

Simulations on the sensitivity of rock structure models to field mapped parameters

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Abstract

The measurement of discontinuity structures in the field is subject to well documented statistical biases and practical limitations. As a result, a significant level of professional judgement is required by the practitioner when determining which parameters require the most attention during the measurement process. The following paper describes the use of a polyhedral modelling algorithm to simulate rock mass structure under various assumptions regarding discontinuity parameters (e.g. trace lengths, spacings). Such simulations may assist in determining the relative importance of the parameters being measured and this is discussed.

INTRODUCTION

The modelling of rock mass structure using computer based synthetic models is now standard practise in civil and mining engineering. Such techniques combined with field mapping of observable defects or discontinuities can provide better understanding of the rock mass geometry and, as a consequence, rock mass behaviour and stability. As with all modelling, the quality of the analysis is highly dependent on the integrity of the input data. However, the complex nature of rock masses and the finite resources available to the practitioner necessitates some form of data simplification and/or approximation prior to and during model construction. Typical examples of such simplification include:

- Idealised representations of the exposed rock surface
- Enforcement of a limited simulation volume for the model
- Limiting the number of modelled defects to a number less than that known (or predicted to exist) in the field
- Assumed homogeneity in rock properties within a geological domain/s and/or limiting the number of domains

Formal assessment of the impacts of each of these approximations is desirable and guidelines have been established as to how to approach such a study ([1],[2]). Nonetheless, it is often desirable to have some intuition or 'rule of thumb' to use when making assessments regarding which parameters require the most accurate representation in order to create a model which is an acceptable approximation to reality. This paper aims to address this for at least some of the approximations enforced during the modelling process.

The mapping of defects or discontinuities in the rock mass (such as joints or fractures, bedding planes, faults etc.) can be performed in a number of ways although all the methods introduce a sampling bias and data must be corrected using sampling statistics. A finite number of discontinuities are mapped either along a line vector or an area, and statistics are used to infer the true 'parent' population of joints responsible for those observed. Of course, certain assumptions are being made in this process, including:

- The parent population is adequately represented by the sample.
- The biases associated with the mapping/measurement process (i.e. orientation, size, truncation and censoring) can be adequately dealt with.

In this paper, we assume in this paper that both these assumptions have been addressed and verified by the practitioner and the decision to use the mapped data has been made.

The mapped discontinuity parameters of interest in this paper are:

- Discontinuity set trace length
- Discontinuity set spacing
- Discontinuity set parameter distributions

We will use polyhedral modelling software to construct rock mass structure models based on discontinuity data defined using these

parameters. The model will allow us to interrogate various rock mass structure quantities such as block size distribution, block morphology and block fragmentation, In doing so, an assessment of the sensitivity of the model to the aforementioned field mapped parameters will be established.

This paper is divided into the following sections. 'Related Work' outlines previous work and 'Methodology' discusses the process used to investigate the sensitivity of the block model to these parameters. 'Results' outlines the simulations that have been performed and 'Discussion' looks at implications of these simulations.

RELATED WORK

The study of the relationships between mapped discontinuity properties and the rock mass block geometry has been of interest for many years. For example, Hudson and Priest [3] studied the relationship between block dimensions and block volumes to the spacing of discontinuities in a given set. This was done under the assumption of persistent joints by analysing the probabilities of intersections of 3 orthogonal discontinuity sets with uniformly distributed spacings (the exponentially distributed case being intractable). Hudson and Priest also asserted that their results (at least for 2-dimensional block sections) were not sensitive to the assumption of set orthogonality.

Sensitivity analyses relating mapped parameters to key-block frequency have been performed by several parties ([4], [5], [6]). The most recent of these by Jimenez-Rodriguez and Sitar [6] found that volumetric intensity and joint radii were critical parameters.

The common limitations of the work described above ([4], [5] and [6]) have been the restriction of the analyses to the formation of wedge structures occurring at the free surface of the model. One may argue that since the primary goal of these studies was the determination of key-block frequency and that therefore the free-surface is the predominant region of interest. However, predictions of the effects of input parameters on the entire simulation volume are important in order to assess the model's ability to represent more complex failure mechanisms (i.e. not limited to simple plane and wedge failures) and indeed its suitability for more complex (i.e. numerical) stability analyses. The ability to perform such analyses has, of course, been dependent on the availability of polyhedral modelling tools capable of modelling the formation of rock blocks internal to the rock mass and, therefore, away from the free surface.

Indeed, Kim et al. [7] recently utilised a polyhedral modelling methodology to study the effect of including finite-persistence in the rock block model constructed from orthogonal joint sets. They limited their analysis to using 3 sets of 10 joints being equally spaced or quasi-equally spaced. They concluded that the effect of finite persistence could be adequately represented by an empirical equation derived by Cai et al. [8] that represents the 'equivalent block size' based on a modification of the non-persistent case. Note, however, that due to limitations in the polyhedral modeller used, their case study assumed that one of the three joint sets was infinitely persistent and that finite persistence of the other two could only be modelled in a statistical sense as opposed to a finite extent in 3-dimensional space. This latter point has several implications, including the inability of their modeller to represent concave polyhedra. This issue will later be discussed in more detail.

Some work was reported by Elmouttie et al. [9] regarding the sensitivity of models to non-orthogonal joint sets for one particular (uniform) spacing model. The analysis utilised a polyhedral modeller capable of detecting rock blocks defined by randomly distributed joints. This modeller is not limited in terms of the complexity or morphology of the blocks defined by the interacting joints and therefore is able to detect both convex and concave polyhedra. This modeller provides a more accurate algorithm for the analysis of block formation in a simulated environment than previous methods. However, the analysis performed in [9] was limited to two extreme cases of persistence – a finite case and an infinite case. The authors concluded that not only did the fragmentation decrease (as expected) with a decrease in persistence but the variability in fragmentation noticeably increased. This is significant as it points to the difficulties in using a single representative block parameter (i.e. mean volume/ spacing/ persistence) to represent the rock mass fragmentation. The work reported below builds on this previous work. It represents an initial attempt to quantify a sensitivity analysis utilising a true polyhedral modeller.

METHODOLOGY

As noted in Kim et al. [7], a sensitivity study of this nature can quickly become intractable if one considers all the potential parameters. We have therefore taken the approach of focussing the analysis on the most commonly assumed parameters for modelling joint interactions and discrete fracture networks (DFN). We have used the Baecher Model [10] as the basis for our DFN generation with the following assumptions:

- Joint spacings are distributed uniformly, negative exponentially or banded.
- Joints are assumed to be circular or elliptical if deformation history is available. For our simulation, squares have been used as approximations to circles to reduced computation time.
- Joint centroids are generated according to a Poisson process, where the centroids are generated independently according to a predicted density within a known volume.
- Joint radii are distributed log-normally, although negative-exponential distributions are also used.

Note that the model assumptions derived above are expressed in terms of the joints themselves as opposed to the mapped traces associated with the sampled population. The issue of how to transform the observed field data to ‘true’ (i.e. bias free) values and then to DFN parameters is a well researched one. For example, to transform the observed mean trace length into a mean joint radius (assuming circular joints), stereological methods can be employed [11] and the relationships of moments of parameters derived [12]. Such methods are useful if the distribution of the DFN parameter (in this case, radius) can be known a priori or assumed to be that of the observed traces, an assumption which is rarely correct [15].

Ideally, a numerical solution to relate the observed trace parameter distribution to the DFN parameter distribution should be utilised ([15],[13]) or at least some verification that the chosen distribution is stereologically consistent with the input distribution should be employed [14]. We have adopted the approach of presenting the sensitivity analysis in terms of the DFN parameters themselves thus circumventing the problem of addressing the multiple transformation methods currently utilised. Note that the practitioner need only know the assumed relationship that they are using to transform from the mapped parameters to the true ones to decide how to modify the results presented herein.

Therefore, this study will assess the sensitivity of the block model to the following parameters:

- Joint radii (derived from observed traces)
- Joint spacings (derived from observed spacings)
- Joint spacing distributions (derived from observed spacing distributions)

Synthetic data has been used for this analysis. In each case, a series of DFNs were constructed to cover the range in the parameter being investigated. For example, for the analysis of joint radius (persistence) sensitivity, multiple DFNs representing the infinite persistence case were generated and then each of these was modified to represent the same realisation but with different joint radii. For each DFN, a polyhedral (block) model was constructed.

The algorithm used for the model construction is a polyhedral modeller developed by the CSIRO ([16],[17]) and full description of the algorithm is outlined in [18]. The algorithm forms a key component of the SIROMODEL structural modelling software developed as part of the Large Open Pit Slope Stability Project [19]. For this study, the algorithm has been used to construct rock block models based on the aforementioned DFNs. These models have then been interrogated to assess the sensitivity of the derived block geometries to the parameter being investigated.

RESULTS

The DFN used for these models were constructed using 3 orthogonal joint sets. In each case, the radial distribution was assumed to be log-normal but the spacing model was either negative exponential, uniform or banded. The latter model refers to an enforced spacing model such that joints were confined to a series of bands separated by the specified mean spacing value, the widths of the bands being limited to 10% of the band separation. DFN were generated inside a simulation volume which was either cubical or quasi-cubical depending on the experiment being performed. An example of a DFN and subsequent block model is shown in Figure 1. An example of the traces associated with a single set of joints is shown in Figure 2.

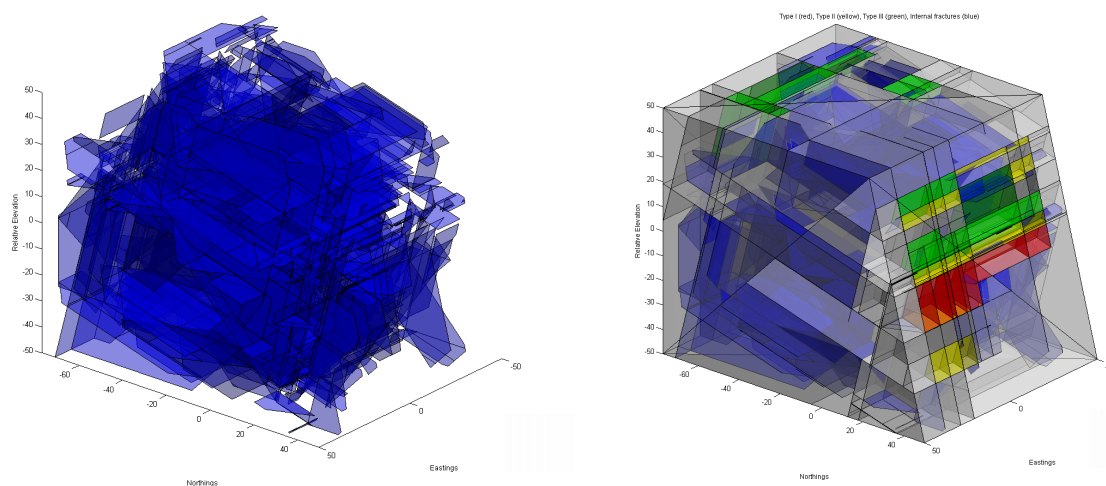


Figure 1 - An example of a DFN used for the simulations (left) and the resulting block model (right)

The model sensitivity to various inputs was assessed in terms of several metrics. These include

- Number of blocks in the model
- Block volume descriptors
- Mean Block sphericity

The last of these is defined as the ratio of the surface area of a sphere with the same volume as the block to the surface area of the block ([20]).

These descriptors have been chosen as a way of assessing the morphology and fragmentation of the rock mass.

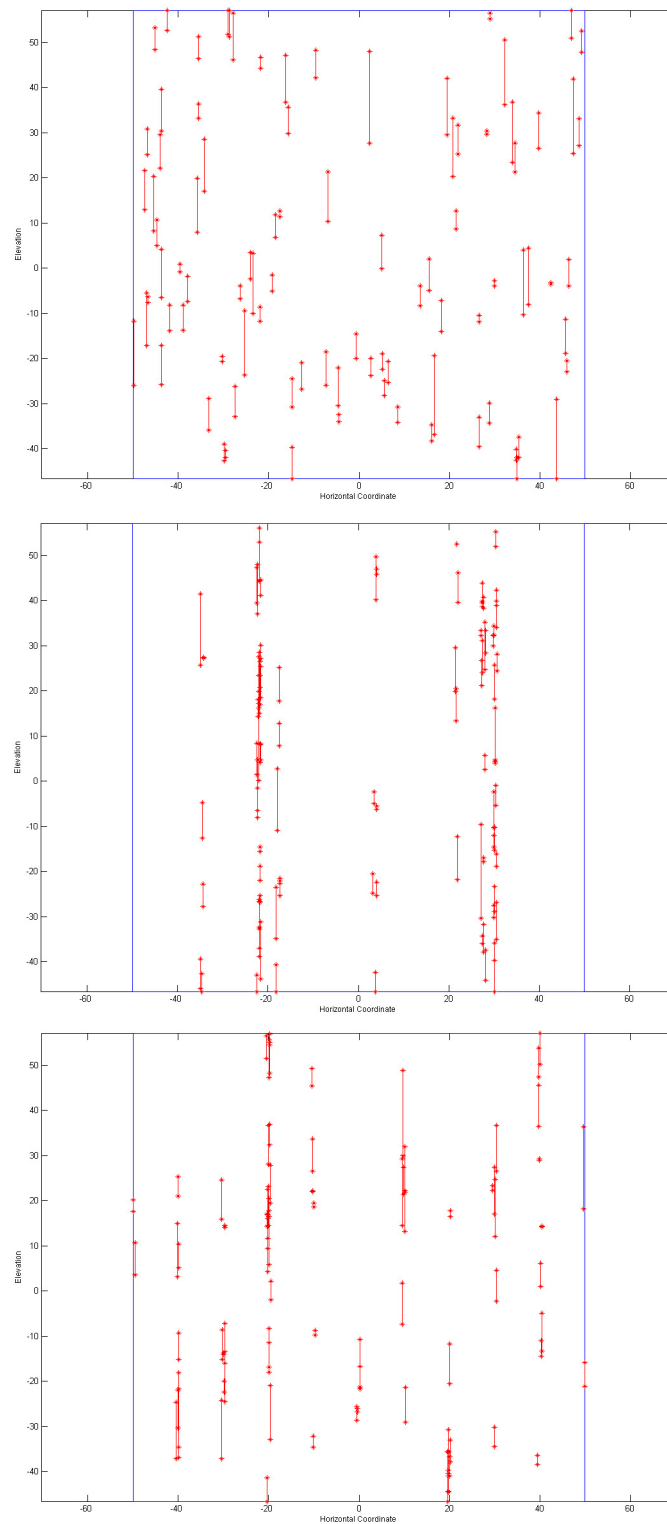


Figure 2 - Examples of generated traces for each spacing model – uniform (top), negative exponential (middle) and banded (bottom)

Joint Persistence

We first address the scenario described by Kim et al. [7]. Each trial was based on an initial DFN containing 3 orthogonal sets of quasi-equally spaced, infinitely persistent joints (9 per set). The simulation volume was a cube with a width of 10m, resulting in a simulation volume of 1000m³ and a mean block volume for the persistent case of 1m³. The DFNs were modified repeatedly so as to reduce the radii of the joints associated with only two of the sets (and hence the persistence of the structures), with the third set remaining persistent. Note that the persistence of this third set guarantees that at least 10 blocks (each being a 'slab' with volume 10% of the simulation cube) will form upon every DFN realisation.

The mean size of the joints in the DFN has been expressed as a persistence factor. This persistence factor for a given set has been calculated as the ratio of the mean joint area to the area of the plane containing this joint truncated to the simulation volume [21]. Thus infinitely persistent here is equivalent to a persistence factor of 1. The overall persistence factor for the three sets combined is determined as $pf = (p_1 p_2 p_3)^{1/3}$ where p_i is the persistence factor of the i 'th set. For the scenario described by Kim et al. [7], $p_3 = 1$.

The results obtained are shown in Figure 3. The vertical axis represents the ratio of the mean block volume for the finite persistence case to that for the persistent case. As such, smaller values imply more fragmented rock. As the persistence factor approaches 1, the DFN associated with the finite persistence case more closely approximates the persistent case and the mean volume ratio approaches 1. Note that the error bars in this (and subsequent) figures represent the standard deviation of the sample means of the parameter and the data-point represents the mean of the sample means. This representation has been adopted since analysing the variance of the means of a set of samples (in this case, each corresponding to a separate DFN) alleviates the need to know a priori the statistical distribution of the underlying parameter via the central limit theorem (e.g. [2]).

The results in Figure 3 are consistent with the hyperbolic relationship between block volume ratio and persistence factor seen by Kim et al. [7] and predicted by Cai et al. [8], however the volume ratios are markedly different. As described earlier, their method for modelling persistence was based on a statistical approach whereby a given joint has a certain probability of intersecting blocks within its plane. Further, their representation of a 'joint' was limited to a rectangle with finite persistence in one dimension but fully persistent in the other, labelled semi-persistent hereafter. For example, a joint with 10% persistence factor could extend fully across the width of the volume (cube) but only 10% along the depth dimension.

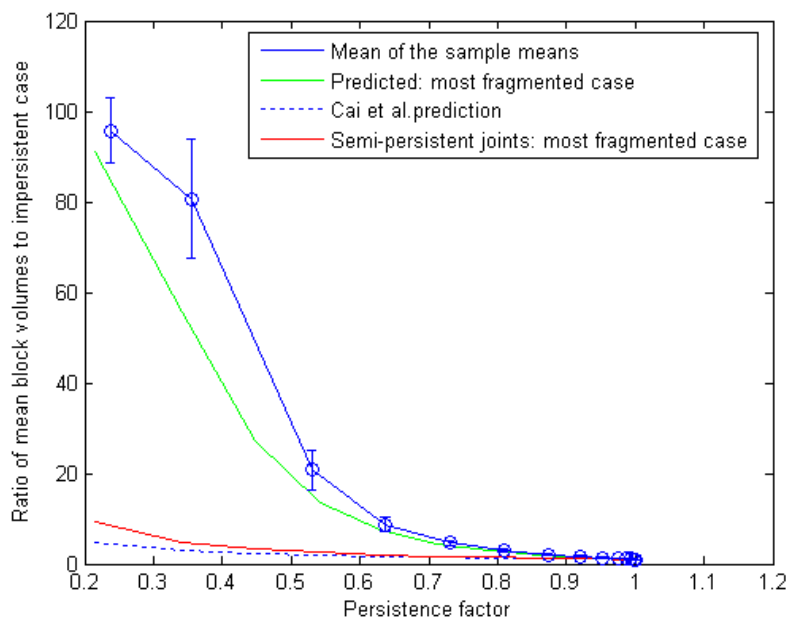


Figure 3 - Model sensitivity assessed similarly to Kim et al. [7]: solid blue curve represents our simulations, solid green a prediction assuming rectangular joints showing maximal intersections, dashed blue is the prediction by Cai et al. [8], and solid red is our prediction of the maximally intersecting case using semi-persistent joints.

Our approach is a geometrical one based on the creation of a DFN, whereby persistence is a deterministic property describing the spatial extent of the structures within the simulation volume. Joints are represented as polygonal approximations (squares in our case) to circles. Therefore the 'radius' of the joint, and hence the area, determines the persistence factor. These differences manifest themselves in [7] as multiple structures per joint plane being created, each structure fully intersecting the block that it encounters and also fully extending along the width (or depth) of the simulation volume. This has two consequences - an increase in the likelihood of block formation, particularly in the simulations of low persistence discontinuities, resulting in a more fragmented rock mass with lower mean block volume and secondly, the complete absence of concave rock blocks. Such blocks occur in nature due to the presence of partially through going joints or fractures. An example of a concave block detected in our simulations of the Kim et al. [7] scenario is presented in Figure 4.

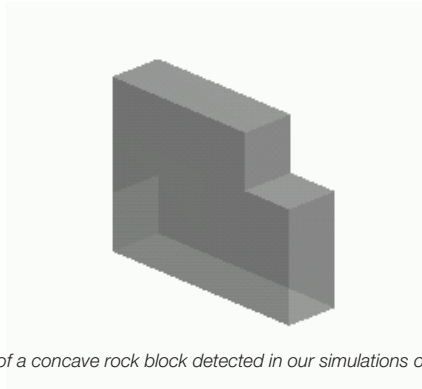


Figure 4 - An example of a concave rock block detected in our simulations of the Kim et al. [7] scenario

Figure 3 also shows the predicted curves for the most fragmented case for both our rectangular joint representation and the semi-persistent joint representation used by Kim et al. [7]. The most fragmented case corresponds to all discontinuities from the two impersistent sets originating in the same part of the simulation volume, thus increasing the number of joint intersections (and therefore block formation) to a maximum. Note that the results based on our simulations are consistent with those predicted. Of course, our DFN simulations have yielded models whose fragmentation is less than the most fragmented case, therefore the volume ratios will be slightly greater than those predicted. As noted earlier, the modelling of persistence as the area of the joints means that for small persistence values, the chances of block formation are heavily reduced. For the scenario where only a few or no blocks form (additional to the 10 slabs that form upon each realisation), the expected ratio of mean block volume compared to the persistent case would be 100:1 (i.e. 10 equal volume rectangular 'slabs' versus the 1000 cubes detected in the persistent case). Indeed, our simulations show this ratio to be observed for persistence factors around 0.2 or less.

Interestingly, the predicted curve for the most fragmented case using semi-persistent joints also disagrees with the Cai et al. [8] prediction. This is especially true for low persistence factors where the block volumes predicted differ by a factor of two. Let us consider the smallest persistence factor case for a moment.

The smallest persistence factor modelled by Kim et al. corresponded to the two impersistent sets each having values of 0.1, and therefore the combined factor being $p_f = (p_1 p_2 p_3)^{1/3} = (0.1 \times 0.1 \times 1)^{1/3} = 0.22$. It is therefore surprising that the Figure 19 of Kim et al. [7]. shows data at persistence factors of 0.1. It is possible that they have used an alternate definition of persistence factor for this analysis, however this is not mentioned in their text.

Further, the Cai et al. [8] prediction itself also needs some investigation. For the most fragmented case involving two sets with persistence factors of 0.1, all joints from the two would reside in one of the ten 'slabs', yielding 100 blocks in this slab and leaving the other 9 slabs intact, with a total of 109 blocks forming. The expected mean block volume ratio would therefore be $(9 \times 100\text{m}^3 + 100 \times 1\text{m}^3)/109 = 9.2$ (see red curve in Figure 3), a ratio predicted by Cai et al. at $p_f = 0.1$, not 0.2.

In summary, our simulations indicate that the modelling of persistence in a true geometric sense is critical for deriving more accurate estimates of rock mass fragmentation and rock block morphology. Although the use of polyhedral modellers capable of partial representation of persistence is certainly to be welcomed over analyses assuming persistent joints, the results can still be misleading.

The rest of the paper focuses on simulations we have performed using more densely populated data (30 structures per set) assuming all 3 sets are finitely persistent. As before, the analysis begins with a series of DFNs representing the persistent case and then each iteration consists of gradually reducing the persistence of the structures in these DFNs and noting the effects on the model. The sensitivity analysis is shown in various ways in Figure 5. Note that for completeness, DFNs associated with all three spacing models tested in the paper were included in this analysis.

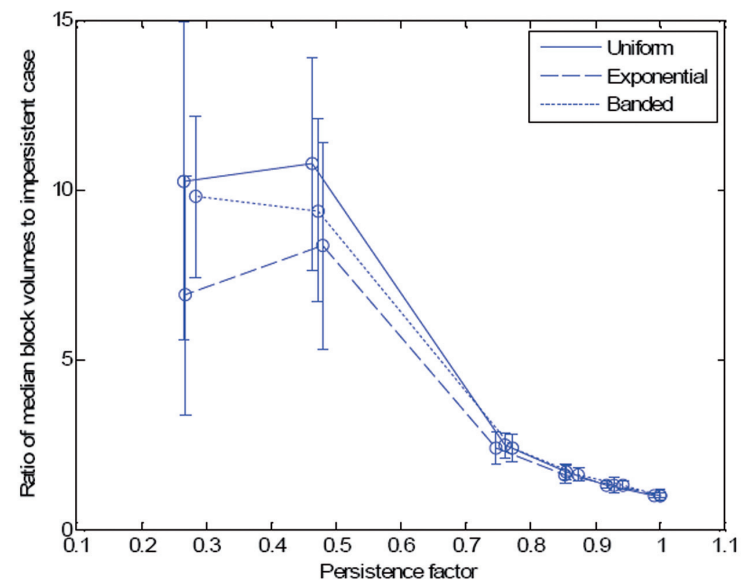
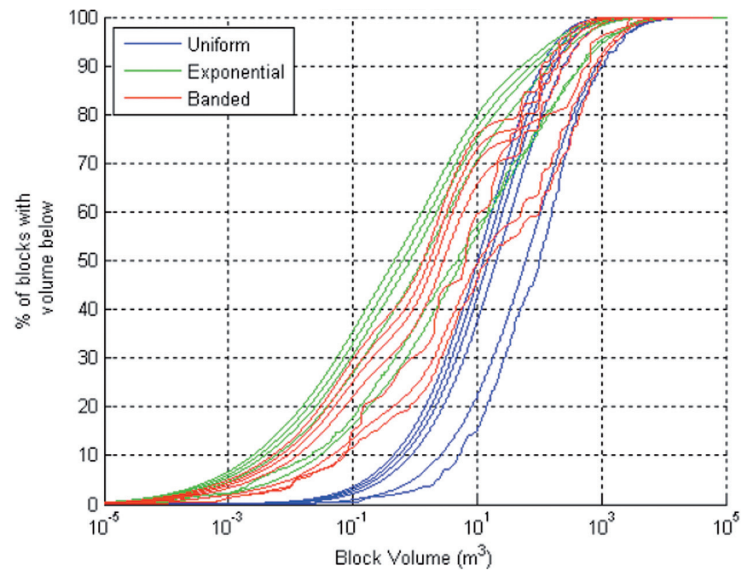
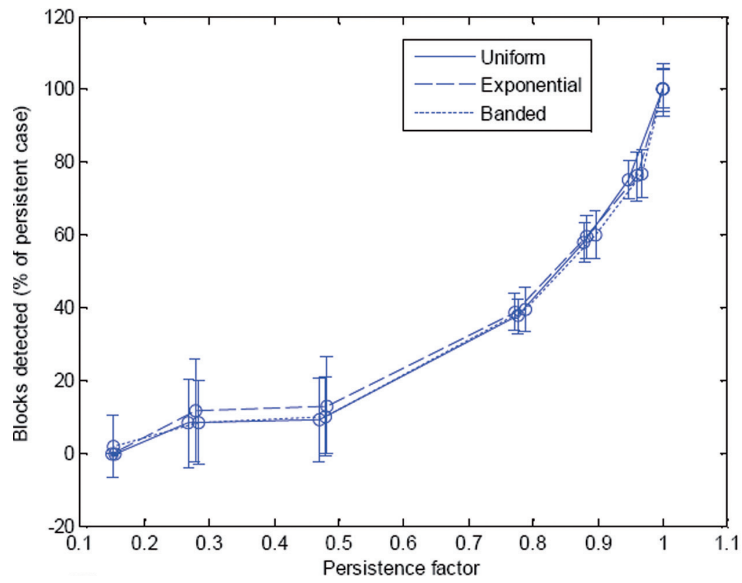
Due to the interactivity of joints in 3 dimensions, the metrics change rapidly with persistence indicating the importance of scaling the DFN structures correctly. The number of blocks detected increases an order of magnitude for a doubling in the persistence factor.

The migration of block size distributions associated with the DFN evolving from persistent to finite persistence are represented by the transition of the curves from left (low volumes) to right (higher volumes). The migration causes at least an order of magnitude change in the estimated magnitude of 50th percentile block volumes.

The mean block volume decreases equally rapidly as persistence factor increases however this trend does not apply to the lower persistence factors. This is due to the finite numbers of joints used in this analysis. For small persistence factors, the numbers of blocks formed decrease rapidly until the majority of the rock mass is un-fragmented with only a small number of blocks forming. Hence these turn-over points represent the models transition from what can be broadly classified as fragmented to un-fragmented rock mass.

The sphericity of the blocks shows a similar trend with the mean block morphology becoming less spherical as the constrained nature of the persistent geometry becomes dominant. For finitely persistent geometries, the 'natural' variation on the generated block morphologies (see Figure 6 for an example of a concave block) averages out to a more spherical result although variance increases. Note that once

again, due to the finite number of discontinuities used, a turnover point is reached where the majority of the rock mass becomes unfragmented and the statistical significance reduces.



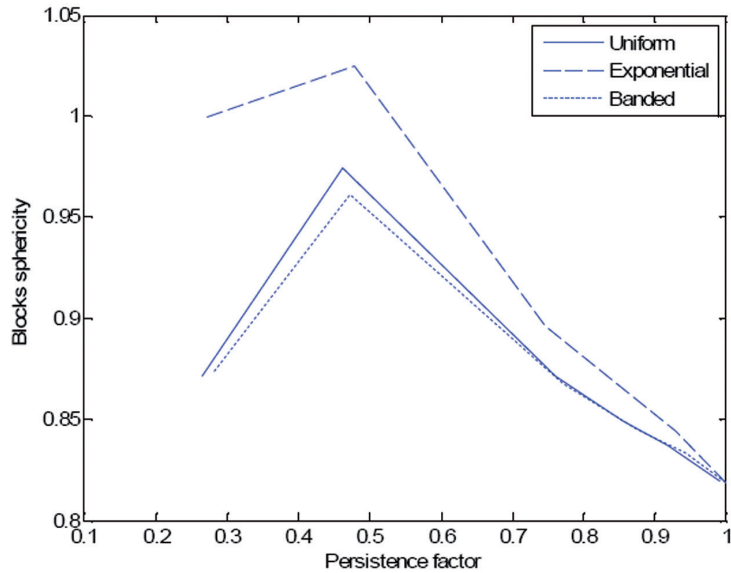


Figure 5 - Model sensitivity to variation in joint radii as measured by several metrics: number of blocks detected, block size distribution migration, block volume ratios, and sphericity.

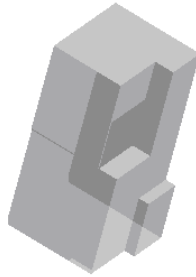


Figure 6 - An example of a concave block detected in simulations

The graph of blocks detected (as a ratio of the persistent case) versus persistence factor in Figure 5 warrants further discussion. Accurate estimation of trace lengths in the field is quite often limited by the size of the sampling window used by the practitioner although the consequences of under-estimation are clear. The fragmentation of the rock mass will be grossly under-estimated. The non-linear nature of the relationship evident in Figure 5 implies that errors made in trace length estimation when the structures being observed are small (much smaller than persistent) are less significant to the blocks detected ratio. This is shown in Figure 7 which shows mean of the data in Figure 5 but also includes two curves representing the effect of a 10% error in persistence factor (essentially the original curve offset to either side). For example, at persistence factors of 0.9, the effect of a 10% error on the upper and lower bound estimates of the ratio would be 40 – 100%!

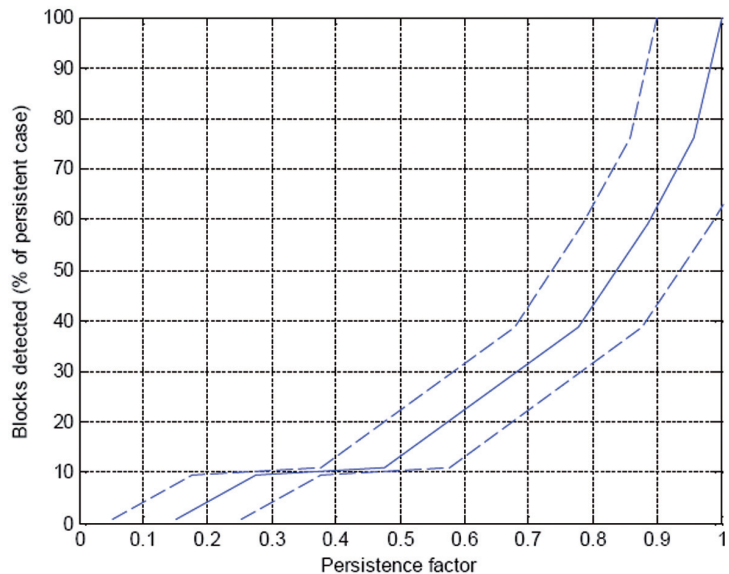


Figure 7 - Sensitivity of the model fragmentation to a 10% error in persistence factor – dashed lines indicate upper and lower bounds

Joint Spacings

A similar simulation to that described for the persistence analysis was performed by taking persistent DFNs corresponding to small spacings and gradually increasing the spacings at each iteration. This simulation was conducted for all three spacing models. The results are shown in Figure 8.

The variation in spacing has been defined as a 'spacing factor' which represents the multiple applied to the spacings of the original DFN. To relate this analysis to the previously discussed analysis using joint persistence, it is noted that the original spacing used was 5m or 5% of the spatial extent of the simulation volume (c.f. persistence factor of 0.05). Spacings were increased to a maximum of 18m (c.f. persistence factor of 0.2). No data was generated for spacing factors larger than these as the numbers of blocks generated reduced quickly making any results statistically insignificant. Thus there are two things for the reader to consider – namely the change in the spacing factor itself (which can be equated to a percentage error from the original 'true' value), and the spatial equivalence of this value to the persistence factor previously discussed.

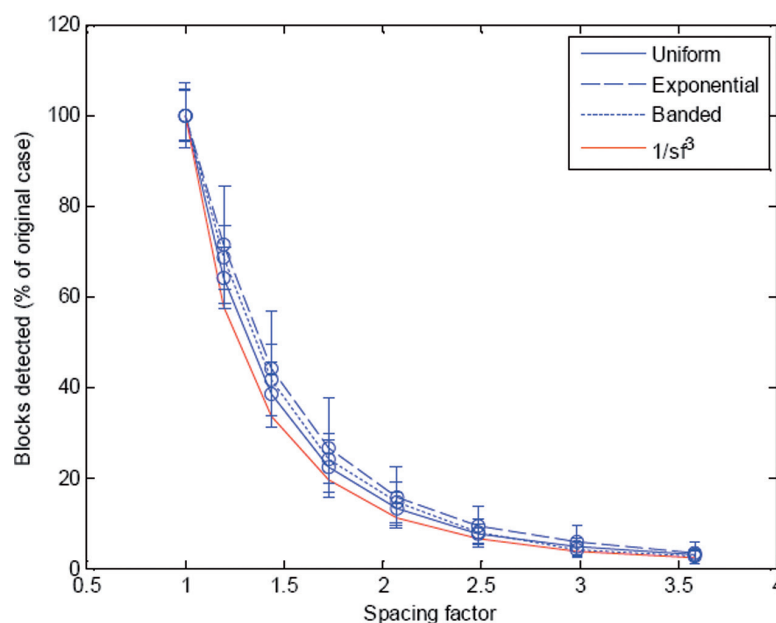
To model this increase, a spatial transformation was applied to the joint centroids of the original DFN increasing their spatial separation in the direction of the joint set normal vector. Of course, by not modifying the original DFN in any other way, we are reducing the numbers of structures present in the simulation volume at each iteration. This has the effect of reducing the volumetric frequency of structures and therefore the number of blocks detected will of course reduce.

For regularly spaced persistent structures, it can easily be shown that a doubling in the spacing reduces the density of blocks by a factor of 8, a sensitivity roughly equivalent in magnitude (but opposite in sense) to that observed for the joint radius variation analysis. As expected, this reduction is also confirmed for irregularly distributed joints (Figure 8). Any deviations from the predicted curve are due to the interaction of the geometry of the simulation volume and the gradually expanding DFNs such that at any given iteration more or less structures will be excluded from the analysis but on average, the number will remain constant.

The migration of the block size distributions associated with the increase in spacing factor is from left (low volumes) to right (higher volumes). Once again, at least an order of magnitude variation in the 50th percentile value (two orders for the exponential and banded models) as a function of the spacing factor is evident however this is now associated with a factor of 3.5 increase in spacing. Note the presence of the 'waves' in the block size distribution curves for the banded model in Figure 8. This is due to the interaction (equivalent to beating in signal processing) of the two distinct spatial frequencies associated with the spacings in this model – coarse spacings associated with the separation of the structure bands and fine spacings associated with the structures within each band.

The block volume chart shows an expected increase in volumes with spacing factor which follows an approximately cubic dependency. The dependency deviates from the cubic relationship due to the methodology of these simulations. The act of increasing the spacings associated with these models results in the presence of large joint spacings within the confined simulation volume reducing more rapidly (in a relative sense) to smaller spaced joints. This result was predictable given the previous discussion on the migration of the block size distribution curves.

The sphericity chart has been presented with the same axis limits as that shown for the persistence simulations. Clearly the variation in sphericity is much less as the act of spacing modification should not (on average) modify the block morphologies.



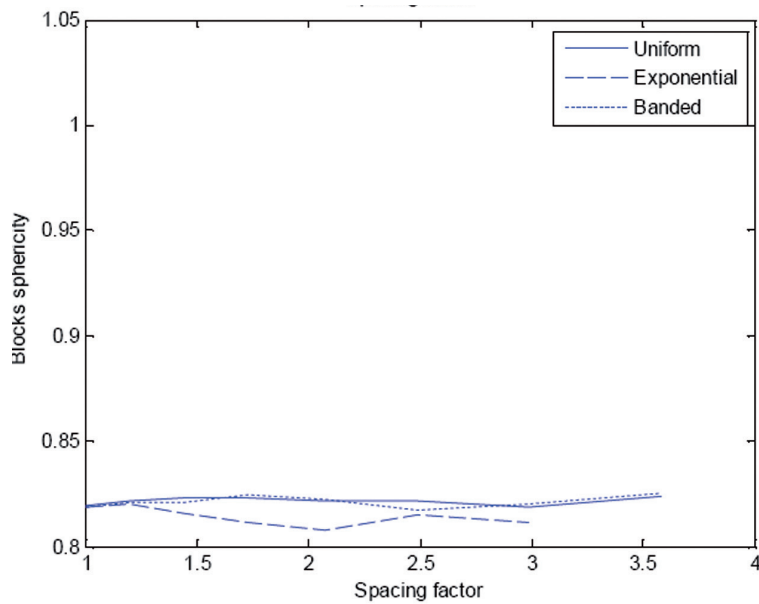
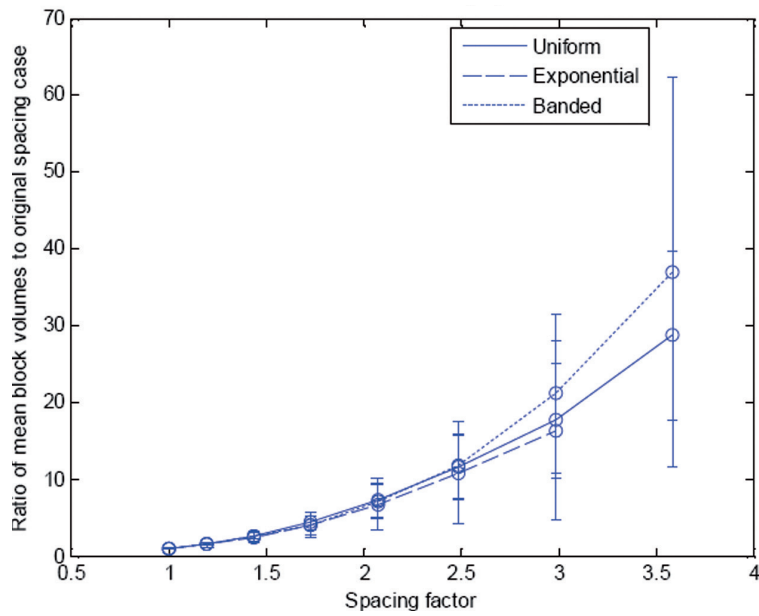
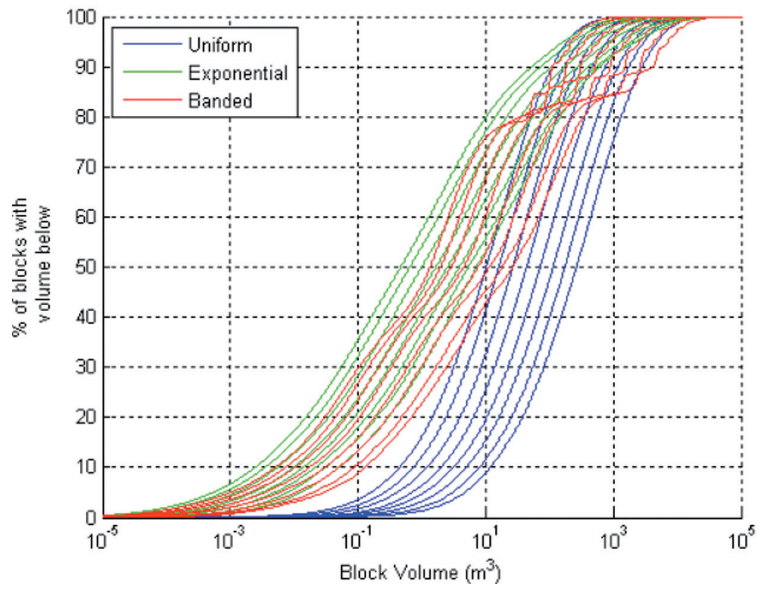


Figure 8 - Model sensitivity to variation in spacing: number of blocks detected, block size distribution migration, block volume ratios, and sphericity (shown with the same axis limits as the persistence case).

CONCLUSIONS

Discussion of sensitivities

The analysis presented above has shown the benefits of using polygonal representation of joints for the analysis of block formation. In particular, the inaccuracies associated with utilising joint representations that do not model persistence in a geometrical sense have been highlighted.

This analysis has been framed in terms of three of the main input parameters required for the modelling of rock mass geometry, namely mean joint persistence, mean joint spacing and spacing distribution function. Block model sensitivity to these parameters has been shown to be high, although some conclusions can be made on their relative importance.

The spacing distribution function (and the trace length distribution for that matter) is by far the most difficult to deal with in practise. The typically small numbers of structures mapped in a given cell or window mean fitting a test distribution to the data seldom results in high 'goodness of fit' measures. The results presented above show that the use of spacing models with implied in-homogeneity (in this case, exponential and banded models) have the potential to make a rock block model more sensitive to uncertainty in input parameters than the uniformly distributed spacing model, particularly when determining block size distribution. For this reason, it is advised that unless the practitioner can be confident in the use of such a model the uniform spacing model is preferable.

On the issue of block size distributions, an interesting 'artefact' of the simulations is the presence of 'structure' in the block size distribution curves associated with the banded spacing model. As stated earlier, this is explained in terms of the interference between the two spatial scales of the spacings associated with this model – finely spaced joints within a band, and coarsely spaced joints separated on average by the stated spacing value. Undoubtedly, such an effect will always be more evident in numerical simulations however it does raise a tantalising possibility. On those occasions where block size distribution of the rock-mass is available a priori (e.g. through sieve analysis), then perhaps the analysis of the shape of the observed block size distribution curve can aid in the choice of a spacing distribution model.

By varying the size of joint radii in a given DFN whilst keeping all other parameters unchanged, we are in effect simulating uncertainty in the initial trace length estimate made during the field mapping procedure. Similarly, altering the spacing of the structures in a given DFN whilst keeping other parameters fixed mimics the uncertainty in that parameter. The data in Figure 7 would imply that accurate determination of persistence is paramount in terms of ensuring that the fragmentation of the rock-mass is understood. However, interpretation of the analysis rests on the likelihood of certain levels of uncertainty being encountered when transforming an observed mean trace length or spacing to a mean radius or 3-dimensional joint spacing.

As stated earlier, the transform from true trace length to joint radius is not a trivial one and is a function of the mapping technique used. Table 1 gives some guidance regarding the relationships for common field mapping procedures ([12]).

Radial Distribution	Areal Sampling	Line sampling
Lognormal radii	$R = \phi x L^3$	$R = \psi x L^5$
Exponential radii	$R = \alpha x L$	$R = \beta x L$

Table 1 - Relationship between observed mean trace length (L) to the mean joint radius (R) for several field mapping procedures. The Greek letters ϕ and ψ represent functions of the variance of the trace lengths while α and β represent constants

For the case of areal scanning, the mean radius of the joints varies as the cube of the observed mean trace length assuming the radii are distributed log-normally. This relationship is much more forgiving in the case of exponentially distributed radii which are dominated by small radii. If one adopts a lognormal radial model for areal mapped joints, the relative error in the mean radii varies with 3 times the relative error in the mean trace lengths ignoring second order effects.

Merits of methodology

The question of how applicable these DFN based simulations are to the real world can also be addressed. The modelling undertaken in this analysis has benefitted from the following simplifications:

- 'Recycling' of the original DFN
- Representation of joints as squares
- Usage of a small number of joints per set
- Use of orthogonally oriented joints

The validity of using particular DFN realisations and modifying these to study issues of persistence and spacing has been assessed. The method relies on the ability of the original DFNs to capture the salient model behaviour sufficiently accurately. To this end, multiple

DFNs were generated for each particular scenario being investigated. For example, the data representing the average block sphericity for uniformly spaced joints with a persistence factor of 0.5 is based on twenty DFNs. Formal assessment of the use of a particular number of realisations requires one to quantify the desired precision of the numerical simulation being undertaken ([1]). As this enforces too restrictive a requirement for the qualitative discussion presented herein, an informal assessment can be made by examining the results presented in the previous sections. The 'smoothness' of the trends shown in Figure 5 and Figure 8 relative to the displayed error bars give confidence that sufficient realisations have been generated to remove any significant statistical noise in the data. The trends appear sufficiently well defined to allow for interpretation of relative quantities (e.g. comparison of average block volumes at different spacing factors).

The use of particular polygonal representations of circles or ellipses in DFNs is the responsibility of the practitioner as it is a trade-off between model fidelity (i.e. with respect to naturally forming structures) and computational complexity. As discussed previously, joint representation can have a dramatic impact on the derived block models but the true significance will be dependent upon the type of analysis performed (e.g. fragmentation versus block morphology). The significance of the use of square joints in this analysis has been assessed by generating a limited number of hexagonal representations of certain DFNs and comparing the derived models. Note that as the persistence factor increases, the significance of the polygonal representation diminishes until it completely irrelevant (i.e. infinitely persistent case). The results are presented in Figure 9 and show that the differences are insignificant, at least for the purposes of fragmentation analysis.

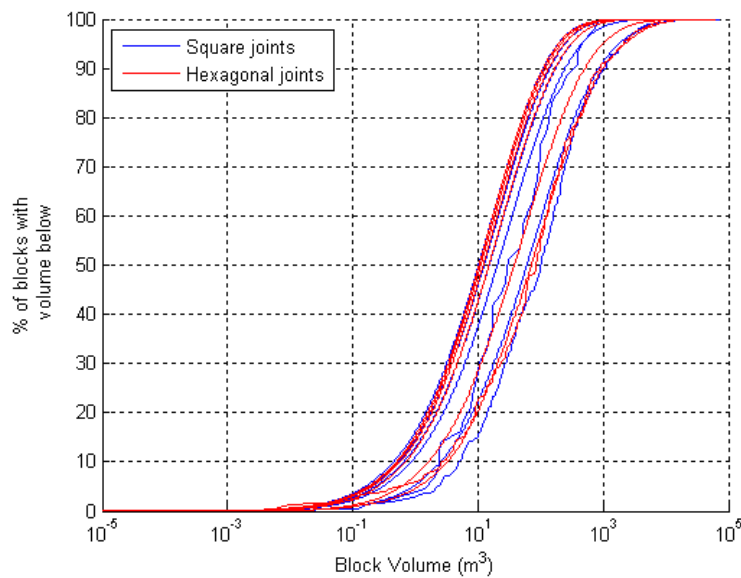


Figure 9 - Block size distribution curves for models utilising both square and hexagonal joints

Modelling of the infinite persistence scenarios is the primary reason for limiting the number of joints per set to small numbers (i.e. tens of joints). This results in a so-called volumetric frequency which is low. For three orthogonal sets, 100 joints per set would yield 1000000 polyhedra (excluding the bounding volume structures)! As this analysis has utilised the same DFNs generated for the infinite persistence case and reduced the structure sizes iteratively to study the finite persistence scenarios, the number of structures initially used was limited to 30 per set and kept constant. In this way, and by looking at relative measures of model metrics, we sought to remove the issue of volumetric frequency from our analysis. Nonetheless, to determine the significance of such small sample sizes, some simulations were performed utilising larger joint numbers (around 3000 per set or 10000 in total) with small persistence factors. An example of a DFN generated for this case is shown in Figure 10.

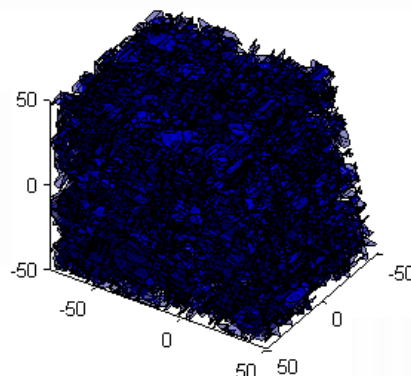


Figure 10 - A densely populated DFN comprising around 10000 joints

Clearly, modelling of the infinite persistence case was not tractable given that 1010 polyhedra would be generated although the finite persistence cases corresponding to very small persistence factors were studied. However, for the infinite persistence case, block volumes could be estimated based on the observed locations of the joint centroids and the orthogonality of the joint sets. The block size distribution curves are presented in Figure 11. These curves are placed well to the left (by about 3 orders of magnitude) of the corresponding curves seen in Figure 5 as ascertained by the 50th percentile value. This is due to the dramatically increased fragmentation associated with the increased volumetric frequency. Further, the separation of the curves (relative to the infinite persistence case) as measured by the 50th percentile value is now markedly larger than seen in the previous simulations. We conclude that as expected, the volumetric frequency of the joints significantly affects the amount of fragmentation observed.

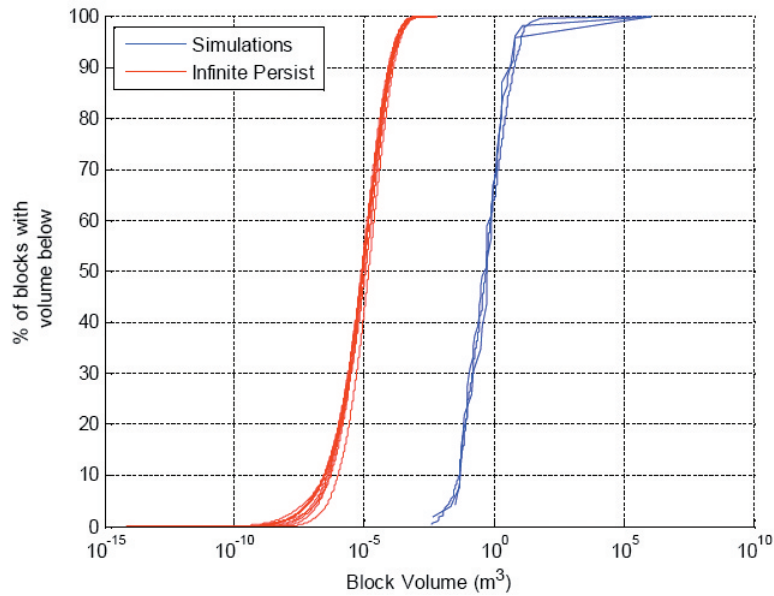


Figure 11 - Block size distribution curves for small persistence factor DFNs containing around 10000 joints. Also shown in red are estimates of the curve for the case of infinite persistence.

To assess the significance of the fourth simplification regarding joint orthogonality, a brief analysis utilising random perturbations on the orthogonal joint orientations has been performed (Figure 12).

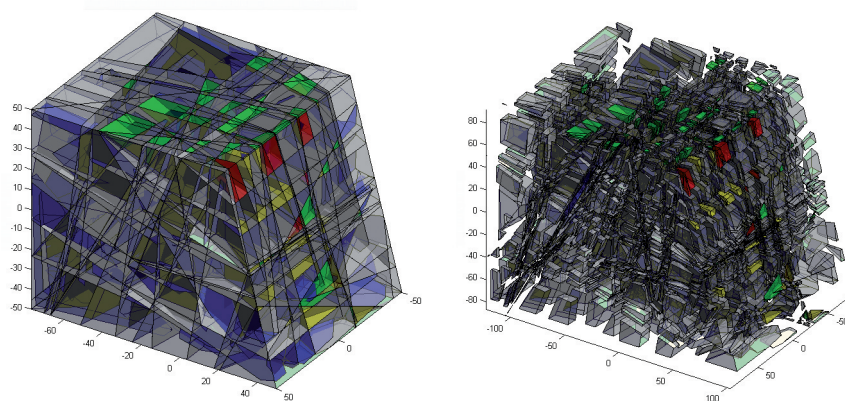


Figure 12 - An example of a block model derived using quasi-orthogonal joint sets - intact and exploded views.

Analysis has once again been limited to the uniform spacing model. The orientations of the orthogonal joints were allowed to vary assuming a standard deviation of 10 degrees, significant enough to allow large deviations from orthogonality to occur and also allow the possibility of joints within sets to intersect each other. These results are preliminary however indications are that the introduction of random orientations does not significantly alter the conclusions made above regarding fragmentation of the rock mass (Figure 13), although clearly the amount of fragmentation associated with these models is greater due to the increased numbers of joint intersections. This is in agreement with the observations by others for both the 2D ([3]) and 3D ([7]) cases.

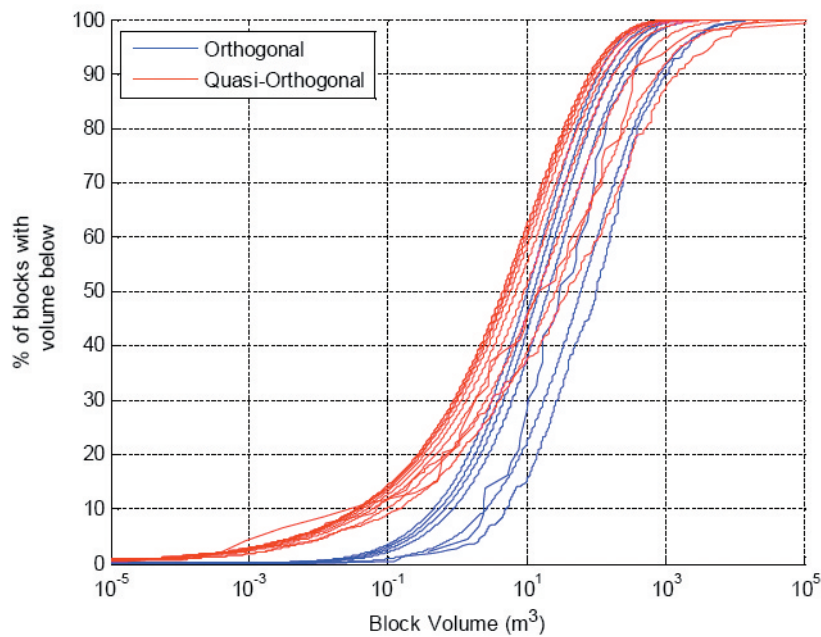


Figure 13 - Block size distribution curves for orthogonal and quasi-orthogonal joint orientations

Future work

The analysis presented herein represents an initial attempt at utilising a fully capable polyhedral modeller to quantify the sensitivities of rock mass geometry models to inputs derived from mapped field parameters. As such, future work should encompass the following:

- The use of field mapped trace parameter data (as opposed to simulated data) combined with measured block size distribution data to validate the concepts presented herein.
- More detailed investigations of the importance of the choice of joint representation
- The inclusion of more parameters such as volumetric frequency and structure orientation
- Testing of alternate distribution functions such as fractal centroid distribution models

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