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Research paper

Behavior of seismic wave propagation with respect to fracture orientations in limestone, Perak, Malaysia

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Abstract

Conventional shallow surface seismic refraction survey is associated with long elastic wavelength thus it is often ignoring the existence of cracks and fractures underneath. Fracture has essential effect on reducing seismic velocity. This paper highlights the velocity variation in different direction with respect to preferred orientation of fracture sets of limestone in a quarry located at Chemor, Perak, Malaysia. Multi azimuth seismic refraction survey in the orientation of fan shooting is utilized to records seismic velocity from different azimuth. Slowness concept is used to study the responses of seismic wave velocity in regards to the discontinuity orientation. The analysis of the results indicate seismic wave propagates faster in the direction parallel with the strike of the fracture. The seismic wave experience largest time delay as the wave propagates perpendicular with the strike direction of the fracture structure. With this behavior of seismic wave in respect to the fractures orientation, it is possible to map the extension of the orientation of subsurface fractures.

Keywords: *Geological discontinuity; seismic refraction; slowness; strike and dip.*

1. Introduction

The structure design of foundation in construction engineering is often determined by the strength of the rock underneath. Geological fractures have essential effects in controlling the strength of subjected rock. However, the fractures are buried and the extension of the fractures are always invisible. The long wavelength of seismic wave often ignores the considerably small geological fractures and the presence of the fractures does not exist in seismic image. In result, it is difficult to identify hidden fractures density and orientation to help engineers build stronger foundation design.

However, Fractures play important roles in influencing the velocity of propagating seismic wave. Seismic wave tends to propagate slower in the rock mass with high density of fractures and joints (Nassir Saeed et al. 2000; Rafek 1985). Furthermore, fractures density is not the only factors delaying the arrival time of seismic signals. One of the factors that is usually ignored is the preferred orientation of the fracture sets. The variation of seismic wave velocities that propagates in different direction are known to be related with the orientation of discontinuity sets (Masuda 1964; Nur and Simmons 1969; Oberti et al. 1979).

Elastic properties of particular rock are governed by the cracks and fractures (Nur and Simmons 1969). Since seismic wave propagation is controlled by the elastic properties of rock mass, the variation of seismic velocities in different directions have help the investigation of elastic anisotropy. Most of the previous papers stated that the variation of seismic velocity in different directions is the result of elastic anisotropy in rock mass associated with the existence of discontinuities (Kleczek and Idziak 2008; Nassir Saeed et al. 2000; Rafek 1985; Stan and Idziak 2005). Elastic seismic wave is known to travel faster in the direction of the strike of the fractures and slower when it is propagating in the perpendicular direction with the strike of the fracture sets (Kleczek and Idziak 2008; Nassir Saeed et al. 2000; Rafek 1985; Stan and Idziak 2005).

Since the existence of seismic anisotropy is induced by discontinuity, this study utilized multi azimuth seismic refraction survey to determine the direction of seismic wave propagation from the fractures orientation that have the largest influence to reduce the velocity. Slowness concept is applied in this study since it can be added and subtracted as vector (Rafek 1985) thus it provides simplicity that help the analysis of seismic anisotropy (Rafek 1985). Such recording seismic wave propagation in limestone formation in Malaysia from different azimuth has never been reported. Thus, this knowledge gap motivates for such study to be carried out. The main objective of this study is to utilize the slowness distinction in each direction to identify discontinuities orientation without the dependency on the availability of outcrops.

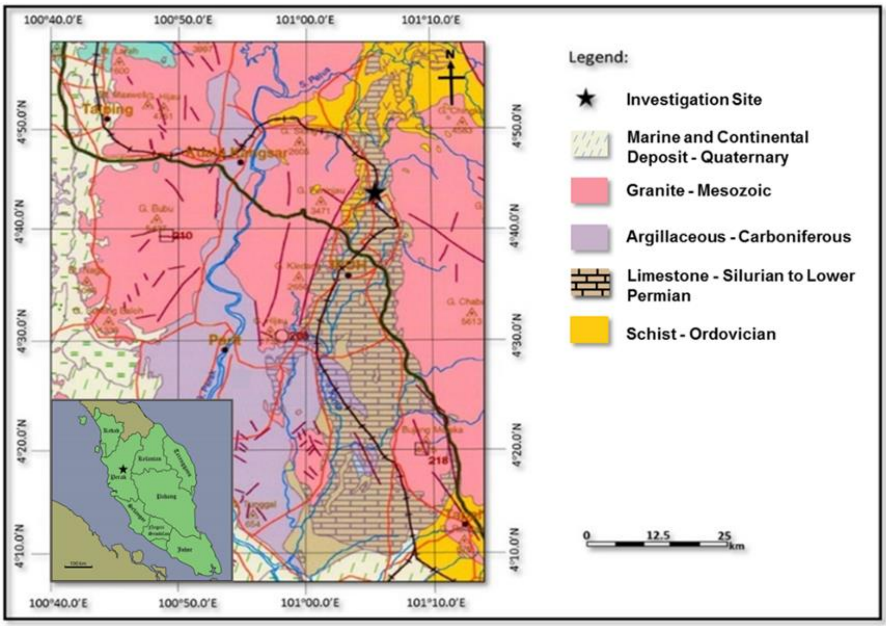

Fig 1: Map showing the study area located in Perak, Malaysia which is part of Kinta Valley Limestone (Modified from Geological Map of Peninsular Malaysia, Mineral and Geosciences Department, 1985).

2. Methodology

The study was performed in a limestone quarry located in Kanthan Hill Chemor, Perak, Malaysia (Figure 1). The limestone is part of Kinta Valley Formation which formed during Silurian to Lower Permian (Khoo and Tan 1983) which is older than the granitic range of Malay Peninsula. The survey is performed in two different location within the same hill formation; Quarry A, and Quarry C.

Measurements of strike and dip orientations are collected from the existing outcrops next to each of the study locations. The collected geological measurements are plotted in two Rose diagrams that representing the general geological structures of both locations.

2D multi azimuth seismic survey lines in the form of fan shooting are set up in two different location within the same quarry. Fan shooting orientation uses thirteen 2D seismic lines that are arranged in a quarter radial with all the lines shares the same geophone point in one end of the survey lines. The radial interval between the lines is 15° azimuthally. The fan shooting orientation can be seen in Figure 2. In Quarry A, Line 8 is extended longer than the other survey lines as can be seen in Figure 2 since it is the only line that have accessible area. The intention of extending survey Line 8 is to record the propagation of seismic wave that travel across the main fracture structure in the Quarry A. Nevertheless, in Quarry C, there are no accessible area to let us set up longer survey lines. Hence in Quarry C, the profile of fan shooting is similar with Quarry A as seen in Figure 2 but with shorter Line 8 that is ends at the centre point of all the survey lines.

Seismic survey is performed using MK-8 seismograph produced by ABEM and having 48-channels of signal receiver. There are seven shot points in each line with fifteen to twenty stacking in each point to increase the signal and noise ratio. The distance interval between receivers in Quarry A is 1.5 m and the receiver's interval in Quarry C is 1.0 m. The seismic sources are generated using sledge hammer that stroke to the metal plate on the ground close to trigger geophone. Once the data acquisition is done, the survey is move to the next survey line which is rotated 15° from the previous line and centred in one end of the line. Data processing using Seispro Geogiga Refractor software. The amplitudes of the signals were gained using Mean Subtraction algorithm to help recognition of the first signal arrival. The velocity data are interpreted with General Reciprocal Method (Palmer 1981).

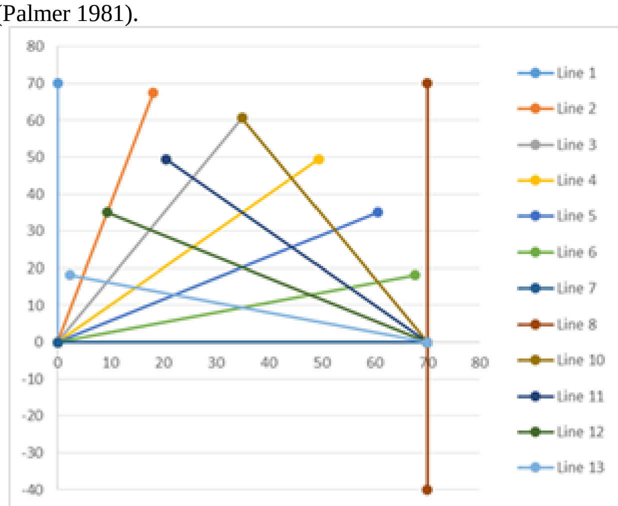

Fig 2: Fan shooting orientation consist of thirteen 2D seismic refraction survey lines. The azimuth interval between each line is 15°. Line 8 is extended to record the seismic wave that propagating crosses the existing main fracture.

The results presented in this paper are focused on the second layers in both quarries to portrays the non-weathered geological layer. The results are analysed in terms of slowness to provide simplicity in the mathematical process. Slowness is the inverse of velocity, 1/v. The advantage of using slowness is it can be added and subtracted as scalar (Rafek 1985). The velocity results and the strike and dip measurements are correlated to see the influence of the fractures to the velocity of seismic wave that are propagating in different directions. The direction with the least slowness value is assumed to be the slowness of the isotropic medium (Rafek 1985). To analyse the effect of fractures to the velocity of seismic wave, the slowness values of each survey line are subtracted with the isotropic slowness of the study area. The residual value of the slowness after subtracted with the isotropic value represents the slowness produces by the fracture sets. Rose diagrams are produced from the geological investigation and radar diagrams are formed to represent the distribution of slowness in every direction. The rose and radar diagrams are merged to provide better view of the effect of fracture sets orientation on the seismic propagation velocity.

3. Results and discussion

There are 262 strike and dip readings recorded over 100 m scan line in the outcrops of Quarry A. However, in Quarry C there are only 153 strike and dip readings set are recorded within 70 m scan line on the outcrops. The distribution of strike and dip of both Quarry A and Quarry C are summarized in rose diagram in Figure 3. The rose diagram represents the preferred strike direction of the fractures at Kanthan Hill.

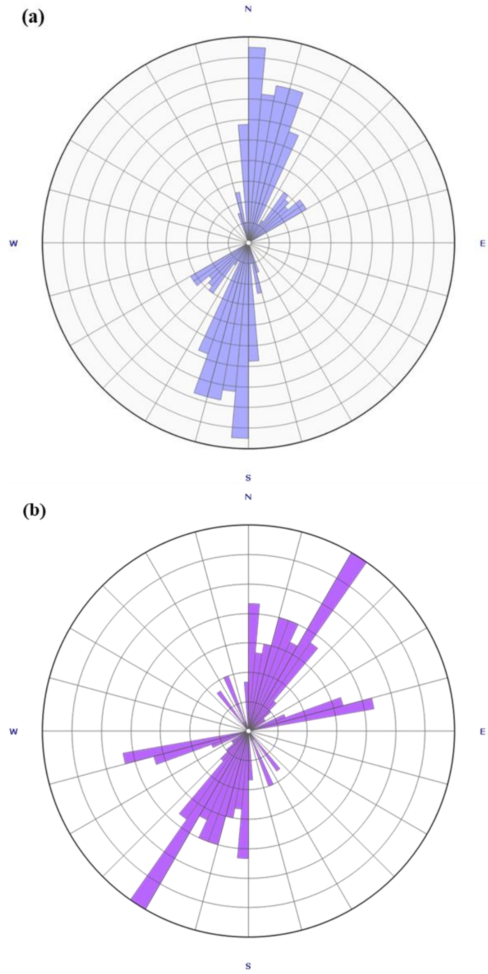

Fig 3: Rose diagrams representing the strike direction of fracture sets in (a) Quarry A, and (b) Quarry C.

In Quarry A (Figure 3a), the fracture sets are generally oriented in the azimuth between 0° to 20°. The strike directions of the fractures in Quarry A were sub-parallel to each other heading towards identical direction. The preferred strike directions are ranging from 0° to 25°. Still, there are small percentage sign of fractures that are having different orientation than the dominant structures. The existence of these minor fractures is expressed in the rose diagram with profile in the direction around 40° to 50°.

While in Quarry C (Figure 3b), major fracture sets are oriented from 20° to 40°. in Quarry C, there are two directions with high concentration of fractures that are in the direction 75° and 140° that is not following the major fracture sets. There are several fractures sets oriented in different azimuthal directions as seen in Figure 3b. From the rose diagram, the majority of the strikes of the fractures are focused in azimuthal bearing 0° to 40° from the North. The fracture set with strike pointing towards 30° to 35° has the highest numbers of frequency. There is a set of fractures that is oriented very distinctively than the dominant fractures. The unique fracture sets having strike in the azimuth 75° and differ by 45° with the dominant fracture sets.

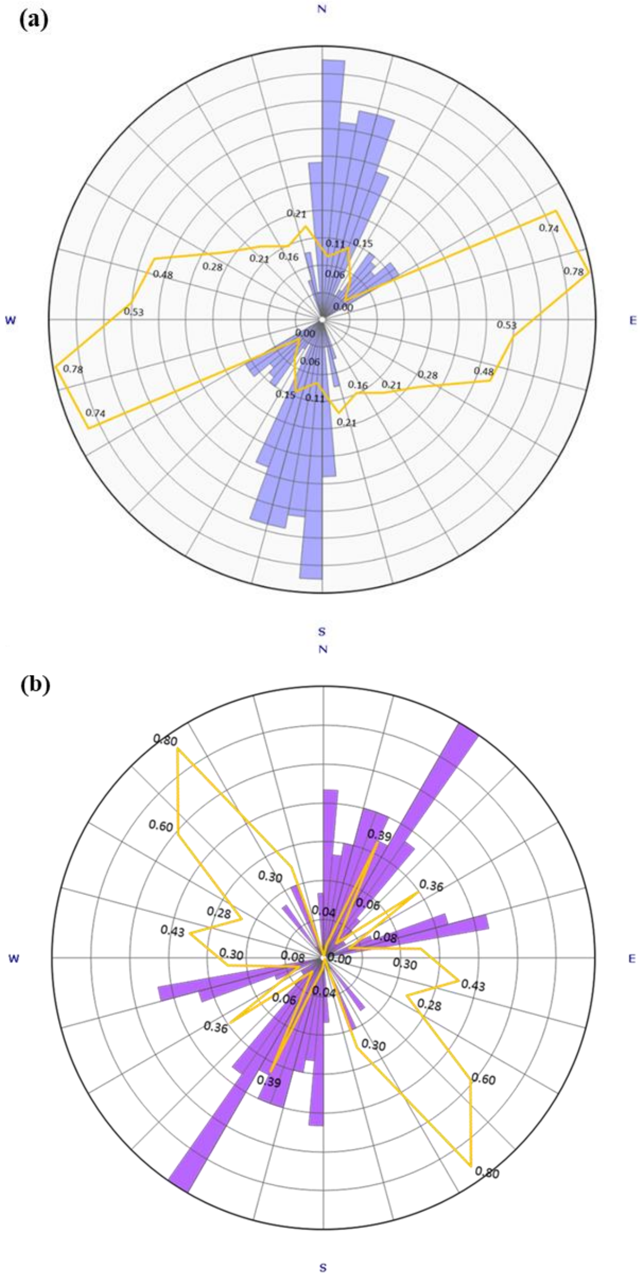

Fig 4: Seismic residual slowness (orange line) of refractor layer in (a) Quarry A, and (b) Quarry C.

There is a large slowness increment between the direction of the major strike and the direction perpendicular with the strike as presented by Figure 4a. The slowness of seismic wave propagating in the direction parallel and sub-parallel to the strike has average value of 0.13 x 10^4 s/m. However, at the direction 70° the slowness increases considerably to 0.74 x 10^4 s/m attaining the peak of 0.78 x 10^4 s/m at 85°. Moving azimuthally further, the slowness gradually decreases as it is approaching the strike direction.

Nonetheless, the lowest slowness is not only directed in the strike direction of the major fracture sets but is also affected by all constituent fractures in the investigation site. Overall, the seismic slowness response of non-weathered layer in Quarry A is lowest in the strike direction. The highest slowness of the refractor in Quarry A was recorded in direction perpendicular to the strike of the general fracture sets.

There are low amplitude zones of the slowness in the direction of major fractures set. The low slowness are in the direction of the North, 40°, and 70° and they are all coherence with that the direction of the strike of three most dominant fractures sets in different orientation. The slowness is at the highest point in the direction perpendicular to the resultant orientation of all the strikes of the fractures set. In this direction, the seismic wave propagation is at the slowest velocity. The highest slowness is at 7.96×10^4 s/m and it is in the direction 145°/325°.

4. Conclusion

The application of fan shooting in determining the velocity of seismic wave that propagating in different directions has identified the behaviour of seismic wave velocity towards the orientation of fractures in Limestone, Perak, Malaysia. The response of seismic wave velocity of the refractor layer is faster in the direction parallel or sub parallel with the fracture and slower in the direction perpendicular with the fractures. Implementation of multi direction seismic survey and by utilizing the behaviour of seismic wave with fracture structures allow the identification of the hidden orientation of geological fractures.

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