

Implementation of joint roughness and waviness into DEM simulations

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1 INTRODUCTION

The objective of this work was to introduce an algorithm which enables the consideration of complicated geometrical aspects of discontinuities into the blocky mesh employed by Distinct Element Method (DEM) calculations. A new code, JProfiler, which can be easily employed or implemented within the DEM simulations, was developed to carry out this task. The developed program has the capability to import arbitrary boundaries as joint roughness or waviness profile of varying scales. Moreover, the developed code enables the simulation of joint filling material explicitly within the DEM blocky mesh. The discontinuity roughness or waviness profiles which are determined during the field surveys, are represented in the form of continuously connected line segments representing joint roughness or discontinuity waviness. Additionally, the thickness of discontinuity filling material can be implemented easily into the DEM blocky mesh in a realistic manner and as a function of actual surveyed discontinuity data. Accordingly, the discontinuity filling materials are treated as individual DEM blocks, which have different mechanical properties, and interact at discrete block boundaries. This capability overcomes the shortcomings of the use of so called “hard contacts” with straight edges employed within most discontinuum codes. The successful application of the developed algorithm and the significance of modelling discontinuity geometry was illustrated by an example.

The mechanical behavior of jointed rock mass is always controlled by the mechanical and strength properties of discontinuities and the mechanical properties of discontinuities are directly affected by joint roughness, strength, cohesion, and filling material. Therefore, in a realistic analysis and design of engineering structures in rock, the role of the aforementioned parameters must be included, in particular, under complex loading conditions.

The shear behavior of discontinuities is a combination of various complex phenomena and interactions, such as dilation, asperity failure, deformation and interaction (Lambert 2008). Barton (1973) proposed to assess roughness with an empirical parameter, joint roughness parameter (JRC), from which the shear strength of the discontinuity can be established. Laser scanner and photogrammetry can be used to demonstrate the surface topography and characterize the geometry and waviness. With advances in laser and scanning technology, the roughness profile of the discontinuities can now be measured with a great detail of accuracy and potentially incorporated into computational codes. Since the first idealized “saw-tooth” description proposed by Patton (1966), various constitutive models were developed that accommodated the effects of asperities (Barton & Choubey 1977, Saeb & Amadei 1992) and their progressive degradation during shearing (Lee et al. 2001, Misra 2002). In an attempt to address this problem, many authors used numerical tools to assess the shear strength of discontinuities. Cundall (2000) employed the DEM (discrete element method) method to demonstrate the damage and asperity degradation as a function of shear displacement. Karami & Stead (2008) successfully combined the FEM and DEM methods to reproduce typical

behavior of rock joints including dilation and asperity degradation. Park & Song (2009) performed numerical shear tests on standard roughness profiles using the DEM method employing the *PFC3D* code. Zhao et al. (2012) and Zhao (2013) used the DEM method to investigate gouge formation and evolution upon shearing.

In the analysis of jointed rock mass, a realistic definition of block interfaces has always been a challenge. In all discontinuum modelling methods, block interfaces are characterized by cohesion and friction angle and are assumed to be of hard contacts with no physical roughness and thickness. Some authors have developed nonlinear joint constitutive models to describe the joint nonlinear behavior (Bandis et al. 1983). However, the use of this approach is associated with difficulties in determining the required input parameters for these nonlinear joint models.

The behavior of jointed rock mass is mainly controlled by the geometry and orientation of discontinuities. The joint surface geometry has a significant effect on the shear strength behavior of rough joints as demonstrated by Patton (1996). In this research a simple but useful technique was developed to include the geometric complexities of discontinuities into DEM blocky meshes. The developed code can be easily implemented into DEM algorithms to enhance the mesh generation capabilities as appropriate to the jointed rock masses. The significance of considering the actual geometry of discontinuities on rock mass behavior was illustrated by an example...

2 DESIGN AND ANALYSIS

In all discontinuum modelling methods, the discontinuity roughness and waviness are ignored. The discontinuity geometric irregularities and roughness's are over simplified and modelled in the form of smooth surfaces characterized by strength properties along these smooth edges. This modelling strategy has been adapted within all discontinuum modelling methods (DEM, DDA, etc.). This oversimplification of discontinuity geometry would lead to erroneous results and significantly affects the actual physical behavior of the jointed rock mass. In order to have a realistic simulation of jointed rock mass behavior, the joint surface roughness profile (or the discontinuity waviness at a larger scale) must be accurately and efficiently characterized and considered in the preparation of blocky mesh used by discontinuum codes. The developed algorithm for roughness simulation, in the form of a new code (JProfiler), can be easily coupled to discontinuum codes such as *UDEC* (Itasca 2019) or *DDA* (Discontinuous Deformation Analysis) aiming at enhancing joint modelling capabilities.

In all discontinuum modelling methods Coulomb's law is used to interpret sliding along interfaces and represents energy loss due to friction. The contacts are straight block interfaces which are resulted by the intersection of two or more joint sets. These contacts have zero thickness with no roughness at any scale. In spite of using joint cohesion and friction angle as input for the contact shear strength model, the actual behavior of joints is not modelled properly by these methods. In Figure 1a the three joint consideration scenarios observed in practice and considered in numerical modelling are shown. Therefore, the results obtained from the aforementioned numerical methods must be used with caution in the design. In order to enhance the capability of the discontinuum modelling methods, a new algorithm was developed to implement the joint roughness and filling material into the blocky mesh used by these methods. In the developed code, the Barton's roughness profiles were digitized and used as the default profiles within the code. Figure 1b presents a schematic illustration of the methodology used in the proposed algorithm and shows the selection and digitization process of a given roughness profile.

In the proposed algorithm, the roughness sampling scale can be selected as a variable. Important features of the developed code, JProfiler, are; the capability to import an arbitrary image as joint roughness profile at varying scales, simulating filling material geometry, and data visualization. Within the developed algorithm, once the appropriate roughness profile is selected, the roughness image is converted into line segments maintaining the overall joint geometry (spacing, dip, dip direction, etc.). The JProfiler code was developed in Microsoft Visual C++ environment and MFC architecture. The developed code can be used as a supplementary program with all DEM methods. Figure 2 demonstrates a blocky mesh prepared with the developed code.

3 RESULTS AND DISCUSSION

As an illustration, the developed algorithm was coupled to the DDA method and used to simulate a cavern which is subjected to dynamic loading associated with a violent fall of ground. In order to evaluate the significance of joint waviness, a simple geometry cavern was considered in a jointed rock mass. Figures 3a and 3b illustrates the initial geometry of the two models prior to the analysis. The spacing for the horizontal and diagonally dipping (at 60 degree) joints sets were 3 and 0.8 m respectively. The rock cover above the opening crown was about 11.5 m. Two series of runs were carried out to evaluate the effect of joint set geometry and waviness. Since DDA assumes rigid contacts in the normal direction large joint dilation may occur as a function of joint sliding for the simulated joint geometry.

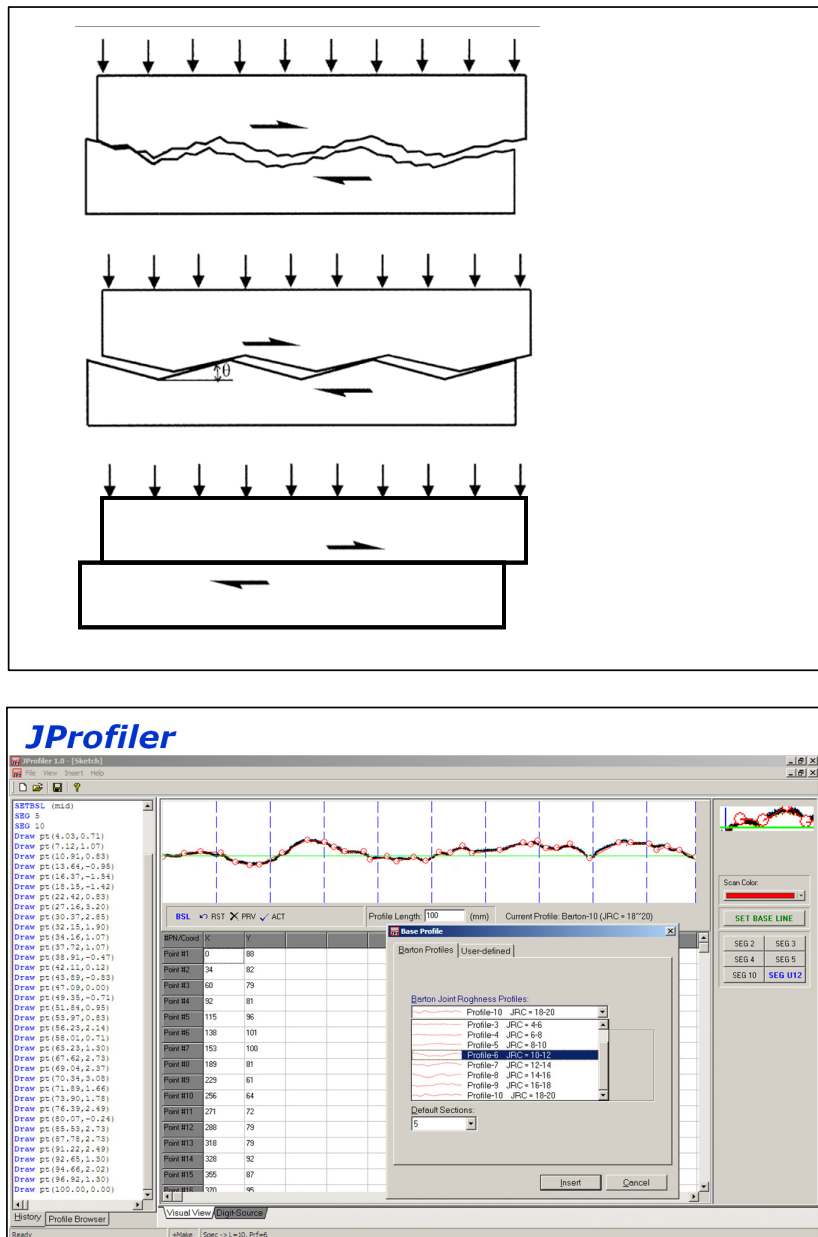


Figure 1. a) Comparison of joint considerations observed in practice and used in modelling, b) Selection and digitization process of a given roughness profile in the developed module.

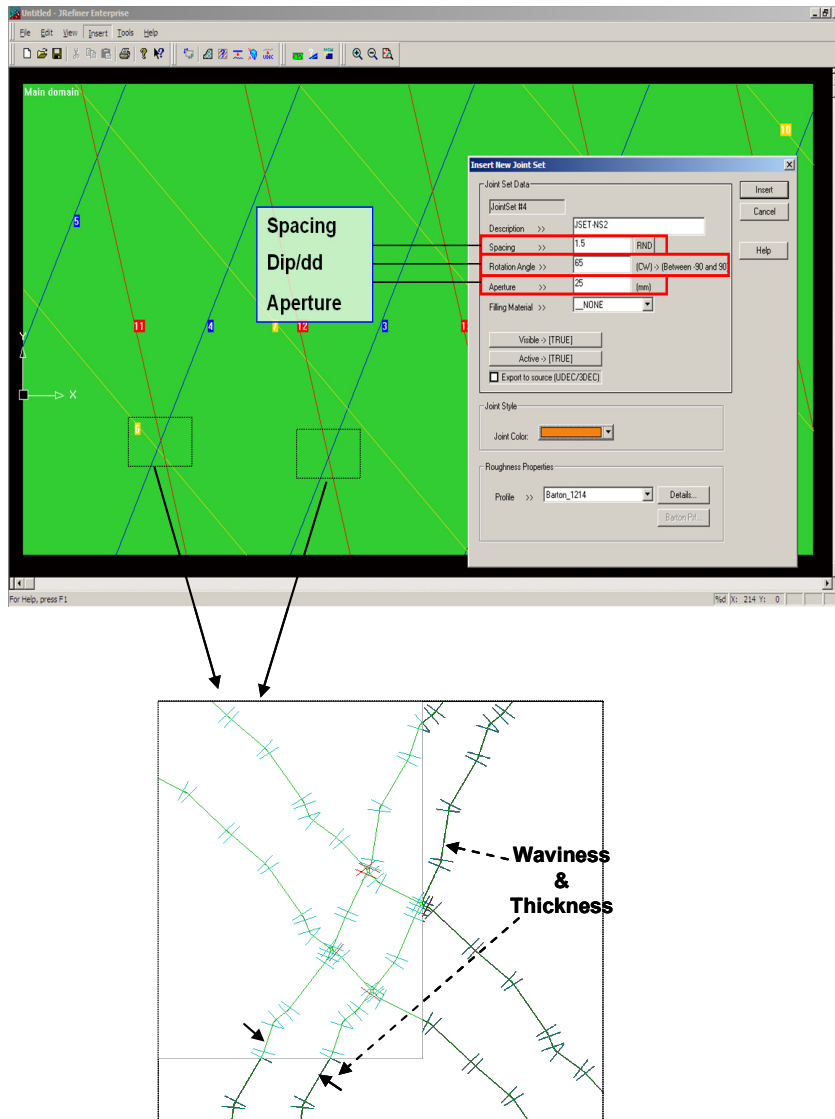


Figure 2. Example of a blocky mesh generated with the JProfiler code including joint roughness and thickness.

In the conducted analyses two scenarios of smooth and wavy joint surfaces were evaluated. In the first model a typical smooth joint surface, which is the common approach in all analytical and modelling methods, was considered for the diagonal set. In the second modelling analysis a wavy geometry was considered for the diagonal joint set maintaining the overall dip angle of the joint set. A density of 2.7 ton/m³, Young's modulus of 50 GPa, and Poisson's ratio of 0.25 was considered for the intact rock blocks in both models. The joint cohesion and tensile strength were assumed to be zero and a 30-degree friction angle was considered for joints in both runs.

In order to assess the significance of joint geometry on model behavior, a dynamic impulse was applied to the top portion of both models. It was assumed that the modelled domain is situated in a main level of an underground mine which has a potential for violent rockbursts. A fixed boundary condition is used in this analysis. It is understood that for a fully dynamic analysis absorbing boundaries must be employed to allow for proper energy dissipations. With regard to the simulated joint geometry, Coulomb sliding is responsible for most of energy dissipation in this model and looking at displacement vectors the dynamic disturbance is fully dissipated by sliding before reaching the model bottom boundary. A blocky fall of ground was

considered to simulate the effect of a rockburst occurring at the upper level. The fall of ground was simulated by a wedge shape block of 32.5 ton in weight ejecting with an initial velocity of 12 m/s from the roof area. This is a typical failure mode in burst prone underground mines where massive rock volumes eject as a result of high stress concentrations. In both runs all input parameters were kept unchanged except the diagonal joint set geometry and a fully dynamic analysis was conducted. This enabled the comparison of analyses results and illustration of the significance of joint geometry in situations that joints are not uniformly smooth and continuous. Figure 3c shows the final analysis result from the first run and the obtained results from the second run is presented in Figure 3d.

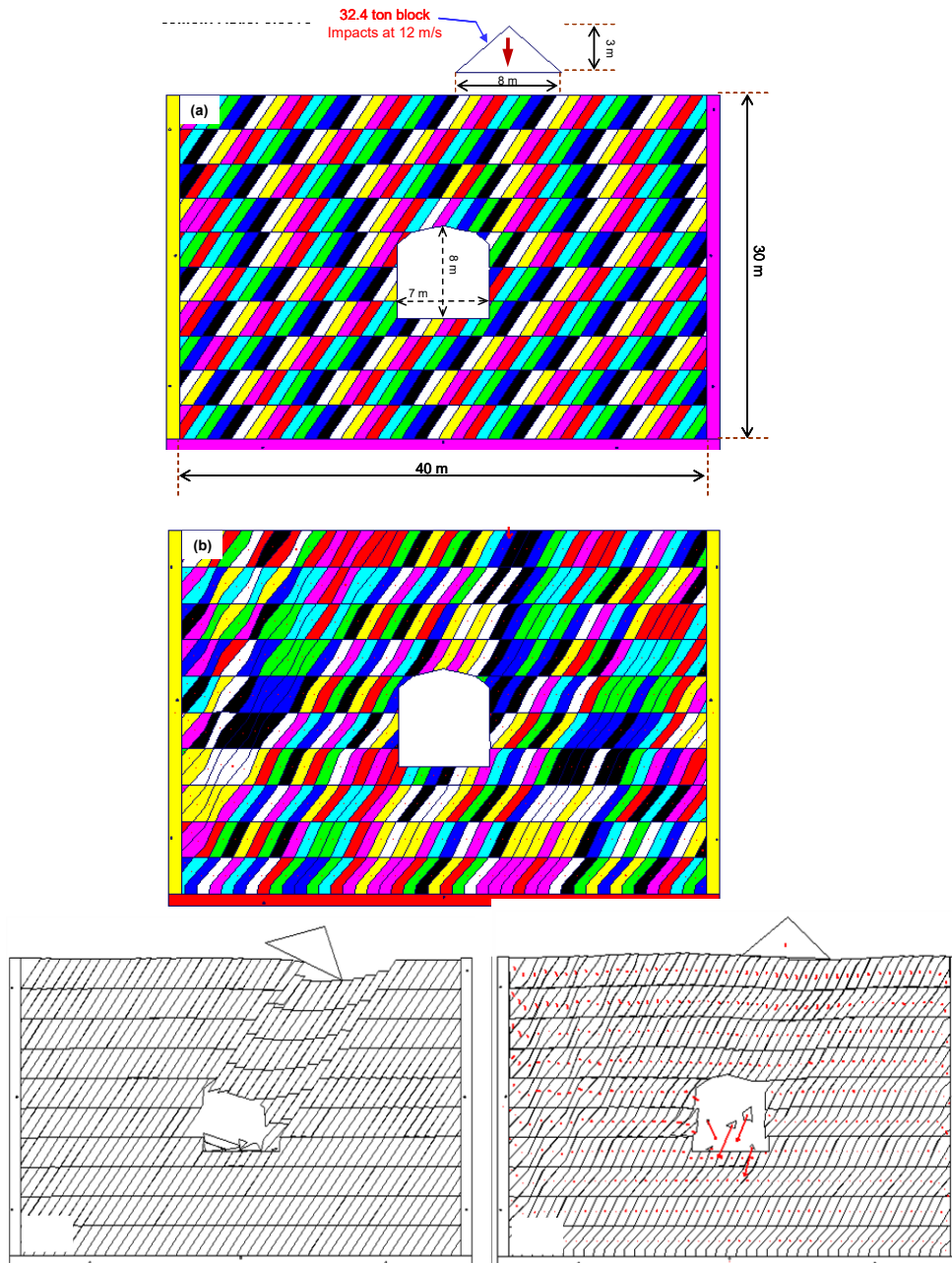


Figure 3. Geometry of a blocky rock mass with a) a smooth joint geometry and, b) a wavy joint geometry, c) Cavern stability analysis results when considering smooth joint geometry), d) Cavern stability analysis results when considering wavy joint geometry.

4 CONCLUSIONS

The impact loading associated with an upper level rock burst was simulated considering the major joint geometry in the analysis. The obtained results show that without considering the waviness of the diagonal joint set, the cavern roof fails under sliding mode completely. In particular, when the load is applied in a dynamic manner, the joint cohesion is lost very quickly upon any slight movement and once the applied load exceeds discontinuity shear strength (often defined by Coulomb criteria) the sliding along joints becomes the dominant failure mode. In the second case, where a wavy joint geometry was considered, the rock mass maintained its integrity in spite of undergoing a high impulsive load on the top portion of the model. When considering waviness, minor block falls are observed in the right corner and left wall and the tunnel host rock mass is slightly disturbed. In the second run, the rock mass behaved in a much stiffer manner under applied loading and failure was limited to small portions around the opening, which can be prevented by any conventional support system. No support system was applied to tunnel walls in these analyses and the intention was to demonstrate the significance of joint geometry on overall rock mass behavior and opening stability.

A simple method was used to include the joint in-situ geometry into the discontinuum modelling techniques explicitly. Most sophisticated joint constitutive models have implemented the effect of roughness implicitly and involve the determination of non-physical parameters. In this work, an efficient algorithm was developed to incorporate the effect of roughness into modelling in a physically meaningful manner. The developed algorithm can be easily implemented within the DEM codes and enable a more realistic discontinuum analysis.

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