al. (2015) proposed a new method to determine crack initiation and damage thresholds using cumulative AE hits (CAEHs). Zhang et al. (2015) studied the AE response in granite, marble and rock salt and showed that the AE response in granite and marble was different from that in rock salt.

2.2. *Effect of fracturing degree on wave velocity*

P- and S-wave velocities in intact rock are affected by a number of factors such as density, porosity, mineralogical composition, anisotropy, weathering, and axial and lateral confining pressures (Saroglou, 2007; Tziallas et al., 2009). The effect of fracturing degree on the wave velocity of intact rock is significant and has not been studied adequately in the laboratory scale. The term fracturing degree refers to the density of fractures in a given volume of rock.

Zhao et al. (2006) performed an experimental study of ultrasonic wave attenuation across parallel fractures and provided further understanding of wave propagation across discontinuities. Nasseri et al. (2007) studied the effect of fracturing degree (induced thermally to Westerly granite) on P-wave velocity. Thermal cracking was shown not only to significantly reduce the mechanical strength but also the dynamic elastic properties of Westerly granite. Azhari and Hassani (2013) investigated the effect of the number, length and orientation of artificially induced discontinuities on wave velocity. They concluded that the decrease of P-wave velocity depends on both fracture density and surface roughness. Huang et al. (2014) performed an experimental study using ultrasonic waves propagating through rock samples with single and multiple parallel joints. They found that the transmission ratio does not always decrease with increasing number of joints while it increases with decreasing joint spacing when this is smaller than a threshold value. Wu et al. (2015) studied the effect of filling materials in rock fractures on the P-wave velocity. They suggested that P-wave attenuation is strongly related to the specific fracture stiffness, regardless of the filling material composition and thickness.

A significant number of relevant studies concern rock masses while relatively few studies are reported on the effect of fracturing degree on wave velocity (e.g. Lee and de Freitas, 1990). Sjögren et al. (1979) and Sjögren (1984) studied the effect of fracturing (through joint frequency) on seismic velocity. They found that wave velocity decreases with increasing fracturing degree based on the results from multiple rock types. McDowell (1993) suggested that the characterization of a rock mass is possible by comparing its wave velocity with the velocity of intact rock and also used joint frequency to quantify the fracturing degree. Eitzenberger (2012) studied the effect of an individual discontinuity on wave propagation in rock masses.

3. Properties and fracturing process of tested rock

3.1. *Laboratory testing of granite*

The physico-mechanical properties of granite were determined with laboratory testing on intact rock samples (Kallimogiannis, 2016). The porosity and density were measured and uniaxial, triaxial compression and Brazilian tests were performed in order to determine the uniaxial compressive strength (UCS), the deformation parameters (elastic modulus E and Poisson's ratio ν), the Hoek–Brown failure criterion envelope and the tensile strength of the rock tested. The properties of the tested granite are presented in Table 1.

The UCS of rock was determined according to ISRM (2007) procedures. The tests were carried out using a servo-controlled loading frame with a capacity of 1.5 MN. The stress rate was kept constant in a range of 0.17–0.35 kN/s and failure occurred within 8–10 min from the start of loading applied. The axial strain (ε_a) during uniaxial compression tests was measured using a linear variable differential transformer (LVDT) mounted at the mid-height of the rock sample. The samples were cylindrical with a height to diameter ratio of 2.5.

The triaxial compression tests were carried out using a 70 MPa capacity triaxial cell placed in the 1.5 MN capacity loading frame. The triaxial cell is a Hoek-Franklin cell for samples of 54 mm in diameter (NX size). Three different confining pressures were applied during the triaxial tests, i.e. 10 MPa, 20 MPa and 30 MPa. The samples had a height to diameter ratio equal to 2 and the loading rate was kept constant (1.5 kN/s).

The recording of the AE signals, during uniaxial testing, was performed with an AE system (type PCI-2, PAC) equipped with a pre-amplifier (type PAC 2/4/6, amplification: 20/40/60 dB) using four piezoelectric sensors (MICRO-100S, PAC), located at opposite sides on the sample surface at different heights. The AE test was performed according to ISRM (2002). Silicone gel was used to achieve bonding of the sensors to the rock surface. The sensors were mounted using rubber tapes on the sample. The bonding was checked before the test, using the pencil lead break (PLB) technique. The locations of the sensors on a rock sample are shown in Fig. 1a. The recording frequency of the AE sensors was 400 kHz. Fig. 1b and c shows a granite sample before and after failure in uniaxial compression test.

The sample diameter for Brazilian tests was 54 mm and the thickness/diameter ratio was equal to 0.5. The load increased at a constant rate (0.15–0.25 kN/s) until failure of the sample occurred within 2–3 min.

Finally, the initial wave velocity of granite was measured in dry and fully saturated conditions using the ultrasonic velocity test (Pundit). The P-wave velocity in saturated samples was higher than that in dry ones, as expected, while S-wave velocity was not affected by saturation.

Table 1
Physico-mechanical properties of tested granite.

Dry density, ρ_d (Mg/m^3)	Porosity, n (%)	UCS (MPa)	E (GPa)	ν	Tensile strength, σ_t (MPa)	Hoek–Brown parameter, m_i	P-wave velocity (m/s)		S-wave velocity (m/s)	
							Saturated	Dry	Saturated	Dry
2.61	1.34	195.5	53.6	0.17	15.7	28	5138.8	4926.9	3164.3	3173.3