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Transmission of elastic waves through a frictional boundary

Resmi Sebastian *, T.G. Sitharam

Department of Civil Engineering, Indian Institute of Science, Bangalore, India

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ABSTRACT

Incident energy gets transmitted, reflected and absorbed across an interface in jointed rock mass leading to energy dissipation and alteration of waves. Wave velocities get attenuated during their propagation across joints and this behavior is studied using bender/extender element tests. The velocity attenuation and modulus reduction observed in experimental tests are modeled with three dimensional distinct element code and results are validated. Normal propagation of an incident shear wave through a jointed rock mass cause slip of the rock blocks if shear stress of wave exceeds the shear strength of the joint. As the properties of joint determine the transmission of energy across an interface, a parametric study is then conducted with the validated numerical model by varying the parameters that may determine the energy transmission across a joint using modified Miller's method. Results of the parametric study are analyzed and presented in the paper.

1. Introduction

Characteristics of rock joints play an important role in wave propagation in rock mass and dynamic waves get attenuated/altered when they pass across joints due to energy dissipation. Modulus reduction that happens due to the presence of joints in a rock mass [1] in a dynamic analysis is of great concern. Knowledge of wave propagation across joints is important in attenuation studies of earthquake engineering and Miller [2] developed an analytical method that is an approximation to various nonlinear models, to quantify the transmission, absorption and reflection of energy incident on the interface. Energy dissipation and slipping of rock blocks occur during the passage of energy across interfaces. Effects of the plane boundary on the propagation of an elastic wave have been a subject of interest for researchers ([2–9]) and influence of interfaces on energy transmission in a jointed rock mass has been studied by theoretical and analytical methods.

Numerical methods have an edge over other methods by providing a simple and a convenient method of solving a problem. Several researchers ([10–12]) have attempted to model the energy propagation across joint using UDEC software, which is a two dimensional distinct element code. Perino [13] and Deng et al. [14] have modeled energy propagation in jointed rocks using 3DEC software. The study conducted on propagation of an energy wave across interface in jointed rocks using experimental and numerical methods is described here. The reduction of shear wave velocity and compression wave velocity across jointed rock blocks is studied with the help of bender/extender elements using jointed Plaster of Paris (POP) samples. Experiment using bender/extender elements is numerically simulated using 3DEC software. A comparison of the S wave velocities and P wave velocities obtained using actual experimental and numerical (3DEC) methods is performed and results are validated. Parametric studies are then conducted on the validated 3DEC numerical model to study the influence of joints and rock material on shear wave velocity reduction and energy transmission, using modified Miller's method.

2. Experimental study

Bender/extender elements are piezoelectric transducers that are used to measure the low strain moduli of geo materials. A piezoelectric material changes its shape when an electric field is applied and generates an electric potential when it is subjected to mechanical deformation. Elastic or small strain measurements are obtained by generating a pulse at one end and detecting the same at the other end by means of the transducers installed on both ends of sample. Many researchers [15–19] used bender elements for testing soil samples at laboratory. Arroyo et al. [20] and Pineda et al. [21] used bender elements for testing rock samples. Bender/extender transducers that can measure S-wave and P-wave velocities are available in series and parallel versions. Series version is a better receiver and parallel, a better transmitter. Bender/extender elements provided by GDS instruments are installed with Resonant Column Apparatus in our lab.

* Correspondence to: Geotechnical Engineering Division, Department of Civil Engineering, Indian Institute of Science, Bangalore-12, India.
Tel.: +91 9986992070.
E-mail address: resmisebastian@gmail.com (R. Sebastian).

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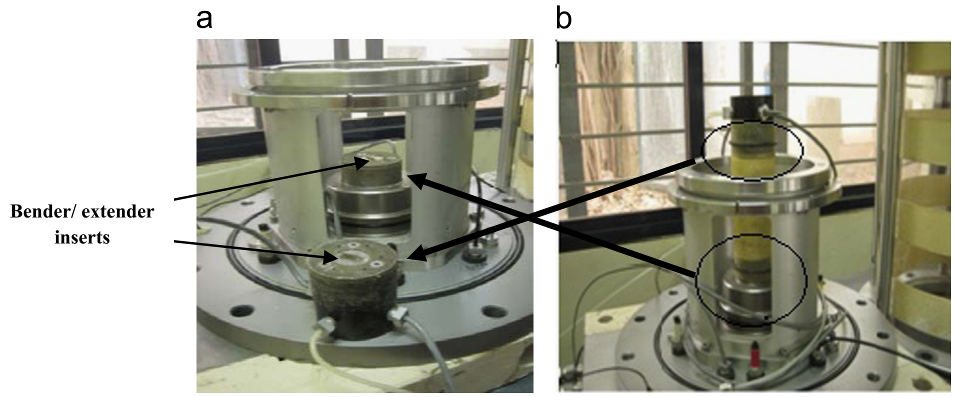

Fig. 1. (a) Bender/extender elements installed in RC Apparatus used in the study, (b) Sample with element inserts in place.

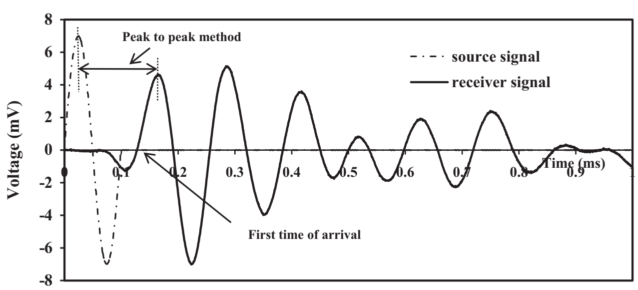

Fig. 2. First time of arrival method and peak-to-peak method.

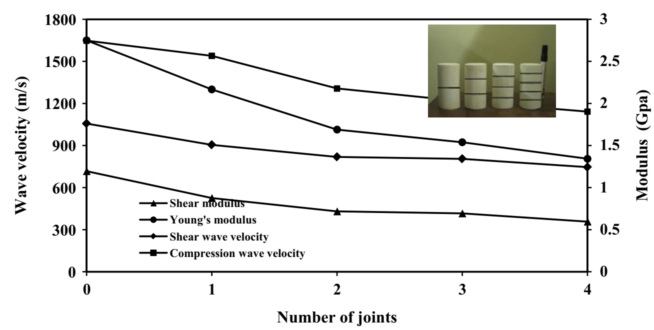

Fig. 3. Velocity reduction and modulus reduction in jointed samples with increase in numbr of joints.

The combined P and S-wave transducers have two element insets (shown in Fig. 1(a)) which are wired differently (polarization – same and opposite) to produce S and P-waves.

Bender/extender element tests were conducted on Plaster of Paris (POP) samples of 50 mm diameter and 100 mm length. POP specimens were prepared by pouring the plaster mix into a casting mold of 50 mm diameter and 100 mm length. Samples attained constant weight in 12–14 days when kept for drying in room temperature and normal humidity conditions. Then, joints were made on POP samples with the help of a cutter. Two grooves were necessary on ends of samples to position transducers and cavity was filled with silicone grease to ensure good coupling. Receiver and source transducers were to be in phase for testing. Frequencies of the input wave could be varied; and the maximum frequency that could be attained in our equipment was 10 kHz. Significance of frequency in determining arrival time of the shear wave and on near field effects have been studied by various researchers ([16,19,22–25]). The usage of a high frequency sinusoidal wave reduced the near field effect and produced clear signal for our experiments on POP samples. Hence 10 kHz was selected for the analysis and was maintained throughout the experiments. Sample with element inserts in place, are shown in Fig. 1(b). A nominal confining pressure of 100 kPa was applied to hold the sample in place. The test was done by triggering a wave at the source transducer and both waves, source and receiver, could be monitored in an oscilloscope with time and amplitude of waves as axes. From the source and receiver waves, travel time of the waves could be obtained and the methods to obtain the travel time of waves are explained below.

2.1. Measuring the travel time

The travel times of the sinusoidal wave were obtained by three popular methods, peak to peak method, first time of arrival method and cross correlation method ([19, 22,23]). In the peak-to-peak method, the time difference between the peaks of receiver and source waves are obtained. The first time of arrival is the time at which the receiver wave starts to get detected in oscilloscope, *i.e.* the time at which the receiver wave starts to rise above the axis of time. (First two methods are shown in Fig. 2). The time shift corresponding to the maximum value of the cross correlation function of source and receiver waves is considered as the time of travel in a cross correlation method.

A pulse was generated to calibrate the system by keeping the transducers 'face to face'; and travel time was measured to obtain the delay introduced by ceramics and electronics. Deduction of the equipment generated delay from the detected travel time is necessary to obtain the actual travel time of the shear wave/compression wave through the material. Wave velocity through the material is directly obtained from the travel distance of wave and the time of travel. Shear modulus of the material is obtained from

$$G=\rho V_s^2 \tag{1}$$

where ρ is the mass density of material, V_s is shear wave velocity, G is the shear modulus of material, and Young's modulus of the material, E, is computed from

$$E=\rho {V_s}^2(3V_p^2-4V_s^2)/(V_p^2-V_s^2) \tag{2}$$

where V_p is the compressional wave velocity through material. From V_p and V_s of the intact sample, Poisson's ratio was obtained and bulk modulus of material was calculated for substituting in numerical model. Jointed POP samples and velocity reduction and modulus reduction of samples with increase in number of joints are shown in Fig. 3.

3. Numerical study using 3DEC software

3DEC is a three-dimensional Distinct Element Code intended for numerical modeling of rock engineering projects. The software