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Evaluation of P- wave velocity in different joint spacing

M. Fathollahy[1], A. Uromeiehy[2] and M. Ali Riahi[3]

[1] *Dept. of Earth Science, University of Kurdistan, Sanandaj, Iran*
[2] *Dept. of Engineering Geology, Tarbiat Modares University, Tehran, Iran*
[3] *Institute of Geophysics, Dept. of Earth Physics, Tehran, Iran*

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ABSTRACT P-wave velocity measurements can be used to evaluate the rock mass quality. Multiple factors including joint spacing can potentially affect P-wave velocity. This paper explores P-wave velocity variations as a function of joint spacing in Andesite rock samples. Samples were collected from boreholes from a dam site under construction. Physical and lithological properties of the samples were determined; artificial joints of 2 and 5 cm spacing were also created in the samples. In order to perform measurements of the P-wave velocity in samples, transducers were attached to the both ends of the samples while applying the ultrasonic waves. The results show a good correlation between the wave velocity number of joints and their spacing. They indicate that the decrease of wave velocity depends primarily on the joint spacing rather than the number of joints.

Key words: P-wave velocity, spacing, joint number, Andesite.

1. Introduction

Ultrasonic measurement is one of the non-destructive geophysical methods commonly used by engineers working in various fields such as mining, geotechniques, civil and underground engineering, as well as oil, gas and mineral exploration (Kahraman, 2007; Cha *et al*., 2009; Kassab and Weller, 2015). Ultrasonic measurements have been employed in the field for geophysical investigations and in the laboratory to determine the dynamic properties of rock (Kahraman, 2002a). Since these techniques are cheap, not time consuming and non-destructive, their applications to investigate rock properties are increasing. Ultrasonic techniques have been used in many areas such as the assessment of grouting (Turk and Dearman, 1987), determining blasting efficiencies in rock mass (Young *et al*., 1985), determination of the degree of weathering and fracturing (Carvalho *et al*., 2010), estimation of the fractured zone development around the underground openings (Hudson *et al.,* 1980), monitoring the stability of rock structures (Kaneko *et al*., 1979), assessment of geotechnical properties of some rock materials (Yagiz, 2011), evaluation of geomechanical properties (Yasar and Erdogan, 2004; Sheraz *et al*., 2014), estimation of concrete strength (Hobbs and Tchoketch Kebir, 2007; Trtnik *et al*., 2009), evaluation of joint anisotropy (Kano and Tsuchiya, 2002), and evaluation of rock density (Gardner *et al*., 1974; Gaviglio, 1989).

An approximate relationship between the petro-physical properties of rocks and P-wave velocity (V_P) has been shown by Del Rio (2006) and Khandelwal and Ranjith (2010). Generally, there are two elements affecting the rock behaviour: 1) intrinsic parameters, e.g., mineralogy, porosity, density, water content (saturation degree), and compressive strength, and 2) fracture characteristics, e.g., joint density, texture, roughness, orientation, infilling, and opening. Some investigations were focused specifically on the cracks in the rocks attempting to understand the relation between the P-wave velocity characteristics and the fracture properties. This plays a crucial role in developing a certain number of physical models, showing that the waveform, amplitude and velocity of transmitted waves are greatly influenced by the manner and nature of the fractures, and also by the size, number, thickness, aperture, infilling and other properties of the fractures (Schoenberg, 1980; Fehler, 1982; Sassa and Watanabe, 1995; El Azhari and El Amrani, 2013).

Experimental studies by Kahraman (2002b) on three types of naturally fractured rock (i.e., granite, marble, and travertine) showed that P-wave velocity decreases with increasing fracture roughness coefficient (FRC). Furthermore, values of V_P depend on the hardness of the rocks, assessed by the rebound number of the Schmidt hammer (RN), and number of joints (JN). Results showed V_P decreases with increasing joint number; also the rocks with greater strength showed higher sound velocity index (SVI) (Kahraman, 2001). Altindag and Guney (2005) investigations on the relationships between V_P and joint density (J) confirmed the results of Kahraman (2001), namely the decrease of V_P with an increasing number of joints. Furthermore, they highlighted a good polynomial correlation between the number of joints and the reduction rate in V_P (%), indicating P-wave velocities were rapidly attenuated with increasing joint density. The experimental studies of El Azhari and El Amrani (2013) focused on the two types of building stones (calcarenite and marble); artificial joints created in samples and the diminution of the P-wave were measured as a function of orientation and the number of joints. The results revealed that P-wave velocities diminish and their rate is closely dependent on the number and orientation of the fracture planes (Kano and Tsuchiya, 2002; El Azhari and El Amrani, 2013).

Altindag (2012) reviewed previous studies that had been done on sedimentary rocks. The raw data of 97 samples were subjected to statistical analysis and the relationships between P-wave velocity and physical-mechanical properties were investigated by simple and multi-regression analysis methods.

As mentioned, the seismic methods based on wave velocity have been used in underground exploration for many years. These methods are easier, faster and cheaper than direct (e.g., geotechnic exploration) methods but their results are not as reliable. To augment the precision of the results, all factors (such as opening, roughness, filling, joint density, etc., that affect the P-wave velocity, should be determined.

The aim of this study is to investigate how joint number and spacing affect P-wave velocity. Results of this study inform the general way of wave transmission in rock masses and explain the effect of joint density and joint spacing on P-wave velocity.

2. Study area and rock samples

The rock samples were selected from dark green Andesite units of Eocene in Sanandaj-Sirjan zone in the NW of Iran (Fig. 1), which has been selected as a site to construct a large dam about 120 m high. More than 100 rock core samples extracted from a 10-20-m depth were taken from boreholes around the dam axis. Petrographical and petrophysical techniques in this research as well

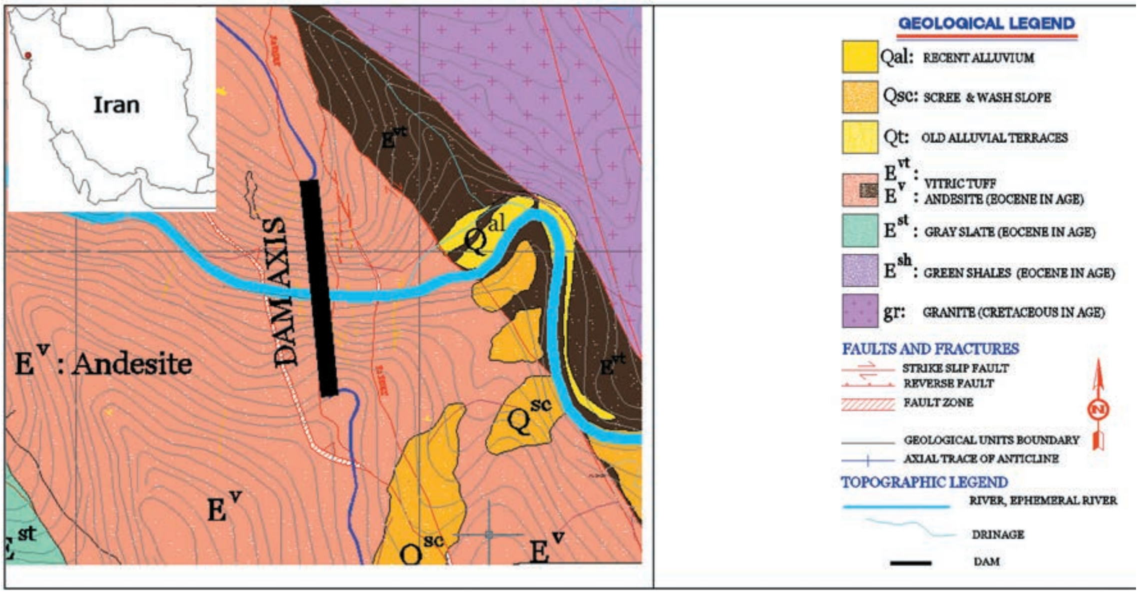

Fig. 1 - Geology map of the study area; the line in the middle of the map shows the dam axis located on the Andesite rock units.

as previous studies were used to determine the rock types. In this research, 12 thin sections were studied to assess the petrographical characteristic, while in previous studies done for planning the construction of the dam, more than 25 samples were studied from petrographical point of view. This Andesite rock unit is made up of igneous rocks that are classified as “good” according to a rock engineering classification (Hoek, 2000). A close view of the surface condition and rock petrographical characteristics is shown in Fig. 2.

3. Measuring instruments

V_P measurements were carried out with an ultrasonic instrument (Proceq Pundit Lab / Pundit Lab+) that complies with many standards [EN 12504-4 (Europe), ASTM C597-02 (North America),

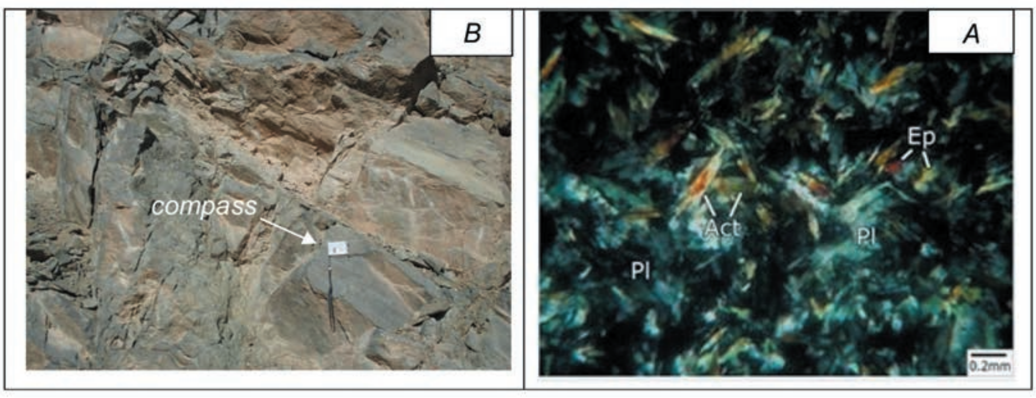

Fig. 2 - Close up view of petrographical characteristics (A) and surface (B) rock condition in the dam axis.

BS 1881 Part 203 (UK), ISO1920-7:2004 (International), IS13311 (India), CECS21 (China)]. The device includes two transducers (a transmitter and a receiver) that generate the ultrasonic waves (54 kHz). According to the standard, the transducers should be applied on the two parallel faces of a rock specimen having a determined length (*L*) and trigger a series of ultrasound pulses. The device calculates the time interval (*t*) between the start and the reception of the pulses. The V_P in the specimen is calculated from the simple relation ($Vp = L/t$) and it is expressed in m/s.

4. Experimental works

4.1. Sample preparation and determination of physical properties

Samples were prepared by selecting sound samples in boreholes, cutting, and smoothing their ends. In order to determine their physical properties, the relevant tests were done according to ISRM standards (porosity was detected by saturation methods). Table 1 shows the physical properties of the rock samples.

4.2. Sound velocity tests

Initially, P-wave velocities were measured in the direction parallel to the core axis and then artificial joints were generated by cutting each sample perpendicular to the core axis (by diamond bladed saw) and coupling the samples.

Table 1 - Physical properties of rock samples.

Row	Saturated density (g/cm^3)	Dry density (g/cm^3)	Porosity (n%)	W% (water absorption)
1	2.89	2.88	0.82	0.29
2	2.90	2.89	0.97	0.33
3	2.92	2.90	1.12	0.39
4	2.92	2.91	0.97	0.33
5	2.93	2.92	1.27	0.43
6	2.95	2.94	1.37	0.46
7	2.95	2.94	1.04	0.35
8	2.95	2.94	1.05	0.36
9	2.97	2.96	1.07	0.36
10	2.97	2.96	0.84	0.28
11	2.98	2.97	0.97	0.33
12	2.98	2.97	0.97	0.33
13	2.92	2.90	1.12	0.39
14	2.95	2.94	1.04	0.35
15	2.93	2.92	1.27	0.43
16	2.90	2.89	0.97	0.33
17	2.92	2.91	0.97	0.33
18	2.89	2.88	0.82	0.29
19	2.97	2.96	1.07	0.36

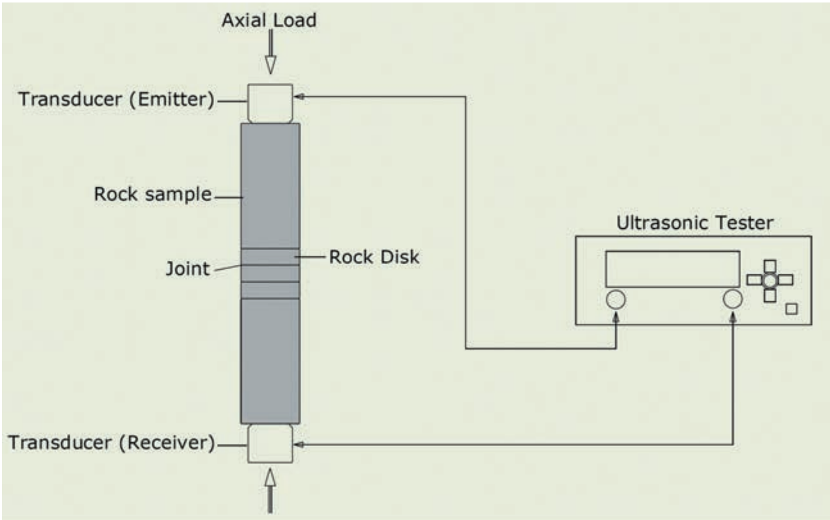

Fig. 3 - V_P measurement on samples in laboratory.

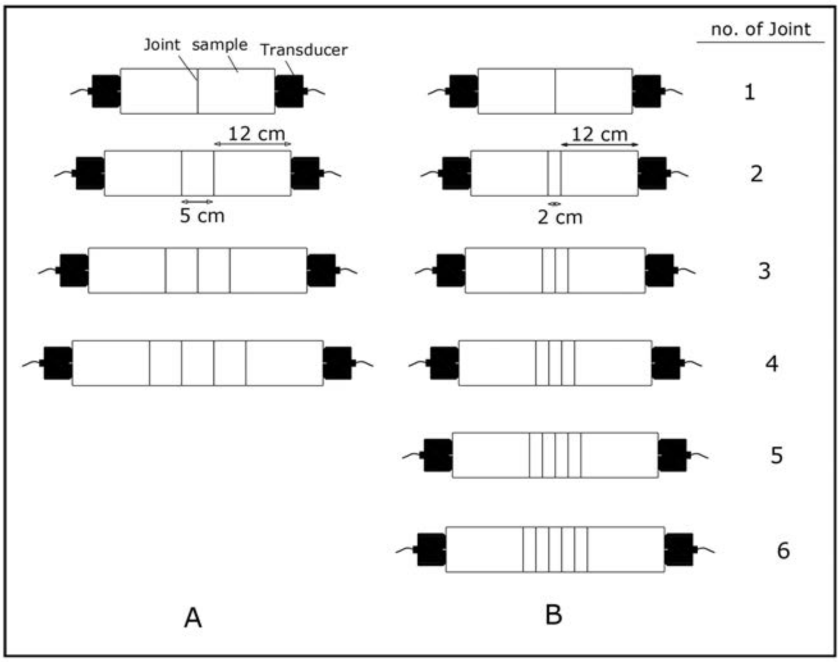

Fig. 4 - Increasing joints with different spacing in one set of samples.

After cutting the intact sample in half, the samples were placed in 5 cm pieces and velocities were measured, then 2 cm pieces were produced and placed between the two samples and testing was repeated. Meanwhile, the main samples were uniform at all stages of testing and, thus, their characteristics were maintained. Only the effect of increasing the number of joints with different spacing has been assessed.

Joints were increased by adding disk shape samples from the same rock sample with lengths of 5 and 2 cm between the two parts of cut samples (Figs. 3 and 4).

The procedure was repeated for 9 sets of Andesite samples and 2 sets of Teflon as a control sample under laboratory conditions and applying 0.1 MPa Axial loading. Measurements of V_P were performed according to the ASTM standard [measurements of ultrasonic wave velocities in natural stones (D 2845-00) (ASTMA 2000)]. In this regard, a precaution has been taken to ensure a better quality of the measurement: ultrasonic couplant (part: 710 10 031, Part and Accessories of Unit, Punditlink_ENU) was applied between the transducers and specimen to minimize wave loss at the interface.

The joints were created with the utmost precision in cutting and smoothing, though ultrasonic couplant was still applied at the interface of joints to obtain a better connection between joint surfaces. Regarding the smoothness of joint, couplant thickness is negligible. Due to the small thickness of the gel, its impact on speed is negligible. However, even if there is any effect, this is the same in all tests, so that the total effect is null.

5. Andesite rock samples

As above mentioned, sound velocity tests were carried out on the sets of samples (Table 2). The results show decreases in the P-wave velocity by increasing the joint number in all sets. Fig. 5 shows P-wave velocity versus increasing joints with different spacing in 2 samples.

To evaluate the variation of P-wave velocity by increasing the joint number with different spacing, the velocity reduction ratio (*VRR%*) was defined as a ratio between the wave velocity deviations of jointed rock and the wave velocity of intact rock:

$$VRR\% = \frac{V0 - V1}{V0} \times 100 \ . \tag{1}$$

Table 2 - Results of V_P measurement on samples.

No. of joint			Samples								
			G1	G2	G3	G4	G5	G6	G8	G9	G16
0	Vp (m/s)		5778	5764	5689	5685	5669	5869	5766	5536	6024
1		Spacing = 2cm	5522	5459	5284	5409	5479	5601	5563	5417	5883
2			5478	5366	5291	5373	5453	5574	5437	5359	5830
3			5430	5321	5246	5340	5408	5520	5404	5346	5764
4			5356	5205	5025	5269	5360	5453	5366	5315	5725
5			5318	5131	4776	5215	5283	5404	5246	5280	5684
6			5256	4976	4358	5136	5139	5260	5105	5177	5430
1		Spacing = 5cm	5522	5459	5284	5409	5479	5601	5563	5417	5883
2			5442	5328	5253	5362	5407	5556	5550	5342	5765
3			5423	5289	5226	5330	5389	5520	5542	5331	5716
4			5394	5275	5199	5287	5356	5473	5522	5308	5685

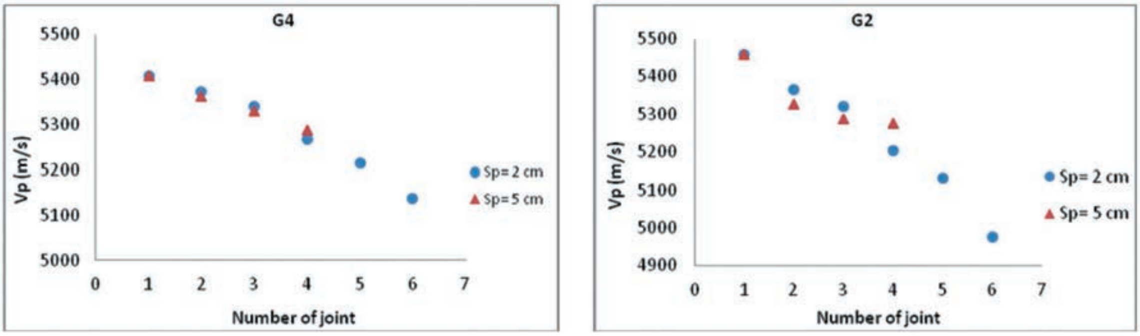

Fig. 5 - P-wave velocity vs. increasing joints with different spacing in two Andesite rock samples.

The results show *VRR%* had an increasing trend for increasing joint number, but the rate is different for the different joint spacings. Table 3 shows the *VRR%* in each steps and Fig. 6 shows the average of *VRR%* versus joint number in all of the Andesite samples.

6. Presentation of results in Teflon (control) samples

As it is known, rock is not a homogenous material. Therefore, to avoid the effect of inhomogeneity on results, the above tests were done on Teflon samples as a control.

Teflon is a relatively homogeneous polymer that is synthetically produced under controlled conditions. Smooth artificial joints can be created in Teflon with great accuracy. Table 4 presents the results of the same joint patterns as had been made previously on rock samples shown in Fig. 4; Fig. 7 shows the variation of *VRR%* versus increasing joint number with 2 and 5 cm spacing.

As can be seen, VRR percentage of the Teflon samples is less than the rock samples. As aforementioned, this criterion calculates the amount of decrease in velocity compared to the intact matter, and since the wave velocity in Teflon is less than of the rock, a smaller VRR percentage is obtained.

Table 3 - P-wave *VRR%* in different joint number.

No. of joint			Samples									VRR% (average)
			G1	G2	G3	G4	G5	G6	G8	G9	G16	
1	VRR%	Spacing = 5cm	4.43	5.29	7.12	4.86	3.35	4.57	3.51	2.15	2.35	4.41
2			5.19	6.91	7.00	5.49	3.81	5.03	5.70	3.20	3.23	5.29
3			6.02	7.69	7.79	6.07	4.61	5.95	6.27	3.43	4.32	5.98
4			7.31	9.70	11.67	7.32	5.45	7.09	6.93	3.99	4.97	7.43
5			7.96	10.98	16.05	8.27	6.81	7.93	9.01	4.63	5.65	8.96
6			9.04	13.67	23.40	9.66	9.35	10.38	11.46	6.49	9.87	11.68
1		Spacing = 5cm	4.43	5.29	7.12	4.86	3.35	4.57	3.51	2.15	2.35	4.41
2			5.82	7.57	7.67	5.68	4.62	5.34	3.74	3.51	4.31	5.49
3			6.15	8.24	8.14	6.25	4.94	5.95	3.88	3.71	5.12	5.91
4			6.65	8.49	8.62	7.00	5.52	6.75	4.22	4.12	5.63	6.42

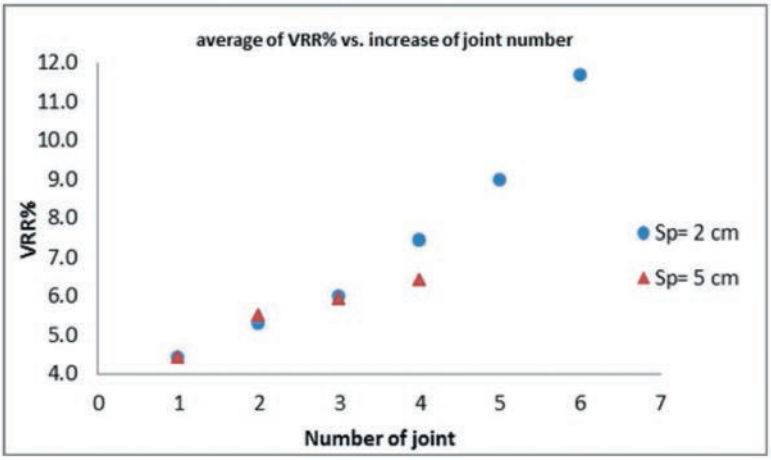

Fig. 6 - Average of *VRR%* vs. increase of joint number with different spacing in Andesite rock samples.

The P-wave velocity value variations in relation to joint spacing is shown in Fig. 8. In this section, spacing of joints was increased was increased by 2, 5, and 12 cm increments.

6.1. Evaluation of the test results

The results show the *VRR%* value, with a spacing of 5 cm, is more than spacing of 2 cm for the first 3 joints, but by increasing number of joints, the result is reversed.

As seen from the results, the variation of P-wave velocity follows the density of the joints.

Density of joint (*Dj*) is defined as the number of joints per unit of length in centimetres:

$$Dj = \frac{Number\ of\ joints}{length\ (cm)} \tag{2}$$

Table 4 - Results of V_p measurement on Teflon samples.

Teflon sample		No. of joint	Vp (m/s)	VRR%	Length (mm)	Dj
Intact sample	Spacing = 5cm	0	2285	0	-	-
GT1		1	2274	0.5	239.47	0.04
GT1,T5-1		2	2270	0.7	289.15	0.07
GT1,T5-1,T5-2		3	2264	0.92	339.07	0.09
GT1,T5-1,T5-2,T5-3		4	2263	0.96	389.22	0.10
GT1,T5-1,T5-2,T5-3,T5-4		5	2262	1.0	439.37	0.11
GT1	Spacing = 2cm	1	2274	0.5	239.47	0.04
GT1,T2-1		2	2271	0.6	259.57	0.08
GT1,T2-1,T2-2		3	2270	0.6	279.72	0.11
GT1,T2-1,T2-2,T2-3		4	2259	1.1	300.02	0.13
GT1,T2-1,T2-2,T2-3,T2-4		5	2256	1.3	319.89	0.16
GT1,T2-1,T2-2,T2-3,T2-4,T2-5		6	2253	1.4	340.24	0.18
GT1,T2-1,T2-2,T2-3,T2-4,T2-5,T2-6		7	2249	1.6	360.51	0.19

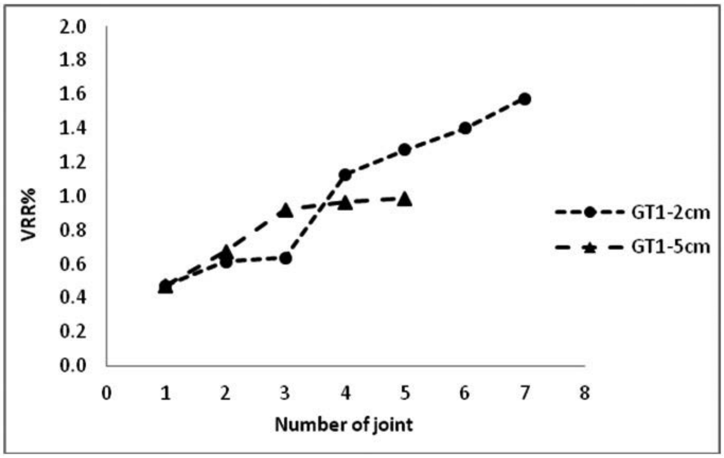

Fig. 7 - *VRR%* vs. increase of joint number with 2 and 5 cm spacings in index samples, *VRR%* at 2 cm spacing is higher than for 5 cm spacing.

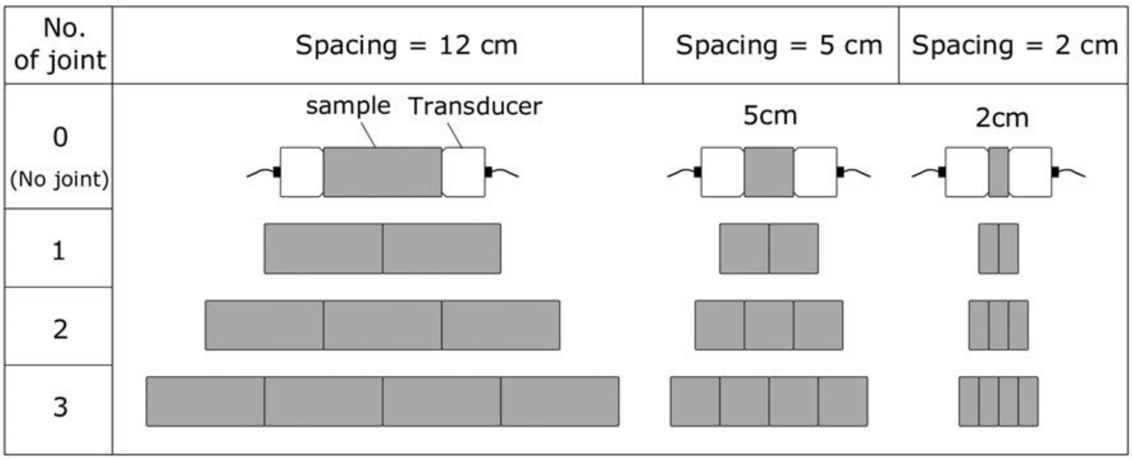

Fig. 8 - Results show that for the same joint number, *VRR%* at lower spacing is higher than for other spacings (Table 5 and Fig. 9). The increasing of *VRR%* in lower spacing shows a significant gradient. In other words, the rate of increase of *VRR%* in lower spacing is larger.

Table 5 presents the *VRR%* values and Fig. 9 shows the *Dj* vs. *VRR%* in Teflon samples. This trend can also be seen in rock tests.

The results also indicate that the rate of *VRR%* for shorter spacing is more than for the larger spacing. This means that the shorter spacing causes a greater diminution of the wave velocity compared to the larger spacing. Up to 3 joints, wave diminution in spacing of 5 cm is more than spacing of 2 cm because of the effect of spacing length in wave velocity diminution. However, with a greater number of joints, because of intensification of wave diminution of closed joint surfaces, attenuation is more pronounced. Notably, previous researchers have studied the effect of increasing the number of joints on the wave, though none of them has included the spacing effect as in this study.

Table 5 - Results of effect of joint spacing on V_P.

sample	spacing	No. of joint	Vp (m/s)	VRR%	Length (mm)	Dj
T2-1	2 cm	0	2393	0.0	20.1	0.00
T2-1,T2-2		1	2313	3.3	40.25	0.25
T2-1,T2-2,T2-3		2	2294	4.1	60.55	0.33
T2-1,T2-2,T2-3,T2-4		3	2272	5.1	80.42	0.37
T2-1,T2-2,T2-3,T2-4,T2-5		4	2270	5.2	100.77	0.40
T2-1,T2-2,T2-3,T2-4,T2-5,T2-6		5	2249	6.0	121.04	0.41
T5-1	5 cm	0	2321	0	49.68	0.00
T5-1,T5-2		1	2300	0.9	99.6	0.10
T5-1,T5-2,T5-3		2	2272	2.1	149.75	0.13
T5-1,T5-2,T5-3,T5-4		3	2261	2.6	199.9	0.15
T1	12 cm	0	2284	0.0	119.67	0.00
T1,T2		1	2274	0.4	239.47	0.042
T1,T2,T3		2	2261	1.0	359.89	0.056
T1,T2,T3,T4		3	2254	1.3	479.39	0.063

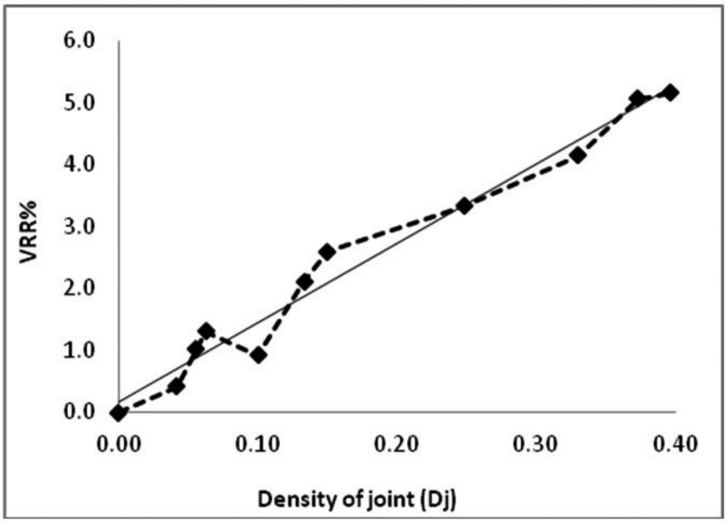

Fig. 9 - *VRR%* vs. increase of joint number with different spacing in index samples, *VRR%* is greater in lower spacing with identical joint number.

7. Conclusions

This study was carried out on igneous (Andesite) rock types to investigate the effect of joint numbers and spacing on P-wave velocity. First, the P-wave velocities were measured on the core samples. Second, the samples were cut perpendicular to the core axis to create artificial fractures and then P-wave velocities (V_P) were measured. To study the effect of joint number, disk samples with a thickness of 2 and 5 cm were added to the cut samples. P-wave velocity was measured systematically by adding additional joints with spacing of 2 and 5 cm. By measuring P-wave velocity with different joint numbers, and comparing the measured velocities at each stage with the intact sample P-wave velocity, the *VRR%* was defined.

The following results can be derived from the interpretation of the experiments. *VRR%* values increase with increasing joint number:

1. *VRR%* variation depends on the joint spacing; for joint numbers less than 3, the *VRR%* is higher with 5 cm joint spacing; however, for joint numbers greater than 3, the results are reversed;
2. according to the obtained curves, the rate of *VRR%* in lower spacing is steeper, it means lower spacing causes a greater diminution of P- wave velocity;
3. totally *VRR%* follows the joint density (*Dj*) directly.

We propose this research be carried out on different rock types with different joint spacing to learn how the P-wave velocity varies with spacing and investigate whether *VRR%* depends on rock type or not.

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Corresponding author: M. Ali Riahi
Institute of Geophysics, Dept. of Earth Physics
North Kargar Ave., Tehran, Iran
Phone: +98 2161118219; fax: +98 2188009560; email: mariahi@ut.ac.ir.