Dynamic Mechanical Behavior of Rock Materials

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ABSTRACT

Dynamic rock mechanics investigates the mechanical behavior of rock under dynamic loading conditions and change in mechanical properties of the rock. Loading techniques were almost used for both intermediate and high strain rate tests. In this work, dynamic tests and dynamic mechanical behavior of rock materials were studied. Dynamic tests were discussed to predict the stress-strain behavior. Different dynamic mechanical properties of rock materials including uniaxial and triaxial compressive strength, tensile strength, shear strength and fracture toughness were summarized. The effect of pressure, temperature and water saturation as well as microstructure, size and shape of rock on the mechanical properties of rock materials was considered.

Key words: Dynamic, Rock, Mechanical behavior, Strain.

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1. INTRODUCTION

The influence of dynamic loading on rock is a key factor for various rock engineering problems (1). Different applications of rock dynamics is in earthquakes, mining, energy, environmental and civil engineering. Various environmental parameters such as confined pressure, temperature and ground water as well as rock factors such as microstructure, size and shape of the rock have significant effect on the dynamic mechanical behavior of rock materials (2-5). In recent years, the experimental techniques were developed to characterize the dynamic mechanical behavior of materials (6-8). In previous studies, dynamic experimental techniques were studied for rock-like materials such as concrete, mortar, ceramic and rock materials (9-12). In this work, dynamic experimental techniques and mechanical behavior of rock material have been reviewed. The experimental techniques for intermediate and high strain rate tests and dynamic mechanical behaviors of rock materials were discussed.

2. LOADING METHODS FOR INVESTIGATION OF DYNAMIC BEHAVIOR

Loading techniques have been used for investigation of dynamic behavior of rock materials. The loading techniques for rock materials are illustrated in Figure 1. In the range of \(10^{-8}-10^{-5}\) s\(^{-1}\) strain rate, the creep behavior is considered and creep laws are used (5). In the range of \(10^{-5}-10^{-3}\) s\(^{-1}\) strain rate, the quasi-static stress–strain curve obtained from constant strain rate (CSR) test has been applied to investigate the mechanical behavior (13). The ordinary hydraulic servo-controlled testing machines and hydraulic oil machines, can load specimens at strain rates up to \(10^{-3}\) and \(10^{-1}\) s\(^{-1}\), respectively. The pneumatic–hydraulic machines and drop-weight machines have been developed to reach strain rates on the order of \(10^0\) and \(10^1\) s\(^{-1}\), respectively (1). The mechanical behavior of rock materials at strain rates ranging from \(10^{-1}\) to \(10^1\) s\(^{-1}\) is defined as intermediate strain rate. The loading techniques in the high strain rate, in the range of \(10^1\) to \(10^4\) s\(^{-1}\) are the split Hopkinson pressure bar (SHPB). At high strain rates, there is a transition from nominally isothermal condition to quasi-isothermal/adiabatic condition (14).
Pneumatic–hydraulic machines have developed for studying the intermediate strain rate behavior of rock materials in uniaxial compression. In pneumatic–hydraulic machines, the load is used by movement of a light weight piston driven by expansion of compressed gas. The strain rate is dependent on the relationship between the specimen stiffness and machine stiffness (15). The principle of drop-weight machines is gravitational potential energy, through controlling a hammer with known height and weight. Drop-weight machines have been used to achieve strain rate of $10^6$ s$^{-1}$. The use of drop-weight machines is limited due to their problems including 1) the technique is passive, and testing conditions are determined by trial and error or from empirical parameters, 2) the rate and form of the compressive loading depend on both the specimen and machine compliances, as well as the average energy of the falling weight, 3) great care should be taken in interpreting experimental data because of the coupling effects between machine vibration and wave propagation, 4) the calculated displacement might be inaccurate, 5) the loading rate cannot be well controlled, and thus multi-axial tests are unreliable (16). The loading techniques at high strain rate have been widely utilized with the split Hopkinson bar. The structure split Hopkinson bar is a striker bar, an incident bar and a transmission bar, with a specimen sandwiched between the incident and transmission bars. The strain rate $\dot{\varepsilon}$ is given as follows (17):

$$\dot{\varepsilon} = \frac{(u_1 - u_2)}{L_s}$$

where $u_1$ and $u_2$ are the velocities at the incident bar–specimen and specimen–transmitted bar interfaces, respectively. $L_s$ is the length of strike bar. The conditions of constant stress rate and stress equilibrium need to be satisfied simultaneously for a split Hopkinson bar test. To reach the stress equilibrium condition, it has been suggested that the equilibrium time should be 5–10 times of transit time (18). The end friction between the specimen and the loading device may lead to a complex stress state of multi-axial compression, and rock materials are very sensitive to the confining pressure. Although friction effects can be physically minimized in tests by proper lubrication, they cannot be eliminated completely. The friction could be decreased using numerical simulations by different contact conditions including lubricated, dry and bonded using high-strength adhesive (19). Furthermore, the stress wave loading in high strain rate tests causes inertia to have an influence on measured mechanical properties (20). The magnitude of the inertial contribution to the apparent stress depends also on the density and size of the specimen. Powell (21) has been investigated the radial inertia effects on rock behavior. They observed that the radial stress increased towards the center of the specimen during fracturing, and concluded that failure propagates inwardly in a progressive manner. Three modifications were used to push the Split Hopkinson bar to higher strain rates. These modifications were, 1) decrease of the specimen size, especially the length; 2) direct impact on the specimen; and 3) miniaturization of the entire system (21). The first approach is typically limited by frictional effects (22). A projectile directly impacts on a specimen placed in front of an elastic bar in the second approach. Several miniaturized versions on the millimeter order in diameter have been developed, and the strain rate can reach up to about $10^5$ s$^{-1}$ in the third approach (22).

### 3. Dynamic Mechanical Properties of Rock Materials

The mechanical properties of rock materials are sensitive to loading rate, and enhancement in mechanical properties of rock materials. On the other hand, the dynamic mechanical properties and fracture behaviors of rock materials depend on the loading and measurement technique, testing method and influencing environmental
3.1. Uniaxial Compression Tests
The uniaxial compression tests were conducted under dynamic loading in different measurement type and different size, shape (e.g., cube, cylinder or prism) and aspect ratio of the specimens. The size and shape of the specimen are normally defined by the same value of the ratio \( L_s/D_s \) of 2.5–3.0 for quasi-static tests. Furthermore, the diameter should be close to 50 mm or at least 10 times the average grain size, with the ratio \( L_s/D_s \) taking values of 1:1 and 0.5:1 for small and large specimens, respectively (24).

3.2. Triaxial Compression Tests
In triaxial compression tests, the specimen is placed inside a pressure chamber and isotropically loaded by hydrostatic pressure using various confining fluids (Figure 2) (16). The confining pressure depends on the thickness and material type of the sleeve. Strain gauges are mounted on the sleeve surface to record the stress state of the specimen. General trends exist for: an increase of triaxial strength with increasing strain rate at all confining pressures; an increase of triaxial strength with increasing confining pressure, as had been demonstrated in quasi-static tests; the deformation behavior to become more ductile at HSR; and a lower confining pressure than in quasi-static tests, in particular for sedimentary materials (16, 25).

3.3. Tension tests
There are two types of standard methods including direct tension and indirect tension. Direct tension tests under quasi-static loads are difficult to perform because even very slight misalignments and stress concentrations in the loading system may produce undesirable failure modes. The schematics of four types of split Hopkinson tension bar techniques are illustrated in Figure 3 (26). The limitations on direct tension tests include the following: (1) the same limitations as for quasi-static tests; (2) the complexity of the specimen shape and (3) pulse shaping techniques are hard to apply, thus the condition of stress equilibrium may be violated (27). To overcome these problems, indirect tension methods have been developed. Indirect testing methods provide a convenient alternative in terms of specimen manufacturing, experimental setup and data reduction, to determine the tensile strength (28). The schematic of indirect tension methods is illustrated in Figure 4.

Figure 2. Schematic of triaxial compression tests design

Figure 3. Schematics of four types of split Hopkinson tension bar techniques: (a) a mass is impacted directly on an anvil attached to the incident bar; (b) an anvil is loaded by a compressive wave transmitted through a hollow tube; (c) a pulse is generated by the detonation of an explosive against the anvil; and (d) a pre-stressed bar is connected to the incident bar to produce the loading pulse.
3.4. Shear tests

For higher strain rates, the torsional split Hopkinson bar technique has been developed, which overcomes the limitations of lateral inertia, friction and wave dispersion effects on the experimental results in the traditional Split Hopkinson pressure bar test (29). The dynamic shear strength of the thin-walled tubular specimen, $\tau_d$, is calculated from the dynamic torque, $T_d$, as follows (29):

$$\tau_d = \frac{T_d}{2\pi R^2 B_{ws}}$$

where $B_{ws}$ is the wall thickness and $R$ is the mean radius of the specimen.

3.5. Stress–strain behavior at high strain rate

The strength, strain to failure, Young’s modulus, Poisson’s ratio and brittle/ductile behavior can be evaluated from stress–strain curves. The stress–strain curves are almost evaluated by load transducers and on-specimen strain gauges without considering inertia effects. Methods for determining the stress–strain curve at high strain rate are illustrated in Table 1. Among them, the direct estimation method is recommended to determine the stress–strain curve (7).

| Method                  | Strain history $\varepsilon(t)$ | Stress history $\sigma(t)$ |
|------------------------|---------------------------------|----------------------------|
| One-wave analysis      | $\varepsilon(t) = -(2C_i/L_s) \cdot \int_0^t \varepsilon_{re}(t) \, dt$ | $\sigma(t) = (A_0 E_0/A_1) \cdot \varepsilon_{re}(t)$ |
| Two-wave analysis      | $\varepsilon(t) = -(2C_i/L_s) \cdot \int_0^t \varepsilon_{re}(t) \, dt$ | $\sigma(t) = (A_0 E_0/A_1) \cdot [\varepsilon_{re}(t) + \varepsilon_{tr}(t)]$ |
| Three-wave analysis    | $\varepsilon(t) = (C_0/L_s) \cdot \int_0^t \varepsilon_{re}(t) - \varepsilon_{re}(t) - \varepsilon_{tr}(t) \, dt$ | $\sigma(t) = (A_0 E_0/A_1) \cdot [\varepsilon_{re}(t) + \varepsilon_{tr}(t) + \varepsilon_{tr}(t)]$ |
| Direct estimate        | $\varepsilon(t) = (C_0/L_s) \cdot \int_0^t \varepsilon_{re}(t) - \varepsilon_{re}(t) - \varepsilon_{tr}(t) \, dt$ | $\sigma(t) = (A_0 E_0/A_1) \cdot \varepsilon_{re}(t)$ |
| Foot-shifting          | $\varepsilon(t) = (C_0/L_s) \cdot \int_0^t \varepsilon_{re}(t) - \varepsilon_{re}(t) - \varepsilon_{tr}(t(t + b_0)) \, dt$ | $\sigma(t) = (A_0 E_0/A_1) \cdot \varepsilon_{re}(t)$ |
| Hybrid analysis        | Direct measurement              | One of the above or load transducer |
| Inverse analysis       | Combination of FEM simulation   | Combination of FEM simulation |
|                        | and/or direct measurement       | and/or one of the above |

3.6. Dynamic uniaxial compressive behavior

Dynamic mechanical parameters are usually obtained from stress–strain curves extracted directly from load transducers. In high strain rate testing, the effects of inertia and wave propagation should be considered (30). The increase or decrease with increasing the strain rate means that the critical strain becomes more brittle or ductile at higher strain rate. Young’s modulus decreases slightly and the Poisson’s ratio increases slightly with increasing loading rate. The inverse method employed force and
particle velocities measured at both sides of the specimen, was successfully used to determine the stress–strain curves of concrete and salt. Therefore, the inverse analysis method produces accurate and repeatable results for rock-like materials at high strain rate. There is a definite increase in the uniaxial compressive strength of rock materials under dynamic loading (31).

3.7. Dynamic triaxial compressive behavior
Mechanical loads applied to rock materials are almost not uniaxial (32). The stress–strain curves at high strain rates under 0.1 and 10 MPa confining pressures are approximately consistent with those under 27 and 55 MPa confining pressures in the quasi-static tests, respectively. The used techniques were modified and improved to determine the triaxial compressive strength of rock-like materials precisely. The dynamic strength curve relative to confining pressure is almost parallel to the static one for rock materials. At constant confining pressure, the normalized dynamic triaxial compressive strength increases with increasing strain rate. The dynamic strength curve relative to confining pressure is almost parallel to the static one for rock materials, and the triaxial compressive strength at high strain rate is about 20-100% higher than those obtained in quasi-static tests (33, 34).

3.8. Dynamic tensile behavior
The tensile strength increases with increasing strain rate, whereas the strain decreases. The increase in the tensile strength and the decrease in the strain to failure indicate that the material displays more brittle features in higher strain rate tests. The strain rates of the direct tension results are higher than those obtained by indirect tension testing methods, since the specimen sizes are usually smaller in indirect tension tests. Therefore, attempts have been made to determine the tensile strength–strain curve by means of indirect testing methods under quasi-static loads (35).

4. CONCLUSION
In this work, the dynamic mechanical behavior of rock materials is discussed. Loading techniques used for intermediate strain rate testing of rock materials are pneumatic–hydraulic, completely gas driven and drop-weight machines. At high strain rate, the split Hopkinson bar is widely used, and major developments of this technique for rock materials. The strain rate in tests performed by loading techniques should be well controlled. Mechanical loads on engineering structures are commonly not uniaxial. Loading techniques can be applied for multiaxial stress, such as true-triaxial and compression-shear tests. Dynamic uniaxial and triaxial compressive, tensile and shear strength of rock materials are obtained by quantitative assessment of testing methods.

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