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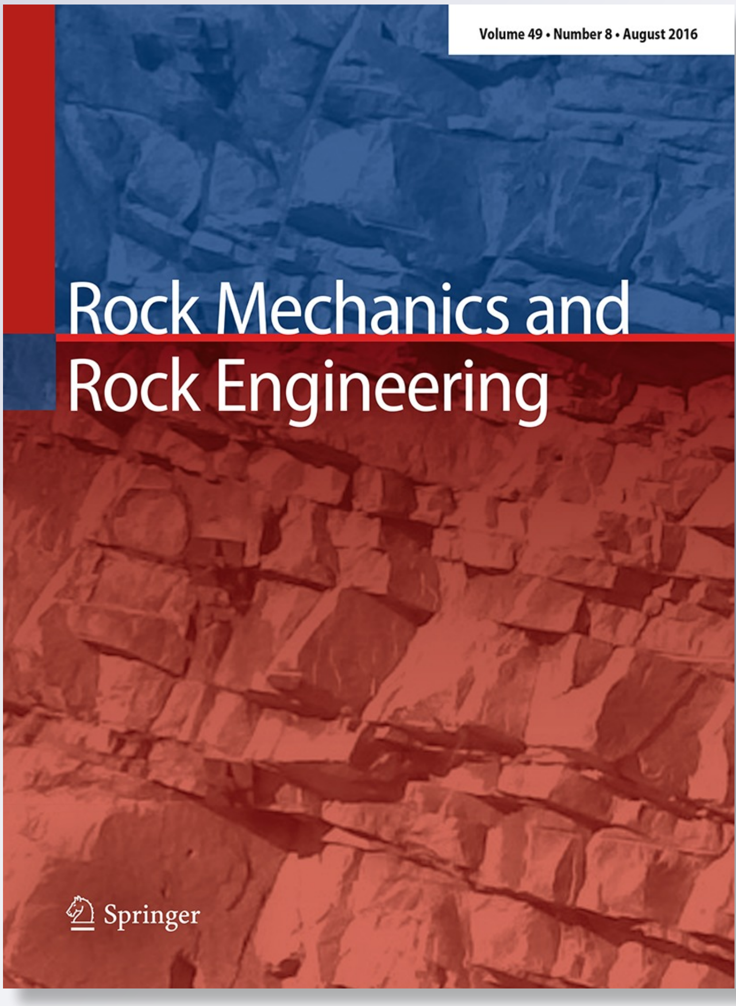

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TECHNICAL NOTE

Evolution of Joint Roughness Degradation from Cyclic Loading and Its Effect on the Elastic Wave Velocity

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Keywords Natural rock joint surface · Degradation · Maximum peak-to-valley height · Joint roughness · Elastic wave velocity

1 Introduction

The application of stress to the rock joint has a significant impact on morphological and mechanical properties of the joint. In particular, the evolution of the joint condition is dramatic on the surface of the weathered rock whose material integrity is altered in a manner similar to the rock joint behavior from weathering effects (Resende et al. 2010). As indicated in Kabeya and Legge (1997), a significant change in the weathered rock joint surface can be induced by the modification of grain properties of the joint surface. The grain size distribution has been found to be strongly correlated with the shear behavior and the joint roughness coefficient (JRC). The open joint or gouge dominates in weathered joints of the rock mass structure, thereby providing access for weathering agents to increase the failure likelihood from a slickenside (Woo et al. 2010). This granular disintegration leads to surface flakes to transform the joint aperture into a wider opening.

In the rock mass rating (RMR) system, the geomechanic classification method for rock masses is associated with the roughness of the rock joint surface as the discontinuity condition (Hoek 2007). Conventionally, the roughness of a rock joint surface is rated and quantified in term of the JRC, which ranges from 0 to 20 (Barton and Choubey 1977). However, the validity of techniques and the accuracy of measurement methods for identifying and classifying rock joint surfaces are generally questioned because of the subjectivity of JRC results. The undulation and unevenness of a rock joint surface are recognized by its peak-to-valley height (Hotar and Novotny 2005) to classify the rock joint surface profile. In particular, Mohd-Nordin et al. (2014) applied the JRC to naturally fractured rock surfaces using the scan line technique through the implementation of the peak-to-valley height. In this regard, the maximum peak-to-valley height (P_{max}) can be used as a meaningful quantitative indicator of the degree of roughness of a rock joint surface.

Previous studies have examined the propagation of elastic waves across multiple jointed rock masses by considering joint surface conditions (Mohd-Nordin et al. 2014; Huang et al. 2014a; Cha et al. 2009). One of the main findings is that the roughness and unevenness of a replicated natural rock joint surface have significant effects on the propagation of elastic waves. However, changes in

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morphological properties of the contact surface of the joint during cyclic loading have yet to be fully reported, although it is assumed that uniaxial confining stress confines the joint surface and changes joint roughness to change the elastic wave velocity in a quasi-static resonant column test. That is, an increase in confining stress increases the elastic wave velocity. In this regard, this study comprehensively evaluates the evolution of the joint surface during the cyclic loading process. In addition, the study examines the effects of changes in a replicated natural rock joint surface on the propagation of elastic waves represented by P- and S-wave velocities.

2 Experimental Setup

To apply confining stress on the replicated rock specimen, a loading bench was designed to provide various levels of the uniaxial load on top of the specimen. The loading bench (Fig. 1) consisted of a frame where the loading arm with the weight was suspended and a base plate that supported the specimen against the loading piston. The adjustable counter weight was designed to counterbalance the loading arm, and therefore 10 times the weight was applied to the top of the specimen. Quasi-static resonant column (QSRC) components consisting of an oscilloscope, a signal conditioner, and accelerometers were placed on the loading bench to evaluate P- and S-wave velocities during normal stress. The acquisition of a signal and its processing were based on previous research (Fratta and Santamarina 2002; Mohd-Nordin et al. 2014). It should be noted that the QSRC test was conducted at the maximum stress level of cyclic loading.

Naturally fractured rock joint surfaces were artificially replicated using dental gypsum, which is a stiff material equivalent to weathered rock. The degradation of the replicated specimen from a low level of cyclic loading may

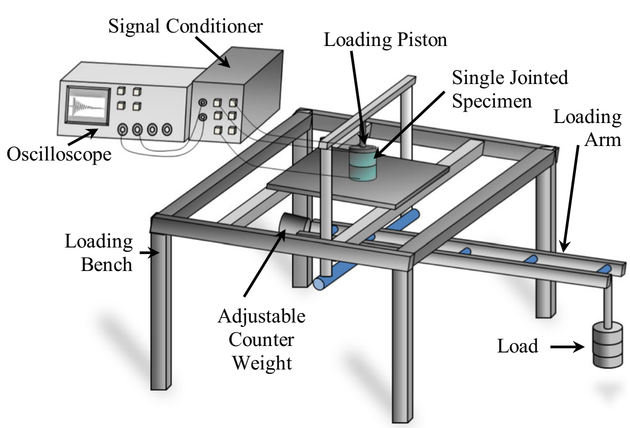


Fig. 1 A schematic diagram of the experimental setup

differ from that of a rock specimen, but the rational geophysical behavior of a jointed rock mass can be investigated using an artificially replicated specimen. Mechanical properties of dental gypsum specimens were standardized by controlling for the ratio of gypsum to water (2:1) and curing them at room temperature (27 ± 2 °C) for 48 h. Table 1 shows the average material properties of the gypsum specimen, and these are identical to those material properties considered in previous studies (Mohd-Nordin et al. 2014). Three types of naturally fractured rock surfaces were replicated from weathered granite, as shown in Fig. 2. Here, joint surfaces of weathering grades II, III, and IV corresponded to JRC = 6–8, 12–14, and 18–20, respectively.

The joint surface profile was scanned using the MitutoyoContracer CV-3000CNC (Fig. 3), which can measure the surface contour with high accuracy. This contour-measuring system with a computer-based numerical control system uses a profiling arm with a stylus needle for continuous measurement across horizontal and inclined surfaces. The speed of the stylus during profiling for the 50 mm measuring range of the joint surface was 5 mm/s, and the image resolution was 0.05 μm. In this lateral profile measurement, profiling accuracy was precise up to ± 2 μm, and alignment straightness was accurate up to 2 μm/200 mm. The average roughness of the specimen surface was determined along eight scan lines dividing the circular section in a regular manner. The degradation of joint roughness from cyclic loading was determined for a single joint. However, the evaluation of the long-wavelength elastic wave velocity in a jointed rock mass requires a QSRC test with a multiply jointed disc. Therefore, it was assumed in this study that changes in joint roughness from cyclic loading in a single joint would reflect those in a multiple joint.

3 Changes in the Joint Surface from Cyclic Confining Stress

3.1 Changes in the Maximum Peak-to-Valley Height

To measure changes in the surface profile as a result of cyclic confining stress, loading and unloading processes were repeated six times, and the surface profile measurement was conducted before and after each loading step. Confining stress was increased in five steps: from 0 to 30, 64, 129, 193, and 260 kPa.

The cyclic confining stress applied to the top of the specimen caused a significant change in the joint surface profile. Table 2 summarizes P_{max} values and corresponding surface profiles monitored from replicated surface of weathering grade II, respectively. P_{max} decreased with an

Table 1 Average material properties of dental gypsum for a 2:1 ratio of gypsum to water

Material properties			
Compressive strength (MPa)	P-wave velocity (m/s)	S-wave velocity (m/s)	Density (kg/m^3)
36.24	3845	2450	1452.40

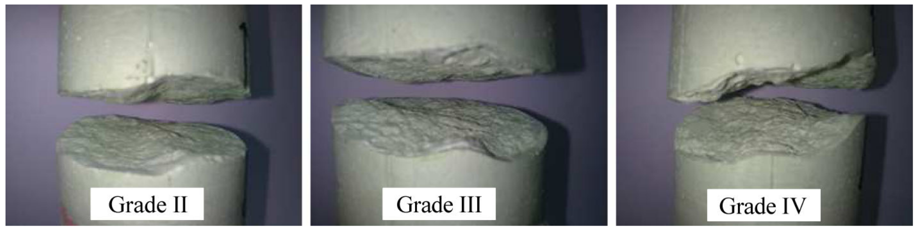


Fig. 2 Three profiles of the joint surface from different grades of weathered granite replicated with dental gypsum

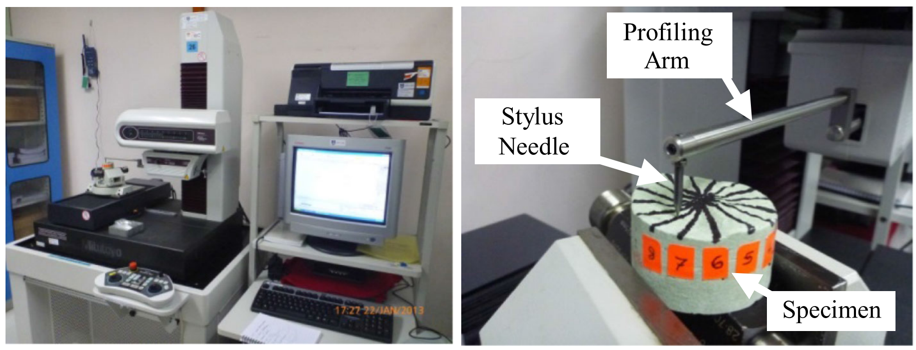


Fig. 3 Surface profile measurement using Mitutoyo Contracer CV-3000CNC from CNC Form Measurement© (2003) application

Table 2 P_{max} for eight scan lines from the surface of weathering grade II

Normal stress, σ_n (kPa)	Maximum peak-to-valley height, P_{max} (mm)								
	1	2	3	4	5	6	7	8	Average
0	3.434	3.689	3.605	4.283	3.358	2.671	4.331	3.824	3.649
30	3.414	3.643	3.593	4.237	3.199	2.654	4.318	3.783	3.605
64	3.396	3.601	3.524	4.180	3.154	2.653	4.260	3.779	3.568
129	3.359	3.470	3.534	4.024	3.105	2.650	4.249	3.773	3.521
193	3.303	3.240	3.517	3.346	3.095	2.635	4.203	3.761	3.388
260	3.113	3.111	3.157	3.293	2.603	2.593	4.194	3.702	3.221

increase in confining stress. In particular, approximately 16–23 % of the rapid reduction was observed for line numbers 2, 3, 4, and 5 between 129 and 200 kPa of confining stress. However, the rest of the scanned line records showed gradual reductions of approximately 3–4 % under the maximum level of confining stress (260 kPa). Table 5 shows the morphological evolution of the joint surface profile from the replicated natural surface of weathering grade II from cyclic confining stress. Reductions in the peak-to-valley height were induced mainly by the degradation of the peak. Accordingly, there were minor changes in overall unevenness from confining stress for a surface with a relative low JRC (weathering grade II). However, joint surfaces became smooth with an increase in confining stress.

Table 3 summarizes P_{max} values and corresponding surface profiles monitored from replicated surface of weathering grade III. As shown in Table 3, P_{max} decreased with an increase in confining stress for all scan lines. More specifically, there were sharp decreases in P_{max} in line numbers 4 and 6 for the level of confining stress between 129 and 260 kPa. The rate of decrease was approximately 12–32 % of the initial P_{max}. On the other hand, the rest of the scan line profiles showed slight decreases of approximately 5–10 % for similar levels of confining stress. As shown in Table 6, the joint surface became smoother with an increase in confining stress as a result of the breakage of micro-scale asperities. In other words, this morphological change in the joint surface implies the degradation of

Table 3 P_{max} for eight scan lines from the surface of weathering grade III

Normal stress, σ_n (kPa)	Maximum peak-to-valley height, P_{max} (mm)								
	1	2	3	4	5	6	7	8	Average
0	6.637	7.536	9.532	8.983	7.303	6.247	4.518	4.068	6.853
30	6.465	7.493	9.445	8.600	7.221	6.212	4.398	4.000	6.729
64	6.449	7.458	9.435	8.457	7.200	6.153	4.348	3.881	6.673
129	6.307	7.291	9.374	8.025	7.113	6.083	4.299	3.966	6.557
193	6.098	7.264	9.159	7.998	7.091	6.050	4.182	3.618	6.433
260	6.037	7.179	9.054	7.966	6.858	4.268	4.051	3.407	6.103

Table 4 P_{max} for eight scan lines from the surface of weathering grade IV

Normal stress, σ_n (kPa)	Maximum peak-to-valley height, P_{max} (mm)								
	1	2	3	4	5	6	7	8	Average
0	6.876	7.537	9.519	8.748	11.114	10.517	8.674	7.600	8.823
30	6.228	6.662	8.948	8.725	11.017	10.479	8.560	6.873	8.437
64	6.089	6.633	8.925	8.544	10.723	10.453	8.559	6.857	8.348
129	5.922	6.568	8.830	8.440	10.679	10.441	8.298	6.702	8.235
193	5.520	6.243	8.254	8.417	10.580	10.403	8.033	6.693	8.018
260	5.515	6.126	8.202	8.223	10.122	9.177	7.600	6.370	7.654

minute peaks and the angularity of undulating surfaces as a result of cyclic loading hysteresis.

Similarly, Table 4 summarizes P_{max} values and corresponding surface profiles monitored from the replicated surface of weathering grade IV. Changes in P_{max} were significantly affected at a low level of confining stress (30 kPa), gradually decreasing to reach the maximum level of 260 kPa. The rate of decrease in P_{max} was approximately 16–20 % in scan line numbers 1, 2, and 8. Table 7 shows typical and physical changes in the replicated profile of the rough joint surface during cyclic loading. Here, significant surface changes started to occur at 30 kPa of confining stress. There were several changes in roughness between the peak and valley of the surface profile. An increase in confining stress flattened the pinnacle and sharp edges and substantially altered the roughness of the replicated natural rock joint surface. As a result, there was a decrease in P_{max} from the evolution of surface roughness, and these morphological changes had a significant effect on JRC classification and elastic wave propagation through the jointed rock specimen.

3.2 Changes in the Joint Roughness Coefficient

The effect of cyclic confining stress on the rough joint surface is associated with morphological changes in the joint surface as well as with the JRC for the classification of rock joint surfaces. According to the description of JRC profile characteristics developed by Barton and Choubey (1977) and enhanced using P_{max} by Mohd-Nordin et al. (2014), five features of the joint surface (smooth, planar, undulating, rough, and irregular) should be evaluated to quantify the JRC.

As shown in Tables 2 and 5, joint profiles obtained from the replicated surface of weathering grade II were initially evaluated as JRC 6–8 because they appeared rough and planar, with an average P_{max} value of 3.65 mm before cyclic loading. However, the average P_{max} value decreased to 3.22 mm, which can be characterized as undulating and planar, and was classified as the JRC 4–6 surface profile after cyclic loading. The JRC of the joint surface obtained from weathering grade III in Tables 3 and 6 was JRC 12–14 before cyclic loading. That is, the surface was rough and undulating, with an average P_{max} value of 6.85 mm. Although surface profiles were rough and undulating, the average P_{max} value decreased to 6.23 mm, causing the degradation of the JRC to JRC 10–12.

As shown in Tables 4 and 7, surface profiles from the replicated surface of weathering grade IV were initially recorded as JRC 18–20 before cyclic loading because the surface was rough and irregular, with an average P_{max} value of 8.82 mm. Although P_{max} values showed trivial reductions to an average of 7.67 mm, surface profiles changed sharply to rough and undulating. Therefore, the joint roughness of the surface after cyclic loading was evaluated as JRC 14–16 in this case. In conclusion, morphological changes in the joint surface and its P_{max} from cyclic loading changed the quantitative index of joint roughness. That is, the repetitive application of confining stress to the joint surface degraded the roughness of the joint surface. This indicates that the change in the high-JRC surface as a result of the application of cyclic normal loading exceeded that in the low-JRC surface by about 3 %.

Table 5 Changes in the joint surface profile from cyclic confining stress for weathering grade II

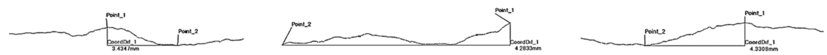
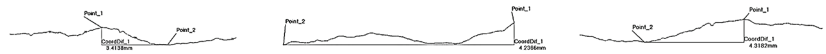
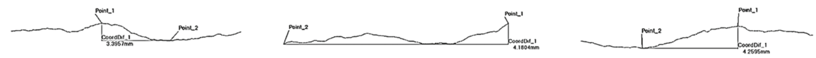
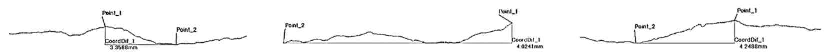
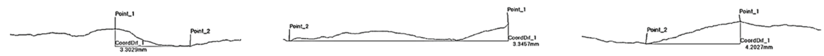
Confining stress, σ_n (kPa)	Surface profile of grade II
0	
30	
64	
129	
193	
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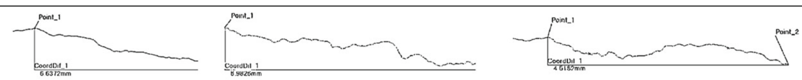
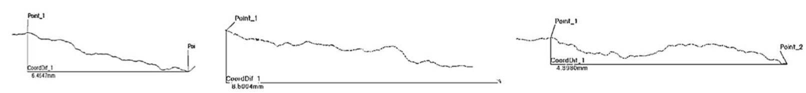
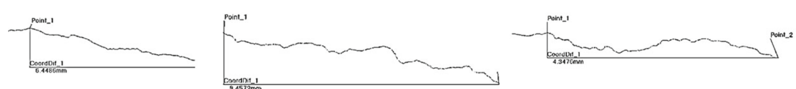
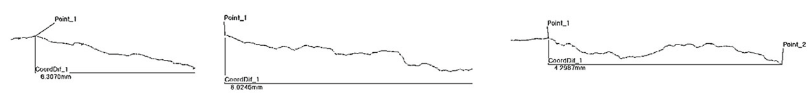
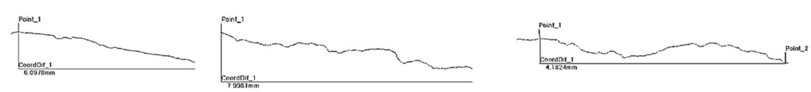
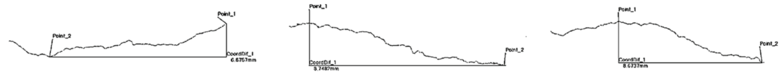
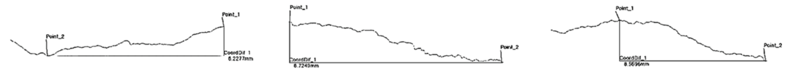
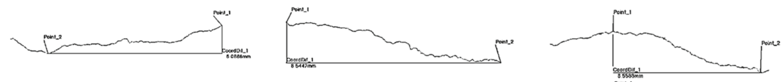
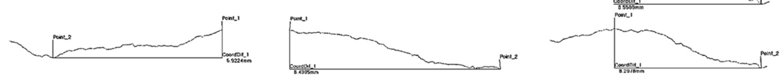
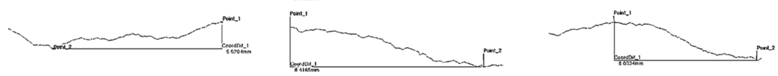
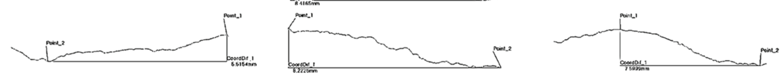
Table 6 Changes in the joint surface profile from cyclic confining stress for weathering grade III

Confining stress, σ_n (kPa)	Surface profile of grade III
0	
30	
64	
129	
193	
260	

4 Effects of Joint Surface Degradation on the Elastic Wave Velocity

The surface profile of a joint is affected by the level of confining stress, hysteresis, and surface stiffness (Jiang et al. 2006). Consequently, it modifies the shear behavior of the jointed specimen. According to Mohd-Nordin et al. (2014), the contact characteristic and degree of roughness or unevenness of the joint surface should be considered as factors influencing the propagation of elastic waves. That is, the velocity of the P-wave and that of the S-wave are dependent on the characteristic of the contact condition between joints. Although the effects of the P-wave velocity (V_P) and the S-wave velocity (V_S) from changes in the joint surface profile have been examined by referring to Mohd-Nordin et al. (2014), changes in morphological properties of the contact surface during cyclic loading and testing have yet to be fully analyzed. In this regard, the present

Table 7 Changes in the joint surface profile from cyclic confining stress for weathering grade IV

Confining stress, σ_n (kPa)	Surface profile of grade IV
0	
30	
64	
129	
193	
260	

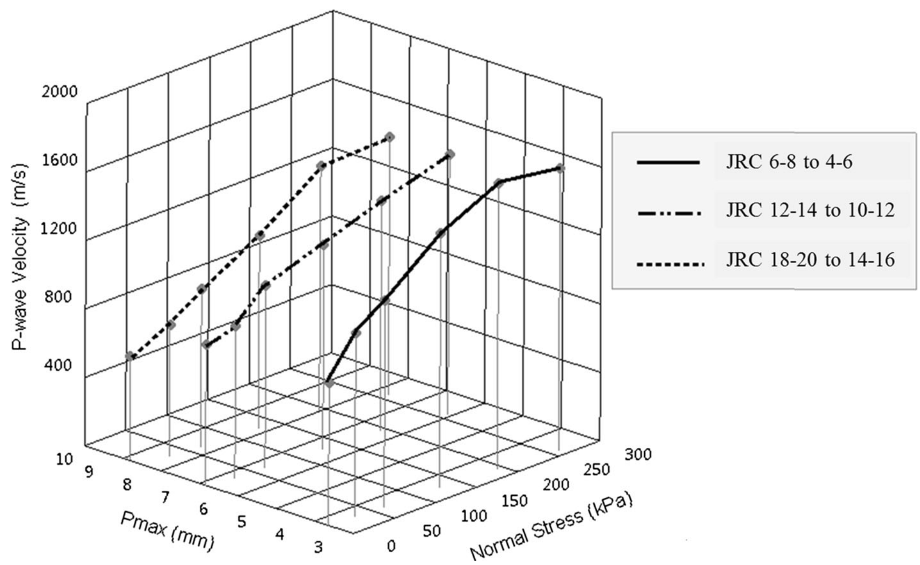


Fig. 4 Characteristics of the P-wave velocity for surface degradation from JRC 6–8 to JRC 4–6, from JRC 12–14 to JRC 10–12, and from JRC 18–20 to JRC 14–16 as a result of cyclic confining stress

study comprehensively evaluates the evolution of the joint surface from cyclic loading and its effect on the velocity of the elastic wave.

Figure 4 shows the effects of joint surface degradation on V_P at different levels of cyclic confining loading from JRC 6–8 to JRC 4–6. The results for initial joint surfaces of JRC 12–14 and JRC 18–20 show similar trends in V_P. According to the results, an increase in the level of roughness reduced V_P, which is consistent with the findings of Kahraman (2002) and Li and Zhu (2012). In addition, an increase in confining stress increased material stiffness, and the contact characteristic between replicated joint surfaces was an important factor influencing changes in V_P. The geometric formation of the roughness characteristic influenced the propagation of the P-wave when the intimate contact characteristic of the joint surface deteriorated with an increase in the JRC. That is, the likelihood of a mismatch in the natural joint surface increased with an increase in the JRC.

As indicated in Li and Ma (2009), the angularity of the joint surface profile influences the incident angle of P-wave propagation. For this reason, Wu et al. (1998) highlight the effect of the joint orientation where the path of wave propagation is perpendicular to the joint strike. Therefore, changes in the angularity of replicated rock surface from confining stress and the joint orientation affected the incident angle of P-wave propagation through the jointed rock mass. However, based on the experimental results, an increase in the level of confining stress reduced micro-scale asperities and flattened the pinnacle and sharp edges, which

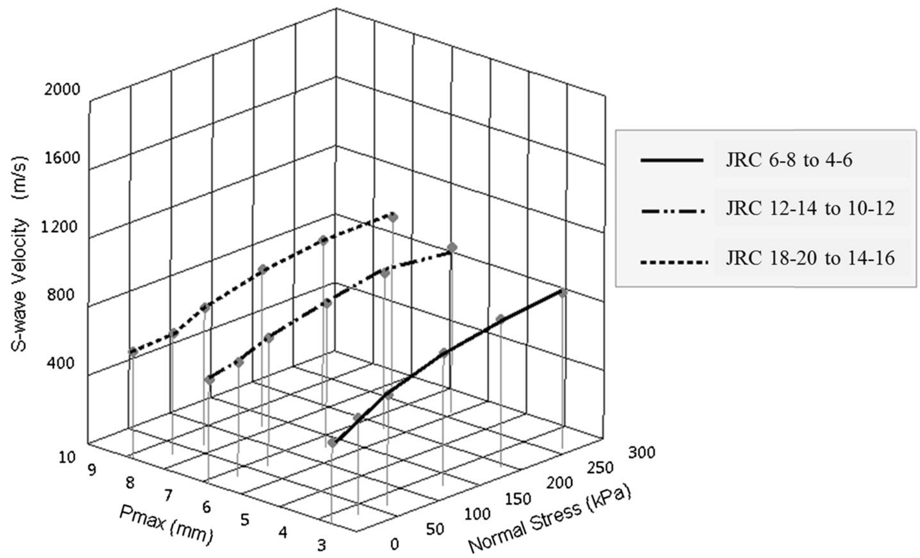


Fig. 5 Characteristics of the S-wave velocity for surface degradation from JRC 6–8 to JRC 4–6, from JRC 12–14 to JRC 10–12, and from JRC 18–20 to JRC 14–16 as a result of cyclic confining stress

represented surface roughness and unevenness, or P_{max}. Consequently, the contact area inferred from P_{max} increased at a small scale, causing an incremental increase in V_P.

Figure 5 characterizes the changes in V_S as a result of joint surface degradation from changes in cyclic confining loading from JRC 6–8 to JRC 4–6, from JRC 12–14 to JRC 10–12, and from JRC 18–20 to JRC 14–16. The shearing process of the rock joint was strongly dependent on the level of joint surface roughness (Jiang et al. 2006). In this study, an increase in confining stress induced a gradual increase in the torsional shear wave velocity (V_S). More specifically, confining stress enhanced the shear stiffness and shear resistance of the joint surface (Mohd-Nordin et al. 2014). The higher the JRC, the rougher the surface was, and therefore the rougher the replicated specimen of a naturally fractured joint surface, the greater the shear resistance was. In addition, an increase in the JRC increased V_S. Despite the degradation of the roughness of the joint surface from cyclic loading, the shear wave velocity was governed mainly by friction and interlocking effects contributed by the roughness and unevenness of the joint surface profile. That is, the shear wave velocity increased with an increase in the JRC because it was governed mainly by friction and interlocking effects induced by the roughness of the joint surface (Huang et al. 2014b).

5 Conclusions

The propagation of elastic waves in jointed rock masses is heavily affected by the condition of the joint. Because the confining stress on the jointed rock modifies the profile of the joint surface, it changes the degree of roughness and unevenness. The present study focuses mainly on the roughness of the joint and the change in roughness as a result of cyclic loading.

This study measures the changes in the joint surface profile and the contact area for a replicated specimen of a naturally fractured surface of weathered rock based on effects of cyclic confining stress. Changes in the surface profile were quantitatively measured using P_{max} index, and these changes were found to be correlated with the JRC and thus with the elastic wave velocity. The change in the high-JRC surface from cyclic normal loading exceeded that in the low-JRC surface.

The effects of changes in the replicated surface roughness and unevenness of the joint surface profile from uniaxial confining loading on the propagation of the long-wavelength P-wave and the torsional S-wave were analyzed, and the effects of the degradation of joint roughness on the velocity of elastic waves were evaluated. An increase in confining stress increased the velocity of the elastic wave. According to the experimental results, a high level of confining stress significantly reduced micro-scale asperities and flattened the pinnacle and sharp edges in terms of surface roughness and unevenness. Consequently, the contact area inferred from the surface profile increased slightly, thereby leading to an incremental increase in V_P. However, despite the degradation of the roughness of the joint surface as a result of cyclic loading, V_S was governed mainly by friction and interlocking effects contributed by the roughness and unevenness of the joint surface profile.

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