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Detection of near surface rock fractures using ultrasonic diffraction techniques

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Abstract. Ultrasonic Time-of-Flight Diffraction (TOFD) techniques are useful methods for non-destructive evaluation of fracture characteristics. This study focuses on the reliability and accuracy of ultrasonic diffraction methods to estimate the depth of rock fractures. The study material includes three different rock types; andesite, basalt and ignimbrite. Four different ultrasonic techniques were performed on these intact rocks. Artificial near-surface fracture depths were created in the laboratory by sawing. The reliability and accuracy of each technique was assessed by comparison of the repeated measurements at different path lengths along the rock surface. The standard error associated with the predictive equations is very small and their reliability and accuracy seem to be high enough to be utilized in estimating the depth of rock fractures. The performances of these techniques were re-evaluated after filling the artificial fractures with another material to simulate natural infills.

Keywords: fracture mechanics; laboratory analysis; material nonlinearities; rock; rock fills

1. Introduction

Discontinuities such as fractures and cracks strongly influence the engineering characteristics of rock masses. The assessment of rock mass characteristics, including their orientation, persistence, spacing, filling material is fundamental in identifying the behavior of the rock mass. At a micro-scale, the discontinuities also control the physical properties and structural weaknesses of natural rock blocks. The industrial applications for natural rock blocks include a step of identifying the structural weaknesses of material before the cutting process in order to ensure the quality of the rock blocks.

Ultrasonic techniques are routinely used to determine the weaknesses zones and physical properties of rocks and ultrasonic pulse velocity test (UPV) has the major advantages of portability, practicality, low cost and non-destructiveness. In applying UPV, fractures play an important role in the wave propagation. Each fracture acts as an attenuating and dispersing medium and reflections occur at these weaknesses zone where there is a great change in acoustic impedance. The acoustic impedance (z) of medium is calculated by multiplying its density (ρ) and its velocity (Vp) and velocity is determined by density and stiffness (k) of medium. Rocks have high density and high stiffness and z, is much higher than air which has low density and stiffness. The change in acoustic impedance along any air/solid fracture interface is the reason of the formation of reflected waves. Thus, the part of the wave energy is transmitted while the part of it travels back into the medium. The transmitted part is detected and enables evaluation of the characteristics of the fracture. The attenuation of seismic waves by variations in structural properties was first treated by Jeffreys (1931), and many researchers have investigated the characteristics of P-wave propagation through fracture zones (e.g., Hudson *et al.* 1980, Hudson 1981, Gladwin 1982, King *et al.* 1986, 1995, Watanabe and Sassa 1995, Hudson *et al.* 1996, Boadu 1997). P-wave velocity is often used to evaluate characteristics of rock blocks, as it is easily obtained by measuring the travel time of transmitted waves (Watanabe and Sassa 1995). Some common applications in fractured rock masses include: rock bolt reinforcement and blasting efficiencies in the rock mass (Price *et al.* 1970, Young 1985, King *et al.* 1986), macro and micro-cracks and the extent of fracture zones developed around underground openings (Meglis *et al.* 2005, Jiang *et al.* 2012), the determination of rock weathering degree (Karpuz and Paşamhmetoğlu 1997, Lednicka and Kalab 2012), fractured rock mass characterization (Boadu 1997), the effect of fracture characteristics (Kahraman 2002, Altındağ and Guney 2005, Wang and Li 2015) and remediation and restoration of historical masonry structures and ancient artefacts (Faella *et al.* 2012, Antonaci *et al.*2013, Vasanelli *et al.* 2015, Pascale and Lolli 2015). Boadu (1997) investigated the relationships between seismic velocity and rock mass parameters. He demonstrated that the P-wave velocity decreased as the discontinuity and/or the linear fracture density increased. Similarly, Kahraman (2001) reported that the P-wave velocity decreases with an increase in the number of joints. As mentioned above, these extensive studies have mostly been conducted to determine relationships between P-wave velocity and rock mass characteristics.

On the other hand, experimental studies are limited on evaluating the depth of fractures in different rock masses, while the UPV is widely used in-situ examination of near-surface fracture depths in construction industries, especially historical structures (Christaras 1998, Tavukcuoglu *et al.* 2010, Faella *et al.* 2012, Antonaci *et al.* 2013, Vasanelli *et*

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al. 2015, Pascale and Lolli 2015, Masato *et al.* 2002, Ogata *et al.* 2006). In this regard, Kahraman *et al.* (2008) has derived equations between the depths of artificial fractures and the P-wave velocity values for nine different rock blocks that can be used to estimate the depth of fractures. Although these equations offer great advantage to obtain the depth of fractures for a few rock types, there is no unified equation that gives the reliable results for all rock types.

To estimate the fracture depth, the UPV based on ultrasonic diffraction techniques such as Tc-To Method (Uomoto 2000), T Method, British Standards Method (BS Method) (BS 1881) and Ellipse Approach (Anwar *et al.* 2007) have been widely used for concrete and historical masonry structures. Tc-To and BS methods are the most typical examples of the "Time of Flight Diffraction (TOFD)" method, in which a transmitting probe and receiving probe are set across a fracture and fracture depth is estimated from the propagation time of pulses diffracted near the fracture tip (Uomoto 2000).

The objective of this investigation is to assess the reliability and the accuracy of ultrasonic diffraction techniques to estimate the fracture depths in different rock blocks. The fractures were artificially created in rock blocks by sawing and the reliability and accuracy of each technique was assessed by comparison of the repeated measurements at different path lengths along the rock surface. Preliminary tests were also carried out to determine the most suitable frequency, using transducers with lower and greater frequency. In addition to transducers, the effect of coupling agents on the UPV measurements was discussed in detail. The performances of diffraction techniques were also evaluated for the infilling conditions in which the fracture was filled with another material.

2. Experimental procedures

2.1 Materials

The typical UPV apparatus, shown schematically in Fig. 1, consists of an electronic pulse generator to activate the timer at the beginning of each excitation pulse interval, amplifier and filters to improve signal quality, and a time-display unit with an arrival time measuring circuit. The transducers consist of a transmitter that converts electrical pulses into mechanical pulses and a receiver that converts mechanical pulses into electrical pulses. An ultrasonic pulse velocity tester (Pundit lab; measuring range from 0.1 to 1999.9 μs; pulse mode 1, 2, 5 or 10 pulses per second; resolution 0.1 μs) and one set of cylindrical piezoelectric transducers (frequency = 54 kHz) were used to measure transit times of pulses (Fig. 1).

The ultrasonic diffraction techniques were performed on three different rock types (andesite, basalt and ignimbrite). The texture of these natural materials is widely different from concrete and mostly considered as anisotropic material. The possible causes of anisotropy in rocks can be identified as crystals and their textural arrangements, grains, pores, lamination and so on. In addition to their textural and structural differences, the macro and micro fractures and cracks that result from large-scale movements of the Earth's crust can also be the reason of the rock anisotropy. In the investigation, the intact rock blocks free of macro-scale discontinuities were collected from building-stone factories and their approximate dimensions (L x W x H) were 500 mm x 250 mm x 125 mm. Artificial fractures were created in the blocks by sawing. The accurate depths of fractures were measured by a digital caliper (sensitivity is 0.01mm) and were found as 32.01, 54.03 and 62.46 mm for ignimbrite, basalt and andesite blocks respectively.

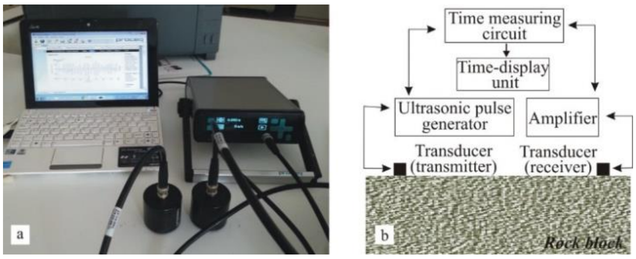

Fig. 1 (a) The typical testing apparatus and (b) indirect UPV measurements on rock sample

2.2 Methods

Ultrasonic diffraction is well-known technique for determining the characteristics of fracture since any fracture causes a transit time delay, which increases as the path length in the fractured zone increases. Thus, it is possible to make use of this effect to locate fractures or voids. In the investigation, experimental measurements were carried out along rock surfaces which were divided into equal intervals. The methods were performed among those divisions. The details of each method were explained in the following subsection.

2.2.1 Tc-To method

In the Tc-To method, also known as the L-L method, the transmitter (T) and receiver (R) transducer pairs are placed at equal distance (x) from the fracture center (Fig. 2a) and the transit time (Tc) is measured. The arrangement of transmitter and receiver at intervals (2x) is necessary to obtain the transmission time (To) of sound specimen. The depth h is estimated using the following equation (Eq.1), in which (x) is the distance between any of the transducers and the fracture center.

$$h = x\sqrt{\left(\frac{T_c}{T_o}\right)^2 - 1} \tag{1}$$

2.2.2 T method

In the T-Method, the transmitter is kept fixed and the receiver is moved to different points on both sides of the fracture. As shown in Fig. 2(b), the transit time is plotted as a function of distance between the transmitter and receiver. There exists a linear trend model when the receiver is moved along the distance between the transmitter and the fracture. The sharp increase in transit time, related with the depth of fracture, is observed when the receiver is placed beyond the fracture. The fracture depth (h) is evaluated as follows (Eq. (2))

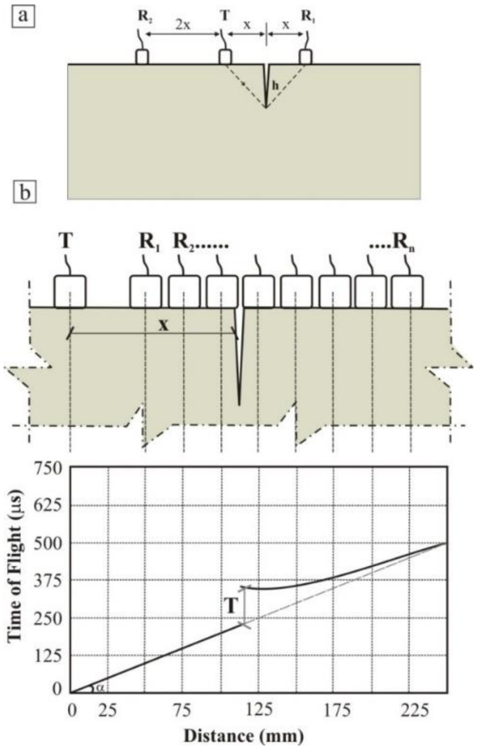

Fig. 2 (a) UPV methods for estimating the depth of fracture based on time of flight (TOF) (a) T_c-T_0 Method and (b) T-Method

$$h = T.cot\alpha.\frac{T.cot\alpha + 2x}{2(T.cot\alpha + x)} \tag{2}$$

where, *h* is the fracture depth, *x* is the distance between the transmitter and the fracture, α is inclined angle of the "time-distance" curve and *T* is time discontinuity at the fracture.

2.2.3 British Standards Method (BS Method)

The British standards method recommended by BS 1881-203 is performed by measuring the transit times across the crack for two different arrangements of the transducer-receiver pairs placed on the surface. One suitable arrangement is shown in Fig. 3(a) in which the transmitting and receiving transducers are placed at a distance (*x*) on opposite sides of the crack and equidistant from it. Two values of (*x*) are chosen and transit times corresponding to these are measured. The following equation (Eq. (3)) was used to determine the depth of fracture;

$$h = x\sqrt{\frac{4{T_1}^2 - {T_2}^2}{{T_2}^2 - {T_1}^2}} \tag{3}$$

where, *x* is the distance between any of the transducers and the fracture center, T_1 and T_2 are the transmit time measured from first and second arrangements of transducers respectively.

2.2.4 Ellipse approach (EA)

In the fractured zone, ultrasonic waves propagate along the shortest path between the transducers and the fracture. The shortest transit time (Tc) is measured as shown in Fig.

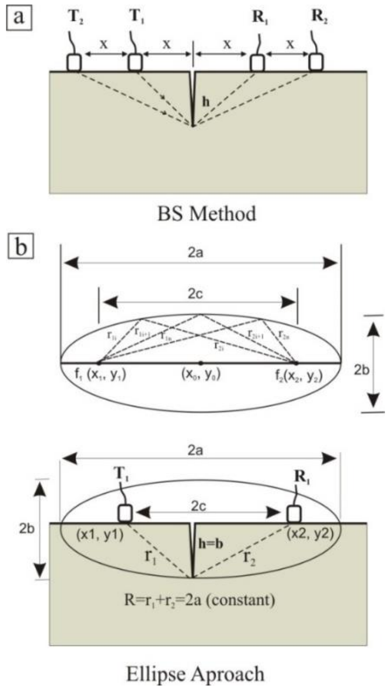

Fig. 3 Other fracture detection methods, (a) British Standards Method (BS Method) and (b) Ellipse approach

3(b). Due to the assumption that the average velocity (Vpa) is almost constant in homogeneous and isotropic materials, the total travel distance (*R*) in fractured zone can be determined by following equation (Eq. (4))

$$R = Vp_a.T_c \tag{4}$$

The total travel distance (*R*) includes two components; the first is the distance from the transmitter to the fracture edge (r_1) and the second is the distance from the fracture edge to the receiver (r_2). The total travel distance (*R*) can be represented as

$$R = r_1 + r_2 \tag{5}$$

As shown in Fig. 3(b), the locus of all points that can satisfy Eq. (5) can be represented by an ellipse. Ellipse, a curve that is the locus of all points in the plane the sum of whose distances r_1 and r_2 from two fixed points f_1 and f_2 (the foci) separated by a distance of 2c is a given positive constant 2a (Hilbert and Cohn-Vossen 1999, Anwar *et al.* 2007). This results in the two-center bipolar coordinate equation (Eq. (6)).

$$|r_{1i} + r_{2i}|_{i=1,n} = R = 2a = constant \tag{6}$$

where, r_{1i} and r_{2i} are the distance from the two foci to the ellipse surface, which will be corresponding to the position of transmitter and receiver in case of the fractured zone and 2a is the longest axis of ellipse corresponding to the total covered distance by the pulse signal around the fracture.

The distance (2c) between its focal points, which will be corresponding to the position of the two transducers, is given by Eq. (7)

$$2c = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{7}$$

where, x_1, y_1 are the Cartesian coordinates of the transmitter, and x_2, y_2 are the Cartesian coordinates of the receiver. The shortest axis (2b) of the ellipse can be obtained from Eq. (8), and the general equation of the formed ellipse can be written as shown in equation (Eq. (9)).

$$b^2 = a^2 - c^2 \tag{8}$$

$$\frac{(x-x_0)^2}{a^2} = \frac{(y-y_0)^2}{b^2} = 1 \tag{9}$$

where, x_o, y_o are the coordinates of the mid-point between the two focal points of transducers. EA provides somewhat better estimates for the depth of fracture on concrete compared to the other tested methods (Anwar *et al.* 2007). Researchers reported that a single ellipse is formed for each measurement and this method facilitates the placing of the transducers on any available surfaces around the crack position that gives the method additional advantages over the conventional methods. In this study, EA has used for first time to estimate fracture depth of rock material.

2.3 Laboratory applications

An ultrasonic pulse velocity tester (Pundit-Lab device) supports a wide range of transducers from 24 kHz up to 500 kHz, making it suitable not only for rock and concrete, but also for other materials such as graphite, ceramics and woods. Transducers with frequency of 54 kHz were chosen for rock blocks in order to have a good compromise between resolution and penetration. This issue will be addressed later in the paper. The dimensions of the rock blocks (500 mm × 250 mm × 125 mm) are suitable for a wide range of frequency. Herein, problems may arise especially when the maximum dimensions of a rock block is less than the wavelength (λ) of the ultrasonic vibrations. The wavelength of vibrations (λ) equals the pulse velocity divided by frequency of vibrations. The smallest dimensions of some tested blocks should be as given in Table 1.

The artificial fracture widths are 7.1 mm for tested rock blocks. This wide crack width for rock blocks is not realistic, but the fracture width does not itself affect the transmission of surface waves (Popovich *et al.* 2000). Pinto *et al.* (2010) showed that there was no apparent influence of different crack widths (crack width of 6, 0.5 and 2 mm, respectively) in the estimates. Any air/solid fracture interface is enough for a transit time delay. This is due to the high difference between acoustic impedances of rock and air and therefore ultrasound waves are reflected rather than refracted.

A series of time of flight measurements (TOF) were conducted on large blocks of ignimbrite, andesite and basalt with machine-flat surfaces in order to assess the most effective experimental technique for rock blocks. The TOF measurements were conducted for various positions of transmitter-receiver pairs along the rock surface to assess the consistency and reliability of these techniques. The surface of rock blocks was divided into equal spacing for systematic measurements for this purpose. The typical created divisions were shown in Fig. 4. The TOF measurements on the surface of sound specimen were carried out as in the case of essential procedures for the T_c-T_0 and the EA methods prior to the creation of artificial fractures.

Table 1 The least dimensions of some tested rocks

Transducer frequency (kHz)	Minimum path dimensions of Basalt (V_{pa}=5253 m/s) and Ignimbrite (V_{pa}=2099 m/s), (mm)	
54 kHz	97.0	39.0
120 kHz	44.0	18.0
250 kHz	21.0	8.0

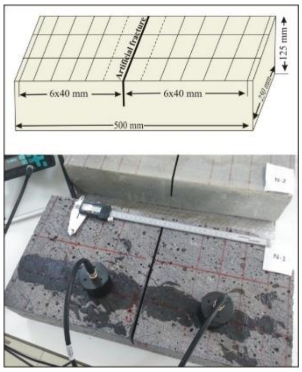

Fig. 4 Schematic illustration of the approximate specimen dimensions and UPV measurement lines on rock surface

Fig. 5 The filled fracture conditions with natural hydraulic lime mortar

Table 2 The results of the pulse transit time variations at the transducer pairs using different coupling agents

The coupling agents	The average pulse transit time values (μs)			
	Calibration rod (25.4μs)	Basalt	Andesite	Ignimbrite
Fine oil	25.4	18.4	21.4	35.3
Liquid soap	25.4	18.4	21.4	35.3
Petroleum Jelly	25.4	18.4	21.4	34.2
Gel	25.4	18.2	21.1	33.7
Grease	25.4	18.2	21.1	33.7

As for the coupling medium, the efficient and uniform energy transmission between the rock specimen and each transducer is achieved by using a thin layer of a coupling medium. The function of the coupling agent is to minimize air gaps between the contact surfaces of the transducers and the specimen. Standards (ASTM or ISRM) do not specify any special coupling agent but there are a number of options such as phenyl salicylate, high-vacuum grease, gel, glycerin, petroleum jelly and mineral oil. Ultrasonic gels are

Table 3 The results of the UPV measurements by Tc-To method

Transducers position (mm,mm)		Distance (mm)		The time of flight (TOF) values of empty fracture (μs)[a]			The time of flight (TOF) values of filled fracture (μs)[a]		
T	R	x	2x	Basalt N-1	Andesite N-2	Ignimbrite N-3	Basalt N-1	Andesite N-2	Ignimbrite N-3
-80	80	80	160	24.9/32.4	30.2/38.9	60.7/65.4	24.9/31.9	30.2/38.4	60.7/63.9
-120	120	120	240	40.1/44.9	47.4/53.4	112.8/118.0	40.1/43.0	47.4/52.0	112.8/116.6
-160	160	160	320	56.4/60.2	63.0/68.1	151.2/154.2	56.4/58.9	63.0/67.2	151.2/153.9
-200	200	200	400	71.6/74.9	79.3/82.9	189.9/192.9	71.6/74.1	79.3/81.7	189.9/192.7
-240	240	240	480	92.2/94.9	96.2/99.3	228.6/231.5	92.2/93.9	96.2/99.1	228.6/230.7

[a]Numbers separated by slash from left to right are the measured transit times for sound specimen and fractured zone. T, transmitte and R, receiver

Table 4 The results of the UPV measurements by T- method

Transducers position (mm,mm)		Distance (mm)	The time of flight (TOF) values of empty fracture (μs)			The time of flight (TOF) values of filled fracture (μs)		
T	R	x	Basalt N-1	Andesite N-2	Ignimbrite N-3	Basalt N-1	Andesite N-2	Ignimbrite N-3
-240	-160	80	8.4	10.9	20.4	8.4	10.9	20.4
-240	-120	120	15.4	16.4	49.4	15.4	16.4	49.4
-240	-80	160	24.4	24.4	64.4	24.4	24.4	64.4
-240	-40	200	30.7	33.7	81.9	30.7	33.7	81.9
-240	0	240	-	-	-	-	-	-
-240	40	280	54.6	65.0	140.0	54.4	61.2	131.1
-240	80	320	58.9	66.9	155.0	57.9	64.7	155.9
-240	120	360	66.6	72.9	171.9	65.4	71.2	170.4
-240	160	400	73.4	79.6	189.4	72.9	75.7	189.1
-240	200	440	80.7	89.1	204.0	80.4	84.1	203.8
-240	240	480	94.9	99.3	231.5	93.9	99.1	230.7

Table 5 The results of the UPV measurements by BS method

Transducers position (mm,mm)		Distance (mm)	The time of flight (TOF) values of empty fracture (μs)			The time of flight (TOF) values of filled fracture (μs)		
T	R	x	Basalt N-1	AndesiteN-2	Ignimbrite N-3	Basalt N-1	Andesite N-2	Ignimbrite N-3
-40	40	40	23.9	29.9	41.1	23.7	27.6	38.0
-80	80	80	32.4	38.9	65.4	31.9	38.4	63.9
-80	80	80	32.4	38.9	65.4	31.9	38.4	63.9
-160	160	160	60.2	68.1	154.2	58.9	67.2	153.9
-120	120	120	44.9	53.4	118.0	43.0	52.0	116.6
-240	240	240	94.9	99.3	231.5	93.9	99.1	230.7

most commonly used agents because of their high viscosity, and non-toxic and antiallergenic properties. For effective and efficient use, coupling agent should have a certain viscosity to minimize the effect of contact surfaces and allow energy transmission without absorption and attenuation. Long (2000) recommended some coupling agents for smooth surface (e.g., silicone grease, medium bearing grease or liquid soap) and rough surface (e.g., water pump grease or thick petroleum jelly). Aydın (2014) reported that a high viscosity medium (e.g., epoxy resin) is needed if S-wave velocity is to be measured. To evaluate the transmissivity features of 5 coupling agents (fine oil, liquid soap, petroleum jelly, gel and grease), the time measurements were made on the testing specimens as well as the calibration rod. As given in Table 2, there is no significant difference between coupling agents but, gel and grease have better transmissivity features due to their high viscosity which helps them fill all available air gaps of contact surface, compared to other coupling media. A thin film of gel was applied uniformly in order to ensure efficient and uniform energy transfer from/to the transducers.

The fracture depth detection techniques were performed both with the empty fracture and the fracture filled by natural hydraulic lime mortar (Figs. 4 and 5). Based on the possible arrangements of transducer pairs for each

Table 6 The results of the UPV measurements by Ellipse approach (EA) method

Transducers position (mm,mm)		Distance (mm)	The time of flight (TOF) and velocity (V_{pa}) values of empty fracture, µs and (km/s)			The time of flight (TOF) and velocity (V_{pa}) values of filled fracture, µs and (km/s)		
T	R	2C	Basalt N-1	Andesite N-2	Ignimbrite N-3	Basalt N-1	Andesite N-2	Ignimbrite N-3
-80	80	160	32.4 (6.425)	38.9 (5.298)	65.4 (2.635)	31.9 (6.425)	38.4 (5.298)	63.9 (2.635)
-120	120	240	44.9 (5.985)	53.4 (5.063)	118.0 (2.127)	43.0 (5.985)	52.0 (5.063)	116.6 (2.127)
-160	160	320	60.2 (5.673)	68.1 (5.039)	154.2 (2.117)	58.9 (5.673)	67.2 (5.039)	153.9 (2.117)
-200	200	400	74.9 (5.585)	82.9 (5.044)	192.9 (2.106)	74.1 (5.585)	81.7 (5.044)	192.7 (2.106)
-240	240	480	94.9 (5.253)	99.3 (4.989)	231.5 (2.099)	93.9 (5.253)	99.1 (4.989)	230.7 (2.099)

technique, the systematic TOF measurements for both two cases were achieved as shown in Tables 3-6. The estimated fracture depth values were calculated by the related equations of techniques and the average of fracture depth values was rounded to the nearest one-tenth.

3. Experimental results

The estimated fracture depth values obtained from T_c-T_0 method and ellipse approach were plotted as a function of distance. As shown in Fig. 6, the estimated fracture depth values are very close to each other in the case of empty fracture, whereas they relatively decrease and vary by distance in the case of filled conditions. These findings can be acceptable because ultrasonic waves pass through the fracture zone filled by natural material with less effort and an increase of energy can be expected. Thus estimated fracture depth values for filled conditions are found to be much lower than those obtained from empty fracture conditions.

The results of all four techniques (i.e., Tc-To, T, BS, and EA) were presented in Table 7. When the estimated values were compared with the measured depth values, it can be asserted that the reliability of the ultrasonic diffraction methods to estimate the fracture depth is very high (especially in the case of empty fracture conditions). Only notable exception was found for anisotropic samples such as basalt and ignimbrite, as the fracture depths were overestimated due to pores, grain boundaries and so on. The anisotropy values were evaluated by the maximum and minimum values of the Vp measured along the three axes (Eq. (10)).

$$Anisotropy\ \% = \frac{(Vp_{max} - Vp_{min})}{Vp_{max}} .100 \qquad (10)$$

The anisotropy values of the rock samples are given in Table 8. The reliability and accuracy of the depth detection techniques can be evaluated on the basis of mean absolute percentage error (MAPE). When the MAPE value approaches zero, the estimated values are closer to the measured values. The MAPE is computed using the following equation (Eq. (11)).

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{Q_i - P_i}{Q_i}\right| \qquad (11)$$

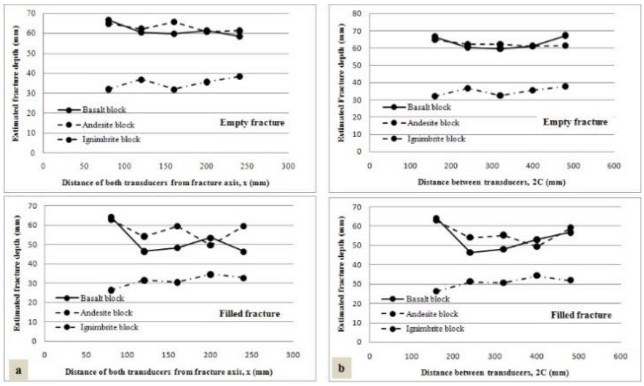

Fig. 6 Estimated fracture depth values for empty and filled fracture conditions (a) Tc-To method and (b) Ellipse approach (EA) method

where, Q_i is the measured value, P_i is the estimated value obtained from equations of each technique, and n is the number of experimental data.

The MAPE values were found to be smaller than 18.0 % in estimating the depth of an empty fracture (Table 7). Although this error seems to be high for different rock samples, the reliability and accuracy of the methods seem to be very high for partially isotropic samples such as andesite. The values of MAPE were found to be smaller than % 4.1 for andesite. In addition, the Tc-To method and ellipse approach provides much more reliable results for partly isotropic samples. As a result, the degree of anisotropy for rocks does not provide an accurate estimate of the near-surface fracture depth. The MAPE value increases as the anisotropy degree of rocks increases.

As for filled fracture conditions, filled material does not yield reliable results and the depth detection techniques commonly underestimate the actual fracture depth because of the apparently higher amounts of energy transmitted. While Tc-To method and the ellipse approach (EA) provide reliable results for empty fracture conditions, these techniques seem to be unsatisfactory for filled fracture conditions.

The overall conclusion is that the Tc-To method and the ellipse approach (EA) provide somewhat better estimates for the rock fracture depth than those of other techniques, especially in partially isotropic and homogeneous samples. The presence of filled material significantly affects the reliability of the results. Additionally, anisotropy as main factor influencing the ultrasonic wave propagation is affected the reliabilities of these techniques.

4. Discussions

Ultrasonic diffraction techniques are widely used in construction industry. These techniques are based on the following principle of UPV: "When the pulse impinges a fracture, the measured transit time corresponds to the pulse that follows the shortest path." This is a significant indicator because any fracture causes a time delay, which increases as the length of fracture path length increases, compared to the transit time of pulses in sound material (Fig. 7). If the ultrasonic pulse velocity for the sound material is known, the difference between the pulse velocities or transmit times enable to calculate the fracture depth of the material. Some restrictions and difficulties of these techniques are discussed in the following paragraphs.

The measurements were carried out by placing both the transmitter and receiver transducers on corresponding positions for each method. Each (piezoelectric) transducer pair may have a nominal frequency between 20 kHz and2 MHz, but the 50–500 kHz range is recommended for practical purposes requiring the determination of the velocity values of rocks (Aydın 2014). In concrete structures however, the presence of the aggregate restricts transducers frequencies to generally below 100 kHz. Transmitted waves recognize complex heterogeneous media as a solid media and are propagated when the generated waves are dominated by low-frequency components. Excitation of waves with high-frequency components over 100 kHz leads to reflection, refraction and mode conversion of waves due to a heterogeneous internal composition among cement pastes, fine aggregate, and coarse aggregates in concrete (Ahn *et al.* 2017). Thus, transducer pairs with a frequency range between 20 kHz and 100 kHz are typically used to detect internal defects or estimate near surface crack depth of concrete. In rocks, these internal characteristics are related to grain size and are known as "texture". While small crystals, of less than 1 mm are only visible with a magnifying lens or microscope in fine-grained texture,

Table 7 The results of average estimated fracture depth values for all techniques

Rock type & No	Fracture type	Test techniques	Estimated fracture depth (mm)	Measured fracture depth (mm)	Error (%)
Basalt N-1	Empty fracture	Tc-To method	61.33	54.03	14.0
		T method	57.86		7.1
		BS method	48.70		9.9
		Ellipse Approach	63.03		16.6
	Filled fracture	Tc-To method	51.65		4.3
		T method	53.46		1.0
		BS method	53.16		1.6
		Ellipse Approach	53.69		0.6
Andesite N-2	Empty fracture	Tc-To method	63.04	62.46	0.9
		T method	65.01		4.1
		BS method	61.06		2.2
		Ellipse Approach	62.27		0.3
	Filled fracture	Tc-To method	57.06		8.6
		T method	52.30		16.3
		BS method	52.74		15.5
		Ellipse Approach	56.22		9.9
Ignimbrite N-3	Empty fracture	Tc-To method	35.00	32.01	9.0
		T method	36.28		13.3
		BS method	37.85		18.0
		Ellipse Approach	34.85		8.0
	Filled fracture	Tc-To method	31.03		3.0
		T method	31.32		2.1
		BS method	33.58		5.0
		Ellipse Approach	30.86		3.6

Table 8 the values of anisotropy for each rock block

Rock Type & no	Vpx (km/s)	Vpy (km/s)	Vpz (km/s)	Anisotropy %
Basalt N-1	4.464	5.405	4.789	17.40
Andesite N-2	4.246	4.219	4.501	6.20
Ignimbrite N-3	2.405	2.278	2.137	11.17

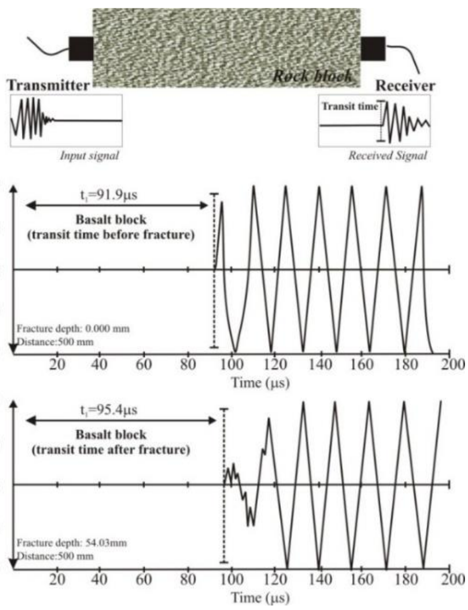

Fig. 7 Direct UPV measurements and the transit time of the signal after the fracture.

Table 9 Experimental results of BS-Method for the estimated fracture depth using three different frequencies

Rock type	Basalt Fine grained rock with gas bubbles			Andesite Fine grained rock			Ignimbrite Medium-coarse grained rock		
Transducer	54 kHz	120 kHz	250 kHz	54 kHz	120 kHz	250 kHz	54 kHz	120 kHz	250 kHz
Fracture depth (mm)	54.03			62.46			32.01		
Estimated fracture depth (mm	48.70	46.57	62.85	61.06	64.11	65.63	37.85	39.27	42.00
Error (%)	9.9	13.8	16.3	2.2	2.7	5.1	18.0	22.7	31.2

coarse grained or mixed texture have large, interlocking crystals and fragments (>1 cm) with fine-grained materials. Although 50-500 kHz frequency range is recommended for practical purposes, there are a number of factors requiring the selection of an alternative transducer frequency. Main factors are related to the texture and contact surface of tested rock. If the high-frequency transducer pairs are used for coarse grained texture, it may not be possible to obtain reliable results because of reflection and refraction in coarse grains. Therefore, the selection of the transducer frequencies for different rock textures plays an important role for propagation without under attenuation. To determine the most suitable frequency range, preliminary tests were carried out for fine and coarse-medium grained rocks using transducer pairs at frequencies exceeding 54 kHz. The test results indicate that high frequency transducer pairs perform about equally well with 54 kHz transducer pairs in estimating the fracture depth for fine-grained rock such as andesite (Table 9). However, high frequency transducers do not have an acceptable performance for coarse grained and porous textures.

The error values reveal that the high frequency transducer pairs significantly overestimate the fracture depth within coarse grained materials. These results demonstrate the most suitable frequency ranges are between 50 and 120 kHz to determine the near surface fracture depth for coarse-grained rocks. The transducer contact surface is also important to provide more accurate results. An effective contact surface must be provided for rocks that have surface roughness. Because the large part of energy transferred from the transducer will not transmit unless the contact between the rock and the transducer is completely achieved.Therefore re-straightening may be necessary to provide a smooth surface in place applications. Besides, ultrasonic transducers are traditionally made in cylindrical or rectangular shapes. These transducers provide strong and well directed signals, however there are some disadvantages associated with their relatively large dimensions with respect to the wavelengths. The main disadvantages to a large transducer include signal distortion, cutting-off of certain frequency components, and the near field effect, which are referred to as the aperture effects in general (Rus *et al.* 2005). Conical-shaped probes are used to provide a point contact (4 mm in contact surface diameter) on the surface of material. These probes may enable more suitable coupling to an irregular or rough surface of rocks since the required specimen contact surface is minimal. In addition, a small contact area also improves the directivity (Sachse 1987, Rus *et al.* 2005). These probes were not used in this investigation and their effectiveness with the different frequencies may be explored for rock materials in further studies. Similarly, 78 kHz and 370 kHz wheel probes are also available for the rapid inspection of smooth surface specimens such as granite and marble (Long 2000).

Additional difficulties exist concerning the path length and material properties. The P-wave velocity is not generally influenced by path length for partly homogenous material. However the heterogeneous nature of the material may become important (Bungey and Millard 1996). Naik and Malhotra (1991) indicated that a typical reduction of Vp is %5 for a path length from approximately 3 m to 6 m for concrete. In heterogeneous material, it is possible that no actual signal might be received for these high path lengths because of attenuation of the transmitted energy due to acoustic impedance mismatch in the medium. Raina *et al.* (2000) reported that the ultrasonic method can only be used with good accuracy to a depth of 0.5 m and not recommended for fractured zone in which the depth of zone is up to 2.5 m.

Ultrasonic diffraction techniques were found to be promising for examining the fracture depths for partially isotropic and homogeneous rock blocks. Although all techniques have both of the advantages and disadvantages, the Tc-To method and the ellipse approach (EA) provided the high prediction performance in order to estimate the depth of near surface fracture. However, the main restrictions of these methods are that they require a certain arrangement of transducer pairs and the average transmission time (To) or velocity (Vpa) in a sound material. These measurements may significantly vary in a real fracture material, since the rock blocks may exhibit anisotropic characters on length scales due to grain size, pores, micro-fracture, cracks so on. Similarly, fracture zone are not completely sound. Thus, crack depth estimates in a lab material may differ from estimates in an actual fractured rock. The BS method or T-method, which take into account the transmission time around the fractured zone, may not have this impact in a real fractured rock and these techniques also do not require the determination of the absolute values of the velocity or transmission time of sound specimen. However, BS method, as with the Tc-To and EA methods require a certain arrangement of transducers. Only T-method does not require any restriction on the arrangement of transducers to estimate the fracture depth. As mentioned above, not all techniques are applicable for extremely heterogeneous clastic rock blocks such as conglomerate and breccia.

5. Conclusions

Ultrasonic diffraction techniques are useful methods to determinate the near surface fracture depth of intact rock blocks. The results indicate that these techniques provide precise data on estimating the depth of visible near-surface fracture. Based on the MAPE values, the Tc-To method and Ellipse approach (EA) provide the reliable results for partially isotropic and homogeneous intact rock blocks.

Some of the restrictions for the UPV such as calibration and improper functioning of the instrument, surface irregularities and weathering state of tested rock, existence of numerous discontinuities, moisture content, and application on non-homogenous rocks are also valid for these diffraction techniques. The infilling condition of the fracture zone significantly affects the reliability of these techniques due to the increase in energy transmission.

The high frequency transducers have not acceptable performance for coarse grained texture. These type transducers significantly overestimate the rock fracture depth. The transducer pairs with a frequency range between 54 kHz and 120 kHz are quite suitable to determine the near surface fracture depth for coarse-grained rocks. Additionally, the coupling agent should eliminate air gaps between the contact surfaces of the transducers and the specimen. Water pump grease and ultrasonic gels are ideal agents for the surface irregularities of specimen, compared to other coupling media.

Ultrasonic diffraction techniques have the main advantage of the UPV testing device such as quick, low-cost, portable and non-destructive. Their performances have been assessed for only a few rock blocks and it is necessary to apply these techniques to the more rock conditions together with the continuous improvement equipment and tools.

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