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Practical estimates of rock block unconfined strength

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1 INTRODUCTION

Understanding the strength and deformability of rock blocks and their contribution to the overall rock mass behavior is key for the rock engineering design of underground and surface excavations in civil and mining engineering projects (Stavrou & Murphy 2018). Rock blocks are volumes of macroscopically unjointed rock material that are delineated by persistent or non-persistent discontinuities and can occur *in-situ* essentially in infinite variety of sizes and shapes (Palmstrom 2005).

It is widely recognized that the Unconfined Compressive Strength (UCS) of intact rock decreases with increasing scale due to an increased inherent heterogeneity as a function of volume and the greater probability of randomly and/or critically orientated defects to create failure paths within larger rock volumes (Hoek & Brown 1997).

In this study, a series of simulated laboratory tests are performed on samples of varying sizes and defect intensities to examine the combined influence of sample scale and pre-existing defects on the UCS of rock blocks. As part of the modelling process, micro-Discrete Fracture Networks (μDFNs) have been embedded into Grain-Based Models (GBMs) within the Universal Distinct Element Code (*UDEC*) (Itasca 2014) to capture both the fracturing of the intact material and the effect of pre-existing defects (Fig. 1). Following the initial calibration of a lab-scale intact (non-defected) rock sample, randomly distributed defects of increased frequency, persistence and strength are integrated in a series of progressively larger in size samples to generate synthetic rock specimens. The results from these experiments are compared with previous studies and the predicted UCS values are analyzed in terms of sample size, defect density, persistence and strength. Based on our numerical findings, guidelines for estimating the strength of defected rock blocks are proposed in an attempt to refine existing empirical relationships (Yoshinaka et al. 2008, Laubscher & Jakubec 2001).

2 DESIGN AND ANALYSIS

A hybrid modelling approach was employed to create Synthetic Rock Block (SRB) samples to investigate the combined effect of size and pre-existing micro-defects on the strength and deformability properties of rock blocks. Once the UCS of the homogenous samples was calibrated, a series of unconfined compression tests were run by integrating the μDFN geometries. The μDFN geometries generated for the purposes of this study were based on various P_{10} intensity and defect trace length (persistence) values. The defect geometrical models were mainly generated by using the DFN generator, FracMan (Dershowitz et al. 2014) (Fig. 2). To minimize the creation of preferential planes of weakness and the potential for anisotropic behavior, the pre-existing defects were assigned an arbitrary orientation between 0^0 and 90^0 with a uniform probability distribution. To investigate scale effects on the strength of defected samples, the current study considers two cases of numerical simulations:

Case 1: Various geometries of randomly distributed "open" defects were embedded into the large-scale calibrated intact GBMs to assess the combined impact of defect intensity, persistence and specimen size. In the adopted approach, the number of defects is proportional to the volume of the specimens. The generated cracks in this stage were modelled as "open defects" and assumed to be purely frictional, with the friction angle and stiffness values being identical to those of the calibrated intact GBMs.

Case 2: Further analysis was undertaken by strengthening the defects for some of the previously generated SRB models to assess the combined impact of defect strength, intensity, persistence and specimen size. A parametric analysis was employed where defect strength (i.e. cohesion and tensile strength) was increased by 50% and 100% in respect to the baseline intact rock strength and these results where compared with the predicted UCS values for defect strength of 0% ("open" defects).

For the purposes of this study, 16 μDFN groups of increasing fracture intensity and persistence were incorporated within the previously calibrated intact GBMs. Table 1 presents the matrix of modelling scenarios.

Table 1. Matrix of modelling scenarios considered to generate SRB models.

Width	Height	Area	Volume	d_e	~No of blocks	P_{10} cases				Persistence cases			
mm	mm	mm^2	mm^3	mm	-	defects / m				m			
50	125	6.25E+03	2.5E+05	63	300	-				-			
100	250	2.50E+04	2.0E+06	125	1100	5	10	20	40	0.01	0.02	0.04	0.10
200	500	1.00E+05	1.6E+07	250	4100								
400	1000	4.00E+05	1.3E+08	501	16200								
Case 1						√	√	√	√	√	√	√	√
Case 2						√	√	√	√	√	-	√	-

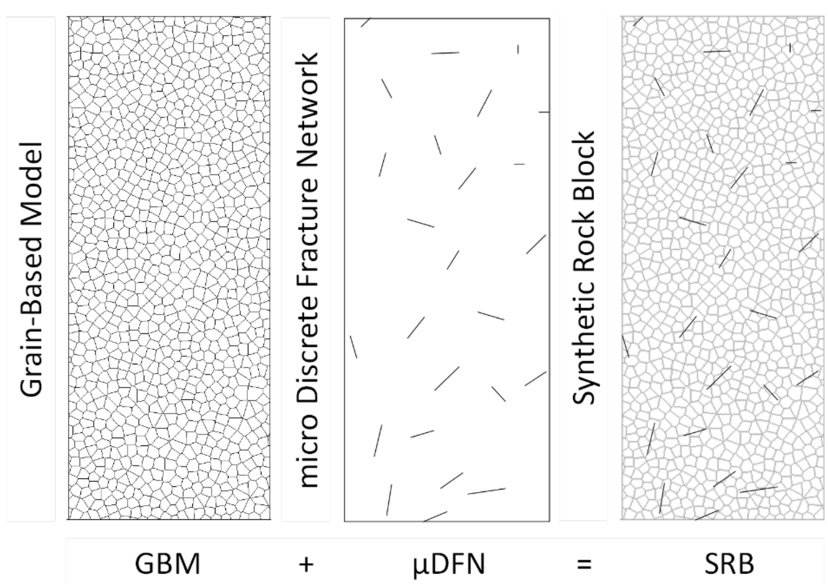

Figure 1. The different components of a Synthetic Rock Block (SRB) model in *UDEC*: intact Grain-Based Model (GBM) and micro Discrete Fracture Network (μDFN).

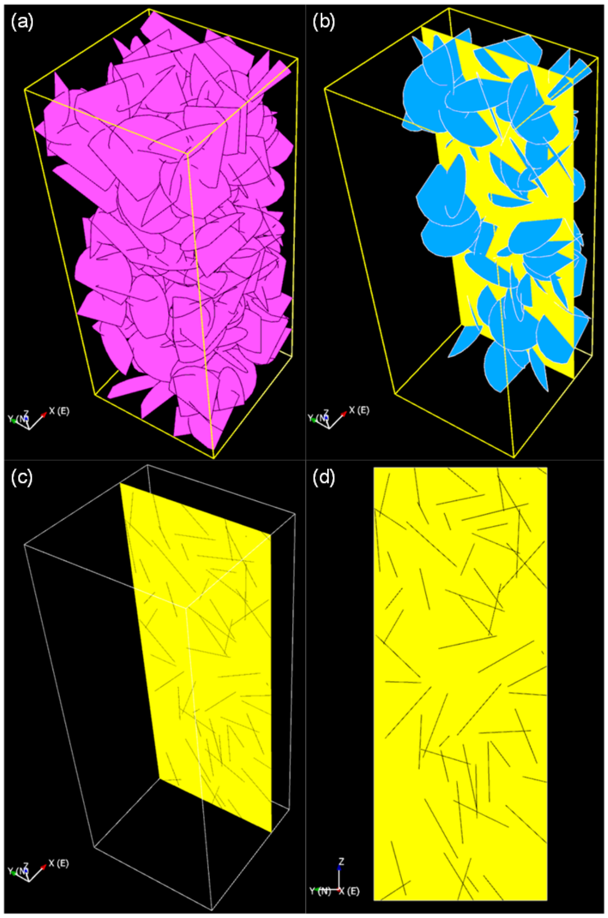

Figure 2. (a) 3D μDFN generated in Fracman, (b) defects intersecting a specific plane, (c) traces generated by the defect-plane intersection, and (d) defect traces imported in the *UDEC* GBM model.

3 RESULTS AND DISCUSSION

The results from the scaling analysis generally suggest that the UCS of rock blocks is strongly influenced by the presence of "open" pre-existing defects and substantial reductions in strength are recorded as defect intensity and persistence increase, impacting the induced failure mode (Fig. 3).

For "Case 1" the results from the SRB scaling simulations were plotted as a function of the μDFN P_{10} and P_{21} defect intensities (Fig. 4). As expected, the reduction of UCS is more profound as defect frequency increases and defects persist. From a P_{10} perspective, the inverse relationship between strength and defect frequency is not unique as four different envelopes delineate the strength decrease as a function of the four different defect lengths of 0.01 m, 0.02 m, 0.04 m and 0.1 m. A similar trend is also revealed when the data are plotted as a function of the P_{21} intensity.

Both Figures 4a & 4b also reveal that the decay of strength follows a power-law trend and that beyond a certain defect intensity RBS remains relatively constant. However, it is important to note that the rate of strength reduction increases with an increase on defect persistence, meaning that strength reaches a constant behavior at smaller fracture intensities as micro-defect length increases. From Figures 4a & 4b it is also clear that a systematic strength loss is observed for defect persistence of 0.01 m, 0.02 m and 0.04 m while for defect persistence of 0.1 m the magnitude of strength reduction has been reduced remarkably, suggesting that strength approaches a horizontal asymptote corresponding to a minimum strength in rock block scale. Because of this progressive strength reduction, when the defect intensities for each case are combined with the defect persistence (i.e. P_{10} or P_{21} × Persistence), a very good clustering of the obtained values is observed in the data set and a unique solution appears to exist when the UCS ratio is plotted against the "Defect Intensity × Persistence – (DIP)" factor (Fig. 5c & Fig. 5d).

For “Case 2”, the progressive increase in defect strength from 0% to 100% of the baseline intact rock strength improves significantly the UCS of the simulated samples as the micro-cracks are “locked” and their effect becomes less important (for the 50% defect strength) or even vanish (for the 100% defect strength). the rate of gain in UCS for the SRB samples with defect persistence of 0.04 m is faster than the strengthening rate of samples with persistence of 0.01 m, meaning that the shear strength of defects overrides the effect of persistence as defect strength increases. This is more obvious at the scenario with defect strength equal to 100% of the baseline UCS where the strength of both samples has approached the scaled non-defected intact rock condition (i.e. 80% of the lab scale UCS) and the effect of persistence has essentially disappeared.

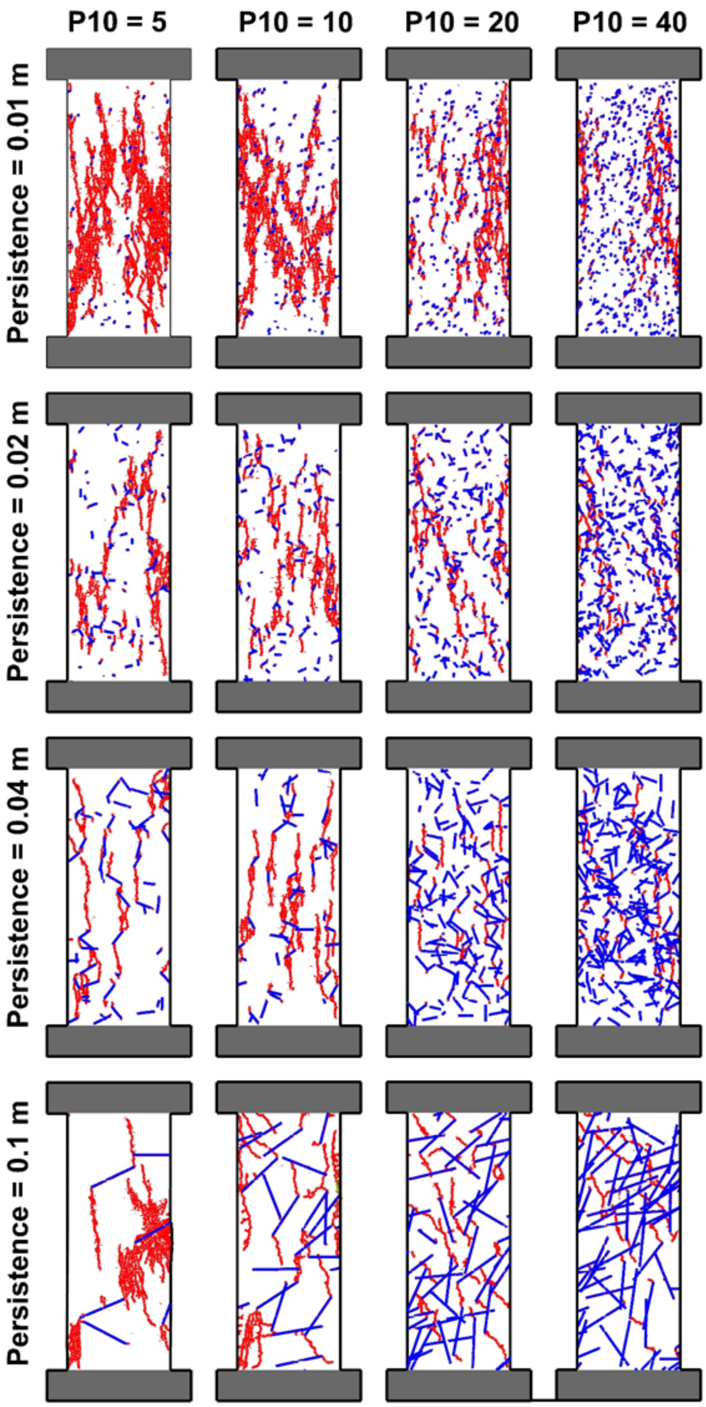

Figure 3. Failure modes for progressively increasing defect intensities and defect persistence. The lines with blue color denote failed pre-existing defects while those with red represent newly generated micro-cracks.

4 CONCLUSIONS

The results of the SRB numerical study are encouraging as certain trends were observed in the UCS reduction in respect to the sample size, defect intensity, persistence and strength. This allow us to standardize the data along specific strength reduction envelopes and to propose generic predictive diagrams that cover a wide range of defect geometrical combinations and strengths. Figure 5 presents a series of charts that express rock block strength as function of sample size, defect intensity, defect persistence and defect strength. In these charts, the fracture intensity (either P_{10} or P_{21}) from the various modelling scenarios has been combined with the persistence of each case (i.e. the DIP factor) to standardize the data variability into one unique solution and to allow for flexibility in the UCS predictions over a wide range of defect geometries and defect strengths. The same inverse strength relationships are presented into three different diagrams to magnify specific defect geometrical regions which otherwise would have been difficult to visualize if were plotted into the same chart. The proposed charts incorporate all the essential factors controlling the unconfined strength of rock blocks (i.e. scaled intact rock strength and defect intensity, persistence and strength).

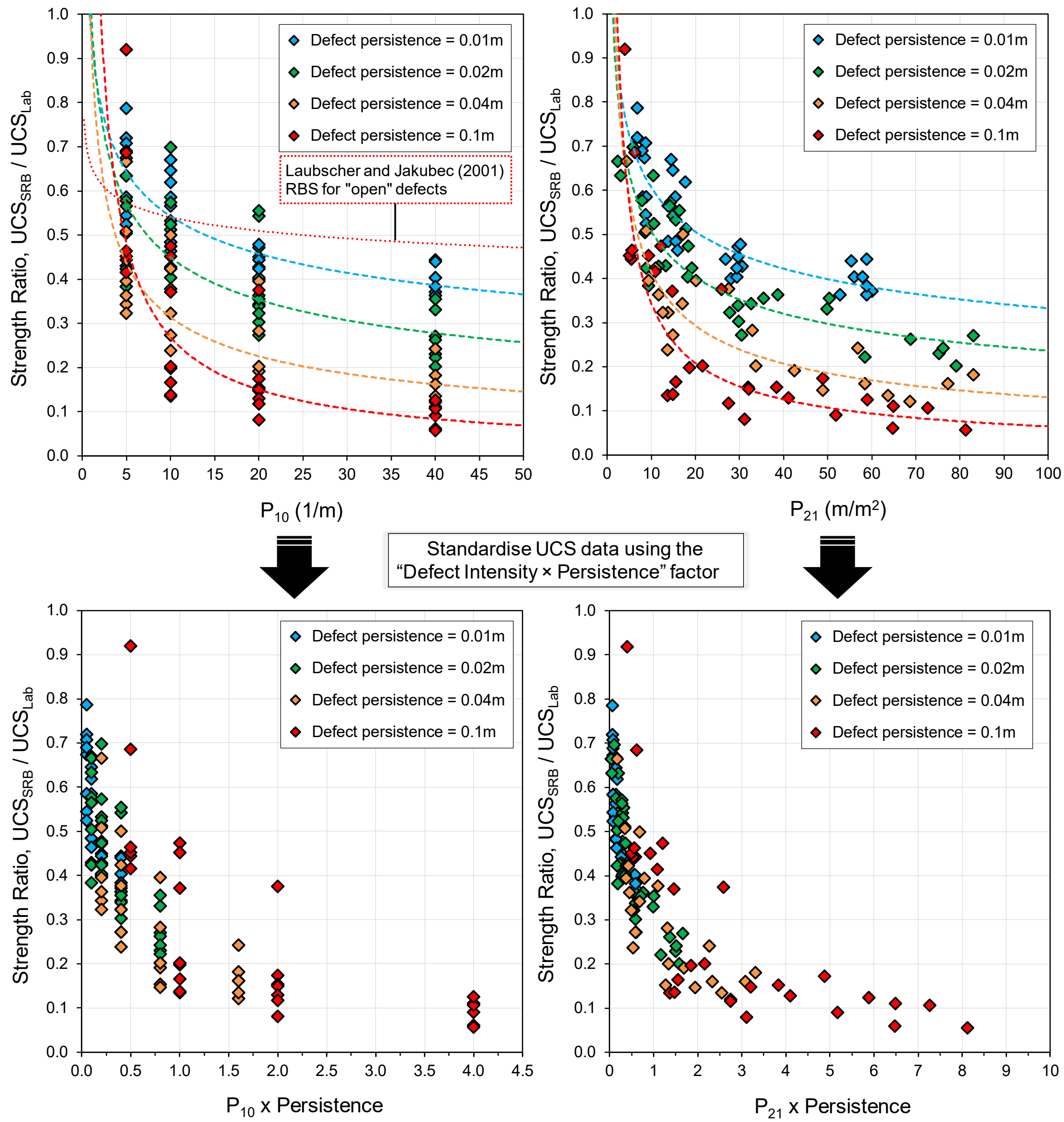

Figure 4. (a) and (b) Normalized UCS values as a function of defect intensity (P_{10} and P_{21}) and defect persistence. Also shown for comparison is the rock block strength reduction for "open" defects proposed by Laubscher and Jakubec (Laubscher & Jakubec 2001). (c) and (d) Normalized UCS values as a function of the defect intensity (P_{10} and P_{21}) x defect persistence factor.

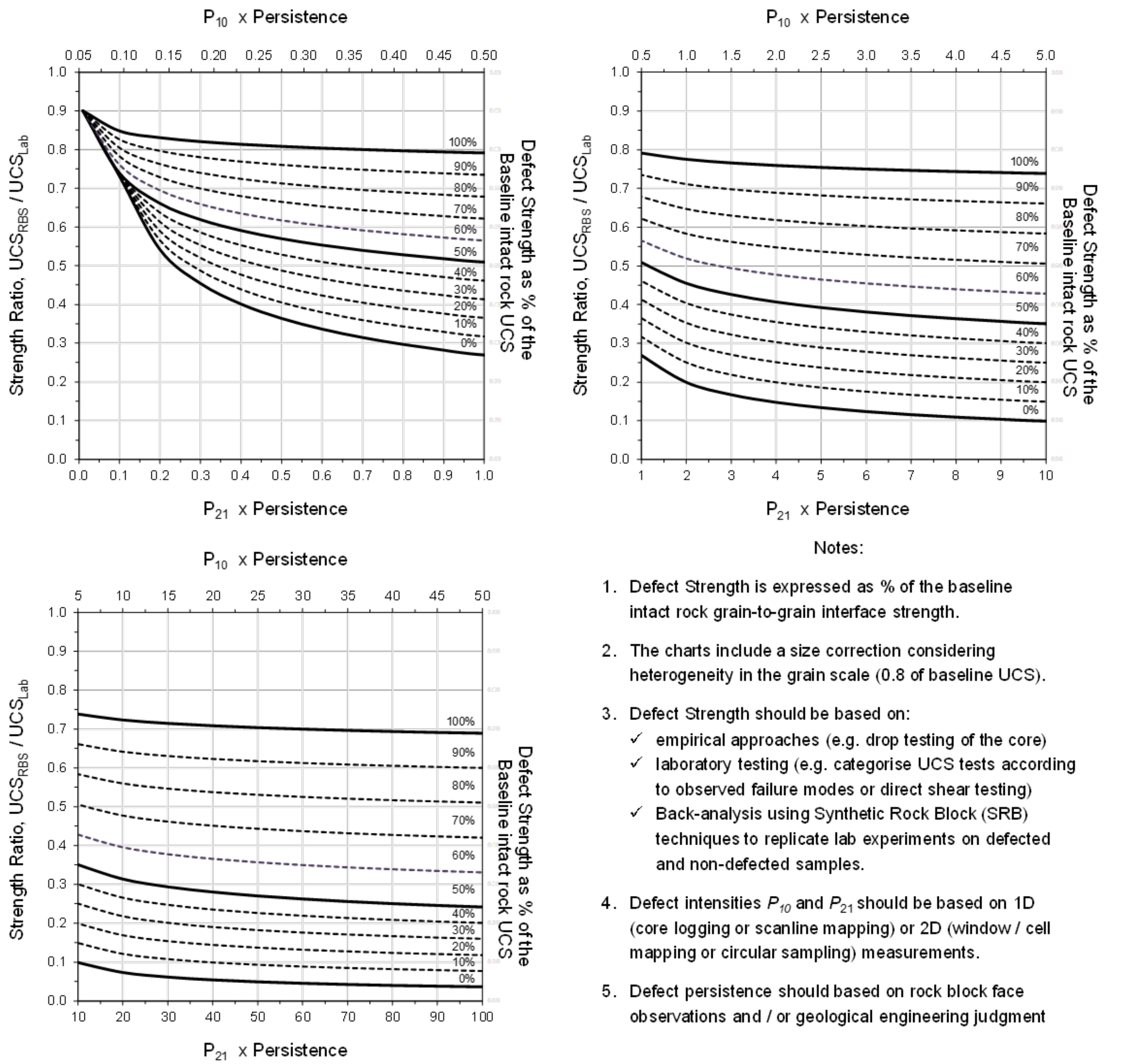

Figure 5. Proposed diagrams for estimating the Rock Block Strength (RBS) as a function of defect intensity, persistence, and strength.

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