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# 3-D ANALYSIS OF ROUGH ROCK JOINTS UNDER SHEAR STRESS

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**ملخص البحث**

أحيانا ما تقع أماكن بعض المشاريع المدنية الرئيسية فى مناطق ذات طبيعة جيولوجية خاصة، مثل نطاقات الصخور ذات الفواصل. وفى مثل هذه الحالات، يكون من الضرورى توافر قدر كاف من المعلومات عن خصائص الكتلة الصخرية الموجودة بالموقع (من حيث معاملات التشكل والمقاومة) وذلك بهدف الوصول إلى تحليل هندسي فعال وتصميم آمن وأسلوب تنفيذ مناسب للمنشآت المطلوبة على الصخور ذات الفواصل. و تعتبر خصائص مستويات عدم الإتصال بين الصخور تؤثر بشكل كبير جدا ليس فقط على سلوك الكتلة الصخرية بل أيضا على نمط الإنهيار المحتمل لبلوكات الصخر. ومن بين الخواص الميكانيكية المختلفة للفواصل الصخرية، يأتى أدائها فى القص فى مقدمة العوامل التى تعبر عن السلوك العام لهذه الفواصل. ولذلك، فإن المعالجة الواقعية والدراسة الدقيقة لمقاومة فواصل الصخور لإجهادات القص أصبحت ضرورة حتمية فى تطبيقات هندسة الصخور للوصول إلى فهم حقيقي لسلوك الكتلة الصخرية. وتساهم خشونة أسطح فواصل الصخور بشكل كبير فى مقاومة هذه الفواصل لإجهادات القص.

لذلك يركز هذا البحث على تحليل عددي ثلاثي الأبعاد لفواصل الصخور تحت تاثير قوى القص. تم مقارنة نتائج التحليل الانشائي بنتائج عملية من تجربة قص مباشر وعددية تم إجرائها من قبل باحثون. وتبين ان نتائج التحليل العددي قريبة جدا من النتائج العملية فيما تخص اجهادات القص على فواصل الصخور، فيما تزيد قيمة الإختلاف مع زيادة الإجهادات العمودية بنسبة 6%.

## 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. The rock joint roughness is represented through the created asperities along the surface of the rock joint. However, there is still a shortcoming regarding the availability of a rational quantitative algorithm that can account for the realistic shear performance of rough rock joints, considering the joint surface roughness. Therefore, a 3D numerical model, based on the Finite Element Method, is proposed in the present study to investigate the influences of the surface roughness on the shear performance of rock joints. The results are compared with previously published experimental reults of large-scale direct shear test and published numerical results performed using Distinct Element Method. The comparison showed that the 3D numerical model using MIDAS GTS NX is more capable of simulating the shear performance of the jointed rock at low normal stress than the DEM. Moreover, the variation between the FE results increases to about 6% at high normal stress.

# 1. 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, 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).

# 2. NUMERICAL ANALYSIS USING FINITE ELEMENT METHOD

The discontinuities of rock can be simulated through FEM as interface elements. The relative displacements between rock elements can be controlled by the input data. Moreover, the numerical model takes the geometric non-linearity in considerations as the direction of loads changes in case of large deformations that may occurs in the elements. In addition, An interface element has been used to simulate the joint surface between the two parts of the jointed rock sample. Coulomb friction model has been used for the interface element.

## 2.1 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 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. Figure (1) demonstrates the proposed geometries of the 3D FE model. The sample has several triangular asperities with 15$^{\circ}$ and 30$^{\circ}$ 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).

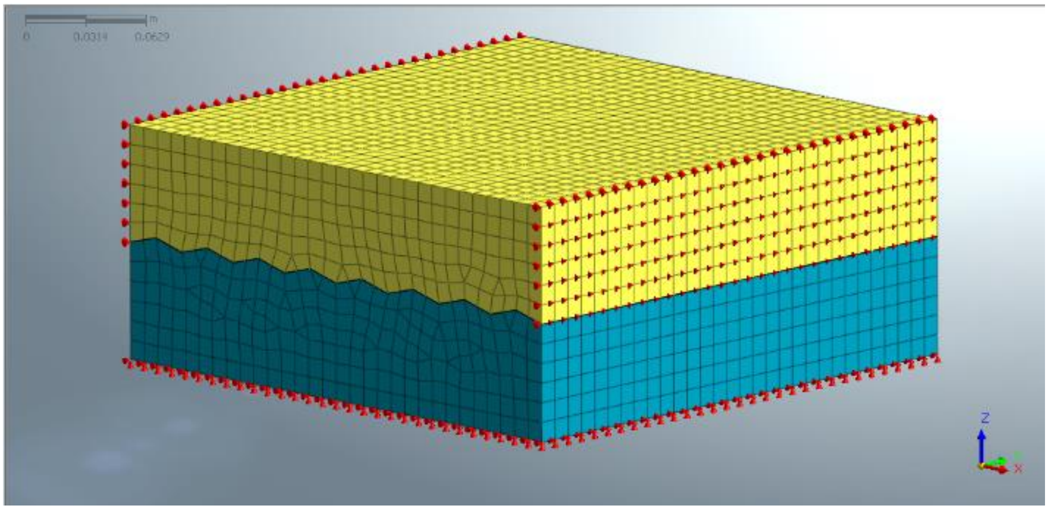

Figure 1. The Numerical Model of 15$^{\circ}$ asperities including the boundary conditions.

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

| Properties | Intact Rock | Rock Joint |
|---|---|---|
| Dry Density (kN/m$^3$) | 12.34 | - |
| Modulus of Elasticity (MPa) | 2281 | - |
| Poisson's ratio | 0.22 | - |
| Cohesion (MPa) | 3.0 | 0.5 |
| Internal angle of friction | 33$^\circ$ | 35$^\circ$ |
| Dilation angle | 0$^\circ$ | 0$^\circ$ |
| 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. Figure (2) illustrates the boudary conditions used in the numerical model.

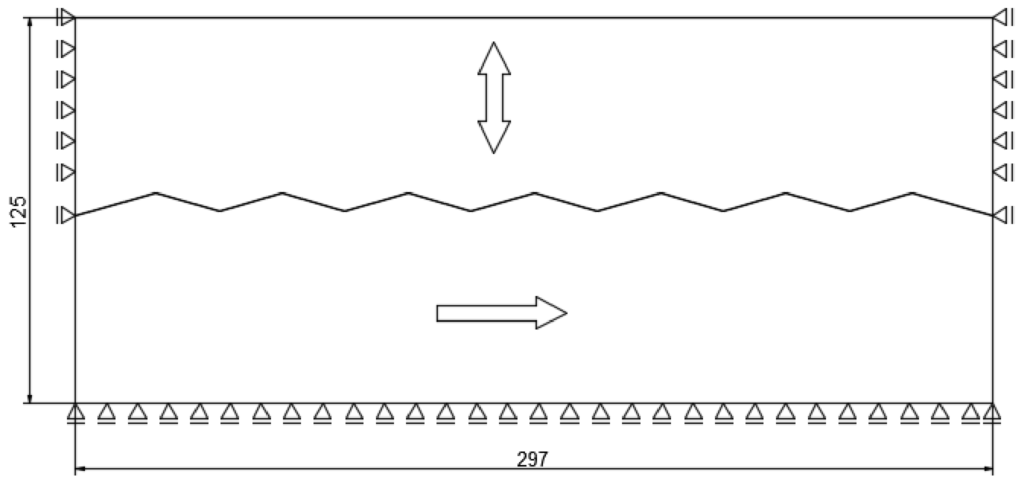


Figure 2. The boundary conditions of the sample including 15$^\circ$ asperities

## 2.2 Loading Criteria

Through this model, staged construction loading criteria is used to simulate the problem accurately. It is possible to change the geometry and loading conditions through the stages of the model. In this model, the two halves of the sample and the discontinuity are generated in the first stage including the own weight of the two halves. In the second stage, the shearing displacement is assigned on the lower half with a value of half the base of the triangular asperities and the normal pressure is assigned on the upper half. The simulated model was repeated several times with different normal pressure values ranges from 0 MPa to 2.04 MPa.

## 2.3 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$^{\circ}$, the normal stiffness was 1750 MPa, Shear stiffness 175 MPa, dilation angle 5$^{\circ}$ and the tensile strength was taken equal to 0.01 MPa. Figure (3) shows the numerical model used by Rao et al. (2010). 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).

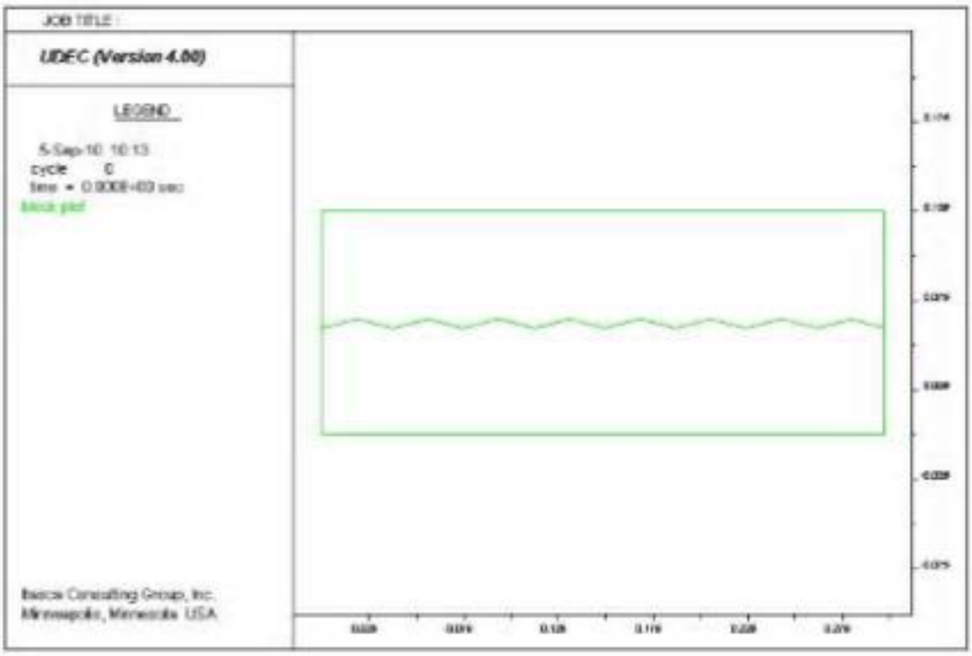


Figure 3. The UDEC model used by Rao et al. (2010).

## 3. 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. Figure (4) shows the deformed shape of the jointed rock. Moreover, Figure (5) and Figure (6) 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$^{\circ}$ triangular asperities and 30$^{\circ}$ triangular asperities.

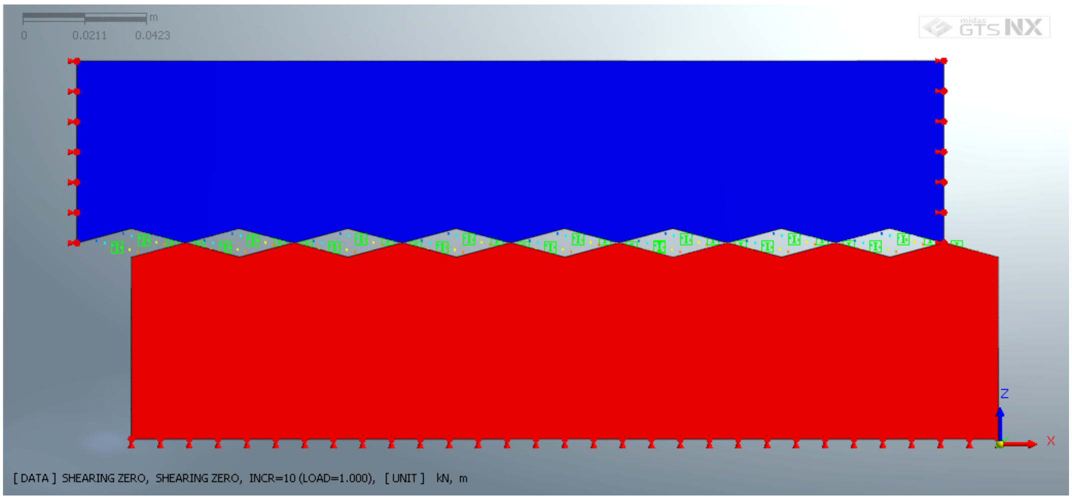


Figure 4. The Deformed Shape of the Numerical Model of 15◦ asperities.

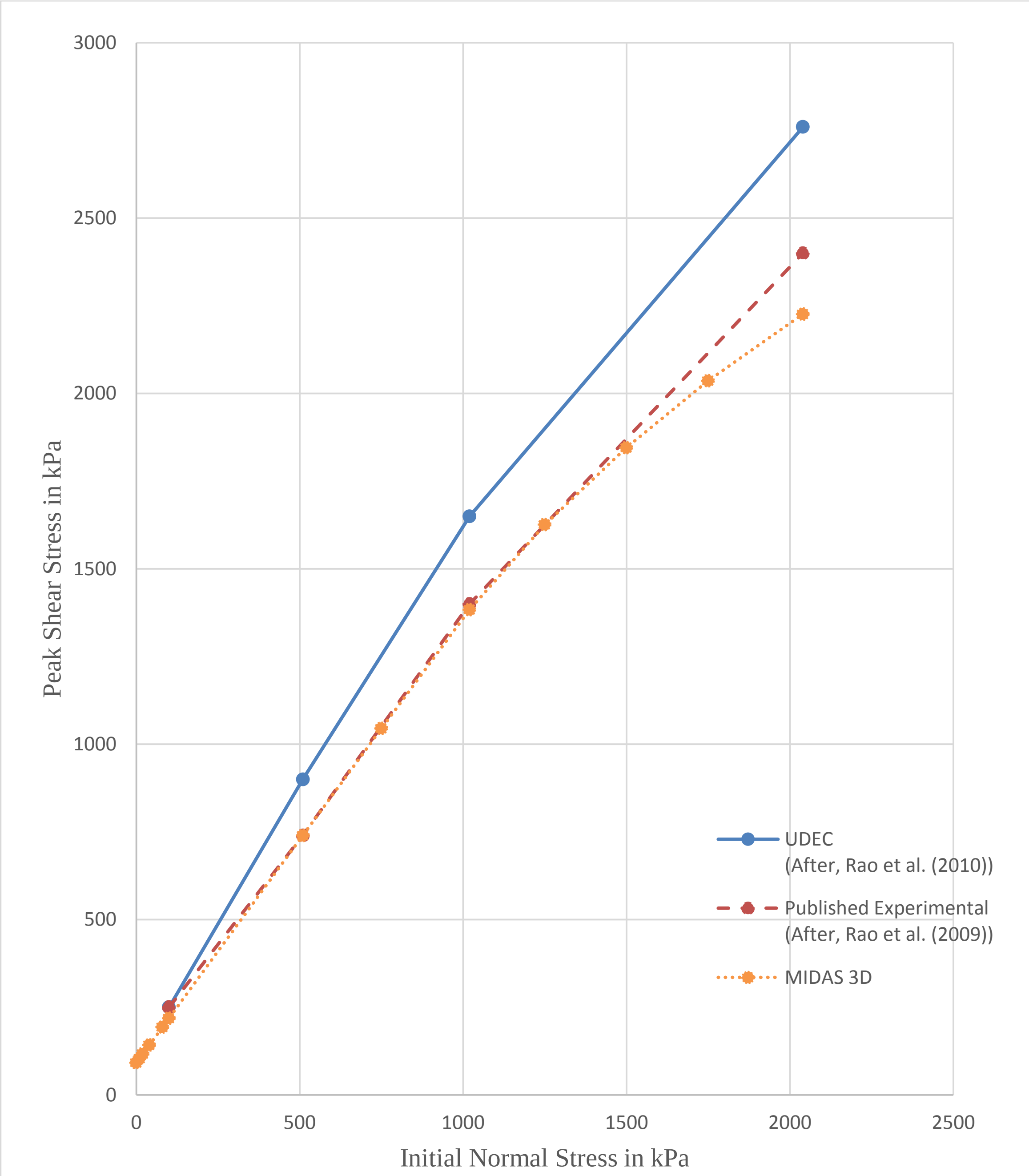


Figure 5. Comparison between the results of DEM, experimental and 3D FEM in case of 15$^{\circ}$ asperities.

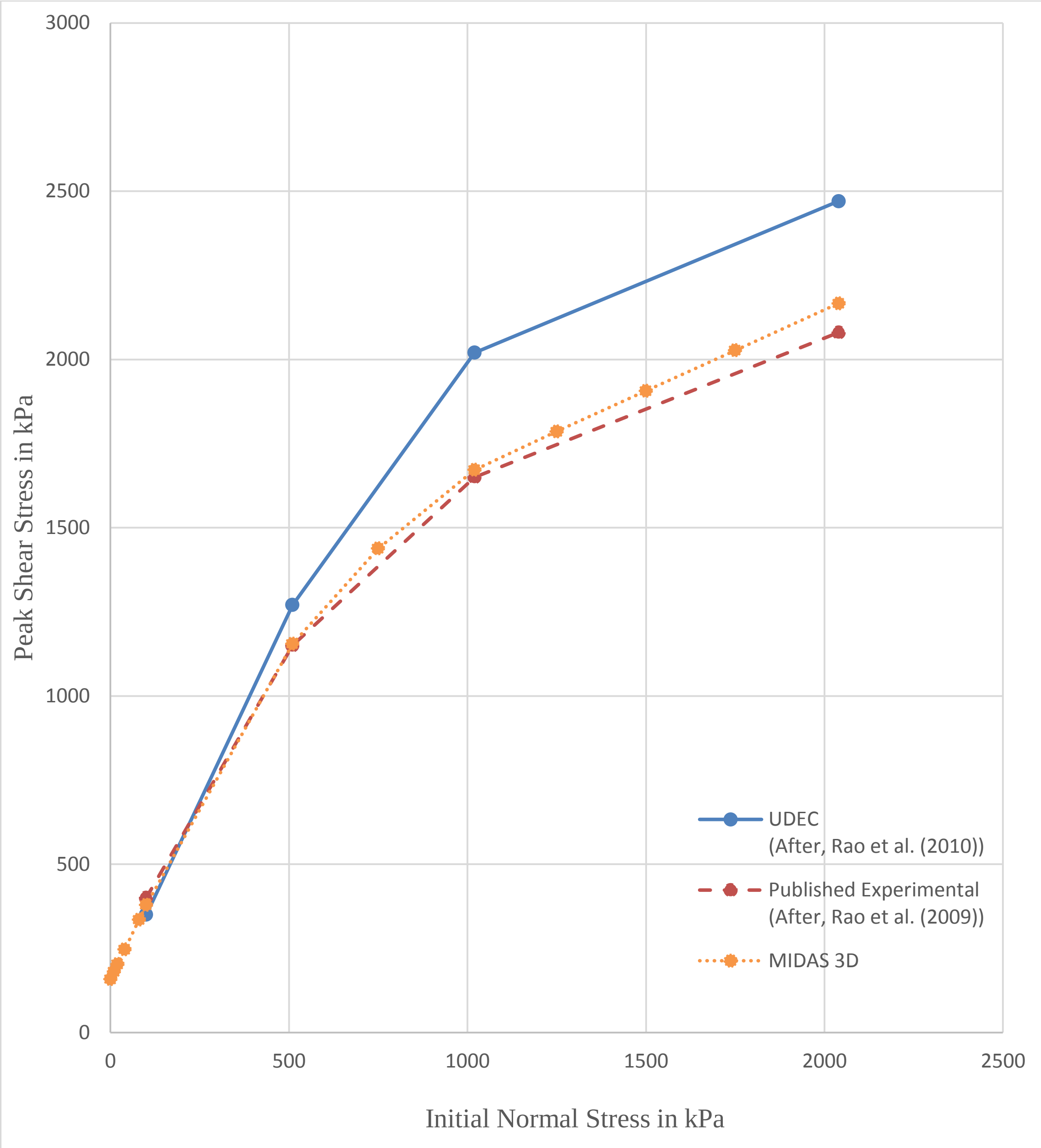


Figure 6. Comparison between the results of DEM, published experimental results and 3D FEM model in case of 30° asperities.

## 4. CONCLUSIONS

A 3D numerical procedure to predict the shear performance of jointed rocks was developed in this study. 3D numerical direct shear tests were performed on two geometric models of jointed rocks with different inclination angles of asperities. The results of the numerical models using FEM is compared to experimental results of large scale direct shear testing apparatus under the same boundary conditions and the physical properties of the sample. Due to the lack of measured data support from laboratory experiments of experimental sample, the physical parameters of the intact rock and the interface of the rock joints were predicted. The results of the FEM are summarized below:

1. FEM was found to be suitable and flexible numerical approach to predict the shear behavior and the properties of the jointed rock mass that can't be obtained from rock samples.
2. The results show that FEM using Midas GTS NX 3D model can highly predict the peak shear stress of the joint at low normal stress. The numerical results over predict the peak shear stress in case of high normal stress and compared by the experimental results by about 6%.
3. FEM can predict the degradation and the shearing of the asperities. The relationship between the peak shear stress and the nominal normal stress showed that it can be divided into three phases, the first phase is at low normal stresses where dilation occurs, the third phase is at high normal stress where shearing of asperities takes place, and the second phase is the transition zone between the other two phases.

## 5. REFRENCES

[1] Barton, N. and Choubey, V. 1977. The Shear Strength of Rock Joints in Theory and Practice, Rock Mechanics, 1:1-54.
[2] Giacomini, A., Buzzi, O. and Krabbenhoft. K. 2008. Modeling the Asperity Degradation of a Sheared Rock Joint using FEM. 8th world congress on computational Mechanics, Venice, Italy.
[3] Patton, F.D. 1966. Multiple Modes of Failure in Rock and Related Materials, Ph.D. Thesis, University of Illinois, Illinois, USA
[4] Rao, K.S., Shrivastava, A.K. and Singh, J. 2009. Development of an Automated Large Scale Direct Shear Testing Machine for Rock, Indian Geotechnical Society '2009, Guntur, India, 238-244.
[5] Shrivastava, A.K. and Rao, K.S. 2010. Numerical Simulation of Direct Shear Test, Indian Geotechnical Conference '2010, Mumbai, Maharashtra, India 1:887-890.