RESEARCH ARTICLE OPEN

Simmulation of Rough Rock Joints under Shear Stress

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ABSTRACT
A mass of jointed rock is usually treated as a discontinuum because it is often associated with a heterogeneous nature that comprises intact rock units separated by discontinuities, e.g. joints, faults and bedding planes. The characteristics of rock joints have major influences on the rock mass behavior and the consequent failure mechanism. The shear performance of the rock joints is vastly affected by the morphology of the joint surface, which stands for the joint surface roughness. Therefore, tilting tests are performed on artificial rock samples to investigate the influences of the surface roughness on the shear performance of rock joints. Moreover, a 3D numerical model, based on the Finite Element Method, is proposed in the present study. The results are compared with experimental results of tilting test and with previously published experimental reults of large-scale direct shear test and published numerical results performed using Distinct Element Method. The numerical model is used then in a parametric study to illustrate the influence of the morphology of the joint surface on the shear strength.

Keywords - jointed rock, joint surface, morphology, roughness, shear strength.

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I. INTRODUCTION

Some sorts of rock joints are formed due to tensile cracking through the intact rock units. Such cracking may take place along the grain boundaries giving rise to asperities on the rock joint surface. These asperities form the so-called "rock joint roughness". The roughness of a rock joint may be a major contributor to its shear strength depending upon various factors, such as the surface morphology, the strength of asperities that is related to the strength of the rock material and the ability of asperities to transmit normal and tangential forces on the joint surface. The morphology of the joint surface stands for the asperity shape, distribution and size in addition to the spacing between the asperities.

Several attempts have been performed to characterize the rock joint roughness, which can be divided into two categories, direct and indirect methods. Direct methods refer to the experimental quantification of the joint roughness influences. Direct Shear tests, multistage triaxial shear tests and tilting tests are effective laboratory methods to reliably assess the effect of roughness on the shear behavior of rock joints. Rao et al. (2009) developed an automated large scale direct shear testing machine to examine rock samples under constant normal load (CNL) and constant normal stiffness (CNS) boundary conditions. CNL is a boundary condition in which a constant value of normal stresses is applied on the upper half of the specimen which permits the upper half to dilate freely, while on the other hand, CNS is applied by performing area springs in the upper half of the specimen to constrain it from any dilation that could occur. Indirect methods, on the other hand, are divided into empirical, analytical and numerical methods. The Joint Roughness Coefficient (JRC) model is one of the first empirical methods introduced by Barton and Choubey (1977). Nevertheless, the main shortcoming of the indirect methods is the lack of the constitutive models and the associated properties of the jointed rocks. Also, the indirect methods models still depend on the empirical characterizations of the joint surface. The first idealized "saw-tooth" description was proposed accounting on the average inclination angle (i) of the asperities (Patton. 1966). This analytical simplified method lessens the precision and the contemplation. The finite Element Method (FEM) was used to simulate the asperity degradation of a sheared rock joint (Giacomini et al. 2008). Moreover, the distinct element method was used in simulating the jointed rock (Shrivastava and Rao. 2010).

In the present study, tilting tests have been performed on artificial rock samples with different morphological joint surface. The results are compared with published experimental results performed by Rao et al. (2009). Rao et al. used an automated large scale direct shear testing machine in examining the shear strength of artificial joint surface using plaster of Paris. Moreover, 3D numerical models have been established to simulate the behavior and strength of jointed rock samples with rough joint under shear stress. The results of the numerical work is to be compared with previously published experimental results of large scale direct shear test and published numerical results performed using the Universal Distinct Element Code (UDEC) based on the Distinct Element Method (DEM).

A study for the influence of the morphology of the joint surface on the shear strength is then done using different geometrical three-dimensional models. By changing the asperities height, inclination angles and the spacing between the asperities, a parametric study has been conducted. The results of the parametric study are then highlighted.

II. TILTING TEST SET-UP AND EXPERIMENTAL PROCEDURE

2.1. Description of Tilting Table

The tilting test table was designed and fabricated for indicating the friction angle of rock joint surface. Fig. 1 and Fig. 2 show the schematic diagrams for the titling test apparatus. The upper table (Fig. 3) tilts the rock sample until sliding occurs on the discontinuity between the lower and the upper portion of the rock sample. The upper table is connected to the lower table by two threaded screws from the front side and two hinges from the back side. The two threaded screws are used to level the upper table to prevent any initial inclination. The two hinges are used so that the upper table can rotate around them. A threaded shaft is used through a threaded hole to tilt the upper table around the two hinges. The threaded shaft has a crank at the end and when that crank is turned, the shaft moves horizontally and pushes the upper table upwards around the two hinges. The shaft is hemispherical to facilitate moving horizontally and pushing the upper table around the two hinges. The upper tilting table is made of steel with dimensions 0.27 m x 0.30 m and 20 mm thick. While the lower table with dimensions 0.40 m x 0.30 m and 20 mm thick. The upper table is equipped with brackets from the three sides 50 mm height and four screws to support the lower portion of the specimen and prevent any displacement during tilting the upper table. A protractor is fixed to the lower table to measure the inclination angle of the upper table with the horizontal direction.

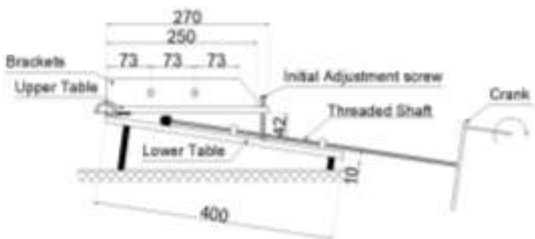

Figure 1: Schematic diagram side view at initial phase

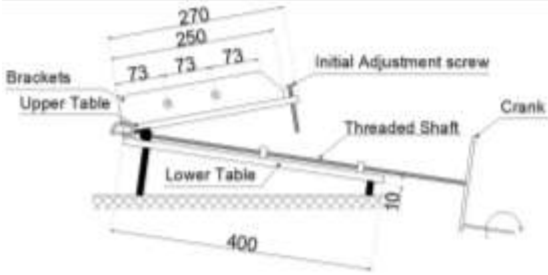

Figure 2: Schematic diagram side view at tilting phase

Figure 3: Side view of the tilting test table

2.2. Test Procedure

The upper table is first levelled by adjusting the two-foot screws at the front using water bubble level meter. The water bubble level meter is placed on the upper table and the screws were adjusted to level the sliding surface at the beginning of the test. The protractor is adjusted so that the inclination angle of the upper table is 0° with the horizontal direction. The crank of the threaded shaft starts to rotate slowly at 2.5°/minute (USBR 6258, 2009). When the upper portion of the specimen starts sliding along the discontinuity, rotating the crank stops, and the angle at which sliding occurs is the sliding angle. The test is repeated several times for each sample and the final sliding angle was taken as the average value for all the inclination angles.

2.3. preparation of the Asperities of the Specimen

Since it is difficult to prepare a rock sample with a specific morphology of the joint surface, laboratory samples made of a mixture between white cement and gypsum is used in the tilting test. The samples were casted several times using different ratios between the using materials. It was found that the ratio 9:1 between white cement and gypsum gives neat dimensions for the specimens after casting them in the molds. White cement is used to increase the strength of the sample and increase the workability so as to be able to form the sample. On the other hand, gypsum is used to decrease the setting time. The mixture with 60% moisture content is mixed in the mixing tank for 5 minutes and then the material is placed in the casting molds (Fig. 4, 5 & 6).

Figure 4: Casting of the mixture in the timber molds

Figure 5: Specimen with 30°-30° asperities

2.4. Testing Results

Tilting test has been performed on 0°-0° asperities, 15°-15° asperities and 30°-30° asperities. The results showed that the sample with 0°-0° asperities (no

Figure 6: Specimen with 15°-15° asperities

asperities) slides at inclination angle nearly equal to 35°.This means that, the angle of friction of the plane joint surface with no asperities is equal to 35° for this specimen (according to USBR 6258, 2009). While, the sample with 15°-15° asperities slides at inclination angle equal to 50°. The 50° is the basic angle of friction for this joint. This result emphasizes the fact that the basic angle of friction for the rock joint (50°) is equal to the summation of the basic angle of friction for the joint surface (35°) and the inclination angle of the asperities existing on the joint surface (15°) (Patton, 1966). The sample with 30°-30° asperities (weighs 5 kg) slides at inclination angle equal to 65°. This is due to the summation of 35° basic angle of friction for the joint surface and 30° inclination angle of the asperities (Patton, 1966).

2.5. Comparison between Tilting Test Results and Direct Shear Results

The tilting test results are compared with the experimental results of direct shear test performed by the automated large scale direct shear testing machine under low normal stress (Rao et. al., 2009). The following Figure (Fig. 7) shows the relation between the inclination angle of the asperities and the friction angle of the joint surface using the tilting test and direct shear test for the same samples under low normal stresses.

III. SIMULATION OF DIRECT SHEAR TEST USING FINITE ELEMENT MODEL

In the present study, the FEM has been exploited to simulate direct shear testing on jointed rock samples with rough joints. In this regard, a 3D numerical model has been established for a jointed rock sample having a square cross section. The proposed width (W) of modeled sample is 297 mm and the sample height (2H) is 125 mm. The 3D FE model has been suggested to simulate a jointed rock sample in a

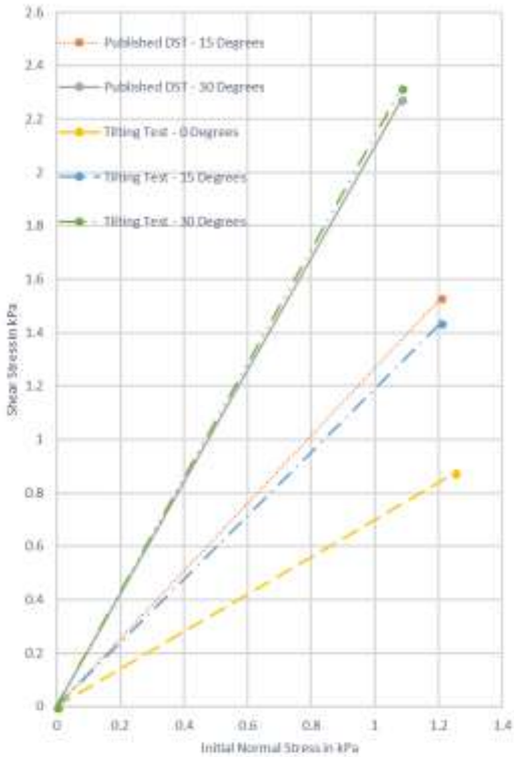

Figure 7: The relation between the joint friction angle and the inclination angle of the asperities using tilting test and published experimental results

direct shear test of dimensions (297 mm X 297 mm X 125 mm). Therefore, the modeled sample was composed of two halves, each is of a height (H) of 62.5 mm. The sample's upper and lower parts are proposed to be totally separated by a rough rock joint. The rock joint roughness has been suggested to be simulated by means of a number of asperities that are distributed along the joint surface. The asperities have been idealized as "saw-tooth" shape, on the basis of Patton (1966) assumption. Furthermore, an interface element has been utilized to simulate the shear performance of the rock joint. Fig. 8 demonstrates the proposed geometries of the 3D FE model. The sample has several triangular asperities with 15° and 30° inclination angle and 5 mm height. Plaster of Paris is used in the simulated direct shear test which is used in the laboratory tests by Rao et al. (2009). The adopted parameters of both the rock material and rock joint are depicted in Table 1.

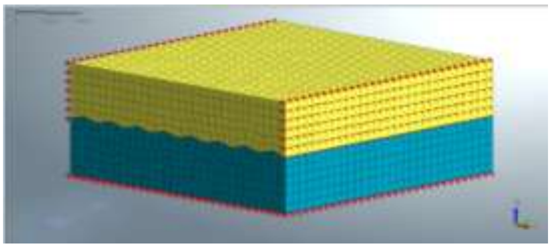

Figure 8: The Numerical Model of 15° asperities including the boundary conditions.

Table 1: The adopted parameters of both the intact rock material and the rock joint

Properties	Intact Rock	Rock Joint
Dry Density (kN/m3)	12.34	-
Modulus of Elasticity (MPa)	2281	-
Poisson's ratio	0.22	-
Cohesion (MPa)	3.0	0.05
Internal angle of friction	33°	35°
Dilation angle	0°	0°
Tensile Strength (MPa)	1.0	0
Normal Stiffness (MPa)	-	1750
Shear Stiffness (MPa)	-	175
Material Model	Mohr-Coulomb	Coulomb Friction

The boundary conditions of the FE model have been proposed such that the numerical model can highly represent the real direct shear test. The lower half of the sample is subjected to horizontal displacement in the x-direction and is restricted from the translation in y-direction and z-direction. On the other hand, the upper half of the sample is subjected to normal pressure in the z-direction and is restricted from the translation in the x-direction and y-direction. Fig. 9 illustrates the boudary conditions used in the numerical model.

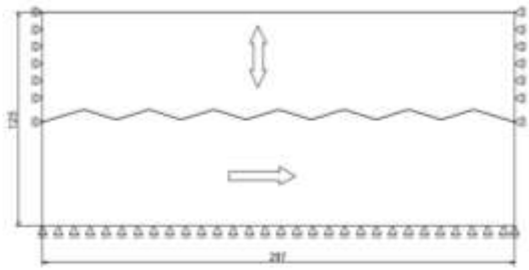

Figure 9: The boundary conditions of the sample including 15° asperities

3.1. Verification models

The results of the numerical models using FEM were compared to the results of a numerical model using Universal Distinct Element Code (UDEC) based on the Distinct Element Method (DEM). A 2D plain strain model has been established by Rao et al. (2010) for the same geometric model but with different properties for the material. The internal angle of friction of the interface was taken as 35°, the normal stiffness was 1750 MPa, Shear stiffness 175 MPa, dilation angle 5° and the tensile strength was taken equal to 0.01 MPa. Moreover, The results of the DEM have been compared with the experimental results using an automated large scale direct shear testing machine for rock developed by Rao et al. (2009).

3.2. Comparison between DEM, Experimental and 3D FEM Results

In the 3D finite element model, the peak shear stress on the joint surface of the rock joint has been determined by dividing the peak shearing force by the actual shearing area.

- The Peak Shear Stress: The maximum shear stress on the joint surface between the two halves of the sample.
- The Peak Shearing Force: The maximum shearing force required to displace the lower half of the rock sample a distance equal to half the base of the asperities.
- Actual Shearing Area: The shearing area between the surfaces of the two halves of the rock sample after the transition of the lower half a distance equal to half the base of the asperities.

The results of the FEM were found to be very close to the experimental results performed by the automated large scale direct shear testing machine in case of low normal stresses with variations between 0% and 1%. while the results varied between 0% and 6% in case of high normal stresses. Also, the 3D model highly predicted the behavior of the relationship between the initial normal stresses and the peak shear stresses. It seems also that the 3D model using FEM is better than the 2D model using DEM as the results were more closely to the experimental results. The variation between the 2D DEM model and the 3D FEM model ranged between 8% in case of low normal stress and increase to 24% in case of high normal stress. Fig. 10 shows the deformed shape of the jointed rock. Moreover, Fig. 11 and Fig. 12 represent the relationship between the initial normal stresses on the upper half of the sample, and the peak shear stresses performed on the lower half of the sample, due to the translation of the lower half with a displacement equal to half the base of the asperities in case of 15° triangular asperities and 30° triangular asperities.

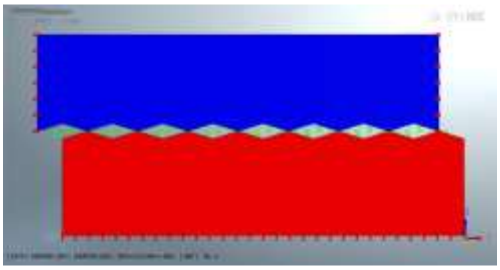

Figure 10: The Deformed Shape of the Numerical Model of 15° asperities.

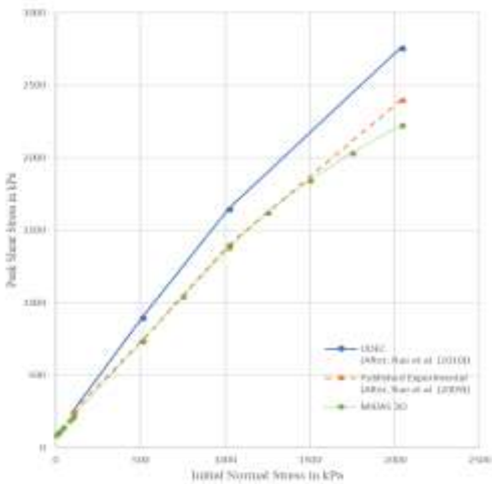

Figure 11: Comparison between the results of DEM, experimental and 3D FEM in case of 15° asperities.

IV. PARAMETRIC STUDY

The performed parametric study is based on the verified model previously discussed. The finite element model was compared to the experimental work done by Rao (2009). 3D finite element model

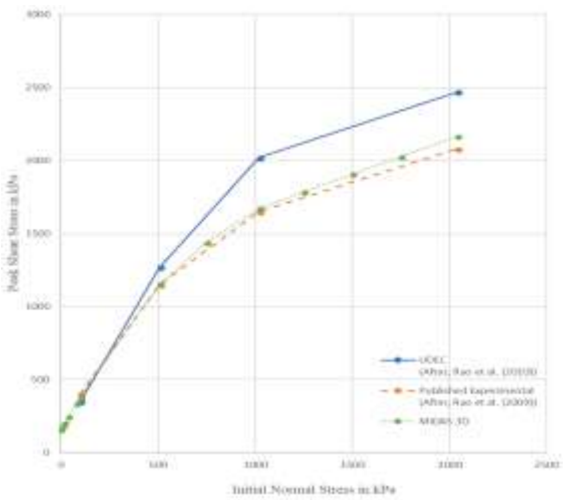

Figure 12: Comparison between the results of DEM, published experimental results and 3D FEM model in case of 30° asperities.

is used during the parametric study. Four different parameters have been studied during this parametric study, asperities height, inclination angle, spacing between the asperities and shape as shown in Fig. 13. The effect of these parameters has been monitored and briefly explained.

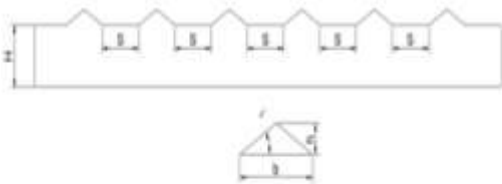

Figure 13: Different parameters used in the parametric study

4.1. Effect of Asperities Height

The effect of joint asperities height has been studied by varying the height of the asperities. The total height of the sample is 125 mm, and it is divided into two halves, each 62.5 mm. The ratio between the height of the asperities (h) and the height of the upper half of the sample (H) varies from 0.04 to 0.32. During the study of the effect of asperities height, the inclination angles have been taken to be 30 degrees as the verified model and there is no spacing between the asperities. The normal stresses were applied on the upper half of the sample and the values were 0 MPa, 0.01 MPa, 0.02 MPa, 0.04 MPa, 0.08 MPa, 0.1 MPa, 0.25 MPa, 0.51 MPa, 0.75 MPa, 1.02 MPa, 1.25 MPa, 1.50 MPa, 1.75 MPa and 2.04 MPa.

The effect of varying the asperities height is shown in Fig. 14. It is found that the friction angle of the rock joints at low normal stress is nearly the same which is equal to 65°. The value of the friction angle is due to the summation of both the basic angle of friction of the joint (which is equal to 35°) and the inclination angle of the asperities (which is equal to 30°). Also, the residual friction angle for the height ratios (h/H) 0.04, 0.08, 0.12, 0.16 and 0.2 was found to be the same and equal to 26°. The zone of the residual friction angle which is called sometimes “The shearing zone” (i.e. It is the zone in which the normal stress is considered relatively high. When subjected to shear stress, crushing and shearing of the asperities occur) starts at different initial normal stresses depending on the height of the asperities (Fig. 15). The shearing zone starts at initial normal stress equal to 0.50 MPa in case of height ratio 0.04. In case of height ratio 0.2, the shearing zone starts at initial normal stress equal to 2.50 MPa.

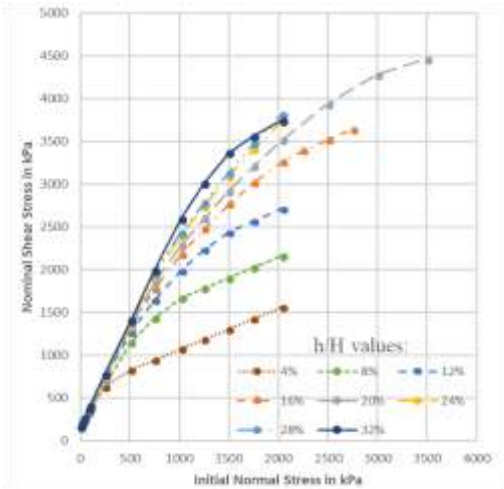

Figure 14: Influence of different height ratios (h/H) on shear behavior

4.2. Effect of Inclination Angles of Asperities

The shear behavior of the jointed rock was affected by changing the inclination angle of the asperities.

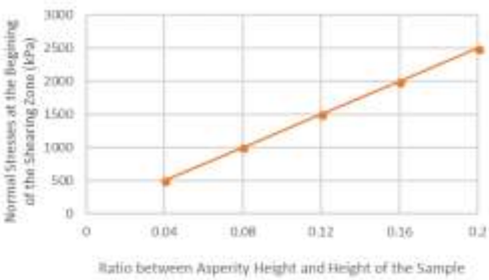

Figure 15: Influence of different height ratios (h/H) on the beginning of the shearing zone

The values of the inclination angles ranged between 7.5° and 45°. The height of the asperities was taken equal to 5 mm and there was no spacing between the asperities. The normal stresses were applied on the upper half of the sample and the values were 0 MPa, 0.01 MPa, 0.02 MPa, 0.04, MPa, 0.08 MPa, 0.1 MPa, 0.25 MPa, 0.51 MPa, 0.75 MPa, 1.02 MPa, 1.25 MPa, 1.50 MPa, 1.75 MPa and 2.04 MPa.

The results showed that the angle of friction for the rock joints at low normal stress are nearly equal to the summation of the basic friction angle of the joint (which is equal to 35°) and the inclination angle of the asperities (Fig. 16). It was found also that the ending of the sliding zone (i.e. It is the first zone in the shear stress-normal stress relationship. In this zone, the normal stress is considered as low and the rock samples slides over the asperities when subjected to shear stress) depends on the inclination angle of the asperities. The performance of the jointed rock sample subjected to 2.04 MPa normal stress is in the sliding zone in case of inclination angle of asperities equal to 7.5°. The values of normal stress at which the sliding zone ends started to decrease by increasing the inclination angles of the asperities. In case of asperities of inclination angle 15°, the sliding zone started to end when subjected to 1.50 MPa normal stress. While in case of 45° asperities, the sliding zone ends at normal stresses equal to 0.04 MPa.

4.3. Effect of Spacing between Asperities

The effect of changing the spacing between the asperities of the rock joints has been studied by varying the spacing several times through the

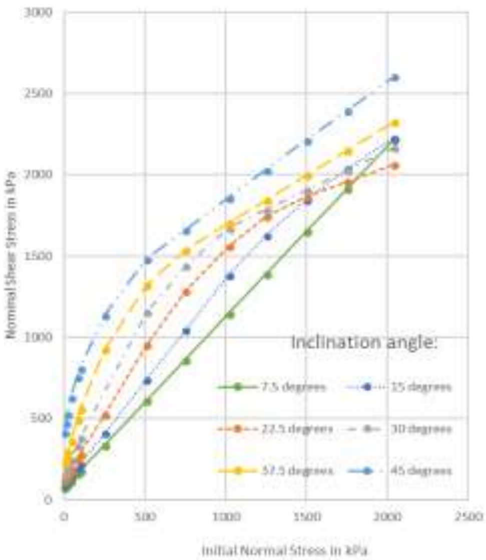

Figure 16: Influence of different inclination angles of asperities on shear behavior

numerical model. The variations started with no spacing between the asperities and ends with a ratio between the spacing between the asperities (S) and the breadth of the asperities (b) of 8.7. The asperities were taken with 30° inclination angles. And the height of the asperities was 5 mm. The upper sample was exposed to normal stress which ranged from 0 MPa to 2.04 MPa. The results showed that the basic friction angle of the joints for the used material does not depend on the spacing between the asperities and it is nearly the same at low normal stress and equal to 65° (Fig. 17). The value of the friction angle is due to the summation of the friction angle of the joint surface (which was 35°) and the inclination angle of the asperities (30°). The residual friction angle for the used material does not depend on the spacing between the asperities and is nearly the same under high normal stress and equal to 26°. The shearing zone is the main factor affected by changing the spacing between the asperities. The shearing zone starts at initial normal stress 1.02 MPa in case of no spacing between the asperities. While on the other hand, the shearing zone starts at no initial normal stress in case of spacing ratio (S/b) equal to 8.7. This means that, in case of large spacing between the asperities, the roughness of the asperities has small effect on the friction angle of the joint surface and the basic friction angle increases as the spacing between the asperities decreases.

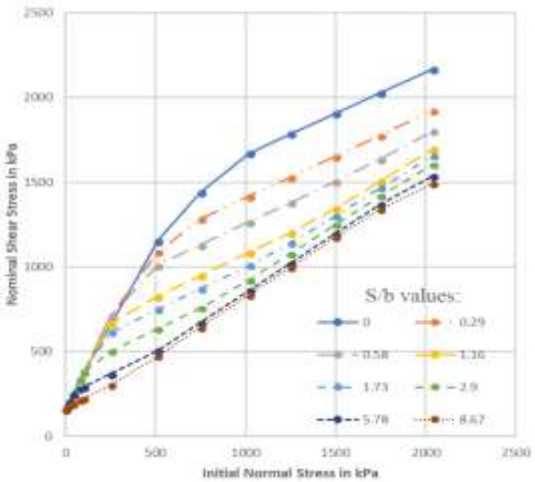

Figure 17: Influence of different spacing ratios (S/b) on shear behavior

4.4. Effect of the Shape of the Asperities

The variation in the shape of the asperities during the parametric study is done by changing the triangular asperities into saw-tooth asperities. During the parametric study the height of the asperities was taken equal to 5 mm. The inclination angle of the asperities was 30 degrees and there was no spacing between the asperities. Also, the upper sample was exposed to initial normal stress which ranged from zero to 2.04 MPa.

The results showed that the relation between the peak shear stress and the initial normal stress is affected by the shape of the asperities in case of small spacing between the asperities (Fig. 18). While the effect of the shape of the asperities vanishes gradually as the spacing between the asperities increases to 50 mm (Fig. 19). In case of small spacing between the asperities, it was found that the results are nearly the same for both the triangular asperities and the saw-tooth asperities at low normal stress. The results were nearly the same till the case of initial normal stresses equal to 0.10 MPa. After the end of the sliding zone, the difference between the shape of the asperities starts to appear and the shear stresses was found to be higher in case of saw-tooth asperities. The difference between the shear stresses in case of triangular asperities and the shear stresses in case of saw-tooth asperities disappears gradually as the spacing between the asperities increases till it vanishes in case of spacing between the asperities of 50 mm.

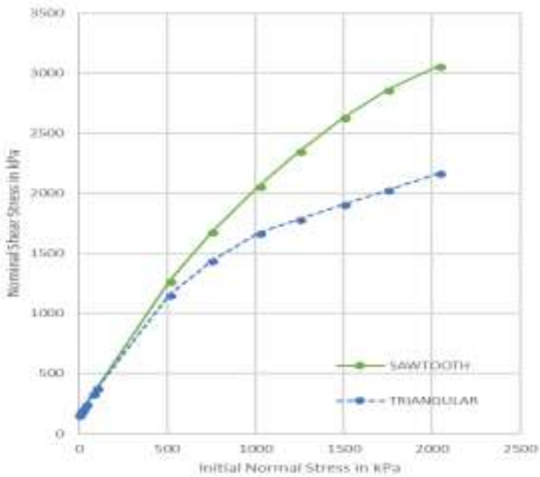

Figure 18: Influence of different types of asperities on shear behavior (No spacing between asperities)

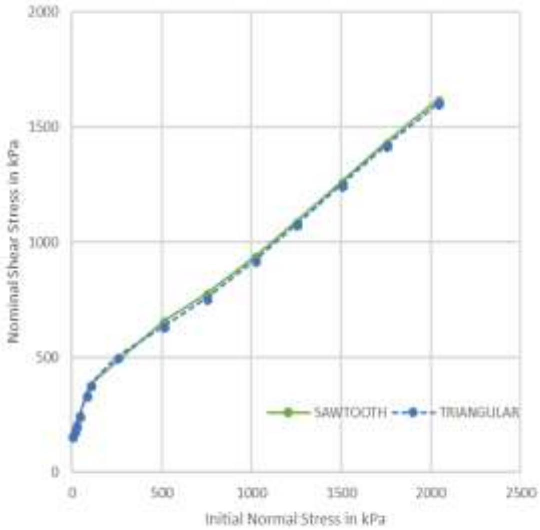

Figure 19: Influence of different types of asperities on shear behavior (Spacing = 50 mm)

V. CONCLUSIONS

The following conclusions were drawn from this research

1. The tilting tests emphasize the fact that the basic friction angle of the rock joint is equal to the summation of the basic friction angle of the joint surface, and the inclination angle of the asperities.
2. Finite element method was found to be suitable and flexible numerical approach to the shear behavior and the properties of the jointed rock that can not be obtained from small intact rock samples.
3. The results showed that the 3D FEM can highly predict the peak shear strength of the joint at low normal stress. The numerical results over predict the peak shear strength in case of high normal stress and the variation between the numerical results and the published experimental results reaches nearly up to 6%.
4. 3D FEM can predict the degradation and the shearing of the asperities. The relation between the peak shear stress and the nominal normal stress was found to be bilinear. The friction angle of the joint decreases as the nominal normal stress increases. The residual friction angle of the joint is relatively close to that of the experimental results.
5. The results showed that the height of the asperities does not affect the basic friction angle of the rock joints. And the normal stress level needed to initiate the shearing of the surface asperities remarkably increases by increasing the asperities amplitude.
6. The results showed that the angle of friction of rock joints increases as the inclination angle of asperities increases at low normal stress for the same amplitude.
7. The results showed that the spacing between the asperities considerably affects the shearing of the asperities. As the spacing between the asperities decreases, the shear strength of the asperities increases and the influence of the morphology of the surface increases.

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