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Technical Note

Correlations between ultrasonic pulse wave velocities and rock properties of quartz-mica schist

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ABSTRACT

Physico-mechanical properties are critically important parameters for rocks. This study aims to examine some of the rock properties of quartz-mica schist (QMS) rocks in a cost-effective manner by establishing correlations between non-destructive and destructive tests. Using simple regression analysis, good correlations were obtained between the pulse wave velocities and the properties of QMS rocks. The results were further improved by using multiple regression analysis as compared to those obtained by the simple linear regression analysis. The results were also compared to the ones obtained by other empirical equations available. The general equations encompassing all types of rocks did not give reliable results of rock properties and showed large relative errors, ranging from 23% to 1146%. It is suggested that empirical correlations must be investigated separately for different types of rocks. The general empirical equations should not be used for the design and planning purposes before they are verified at least on one rock sample from the project site, as they may contain large unacceptable errors.

1. Introduction

In rock mechanics, ultrasonic pulse wave velocity tests are becoming very popular due to their non-destructive nature, high precision and low cost. Three types of sonic velocity methods are available: ultrasonic technique, low frequency sonic wave technique and frequency resonant technique (Soroush and Qutob, 2011). Among these methods, the ultrasonic technique is the most convenient to be used in rock mechanics. In this technique, transition time of a traveling elastic pulse wave is measured between two points in a core plug, and thus the compressional and shear waves (P- and S-wave) velocities can be calculated. This technique is frequently employed to investigate certain properties of rocks.

There are a number of factors that influence the ultrasonic pulse wave velocity of rocks, e.g. density, rock type, shape and grain size, porosity, anisotropy, pore water, confining pressure, temperature, and rock mass properties. In addition, weathering, alteration zone, bedding planes and joint properties (filling materials, roughness, water, dip and strike, etc.) also influence the sound velocity (Fener, 2011).

The relationships between P-wave velocity and other rock properties have been investigated by various researchers. The transition time of the waves depends on the density of minerals forming the rocks (Birch, 1961). The relationship between the wave velocity and the density of rocks is usually considered to be linear (Youash, 1970). Relationships between compressional and shear wave velocities in elastic silicate rocks have been studied by Castagna et al. (1985). They concluded that the shear wave velocity is linearly related to the compressional wave velocity for both water saturated and dry elastic silicate sedimentary rocks. The wave velocity also depends on the porosity (void proportion and pore size distribution), and the possible anisotropic arrangement of the particles forming the material (Gaviglio, 1989). Study of measurements of ultrasonic wave velocity in volcanic rocks and its correlation with micro-texture was carried out by Vanorio et al. (2002). The relation between the uniaxial compressive strength (UCS) and the laboratory P-wave velocity of sandstones was analyzed by Chary et al. (2006), and a good correlation was found between the UCS and P-wave velocity. Fener (2011) studied the effect of rock sample dimension on the P-wave velocity. Rodríguez-Sastre and Calleja (2006) calculated the elastic modulus of slates from ultrasonic wave velocity measurements. Results of the study showed a good linear correlation between the increase in the inclination angle of the foliation and the dynamic elastic constants, but this was less marked for Poisson's ratio (μ). Good correlations between

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P-wave velocity, porosity and density were found by Rahmouni et al. (2013). Khandelwal (2013) investigated the relationships between different physico-mechanical properties of various rock types and the P-wave velocity. He concluded that the empirical equations are practical, simple, and accurate enough to be used in general practice to obtain important static physico-mechanical properties of different rocks for the design and planning of excavation with greater safety and stability. Effect of core size on the ultrasonic pulse wave velocities of dry and saturated limestone samples was studied by Ercikdi et al. (2016). It shows that the ultrasonic pulse wave velocities of limestone samples change with increasing sample size, and the dry samples produce consistently 1.03–1.46 times higher ultrasonic pulse wave velocities than the saturated samples at greater sample lengths (75 mm, 100 mm and 125 mm). Wang et al. (2016) studied the correlation between the dynamic and static elastic parameters of rock. They found that the dynamic Young's modulus was greater than the static one under the same condition, and a linear correlation was found between the static and dynamic Young's moduli. Nourani et al. (2017) studied the classification and assessment of rock mass parameters in Choghart iron mine using P-wave velocity. The results showed that the rock mass rating (RMR) and Q values have a close relation with P-wave velocity parameters, including P-wave velocity in field (V_{PF}), and P-wave velocity in laboratory (V_{PL}).

The relationships between the P-wave velocity and rock density and modulus of elasticity have been extensively investigated. It was reported that the rock density increases as the velocity increases, and an exponential relation exists between the density and the elastic parameters. It was also noticed in some of the previous studies that the rocks have all been subjected to the same statistical analysis, regardless of the differences in their geological origins.

The present study aims to understand the correlations between elastic wave velocities and some of the physico-mechanical properties of quartz-mica schist (QMS) metamorphic rocks only. Moreover, attempt has been made to estimate the static elastic constants of the rocks from the dynamic elastic constants measured with the ultrasonic technique. The main objective is to investigate the possibility of replacing the ordinary destructive tests (such as UCS) with non-destructive methods to determine the physico-mechanical properties of rocks.

First, the relationships between the pulse waves (P- and S-wave) velocities and the physico-mechanical properties of QMS rock are investigated using the simple regression analysis. All the data are then subjected to multiple regression analysis. Some empirical equations with high correlation coefficients are derived and the results are also compared to the values obtained from the empirical equations given by other authors.

2. Sampling of data and methods

Thirteen QMS rock samples of 54 mm in diameter, collected from a project at Himachal Pradesh, India, are used in this study. The relationships between P- and S-wave velocities and rock density, porosity, UCS, and static and dynamic moduli of elasticity are investigated. All these tests are carried out in accordance with the International Society for Rock Mechanics (ISRM) suggested methods (Bieniawski and Bernede, 1979).

2.1. Test procedures

2.1.1. Identification of water-related properties

(1) Bulk density (dry/saturated), water content (saturated) and apparent porosity

Representative samples of rock blocks, weighing approximately 5–15 g, are selected. The minimum size of each block is such that its minimum dimension is at least ten times the maximum grain size. Each block produces at least two samples. Each sample is brushed to remove loose material. The samples are placed in a container, dried in oven to a constant mass at temperature of 105 °C, and then cooled for 30 min in desiccators. Subsequently, the mass (A) of the oven-dried sample is determined, and the bulk volume (V) of the sample is measured using the mercury-displacement method. The mercury adhering to the sample is carefully removed, ensuring that no fragments are lost.

A special saturation chamber is used to saturate the samples, in which the samples are kept immersed in water and vacuum is applied for a period of 6 h. Then the mass (B) of the saturated samples is determined. The above steps are repeated for each sample, and the properties are computed as follows:

$$\rho_{dry} = A/V \tag{1}$$

$$\rho_{sat} = B/V \tag{2}$$

$$w_{sat} = \frac{B-A}{A} \times 100\% \tag{3}$$

$$\eta_a = \frac{B-A}{V} \times 100\% \tag{4}$$

where ρ_{dry} and ρ_{sat} are the densities of dry and saturated samples, respectively; w_{sat} is the water content at saturation; and η_a is the apparent porosity.

(2) Grain density

The mass (C) of a clean dry specific gravity (grain density) bottle plus stopper is determined. The bottle is filled with kerosene oil (which is non-reactive with the rock) and is brought to equilibrium temperature in a constant temperature bath, and the liquid level is adjusted accurately to 50 mL mark. Then the specific gravity bottle is removed from the constant temperature bath, the stopper is replaced and its mass (D) is determined. The specific gravity bottle is emptied and dried.

The samples of a given rock block, weighing 30–50 g, are crushed together, and ground to a grain size not exceeding 150 μm, and then oven-dried. Two representative samples with each of the pulverised material of about 15 g are selected and added to separate the bottle with the aid of a funnel (in other words, each sample is tested in duplicate). The mass (E) of the "bottle + sample + stopper" is determined.

Sufficient kerosene oil is added to the bottle containing the sample to fill 3/4 of the bottle and thoroughly wet the sample. The specific gravity bottle is then placed in the constant temperature water bath and slowly boiled to remove the air adhering to the particles. Then the bottle is removed from the water bath and cooled, and the kerosene oil is added to adjust the liquid level to 50 mL mark. The mass (M) is determined.

The above steps are repeated for each pulverised sample. The grain density (in g/cm^3) is computed as follows:

$$\rho_{grain} = \frac{0.8(E-C)}{(D-C)-(M-E)} \tag{5}$$

where 0.8 g/cm^3 is the density of kerosene oil.

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