The effect of joint condition and block volume on GSI and rockmass strength estimation

M. Pitts & M. Diederichs
Dept. of Geological Sciences and Geological Engineering
Queen's University, Kingston, Ontario

2011 Pan-Am CGS Geotechnical Conference

ABSTRACT
Rock mass classification schemes are useful for estimating design parameters, design of excavation or support, and communicating information about rock masses. One such system is the geological strength index (GSI), which is widely used in tunnel and mine design because it produces quantitative values that can be used to calculate the strength and deformation properties of a rock mass. At a preliminary stage, this can reduce the need for costly in-situ tests to design support and excavation systems. GSI is based on qualitative inputs about joint condition and joint spacing that make it somewhat subjective. To use the system properly, experience in the geotechnical sector is often required. To make GSI more standardized and easy to use, previous authors have proposed relationships between block volume, joint condition, and the GSI value for a rock mass. In the past, such relationships have been crudely calibrated based on case studies with sparse measurement data.

This study takes a more rigorous, albeit virtual verification and calibration route using finite element models with discrete joint elements to test relationships between rockmass GSI and actual joint spacing, joint condition and joint persistence. Rock blocks with defined combinations of these parameters are tested for overall strength. The results are compared to strength predictions from GSI and from equivalent material models. This study illustrates the importance of considering joint persistence in the GSI system, a parameter not explicitly included. Joint orientation and model size are also considered. Recommendations are made for model construction and the use of a quantified approach to GSI estimation and rockmass strength conversion.

RÉSUMÉ

Les systèmes de classification des massifs rocheux sont très utiles afin d'estimer les paramètres de conception, de planifier des méthodes d'excavation ou de support, ainsi que de communiquer l'information au propos des massifs rocheux. Un de ces systèmes sont utilisées l'ISG (indicateur de solidité geologique). L'ISG est avantageux dans le dessin des projets minières et des tunnels, parce qu'il produit des valeurs quantitatives qui peuvent être utilisés afin d'évaluer la solidité ou la déformation des massifs rocheux. À l'étage préliminaire ceci peut réduire le besoin d'épreuves d'analyse coûteuses qui bénéficient le dessin de ces projets. ISG est basé sur des entrées qualitatives de la condition et de l'espacement des joints ce qui le rend un peu subjectif. Afin de bien utiliser ce système, il est souvent nécessaire d'avoir de l'expérience dans le secteur geotechnique. Dans le but de normaliser l'ISG et de le rendre plus facile à utiliser, des auteurs ont suggérés des rapports entre la valeur du ISG des massifs rocheux et divers caractéristiques incluant le volume des blocs et la condition des joints. Autrefois**,** ces rapports étaient fondés sur des études de cas avec des données éparses.

Bien qu'elle soit virtuelle, cette étude prend une démarche rigoureuse. Un modèle utilisant des éléments finis ayant des éléments de joints distincts est employé pour évaluer les relations entre l'ISG et l'espacement, l'état, ainsi que la persistance actuelle des joints. Des blocs rocheux définis par des combinaisons de ces paramètres sont analysés pour évaluer la solidité de l'ensemble du système. Les résultats sont comparés aux prédictions de solidité que l'ISG a procuré, ainsi que ceux d'autres modèles équivalents. Cette étude illustre l'importance de la considération de la persistance des joints, un paramètre qui n'est pas inclus explicitement, dans l'ISG. L'orientation des joints et la taille du modèle des massifs rocheux sont également considérés. Des recommandations pour la construction des modèles, ainsi que l'utilisation d'une démarche quantitative de l'estimation de l'ISG et la conversion de la solidité d'un massif rocheux sont établies dans ce rapport.

1 INTRODUCTION

Accurate modeling of rock masses requires inputs of deformation modulus and strength. These variables can be determined through costly in-situ tests on the rock mass, some of which can only occur after some excavation. Tests include plate loading and in-situ block shear tests to determine deformation and shear strength respectively. GSI relates properties of the intact rock to those of the jointed body, greatly reducing the cost of such tests (Cai et al. 2004).

2 CALCULATING ROCK PROPERTIES

Rock mass strength can be calculated using Mohr-Coulomb or Hoek-Brown equations. Each of these relies on rock mass properties that can be determined through careful and potentially expensive testing. The Mohr-Coulomb failure criterion is shown below, where σ_1 and σ_3 are the major and minor principle stresses:

$$\sigma_1 = ((2c \cos\varphi) / (1-\sin\varphi)) + ((1+\sin\varphi) / (1-\sin\varphi))\, \sigma_3 \quad [1]$$

The Mohr-Coulomb equation relies on the cohesive strength, *c*, and angle of friction, φ, of the rock mass.

These can be determined from block shear tests The Hoek-Brown failure criterion, used for more jointed rock masses, is expressed by the equation:

$$\sigma_1 = \sigma_3 + \sigma_c \left(m_b (\sigma_3 / \sigma_c) + s \right)^a \qquad [2]$$

where σ_c is equal to the uniaxial compressive strength of the intact rock. This should be determined through uniaxial tests, but may be estimated in the field using Schmidt Hammer readings or point load tests.

The Hoek-Brown constants m_b, s, and a, represent rock mass properties, and are often necessary inputs in modeling. These values cannot be directly evaluated experimentally although back analysis of field response is possible. Using GSI in combination with intact rock values, these rockmass variables can be calculated using the formulas below (Hoek et al., 2002).

$$m_b = m_i \exp[(\mathrm{GSI}-100)/(28-14D)] \qquad [3]$$

$$s = \exp[(\mathrm{GSI}-100)/(9-3D)] \qquad [4]$$

$$a = 0.5 + (e^{-\mathrm{GSI}/15} - e^{-20/3})/6 \qquad [5]$$

where m_i is a material constant based on the rock type, D is a factor representing damage caused by blasting and stress relaxation, and GSI is the geological strength index (Hoek et al., 2002). The GSI value is clearly very useful in determining these Hoek-Brown constants of a given rock, without resorting to costly lab tests. The GSI system can be used on a variety of rock masses with different degrees of jointing, and is useful for determining the necessary support for rock that is underground and not readily accessible. These variables can be used to determine the strength of a rock.

The elastic deformation, E, can also be calculated using the GSI value of a rock mass. This is done through a number of empirical equations (Hoek and Diederichs 2006)

GSI values provide useful quantitative outputs, but are determined using common qualitative geologic terms. This makes GSI values somewhat subjective, and dependent on the individual experiences of the engineer assessing the rock mass. To help standardize GSI readings and make the classification system more useful to less experienced geologists, Cai and Kaiser (2004) related GSI to quantitative values for block volume and joint condition as shown in Figure 1.

This study will look at how the joint properties of rock masses in Phase2 modeling software from Rocscience effect the GSI. Block volume and joint condition factor are used to build a model, and the GSI is then calculated from the resulting uniaxial compressive strength, using the equation:

$$\sigma_c = \sigma_{ci}\, s^{a} \qquad [6]$$

where σ_c is the UCS, σ_{ci} is the UCS of the unjointed rock mass, and s and a are the Hoek-Brown rock mass parameters determined by the GSI. This equation is derived from Equation (2) for uniaxial loading conditions.

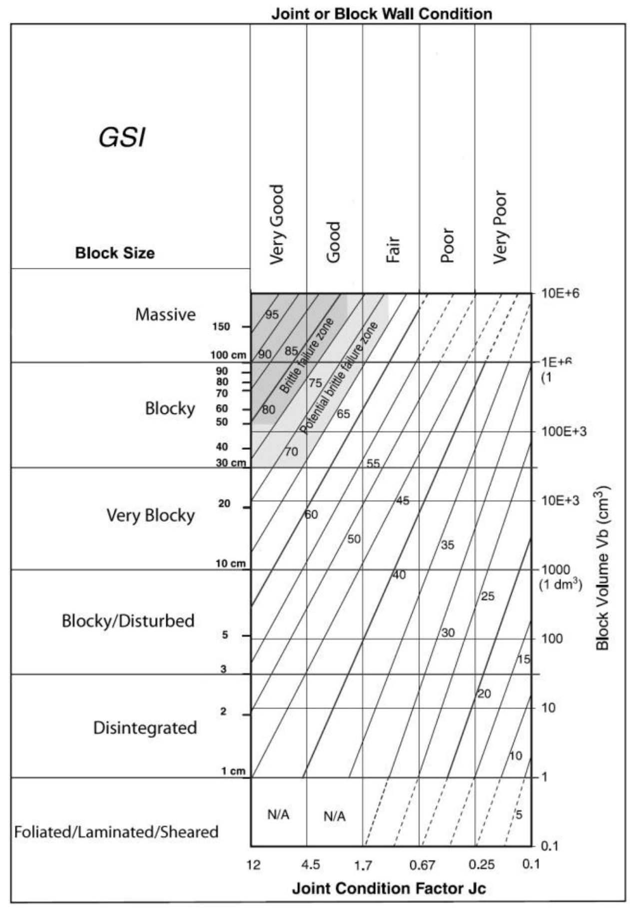

Figure 1. Relationships between GSI values and block volume and joint condition Cai et al. (2004)

3 MODELLING ROCKMASSES IN PHASE 2

Cai and Kaiser (2004) relate GSI to block volume and joint condition. These values determined the joint spacing and strength values, respectively. Blocks have the same boundary conditions while joint spacing and strength values change. The majority of the blocks were tested with dimensions of 2 x 2 m; some 4 x 4 m models were tested to compare the effect of rock mass scale.

The models are all composed of the same material. The unjointed material has a UCS of 100 MPa, and a GSI of 100. The GSI measured is therefore the result of the joints within the rock mass, not the rock itself.

3.1 Determining Volume

The block volume of a rock mass can be determined by this equation from Cai et al. (2004):

$$V_B = s_1 s_2 s_3 \,/\, \left((p_1 p_2 p_3)^{1/3} \sin\gamma_1 \sin\gamma_2 \sin\gamma_3 \right) \qquad [7]$$

where s_i is the space between joint sets, γ_i is the angle between joint sets, and p_i is the persistence of a joint set. In this study, the joint sets are always perpendicular to each other. Because sin90 = 1, the portion of the denominator related to relative joint angle is equal to 1.

$$V_B = s_1 s_2 s_3 \,/\, (p_1 p_2 p_3)^{1/3} \qquad [8]$$

To represent the three dimensional nature of a rock mass in the two dimensional Phase 2 platform, one joint set was assumed to be parallel to the rock face shown on the screen, with a spacing of 1m and a persistence of 1. The remaining joints have equal spacing and persistence. The block volume is now represented by the equation:

$$V_B = s_1 s_2 \,/\, (p_1 p_2)^{1/3} \qquad [9]$$

where s_1 is equal to s_2, and p_1 is equal to p_2. The block volume is taken from the GSI chart (Figure 2). Joint persistence values of 0.3, 0.5, 0.8, and 1 were tested, to determine how joint persistence might affect the calculated GSI.

All models had the same joint conditions. A central point on the bottom of the model was fixed in both the x- and y-directions, while the rest of the bottom was fixed in the y-direction only. All other sides of the model were free to move.

3.2 Determining the Joint Condition, J_C

In Phase 2, the strength of a joint is determined by several variables. All systems require a value for normal and residual joint stiffness. In this experiment, all models use the default values given by Phase 2. Normal stiffness is equal to 100,000 MPa and residual stiffness is equal to 10,000 MPa. The joints are assumed to be dry: internal pressure is equal to 0 MPa.

Phase 2 allows users to enter joint properties using different systems (Mohr-Coulomb, Barton-Bandis, and Geosynthetic Hyperbolic). The Barton-Bandis system uses the joint roughness coefficient (JRC), joint wall compressive strength (JCS) and residual friction angle (φ_r) as necessary inputs. This system is used because it relates to the joint condition, J_c, which is given in Cai and Kaiser's GSI chart. The equation for J_c is:

$$J_c = (J_s \times J_w) \,/\, J_a \qquad [10]$$

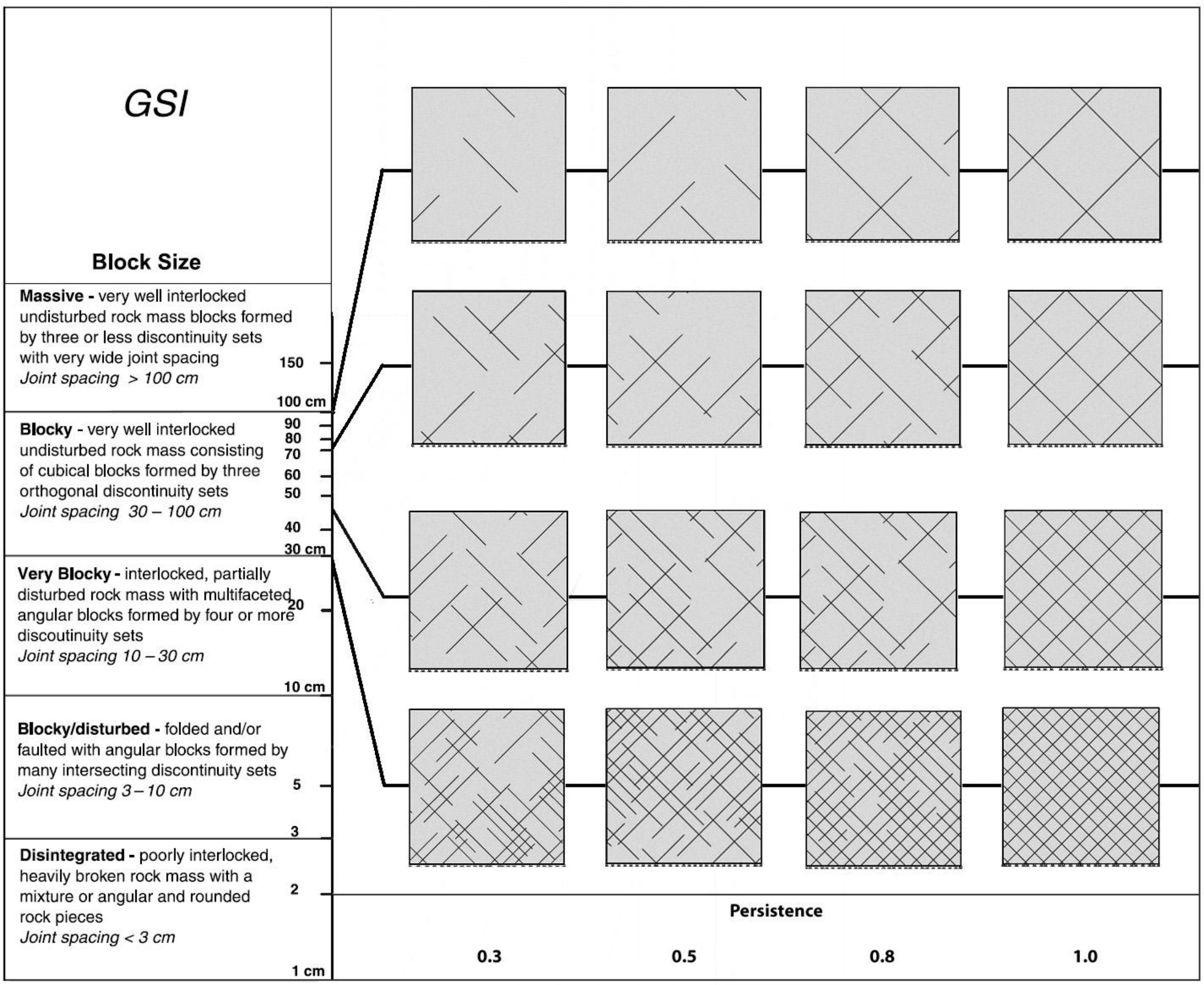

Figure 2. Models with different block volume and joint persistence were tested as shown (2m sample).

where J_s is joint smoothness, J_w is the waviness coefficient, and J_a is the alteration (Cai et al., 2004). J_s and J_w can be simplified using the equation:

$$J_r = J_s \times J_w \quad [11]$$

where J_r is the joint roughness in the NGI Q system (Palmstrom 2000). The joint condition can now be expressed as:

$$J_c = J_r / J_a \quad [12]$$

Jr relates to JRC as seem in Figure 3 (Barton 1993), below. The JRC value depends on the the block size of the sample. Because this study is meant to be representative of all block sizes, both values were used for each model, resulting in a high and low estimate for GSI.

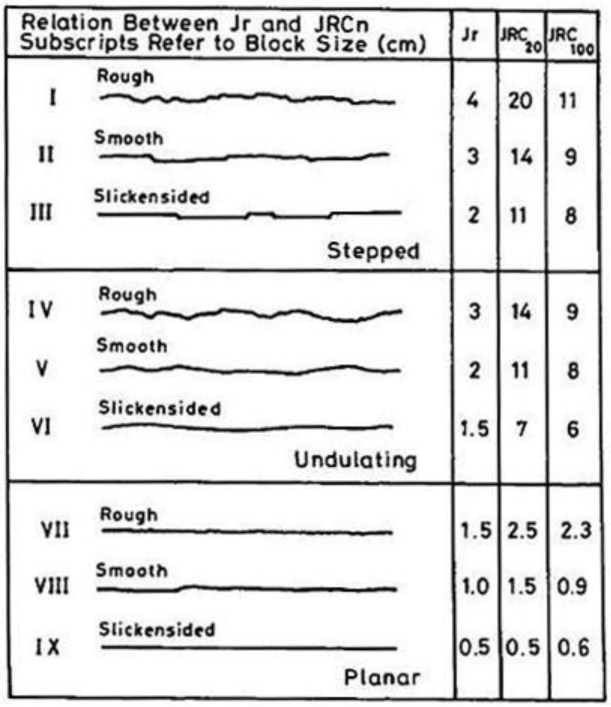

Figure 3. The relationship between Jr and JRC depends on the length of the joint. (Barton, 1993)

The joint wall compressive strength, or JCS, was originally divided evenly across the GSI chart, ranging from 10 to 100. Like the residual friction angle, this was altered to more closely approximate the GSI curve. The final values used can be found in Figure 4.

The joint alteration value, J_a, relates to the residual friction angle, φ_r. This relationship is an approximation based on the mineralogical properties of alteration products of joints. A single J_a value therefore creates a range of possible residual friction angles. The input values of φ_r were chosen to agree with this correlation (Barton et al., 1974) as in Table 1, while providing a relatively equal distribution between models. Final values can be seen in Figure 4.

Table 1: Conversion between residual friction angle and joint alteration (based on Barton et al., 1974)

Joint Alteration Number	**φ_r**	**Ja**
Rock walls in contact:		
Clean, tight joints	>25°	0.75 - 1.0
Slightly altered joint walls	25 - 30°	2
Silty or sandy clay coatings	20 - 25°	3
Soft clay coatings	8 - 16°	4
Gouge or filling < 5 mm thick		
Sandy particles or fault breccia	25 - 30°	4
Stiff clay gouge	16 - 24°	6
Soft or swelling clay gouge	6 - 12°	8 - 10
Thick continuous clay zones	6 - 24°	10 - 20

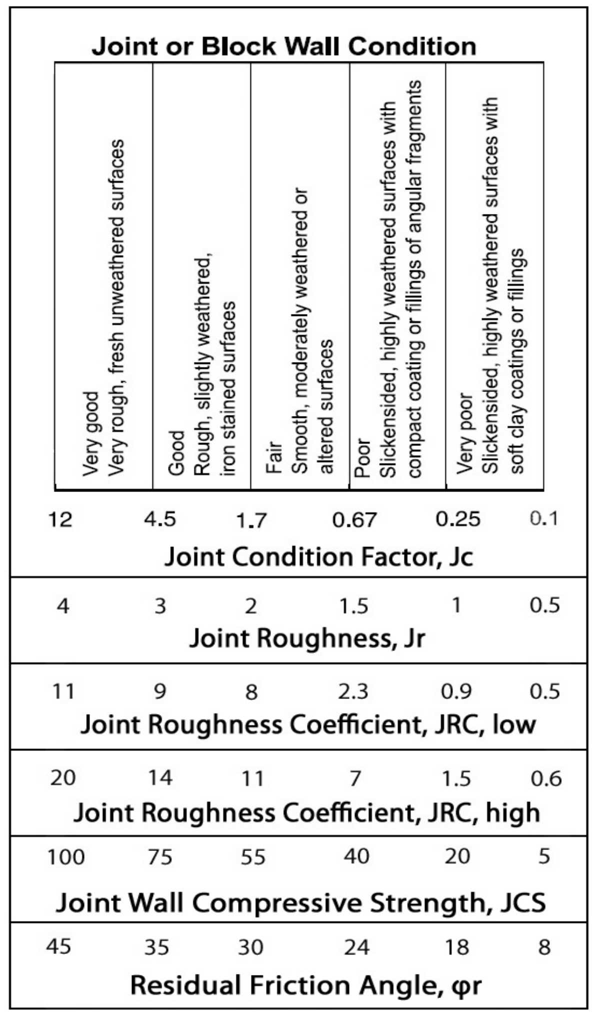

Figure 4. Each model was tested with a variety of joint condition inputs.

Using the major Barton-Bandis inputs mentioned above, JRC, JCS, and φ_r, the joint conditions could be input into Phase 2. Models with the same geometry - equal joint spacing and persistence - were run with different joint conditions, effectively sampling across the GSI-chart.

4 RESULTS

4.1 Block Volume and Persistence

The effect of persistence on GSI appears to be greater than first believed. The results shown below in figure 5 use the block volume calculated without taking into account persistence. Actual GSI, back calculated from the modelled UCS result, correlate with predicted GSI values for a persistence of 0.5 (50% continuity on a given joint plane)

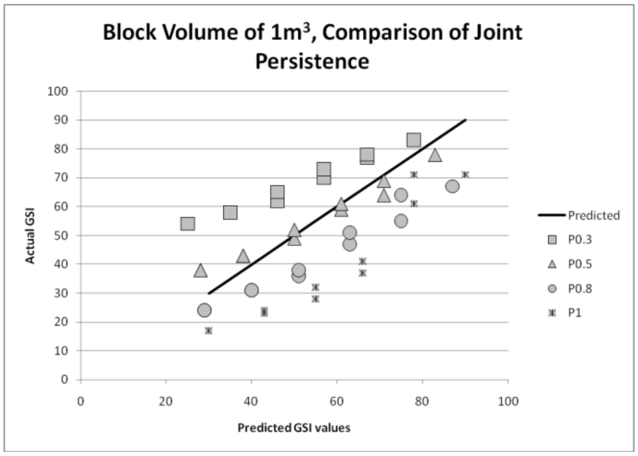

Figure 5. Rock masses with equal different joint persistence values have different GSI values, although they are of similar block volume.

When the block volume is calculated using equation 9, from Cai et al. (2004), the GSI can be used more reasonably to account for joint persistences of 0.3 or 0.5, depending on the block volume. The results of using this method of volume calculation are shown below, in Fig. 6.

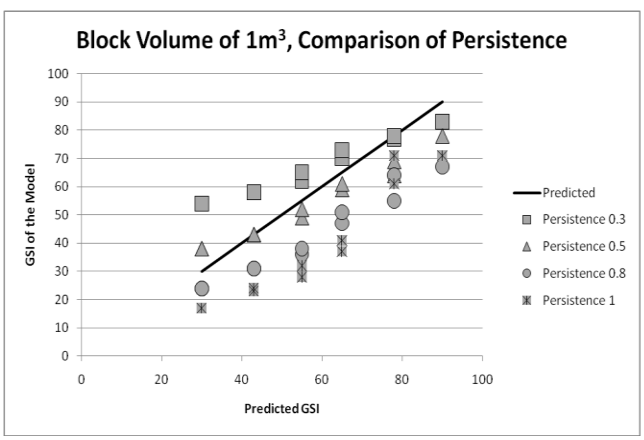

Figure 6. Rock masses where block volume was calculated to factor in joint persistence.

The proposed correction for block size does tend to shift the predicted values more in line with expectations (correlation with low persistence at high GSI and with high peristence at low GSI).

Factoring persistence in to the volume calculation is not enough to adequately describe the rock mass strength. In addition, the GSI predictions overestimate the actual rockmass strength in the PHASE2 models for smaller block sizes as shown in Figures 7 and 8. This is in part due to the boundary conditions (constant or zero confinement) in the models. GSI is intended for prediction of strength around excavations where the boundary conditions for a rockmass unit tend to be low confinement on the excavation side but strain controlled or limited away from the excavation. This limits block kinematics in situ whereas the blocks are free to mobilize readily in the block test. This likelihood of spurious block movement and apparent yield increases with decreasing block size within the finite model sample (2m x 2m in this case).

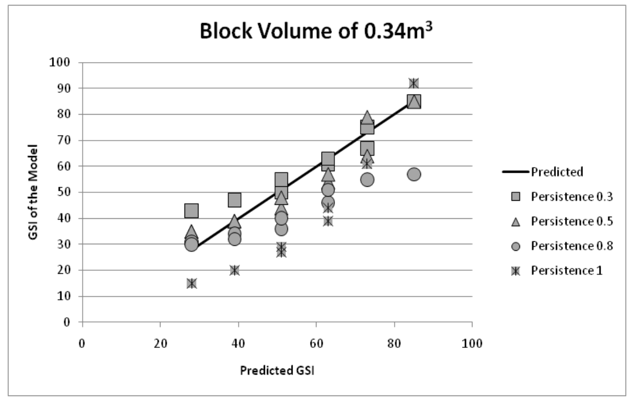

Figure 7. 70cm block size with correction of block volume according to Cai et al 2004.

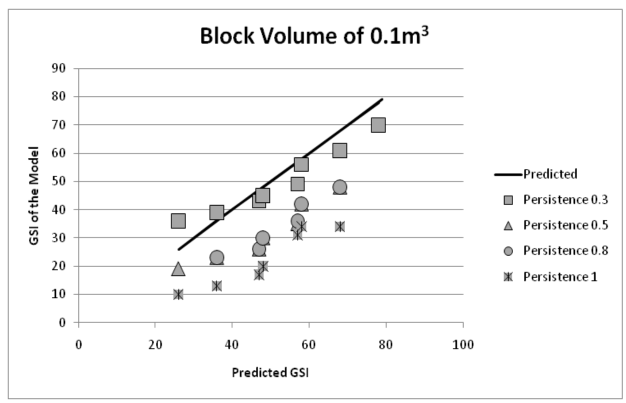

Figure 8. 45cm block size with correction of block volume according to Cai et al 2004.

4.2 Joint Orientation and Scale

The joint angle orientation is not considered in Cai and Kaiser's quantitative GSI model. Because of the two dimensional nature of the modeling software, one joint is considered fixed. It is upright and parallel to the model, with a joint spacing of 1m. The orientation of the remaining two joint sets were varied in this study although all three joint sets were always 90° with respect to each other. Joints were tested at 0°/90°, 15°/75°, 25°/65°, 30°/60°, and 45°/45° with respect to the force applied. The results are shown in Figure 9.

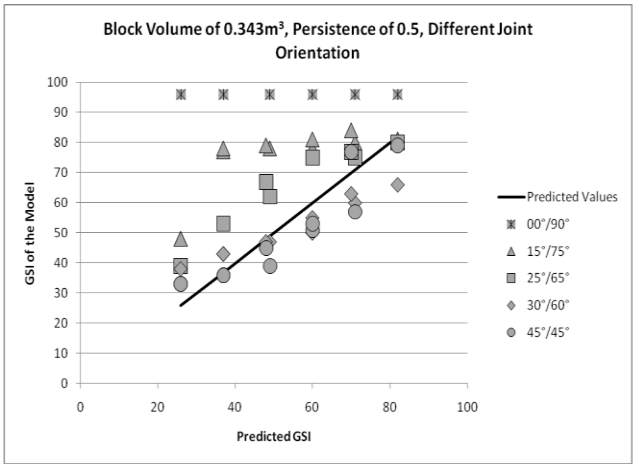

Figure 9. The GSI values of a rock mass change dramatically with joint orientation

The joint sets at a 0°/90° orientation fail at the same point, regardless of the joint strength. All these rock masses have a UCS of 80.5 MPa, and a GSI of 96. At this orientation, joint condition or block size has no obvious effect. The effective GSI value (based on model UCS) was lowest when the joint orientation was either 30°/60° or 45°/45°. The effect of orientation is greatest for the mid-range of GSI (45-55). For poor GSI models, all but the upright joint configuration resulted in low strength.

Models were also run at different scales. To determine if the size of the model had any effect on GSI, models 4m x 4m were run in addition to the 2m x 2m models used for the majority of the testing. The results are shown in Figure 10.

When joint persistence was very high (p = 1) or very low (p = 0.3) there was little difference in the GSI values of the rock masses. With joint sets of moderate persistence (0.5 - 0.8) a larger size causes decreases the GSI. This is because the likelihood of block formation increases with area.

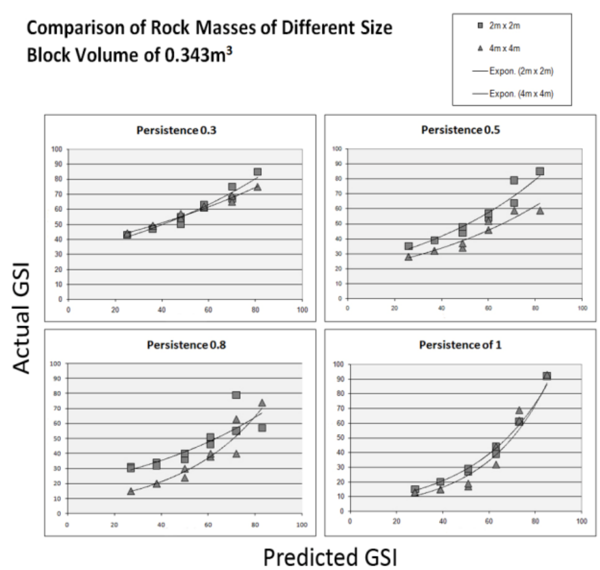

Figure 10. The size of the rock mass tested can have an effect on GSI for certain joint persistence values.

5 DISCUSSION AND CONCLUSIONS

It is possible to create composite models composed of continuum blocks separated by discrete joint elements and test the response of a jointed rockmass.

The boundary conditions of such a test are critical as is the interpretation of yield in the model. As jointing increases, the possibility of a small block separating from the model and creating an indication of yield is high. Such calibration models may underestimate the practical strength of a rockmass at the excavation scale.

Persistence can be accommodated through the adjustment of block size in a quantified calculation of GSI. This adjustment as proposed by Cai et al. 2004 may not be sufficient to capture the strengthening influence of rock bridges between blocks.

Models using joint parameters estimated from surface character as per published schemes in the literature do not capture the strength influence of the GSI system. More work is needed to capture the correct method of assigning joint strength parameters to correspond to the GSI system.

ACKNOWLEDGEMENTS

The writers would like to acknowledge the contribution of the members of the Queen's Geomechanics Group. Funding was provided through NSERC.

REFERENCES

Barton, N. 1993. Predicting the Behaviour of Underground Openings in Rock, Proc. Workshop on Norwegian Method of Tunneling, CSMRS-NGI Inst. Cooperation Prog., New Delhi, India.

Barton, N.R., Lien, R., Lunde, J. 1974. Engineering classification of rock masses for the design of tunnel support. Int. J. Rock Mech & Min Sci. 4: 189–239.

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. Int. J. Rock Mech. & Min. Sci. 41:3–19.

Hoek, E., and Brown, E.T. 1980. Underground excavations in rock. London: Institution of Mineralogy and Metallurgy.

Hoek E., Carranza Torres C., Corkum B. 2002. Hoek–Brown failure criterion—2002 edition. In: Proceedings of the Fifth North American Rock Mechanics Symposium, Toronto, Canada, vol. 1, p. 267–73.

Hoek, E. and Diederichs, M. 2006. Empirical Estimation of Rockmass Modulus. International Journal of Rock Mechanics & Mining Sci. 43: 203–215

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

Palmstrom, A., 2000. Recent developments in rock support estimates by the RMi. J. Rock Mech. Tunnel. Technol. 6, 1–9.