ESTIMATION OF THE IN SITU BLOCK SIZE IN JOINTED ROCK MASSES USING THREE-DIMENSIONAL BLOCK SIMULATIONS AND DISCONTINUITY MEASUREMENTS

*A. Kluckner, P. Söllner and W. Schubert
Institute for Rock Mechanics and Tunnelling
Graz University of Technology
Rechbauerstraße 12
8010 Graz, Austria
*(*Corresponding author: kluckner@tugraz.at)*

M. Pötsch
3GSM GmbH
Plüddemanngasse 77
8010 Graz, Austria

ESTIMATION OF THE IN SITU BLOCK SIZE IN JOINTED ROCK MASSES USING THREE-DIMENSIONAL BLOCK SIMULATIONS AND DISCONTINUITY MEASUREMENTS

ABSTRACT

The *in situ* block size is a key parameter in the geomechanical characterization of rock masses. It describes the fracturing of the rock mass and thus is a measure for the degradation of the rock mass strength. Several classification systems use the *in situ* block size. For instance, the Geological Strength Index (GSI) requires the "blockiness" and joint surface condition factor as key input parameters. The "blockiness" has recently been related to the *in situ* block volume (Cai et al., 2004).

Due to the limited information about the internals of a rock mass, it is not possible to determine the *in situ* block size directly. Currently, the *in situ* block size is determined by calculations using oversimplified models, vague estimations or, due to the lack of relevant information, it is neglected.

As remote measurement systems have become available for rock mass characterization, a more comprehensive record of discontinuities can take place. Measurements can be performed on exposed rock outcrops and in particular on tunnel faces and walls, delivering the location, orientation, spacing and persistence of discontinuities at an arbitrary number and locations. An estimation of the *in situ* block size at the same level of sophistication is still not available.

This paper aims at examining the relationship between visible and measureable information at the rock surface, and the *in situ* block size. Three-dimensional block model simulations were performed using the block model engine of the distinct element code 3DEC. Initial investigations focussed on the minimally required observation area in order to obtain reliable block size distributions. Based on a representative volume element, a reference distribution of the block area at the observation area for a specific discontinuity system was determined. Subsequently, the size of the observation area was decreased stepwise and each new distribution was compared to the reference distribution. For all analyzed systems, it turned out that the mean block area must be smaller than 1% of the observation area to achieve a reliable block size distribution.

Further simulations focussed on discontinuity systems with three non-persistent sets. The results were compared to the formula proposed by Cai et al. (2004). A transformation factor T was introduced which replaces the persistence terms in Cai et al.'s proposed formula. The factor describes the correlation between block volumes generated by persistent and corresponding non-persistent discontinuity sets. The simulations included the variation of the discontinuity set spacing, persistence, and orientation. The mean and additionally the 25%-, 50%- and 75%-quantiles of the block size distribution were analyzed. Examining all values for the transformation factor the distribution can be described by a power function with a negative exponent. The function depends on the persistence only.

Finally, the results of random simulations were compared to the analytical formula using the transformation factor. The predicted mean and selected quantiles show a good agreement with the simulation results. It gives a comprehensive picture about the block size distribution in discontinuity systems with three non-persistent sets.

KEYWORDS

Rock mass characterization, *In situ* block size, Block model simulation, Non-persistent joints

INTRODUCTION

The *in situ* block size is a key parameter in rock mechanics. The knowledge of the *in situ* block size is important for excavation and support design of underground structures, for blasting design in quarries, and for slope stability analysis. For instance, the block size of a jointed rock mass in relation to the size of the excavation is determinant for the ground behavior, and thus the determination of representative values for the block size is important.

A block is delimited by at least four joints. The size of the block is a result of each joint set´s spacing, orientation and persistence. Where the rock mass consists of three main joint sets (Figure 1) with the parameters measured at site (e.g. mapping exposed rock surfaces, geophysical borehole logging) or at drill cores, the block volume can be calculated as follows (Palmström, 1982):

$$V_b^0 = \frac{s_1 \cdot s_2 \cdot s_3}{\sin \gamma_1 \cdot \sin \gamma_2 \cdot \sin \gamma_3} \tag{1}$$

s_1, s_2 and s_3 are the spacing in each joint set. γ_1, γ_2 and γ_3 are the angle between the joint sets. Equation 1 is valid for persistent joints only. Other joints, not belonging to the three joint sets are neglected.
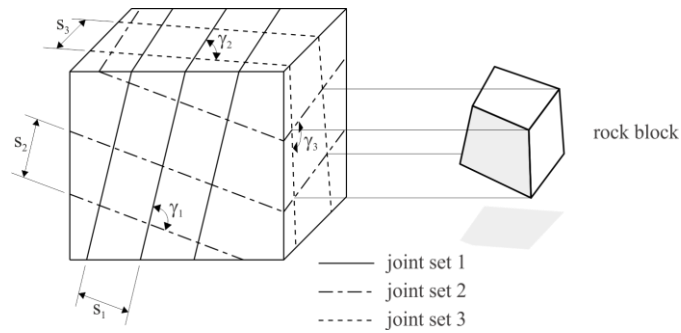

Figure 1 – Block delimited by three joint sets (modified from Cai et al., 2004)

In the geomechanical characterization, the *in situ* block size describes the fracturing of the rock mass. As the rock mass strength and the behavior depends, inter alia, on the degree of fracturing and on the interlocking of blocks (Cai et al., 2004; Hoek, 1983), the joint persistence must be considered in calculating the block volume. Cai et al. (2004) propose to determine an equivalent block volume for non-persistent joints:

$$V_b = \frac{s_1 \cdot s_2 \cdot s_3}{\sqrt[3]{p_1 \cdot p_2 \cdot p_3} \cdot \sin \gamma_1 \cdot \sin \gamma_2 \cdot \sin \gamma_3} \tag{2}$$

p_1, p_2 and p_3 are the persistence of the joints in each joint set. The ratio of the equivalent block volume with non-persistent joints ($p_i < 1.0$) to the block volume with persistent joints is

$$\frac{V_b}{V_b^0} = \frac{1}{\sqrt[3]{p_1 \cdot p_2 \cdot p_3}} > 1 \tag{3}$$

To account for an increase in rock mass strength and stability due to rock bridges at non-persistent joints, the equivalent block volume V_b has to be applied in the geomechanical characterization.

In several characterization (Austrian Society for Geomechanics, 2010) and classification systems (Barton et al., 1974; Bieniawski, 1973; Hoek et al., 1995; Palmström, 1995) the block size is an important part, either in a qualitatively or quantitatively way. These systems were or are modified and improved continuously by various authors. For instance, the chart to determine the Geological Strength Index (GSI) by Hoek et al. (1995) was supplemented by Cai et al. in 2004. To the original, descriptive chart, the authors added the quantification of two input parameters to determine the GSI – the block volume (quantitative) for the structure (qualitative), and the joint condition factor (quantitative) for the surface condition (qualitative). Equation 2 accounts for the presence of non-persistent joints, in the original chart qualitatively described by the degree of interlocking. Hence, it is possible to classify jointed rock masses with measurable field parameters.

To determine the block size, joint parameters have to be investigated beforehand. The characteristics of the discontinuity system can change within a short distance, especially for large structures (e.g. tunnels, underground powerhouses) or structures at great depths (e.g. mining of ore bodies). Data gathered from subsurface investigations or field mappings can never represent the entire rock mass volume of interest. The available data have to be extrapolated and parameters required in addition have to be estimated to obtain a full picture of the expected rock mass.

In collaboration with 3GSM GmbH, the Institute for Rock Mechanics and Tunnelling initiated investigations to study the relationship between visible and measurable information at the rock surface, and the *in situ* block size. The aim of the investigations is to improve the utilization of information measured on exposed rock surfaces, and on that basis to estimate the block size and its distribution in a more realistic way.

As a first step, three-dimensional discrete element models are analyzed to verify the equation for the equivalent block volume (Equation 2) proposed by Cai et al. (2004). The results are presented in this paper.

METHOD

The discrete element method in three dimensions implemented in the computer program 3DEC (Itasca Consulting Group, 2011) is used to create a virtual rock mass model. The reference model (Figure 2) features a cubic shape with 10 m in length, height and width.
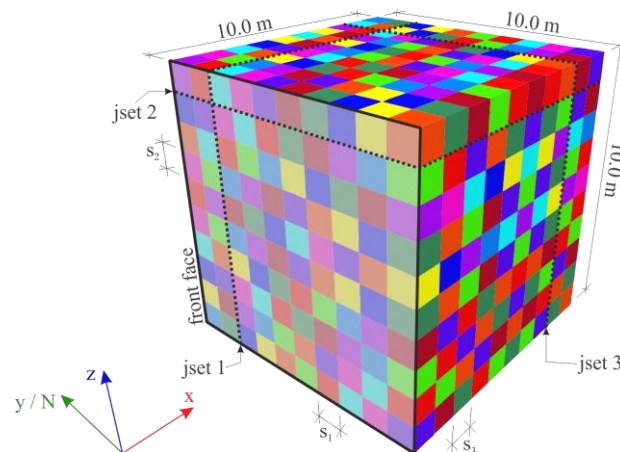

Figure 2 – Numerical reference model

For each joint set the spacing s [m], the dip direction [°], the dip angle [°] and the persistence p [m/m] must be specified. The number of joints within a joint set is chosen in a way that the entire model is affected by the generation of joints. The same applies for the joint length. All investigations are performed

with three joint sets. The origin of the Cartesian coordinate system is located in the center of the model. For each simulation, the distribution of the block area at the front face and of the volumetric block size is determined and analyzed. In order to obtain distributions in a consistent way, the initial point for joint generation is set to the center of the front face.

PRELIMINARY INVESTIGATIONS

Boundary blocks

In Figure 3, a model face with a height and width of 10 m is illustrated.
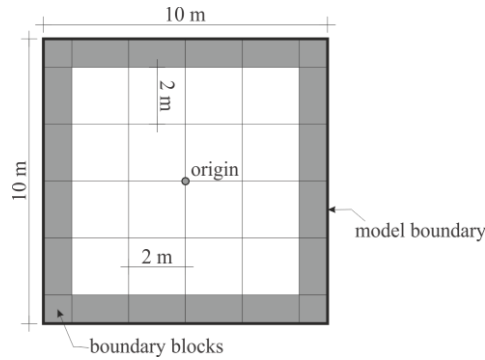

Figure 3 – Fictitious example to illustrate the definition of boundary blocks

If the joint spacing of both, the horizontal and vertical joint set, is for example 2 m, and the initial point of joint generation corresponds with the center of the face, the blocks at the model boundary are smaller than the inner ones. The model boundary equals a fictitious, non-natural boundary. These small blocks would bias the results (distribution for a specific discontinuity system). Therefore, all blocks with contact to free space in y- and z-direction are neglected. Hereinafter these blocks are constituted as boundary blocks. The same applies in the case where the analyzed area is delimited by a mapping window (Figure 4).
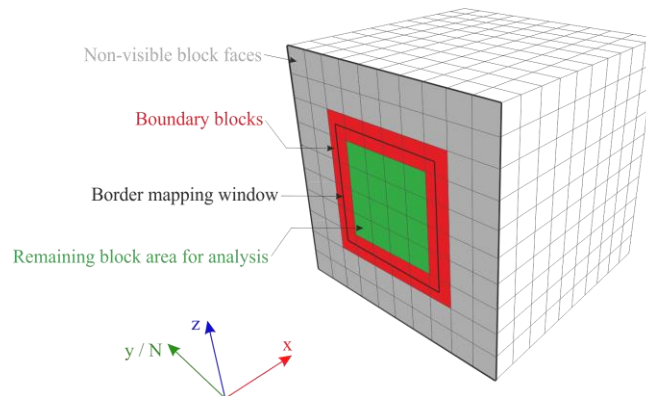

Figure 4 – Three-dimensional block model. The border of a fictitious mapping window delimits the remaining area to be analyzed. In order not to divert the distribution of the block area at the front face, the boundary blocks criterion is applied

Replication of simulations

The rock bridges are determined arbitrarily along the joint trace. Joint gaps (rock bridges) are placed randomly for each new simulation. Hence, each simulation with the same discontinuity parameters results in a different distribution of the block sizes (area at front face, volume). Four cases are analyzed to determine how many simulations with the same discontinuity parameters are necessary to obtain the entire scope of possible distributions. The joint parameters of each case are given in Table 1.

Table 1 – Joint parameters of case 1 to 4

case		dip direction [°]	dip angle [°]	spacing [m]	origin [x, y, z] [m]	persistence [m/m]
1	joint set 1	0	90	0.5	0, 0, 0	0.8
	joint set 2	0	0	0.6	0, 0, 0	0.8
	joint set 3	90	90	0.7	0, 0, 0	0.8
2	joint set 1	0	90	0.5	0, 0, 0	0.4
	joint set 2	0	0	0.6	0, 0, 0	0.4
	joint set 3	90	90	0.7	0, 0, 0	0.4
3	joint set 1	20 ± 5	70 ± 5	0.5	0, 0, 0	0.8
	joint set 2	0 ± 5	10 ± 5	0.6	0, 0, 0	0.8
	joint set 3	90 ± 0	90 ± 0	0.7	0, 0, 0	0.8
4	joint set 1	0	90	0.3	0, 0, 0	0.8
	joint set 2	0	0	0.4	0, 0, 0	0.8
	joint set 3	90	90	0.5	0, 0, 0	0.8

Each case passes six cycles. Each cycle is done twice (1st run, 2nd run) and with the according replication r (1, 5, 10, 25, 50 and 100) of the simulation. The procedure is summarized in Table 2.

Table 2 – Summary of simulation cycles for each case

test run	replication r					
1st run	1	5	10	25	50	100
2nd run	1	5	10	25	50	100

Figure 5 shows two cumulative distributions of case 4. The result of a simulation with one replication is shown in the left diagram, while the right diagram shows the result of fifty replications.
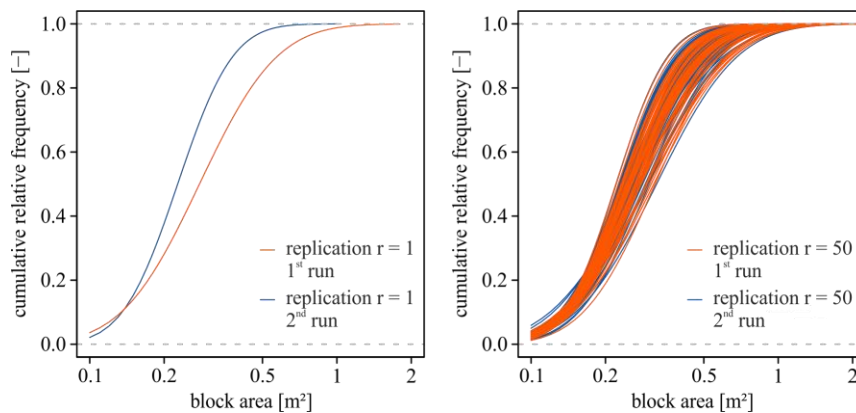

Figure 5 – Cumulative distributions of the block area of the simulated case 4 to illustrate the difference in the scope of distributions for two different values of replication

If the simulation is replicated once, the two distributions deviate significantly. However, if the simulation is sufficiently replicated (right diagram in Figure 5 fifty times) both, the first run as well as the second run yield the same scope of possible distributions. Figure 6 summarizes the results of all simulation cycles of case 4.
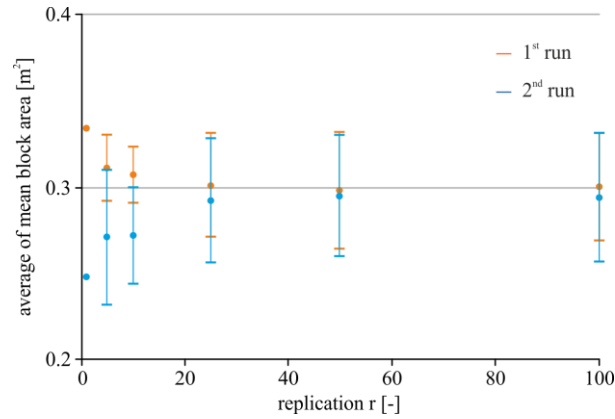

Figure 6 – Summary of the results obtained from simulated case 4 (points represent mean values; horizontal marks represent mean values plus/minus the standard deviation)

With increasing replication, the distribution of the first test run matches better with the distribution of the second test run. This finding was confirmed by all investigated cases. In order to obtain statistically representative results all further simulations are replicated 100 times.

Minimally required size of mapping window

Figure 7 depicts a jointed rock mass and two different mapping windows. Using mapping window 2 only the orientation of the joints can be obtained. The mapping window is too small. In comparison, mapping window 1 is large enough to quantify all necessary parameters of both joint sets.
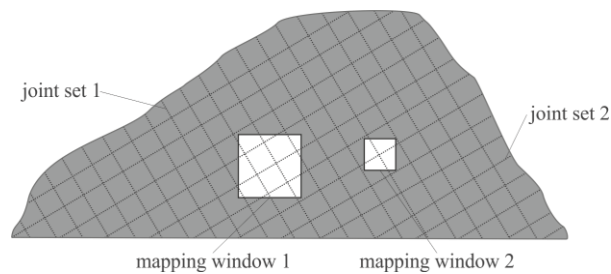

Figure 7 – Sketch of a jointed rock mass with two mapping windows different in size

Consequently, there has to be a ratio between the average block area at the front face and the size of the mapping window that must not be exceeded. 51 cases are analyzed to determine the minimum size of the front face of the numerical model to obtain reliable block size distributions. The joint parameters of each case can be found in Söllner (2014). The spacing, the orientation as well as the persistence of the joint sets are varied. For each case, beginning with the reference model, the size of the front face is systematically decreased (Figure 8).

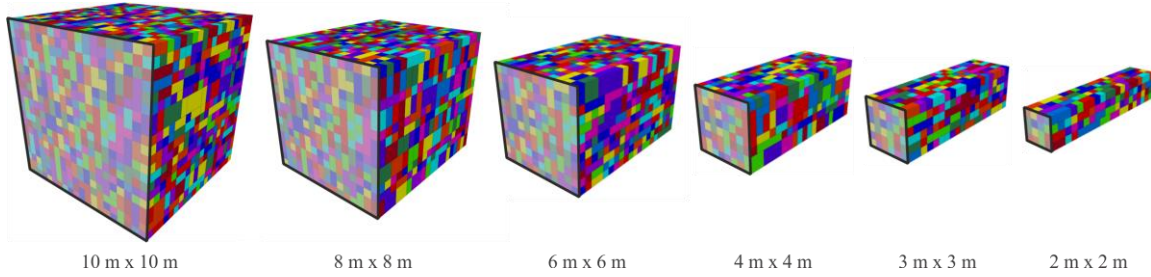| 10 m x 10 m | 8 m x 8 m | 6 m x 6 m | 4 m x 4 m | 3 m x 3 m | 2 m x 2 m |

Figure 8 – Illustration of the systematic minimization of the numerical model in y- and z-direction

For specific discontinuity parameters, the front face may become too small. Due to the boundary blocks criterion an execution of the simulation is not possible at all. Figure 9 illustrates this scenario. The spacing of both joint sets is 2 m. As long as the size of the front face is larger than 4 m x 4 m, blocks can be identified. However, for a size of 4 m x 4 m the boundary blocks criterion leaves no blocks for the analysis. Hence, the minimum size of the front face is 6 m x 6 m and the maximum ratio between the average block area at the front face and the size of the mapping window is then set to (2 x 2) / (6 x 6) = 0.11.
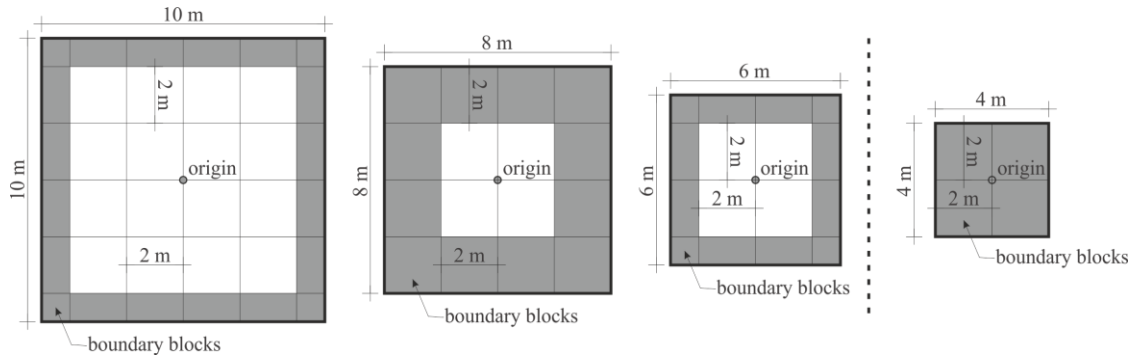

Figure 9 – Fictitious example to illustrate the determination of the maximum ratio of the average block area to the size of the front face

The joints in the illustrative example are persistent and feature the same spacing. A uniform distribution of the block area is the result. The joints in the analyzed cases are all non-persistent (p < 1.0). Figure 10 depicts the identified maximum ratio. It has to be noted that a maximum ratio is identified only if the boundary blocks criterion becomes effective. Therefore, Figure 10 does not depict a ratio for all cases.
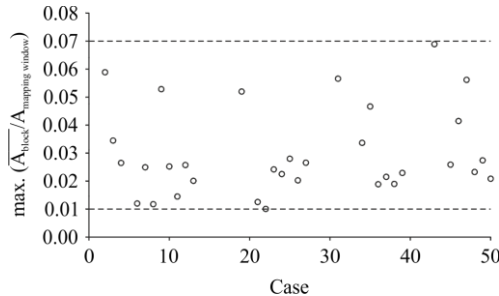

Figure 10 – Maximum ratio of the average block area at the front face to the size of the mapping window for the analyzed cases; ratios are depicted only if the boundary blocks criterion becomes effective

The ratios are all located in the range of 0.01 to 0.07. For a ratio within this range, it is possible that the boundary blocks criterion becomes effective. A ratio less than 0.01 leads to reliable results in any case. The determination of the block size distribution for cases where the ratio is greater than 0.07 should be avoided. Figure 11 illustrates the summarized findings in a nomograph.
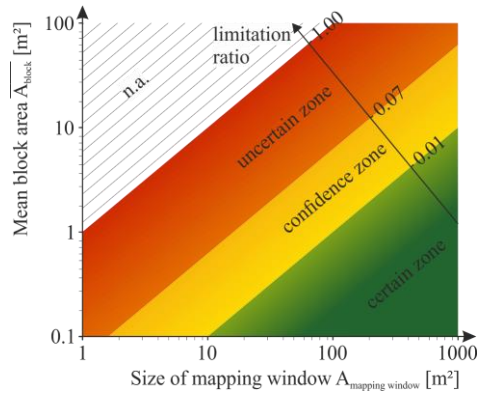

Figure 11 – Nomograph for the determination of the minimum required size of the mapping window in relation to the average block area. Both, the ordinate and the abscissae are in logarithmic scale

BLOCK SIZE ESTIMATION

The results of previous simulations (51 cases) are used to verify Equation 2 proposed by Cai et al. (2004). For each case, the ratio of the equivalent block volume with non-persistent joints to the block volume with persistent joints is calculated (Equation 3). The ratio hereinafter is termed as the transformation factor T. In order to characterize the non-uniform block size distribution (Figure 5), the mean value as well as the 25%-, 50%- and 75%-quantiles of the block size are determined.

The investigations have shown that the ratio is independent from a variation in joint set spacing. For two cases with equal orientation and persistence of the joints but different joint spacing, the transformation factor yields the same value. However, a distinct deviation has been found for cases where the value for the joint persistence was varied. In Figure 12, the calculated values of the transformation factor (coloured dots) are plotted. Each colour represents the transformation factor for either the mean value (blue), 25%- (orange), 50%- (brown) or 75%- (green) quantile of the equivalent block volume.

$$T_{75\%} = 1.11 \, [(p_1+p_2+p_3)/3]^{-2.87}$$

$$T_{mean} = 1.01 \, [(p_1+p_2+p_3)/3]^{-2.86}$$

$$T_{50\%} = 0.76 \, [(p_1+p_2+p_3)/3]^{-2.39}$$
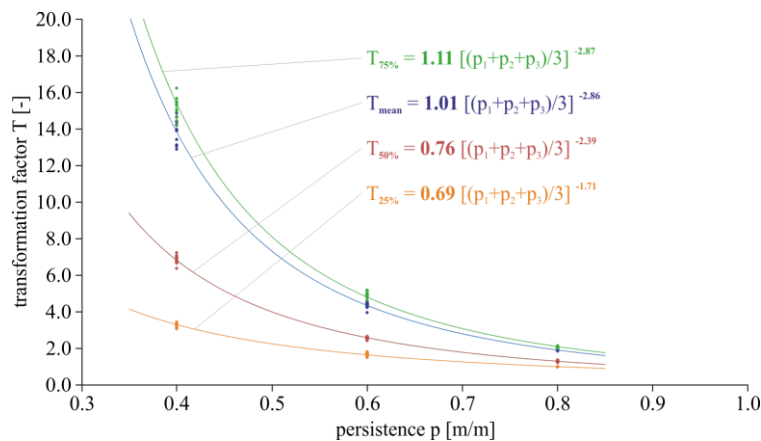
$$T_{25\%} = 0.69 \, [(p_1+p_2+p_3)/3]^{-1.71}$$

Figure 12 – Transformation factor T depending on the average joint persistence

Analyzing the distribution of the values, a trend can be observed. With decreasing persistence, the value for the transformation factor increases. The distribution can be best described by a power function with a negative exponent, depending on the joint persistence only. The equations are given in Figure 12.

A new analytical formula for the determination of the equivalent block volume with non-persistent can be derived by replacing the persistence term in Cai et al.´s formula (Equation 3) with the transformation factor:

$$V_{b,\{mean,\,25\%,50\%,75\%\}} = \frac{s_1 \cdot s_2 \cdot s_3}{\sin \gamma_1 \cdot \sin \gamma_2 \cdot \sin \gamma_3} \cdot T_{\{mean,\,25\%,50\%,75\%\}} \qquad (5)$$

In order to validate the developed formula several cases are analyzed. The joint parameters of each case can be found in Söllner (2014). The spacing, the orientation as well as the persistence of the joint sets are varied. In contrast to the cases of previous investigations, also discontinuity systems with non-orthogonal joint sets ($\gamma_i \neq 90°$) are considered. In Figure 13, the block volumes obtained from the numerical simulations are compared to the block volumes determined with Equation 5.
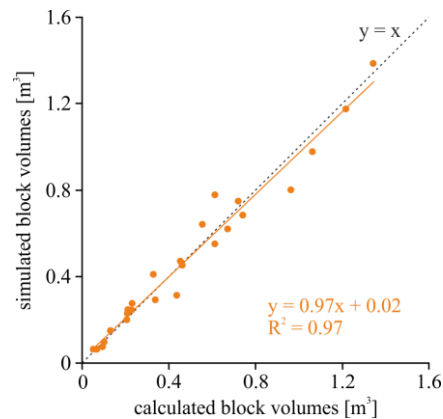

Figure 13 – Comparison of simulated to calculated block volumes for the evaluation cases

Figure 13 demonstrates the validity of the new proposed formula for the analyzed cases. The calculated block volumes are in good accordance to the block volumes obtained from the numerical simulations.

CONCLUSIONS

In this paper, the equation for the equivalent block volume with non-persistent joints proposed by Cai et al. (2004) was evaluated. Several simulations using the block model engine of the distinct element code 3DEC (Itasca Consulting Group, 2011) were performed. In order to obtain reliable results, boundary conditions for the simulation (boundary blocks, replication, size of the model) had to be considered. A new formula for the equivalent block volume was introduced, replacing the persistence term in Cai et al.´s formula with the transformation factor T. With additional simulation cases, the validity of the new formula could be confirmed.

All investigations presented in this paper dealt with three orthogonal joint sets. The influence of additional joint sets or irregular joints on the block size distribution requires further analysis. Only for the evaluation of the new proposed formula, individual cases with non-orthogonal joint sets were analyzed. For the determination of the transformation factor, the arithmetic mean of the joint set´s persistence was applied (Figure 12). Further investigations on the effect of different persistence values on the block size

distribution are necessary. In terms of practical relevance, the proposed formula has to be tested and calibrated with data from natural rock mass volumes.

Nevertheless, the results presented in this paper are promising. With further investigations, the determination of the *in situ* block size distribution for design purposes and stability analyzes should be possible in a more realistic way.

REFERENCES

Austrian Society for Geomechanics (2010). Guideline for the geotechnical design of underground structures with conventional excavation; ground characterization and coherent procedure for the determination of excavation and support design and construction. Salzburg: Private publishing house. Available at www.oegg.at

Barton, N. R., Lien, R. & Lunde, J. (1974). Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics, 6 (4)*, 189-236.

Bieniawski, Z. T. (1973). Engineering classification of jointed rock masses. *Trans. S. Afr. Inst. Civ. Eng., 15*, 335-344.

Cai, M., Kaiser, P. K., Uno, H., Tasaka, Y. & Minami, M. (2004). Estimation of rock mass deformation modulus and strength of jointed hard rock masses using the GSI System. *International Journal of Rock Mechanics & Mining Sciences, 41*, 3-19.

Hoek, E. (1983). Strength of jointed rock masses. 23rd Rankline Lecture. *Geotechnique, 33*, 187-223.

Hoek, E., Kaiser, P. K. & Bawden, W. F. (1995). *Support of underground excavations in hard rock*. Rotterdam: Balkema.

Itasca Consulting Group, Inc. (2011). 3DEC 3 Dimensional Distinct Element Code v5.0. User´s Guide, Third Edition. Minnesota.

Palmström, A. (1982). The volumetric joint count – a useful and simple measure of the degree of rock mass jointing. In *Proceedings of the IV Congress International Association of Engineering Geology Volume 2* (pp. V.221-V.228). New Delhi.

Palmström, A. (1995). *RMi – a rock mass characterization system for rock engineering purposes*. Ph.D. thesis. University of Oslo, Norway.

Söllner, P. (2014). *Determination of the in situ block size distribution as a parameter for the rock mass characterization based on measurements and statistical methods*. Master´s thesis. Graz University of Technology, Austria. Available at tunnel.tugraz.at