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A testing procedure for determining ultrasonic wave velocity

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ABSTRACT Numerous studies have been performed to apply the ultrasonic wave velocity (UWV) as a fast and non-destructive method to determine required parameters in different engineering fields. During this laboratory study, an ultrasonic testing apparatus was designed to provide accurately the standard conditions of UWV method. This apparatus consists of one holder bench, some steel rods, one load ring, and some other accessories. It properly holds the sample and applies a stress equally distributed to the entire samples during ultrasonic tests, which makes similar, uniform, and controlled conditions and, thus, more consistent results would be possible. The pressure and shear wave velocities of 500 specimens were measured manually and by using the designed testing apparatus. The results show that wave velocities obtained by testing apparatus were higher and more accurate in comparison to manual methods. More precisely, the difference between P-wave velocities gained from two methods was on average of 52 and 93 m/s for intact and rock mass specimens, respectively. The discrepancy in S-wave velocities was higher and reached on average 68 and 101 m/s.

Key words: ultrasonic wave velocity, ultrasonic testing apparatus, test accuracy.

1. Introduction

Ultrasonic testing is commonly used in different fields such as civil, mining, geotechnical, and rock engineering. These techniques are non-destructive and easy to apply both in site for geophysical investigations and in laboratory for the determination of the dynamic properties of rocks (Rummel and Van Heerden, 1978; ASTM D2845-00, 2000; Kahraman, 2002a, 2002b; Ersoy and Atici, 2007; ISRM, 2007; etc.). In this test, the velocities of either P- or S-waves (V_P and V_S) are calculated from the measured travel time and the distance between transmitter and receiver. According to the standards provided (ASTM D2845-00, 2000; ISRM, 2007, 2014), this test can be carried out according to some methods, and the requirements must be met in each method, including preparation conditions and the dimensions of sample, the type of ultrasonic devices, frequency range, etc. Additionally, many comprehensive studies have been done on how to propagate the ultrasonic wave, the best frequency range according to the purpose of the test, the type of samples, test ambient conditions, etc. (Long, 2000; Madenga *et al.*, 2006; Vasconcelos *et al.*, 2008; Fener, 2011; Li *et al.*, 2011; Huang *et al.*, 2014; Perino and Barla, 2014; Karaman *et al.*, 2015; Fathollahy *et al.*, 2017). Nevertheless, some required and important details have not been investigated. A point emphasised in the above-mentioned standard methods is that the transducers must be pressed to the centre of a plane normal to the direction of wave propagation by a stress of about 10 N/cm^2, which leads to improve ultrasonic wave transmission between the transducers and the test specimen. However, there is no instruction or apparatus (including how to apply this stress or how to fix samples) in the standards or literatures. Therefore, a testing apparatus was designed.

1.1. Novel testing apparatus and procedure

The testing apparatus consists of one holder bench, some steel rods, one load ring, and some other accessories. It properly holds the sample and applies a stress equally to the entire samples during ultrasonic tests. Hence, the human errors such as variable and unequal stresses (pressing transducers to samples) caused by operator fatigue over time or switching operator and the slipping or movement of samples are avoided. By using this apparatus, the ultrasonic wave velocity (UWV) test is very simple and convenient and it is easily possible to provide similar, uniform, and controlled conditions with all specimens and to give more reliable results during the tests. A detailed description of the apparatus is presented below.

1.1.1. Sample holder bench

To measure the wave velocity of rock cores, it is necessary to put them in a fixed place and therefore the test can be carried out with more accuracy and less time. To do this, the sample holder bench was designed. As shown in Fig. 1, by positioning rock cores on this bench, they are fixed and no movements are allowed during the ultrasonic test.

1.1.2. Steel rods

To optimize energy transmission between the transducers and the sample under test, it is necessary to apply a stress of about 10 N/cm^2 for pressing transducers to the centre of sample during the ultrasonic test. In order to apply this stress, the steel rods and rotary handle are needed (Figs. 1 and 2). The steel rods have different lengths; hence, according to the different lengths of samples, changing the total length of the rods on both sides of apparatus for the operator is easily possible. There are also three height adjustment screws embedded in three steel columns to adjust (regarding the different diameters of samples) the rod to the centre of samples for applying the required stress.

1.1.3. Load ring

As shown in Figs. 1 and 2, a load ring made of steel, with the external diameter of 220 mm and 5 mm wall thicknesses was used to measure and control the applied stress during the tests. In order to define the embedding strength and resolution of the load ring, calibration was conducted. It should be noticed that the resolution of the ring may be changed by using different material, such as PVC, and different wall thicknesses. All tests carried out in present research used a 5 mm wall thickness load ring.

1.1.4. Transducer holder accessory

Four transducer (two pairs) holders were created to hold P- and S-wave transducers during ultrasonic tests. As illustrated in Fig. 2, a pair of them are used for P-wave transducers, and the other pair are applied for the S-wave transducers. There is a tail in the back of the holders, by

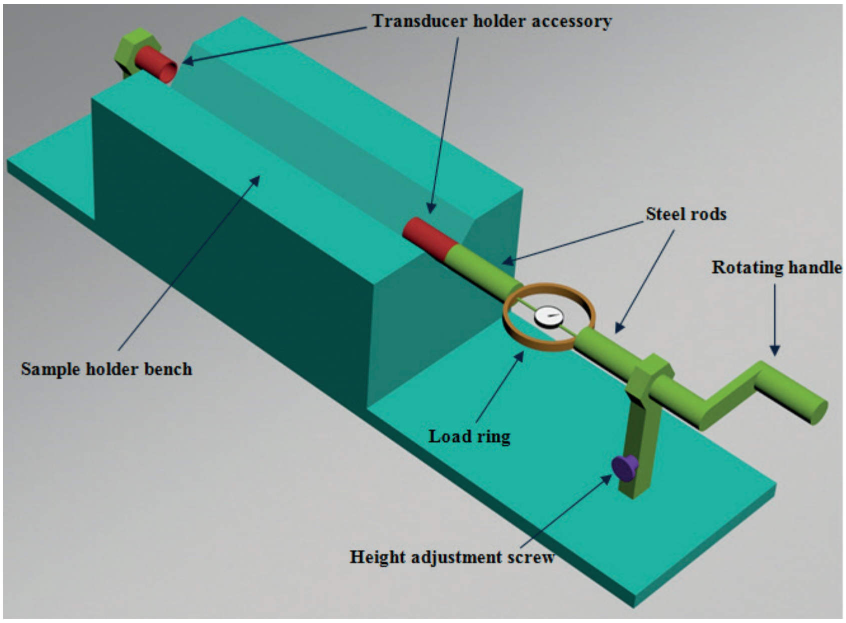

Fig. 1 - Scheme of the ultrasonic testing apparatus designed.

which the steel rods are attached to them. The holders were made of high strength polyamide to transfer a stress of about 10 N/cm^2 from steel rods to transducers. In addition, they are non-conductive (unable to receive and transmit the waves); thus, there will be no wave dispersion and attenuation by them. During the test, a pair of transducers (S or P) are located in their holders and, through two holes at the end of the holders, the Pundit Lab device connects them to the transducers by the interface cable.

1.1.5. Measuring instruments

The measurements of V_P and V_S were carried out with an ultrasonic instrument (Pundit Lab / Pundit Lab+) manufactured by Proceq that complies with many standards [EN 12504-4 (Europe), ASTM C597-02 (North America), BS 1881 Part 203 (UK), ISO1920-7:2004 (International), IS13311 (India), CECS21 (China)]. The device includes two transducers (a transmitter and a receiver) providing ultrasonic waves. Each transducer pair used in this research had a nominal frequency of 54 kHz for P-wave and 500 kHz for S-wave (Fig. 3). According to the measurement principle, the transducers should be applied on the two parallel faces of a rock specimen having a determinate length (L) and trigger a series of ultrasound pulses. The device calculates the time interval (t) between the start and reception of the pulses. The ultrasonic pulse time was measured with an accuracy of 0.1 µs. The V_P and V_S in the specimen are calculated from the simple relation (V_P or $V_S = L/t$) and they are expressed in m/s (Proceq, 2014).

2. Materials and specimen preparation

The rock samples were selected from the Tuff units of Cambrian-Ordovician in the centre of Iran. Approximately 500 homogenous core samples of boreholes were cut and prepared for laboratory tests. The end surfaces of specimens were polished sufficiently and smooth to

Fig. 2 - The ultrasonic apparatus prepared for testing (a), height adjustment screw (b), rotary handle (c), the steel rods with different lengths and transducer holders (d).

Fig. 3 - Pundit Lab device and P- and S-wave transducers.

provide good coupling and receive the stress orthogonally. The direct-transmission transducer configuration requires test specimens with smooth (using fine sandpaper), flat (specified by a maximum gap size between specimen surface and standard straightedge, which accommodates <0.025 mm thick feeler gage), and parallel (<1/100 of wave travel path length) faces (Aydin, 2014). Specimens can be tested dry or fully saturated or at *in situ* moisture content. It should be noted that a total of 500 core specimens, having different lengths (10 to 50 cm) and a diameter of 61 mm, were used in these experiments.

3. Experimental procedure and methods

In the laboratory, direct, semi direct, and indirect methods could be performed for UWV measurement. The direct procedure known to be the most reliable and satisfactory method was performed in the tests, during which the receiver and transmitter must be positioned on the opposite cut end surfaces of the samples used. The UWV was obtained by dividing the length of the sample core and the travel pulse time. A mean UWV value was achieved by averaging the values of five tests on the same lithology type (Karaman *et al.*, 2015).

Ultrasonic pulse method for the ultrasonic testing was performed using the Pundit Lab+ model equipment. A calibration rod with a known velocity or a known transit time should be used to regularly monitor any drift in the measured values. The Pundit Lab should be zeroed using the calibration rod on a regular basis and in particular if the transducer frequency is changed or if the cables are changed. The expected calibration value (usually μs) is marked on the calibration rod. A thin layer of ultrasonic gel (couplant) was put on the surface of the transducers (receiver and transmitter) so as to provide full contact and to remove the air gap between transducers and the calibration rod or specimen surface.

Firstly, the transducers were positioned inside transducer holder accessory and were coupled to the calibration rod putting on sample holder bench by applying couplant to the transducers and both ends of the rod. The rod was subjected to a stress of about 10 N/cm^2 (adjustable and controlled via load ring) by rotating handle, as shown in Fig. 4. Then the "start" button of Pundit device was pressed to transmit and receive the wave and to make the calibration sequence. The display showed the given transit time and below it the measured transit time. This must match the value on the calibration rod (25.4 and 50.6 μs for used P- and S-waves transducers, respectively). After calibrating the apparatus and before putting each specimen on holder bench, the distances (path or specimen length) between the transducers were measured as accurately as possible and, then, they were given to the Pundit device. The remainder of the procedure, including using couplant, coupling, and applying the stress, was the same as for the calibration rod. Finally, by pressing the "start" button, the Pundit device begun to transmit and receive the wave and then wave velocity and transit time for each specimen were displayed (Proceq, 2014). When measurements with the 500 kHz S-wave transducers are performed, it is crucial to use the special S-wave couplant; otherwise S-wave cannot be properly transmitted into the specimen under test. The S-wave couplant is a non-toxic, water soluble organic substance of very high viscosity.

The measurements of UWVs were performed according to the ASTM recommendation. Regarding the measurements of UWV in natural stones (ASTM D2845-00, 2000), the recommendations of standard suggested methods, including sample dimensions, used frequency, applied stress etc. were followed. To confirm the accuracy of the results, the tests of two methods were repeated at least 4 times on each sample to reach the arithmetic average which would be considered as the UWV of each sample.

Fig. 4 - Applying the required stress by rotating handle.

4. Results and analysis

In order to obtain the exact results as well as the best comparison, the UWVs (pressure and shear) of all 500 specimens were achieved manually and by using the designed testing apparatus described above. In this regard, first, the P-wave velocities were measured in all core specimens. Then, S-wave transducers were installed to the Pundit Lab device and the measurement of S-wave velocities was performed. Meanwhile, some effective factors, such as specimen fractures and natural joints, have been carefully considered. Accordingly, the samples were divided into two groups; intact rock and rock mass. A summary of the results is presented in Tables 1 and 2. According to the data, the P- and S-wave velocities of specimens were increased by using the designed testing apparatus, in comparison to manual method. By repeating the experiments and regarding the provision of similar, uniform, and controlled conditions, it could be concluded that results achieved by using the apparatus are more accurate and consistent. On the other hand, some human errors may occur during manual tests and, consequently, motivate the difference between wave velocities obtained from two methods. The discrepancy between these two methods exceeds 15% of wave velocity value. It should be emphasised that, in addition to the slipping or movement of samples, applying variable and unequal stresses (pressing transducers to samples) caused by operator fatigue over time or switching operator were agents which largely made some errors in the results.

Table 1 - The P-wave velocities in some of the studied samples.

Row		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Intact rock	Manual	5265	5081	5550	5238	5546	5141	5319	5322	5458	5366
	By apparatus	5324	5144	5620	5286	5572	5183	5345	5365	5525	5404
Row		P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
Rock mass	Manual	4968	4855	4575	4811	4631	4690	4642	4731	5009	4915
	By apparatus	5027	4897	4723	4932	4904	4776	4812	4862	5096	4952

Table 2 - The S-wave velocities in some of the studied samples.

Row		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Intact rock	Manual	2406	3036	2532	2780	2668	2559	2448	3165	2589	3288
	By apparatus	2485	3141	2563	2856	2785	2684	2491	3277	2705	3344
Row		S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
Rock mass	Manual	2638	2304	2592	2117	2495	2577	2280	2894	2347	2708
	By apparatus	2792	2487	2661	2210	2603	2674	2394	2955	2449	2812

To compare easily the results achieved from manual method with those obtained by the testing apparatus in a more understandable way, the mean values of UWV were calculated in each method as listed in Table 3. Additionally, all data were illustrated in Figs. 5 to 8. As it can be seen from Table 3 and Fig. 5, the difference between P-wave velocities obtained from two methods was on average 52 m/s in the intact specimens. It was higher in the rock mass specimens and reached an average value of 93 m/s (Fig. 6). It seems that using the testing apparatus had more effect on the rock mass specimens. More precisely, the constant and equal stress applied by the apparatus probably leads to further improvement (decrease in wave attenuation) in the passage of ultrasonic wave through the rock mass specimens and, therefore, such discrepancy between two methods was yielded.

Table 3 - The mean values of the UWVs of the studied samples.

-	Mean UWV value (m/s)			
The type of wave	P-wave		S-wave	
Method	Manual	By apparatus	Manual	By apparatus
Intact rock	5350	5402	2639	2707
Rock mass	4729	4822	2510	2611

In the case of S-wave velocities, a roughly similar trend was observed in the results, as shown in Table 3. In this regard, the mean values of 68 and 101 m/s were obtained as the difference between two methods in the intact and rock mass specimens, respectively, as depicted in Figs. 7 and 8. The higher discrepancy in the rock mass specimens had same reason in P- and S-wave velocities tests.

Another important point to be noted here is that the difference between the two methods was higher in S-wave velocities compared to P-wave velocities. It may be explained by the fact that due to the sensitivity and more attenuation of S-wave, the test conditions can make a

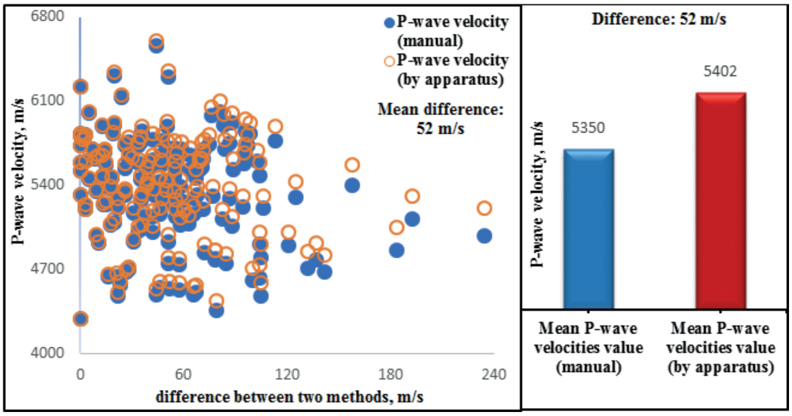

Fig. 5 - P-wave velocity versus difference in P-wave velocities between two methods for intact rock specimens.

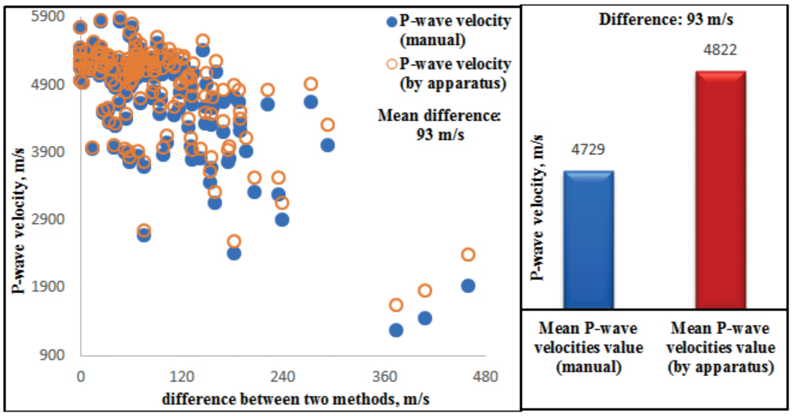

Fig. 6 - P-wave velocity versus difference in P-wave velocities between two methods for rock mass specimens.

significant discrepancy in the results. Hence, changing the test conditions and, then, occurring the measurement errors in manual method probably had a greater effect on S-wave velocities in this study (Figs. 7 and 8).

Generally, it can be found that the manual method gave us the less stable and accurate results, due to the possibility of changing the conditions during the tests. On the other hand, the similar, uniform, and controlled conditions during UWV tests, provided by the testing apparatus, usually led to consistent and reliable results, in agreement with the findings of Long (2000) and Perino and Barla (2014).

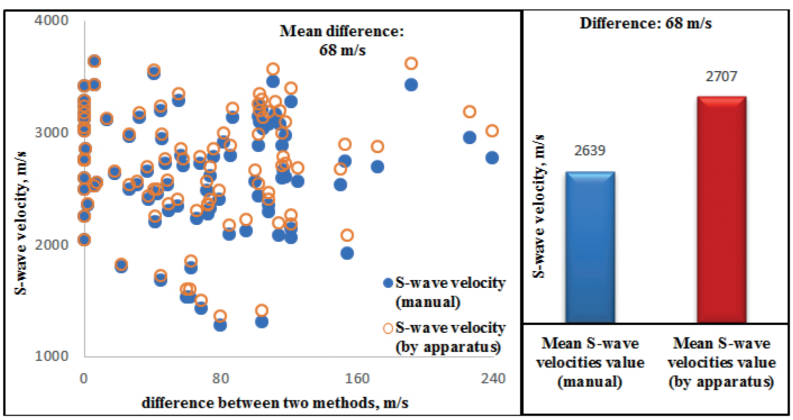

Fig. 7 - S-wave velocity versus difference in S-wave velocities between two methods for intact rock specimens.

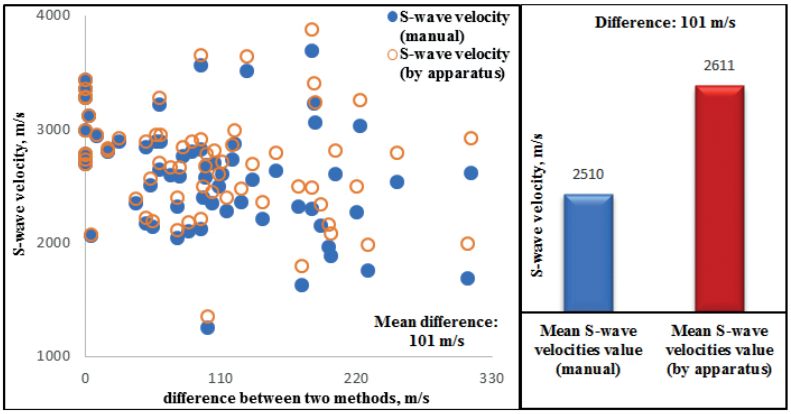

Fig. 8 - S-wave velocity versus difference in S-wave velocities between two methods for rock mass specimens.

As stated in the introduction, this apparatus makes the UWV test easy and there is no need for complex equipment and time-consuming processes. Unlike the previous tools, this apparatus is very simple and yields a rapid and reliable estimate of the wave velocity in the laboratory. In addition, it is comfortable to carry to the field and accomplish the UWV tests on the collected samples, if required. The other purpose of making this apparatus was to minimise laboratory errors during the UWV tests. In this research, using the apparatus improved the repeatability of results and made the wave velocity testing of rocks more convenient and less messy. Moreover, as the reliability and accuracy of the data improved using this apparatus, it is more feasible to compare these results with the data collected *in-situ*.

5. Conclusions

In this study, the testing apparatus was designed to hold the sample properly and to apply a stress equally to the entire samples during ultrasonic tests. According to the findings derived from the present study, the main conclusions were given below:

- it was feasible to accomplish all UWV tests in terms of the similar, uniform, and controlled conditions. Accordingly, the wave velocities were measured with more consistency and accuracy in comparison to manual method;
- the passage of ultrasonic wave through the specimens (decrease in wave attenuation) was improved owing to apply the constant and equal stress during the test, as P- and S-wave velocities were increased by using the designed testing apparatus, in comparison to manual methods;
- the human and measurement errors, such as applying variable and unequal stresses (as a result of operator fatigue over time or switching operator) and the possible slipping or movement of samples, were avoided during the UWV tests;
- the apparatus had more effect on the rock mass specimens, as it made great improvement on the passage of ultrasonic wave in these specimens;
- results obtained using the apparatus demonstrated that it was useful for measuring S-wave velocity due to its sensitivity and more attenuation of S-waves.

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