Identifying uncertainty in estimates of bimrocks volumetric proportions from 2D measurements

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Abstract

Chaotic geological bodies composed of rock inclusions of different lithology and size enclosed in a weaker matrix are often referred to as bimrocks (block-in-matrix rocks). When dealing with these challenging and widespread geomaterials, a major concern for geopractitioners is the estimation of block content, which has been demonstrated to strongly affect the overall mechanical behaviour of bimrocks. Since the estimation of this parameter is not a simple matter, stereological principles are generally applied to infer 3D block contents from 1D or 2D measurements. However, they are often fraught with a high magnitude of error.

In this study, a statistical approach was developed to determine the uncertainties associated with estimates of the 3D block proportions from 2D measurements. A Matlab code was implemented to generate heterogeneous models with a size distribution typical of bimrocks. An uncertainty factor is provided related to the size of the outcrop area investigated and the 2D block content to adjust the initial 2D estimates. It was found that a larger investigation area increases the reliability of the 2D measurements and as actual volumetric block proportion increases, the uncertainty decreases.

The results obtained through this procedure were subsequently compared with previous findings from the literature concerning the uncertainty in estimates of the VBP from 1D measurements. The outcome of this comparison highlights the strength of the procedure described in this paper.

Keywords

Bimrocks, bimsoils, linear block proportion, areal block proportion, volumetric block proportion, uncertainty factor

1. Introduction

Block-in-matrix rocks (bimrocks) are defined as “a mixture of rocks, composed of geotechnically significant blocks within a bonded matrix of finer texture” (Medley 1994). In this definition, the expression “geotechnically significant blocks” indicates that a sufficient mechanical contrast between the blocks and the matrix exists to force failure surfaces to tortuously negotiate around the blocks (Medley 2001). In the last few decades, the term bimrock has been widely and conveniently used by geopractitioners all over the world to indicate many heterogeneous complex formations consisting of rock blocks incorporated within a weaker matrix. Typical geological bodies belonging to bimrocks are melanges, agglomerates, conglomerates, landslide debris and glacial tills (Lindquist 1994; Medley 1994; Sonmez et al. 2004).

The geotechnical significance of bimrocks has been highlighted by a variety of authors with different approaches. In fact, due to the erratic variability of the mechanical properties of these geomaterials, considerable difficulties may arise in their sampling, testing and characterization. As a consequence, a common engineering practice is to ignore the presence of rock blocks, choosing instead to plan engineering works in bimrocks considering the strength of the weakest component only (i.e., the matrix). However, this assumption (i.e. to neglect the presence of the blocks) has caused many technical problems and risks in the design and construction phases (Glawe and Upreti 2004; Medley 2007a, 2007b), due to improper and expensive engineering geological and geotechnical mischaracterizations. In fact, as widely documented in the literature, the overall mechanical behaviour of bimrocks is directly related to their volumetric block proportion (VBP), which means that blocks must be taken into account in the planning, designing and construction phases.

In light of the above, several empirical approaches have been developed and used to estimate the strength and deformability of bimrocks on the basis of their VBP (Lindquist 1994; Sonmez et al. 2004; Adam et al. 2014; Kalender et al. 2014, 2016). Therefore, in order for these approaches to be used, reliable estimates of 3D block contents are required.

The determination of the VBP is not straightforward, and stereological techniques are generally used to overcome this challenge. Specifically, VBPs can only be approximated by measuring linear (LBP) or areal (ABP) block proportions (from exploration core drilling and scanlines and geological maps or image analyses, respectively) and assuming these measurements to be stereologically equivalent to the actual 3D values. However, these assumptions are often fraught with a high magnitude of error and should not be used without due regard for the uncertainty (Medley 1997, 2001; Haneberg 2004).

The aim of this paper is to statistically investigate and assess the degree of error that can be introduced by inferring that the VBP of a bimrock obtained from 2D outcrop measurements (i.e. ABP) is actually the true VBP. In order to do this, a Matlab code was implemented to generate many bimrock models. From the analysis of these models, an uncertainty factor is provided to adjust the initial 2D estimate on the basis of both the

ABP measured and the size of the outcrop area investigated.
Finally, the potential of the procedure proposed in this research is compared to that presented in (Medley 1997), where the uncertainty concerning the estimate of the VBP from 1D measurements (i.e., LBPs) is provided.

1.1 Uncertainty in estimates of VBP

Although several parameters such as matrix strength and block size distributions have been proven to affect the overall mechanical behaviour of bimrocks, the VBP has been experimentally and numerically demonstrated to be the most important factor. In fact, the VBP strongly influences the strength, deformability and failure modes of many heterogeneous formations (Lindquist 1994; Lindquist and Goodman 1994; Medley 2001; Sonmez et al. 2004, 2006; Barbero et al. 2008; Coli et al. 2012; Afifipour and Moarefvand 2014; Kalender et al. 2014, 2016; Zhang et al. 2019). For example, the shape and position of failure surfaces of unstable slopes have proven to be strongly influenced by the number, position and dimension of the blocks (Medley and Rehermann 2004; Barbero et al. 2006; Minuto and Morandi 2015; Napoli et al. 2018; Khorasani et al. 2019; Montoya-Araque and Suarez-Burgoa 2019). Moreover, when tunnelling in these heterogeneous materials, the presence of rock blocks can induce, among other problems, face instabilities, unexpected high stresses on the tunnel lining, obstructions and damage to cutters, with consequent schedule delays and extra costs (Button et al. 2004; DiPonio et al. 2007; Hunt 2014; Gwildis et al. 2018). Hence, the accurate definition of the VBP represents a fundamental issue during earthworks or tunnel design, as this parameter plays a key role in choosing the most appropriate support and excavation method (Button et al. 2004; Hunt 2014; Dhang 2016).
The actual VBP can be accurately measured at the laboratory scale only, by washing and disintegrating a sample (Coli et al. 2009). However, the block content at the laboratory scale is not representative of the VBP at smaller (site) scales. As a consequence, this parameter is usually inferred via 1D or 2D measurements, which consist in the interpretation of borehole drillings and outcrop maps that provide LBP and ABP, respectively. Given enough sampling data, stereological methods can be applied to estimate the VBP from these measurements (Medley 1997, 2002; Sönmez et al. 2004; Kalender et al. 2014). Nevertheless, as reported in the literature, the results provided by these approaches are fraught with uncertainty: the amount of sampling, the actual VBP and the shape and orientation of the blocks strongly influence 1D and 2D measurements, producing biased results (Medley 2001, 2002; Haneberg 2004).
Hence, it is vitally important to quantify the potential errors produced by assuming that 1D or 2D measurements are equivalent to 3D values, by adjusting the estimated VBPs to accommodate the uncertainty.
To date, few studies have been carried out on this topic. Medley's paper "Uncertainty in estimates of block volumetric proportions in melange bimrocks" (1997) is one of the most relevant works, as it investigated the uncertainty in the determination of actual 3D block

size distributions and quantities from 1D measurements (i.e. LBP) for melanges and similar block-in-matrix formations. Medley produced different physical bimrock models (using generally ellipsoidal blocks) with known VBPs and block size distributions, and simulated a great number of model boreholes. On the basis of thousands of randomized realizations of the model boring data and related LBPs, Medley provided a chart to adjust the estimated block content by means of an uncertainty factor defined as the ratio between the standard deviation of the cumulative LBP and the true VBP. This uncertainty factor is a function of the measured block proportion and total length of drilling, expressed as multiples (N) of the known length of the largest block (d_{max}) used in the manufacture of the physical bimrock models. Medley showed that accurate estimations of the VBP from 1D analyses can only be obtained for high VBPs and with a considerable amount of sampling, which can be difficult to achieve because of the generally prohibitive expense of geotechnical exploration drilling.

Few studies have also been carried out to investigate the uncertainty in the estimation of the VBP from 2D measurements (Sahagian and Proussevitch 1998; Haneberg 2004). One of the most relevant studies on this topic was developed by Haneberg (2004). The author performed statistical analyses to explore the amount of bias introduced when actual block sizes (i.e., VBP) are inferred from 2D outcrop projections, such as geological maps or photographs. Ellipsoids with different eccentricities, orientations and distributions (i.e., uniform and random) were used to simulate the rock blocks. The errors produced by these analyses were found to be strongly dependent on the geometry of the problem, especially block shapes and orientations with respect to the outcrop face. The results demonstrated that outcrop sampling almost certainly underestimates block sizes and proportions.

To the authors' best understanding since Medley's work (1997) no further research has been performed using physical bimrock models to provide correction factors to adjust VBPs estimated from site measurements to true VBPs.

Some analytically-based work has been performed to produce mathematically-rich approaches to review uncertainty (Tien et al. 2010, 2011; Lu et al. 2019).

The investigation presented in this paper builds on Medley's work using 2D rather than 1D data. In fact, this research shows that working with 2D instead of 1D data can often be easier, as 2D mapping surveys/photos campaigns are usually cheaper than borehole drillings, and it is generally possible to analyse an outcrop large enough to obtain an ABP value close to the real rock mass VBP. For example, if a landslide repair or a tunnel project is carried out, an outcrop at least equal to the instable area or excavation face should be analysable. Moreover, the ABP obtained should be closer to the VBP than the LBP would be.

In light of the above, in this paper a statistical approach is developed to statistically assess the error rate that can be introduced by assuming the equivalence between the ABP and VBP of a heterogeneous geomaterial. In this regard, an uncertainty factor is provided to adjust on-site 2D block content estimates as a function of the dimension of the outcrop area investigated and the ABP measured.

2. The statistical approach proposed

The purpose of the research described here is to quantify the uncertainty in estimates of real VBPs as inferred from ABP measurements by studying how an increasing size of the investigation area influences the reliability of the 2D measurements. To this purpose, a statistical approach was developed using a Matlab routine implemented to generate bimrock models enclosing spherical blocks of given VBPs and random positions within the 3D domains. The rock inclusions were assumed to have a fractal block size distribution (Medley 1994, 2001; Medley and Zekkos 2011).

The bimrock models were sectioned many times obtaining a great number of section planes on which the ABP was estimated. Statistical analyses were then performed simulating an increasing outcrop face size, by selecting different subsets of planes and combining the results.

2.1 The block size distribution of the bimrock models

Most bimrocks have scale independent or fractal block size distributions, so the relationship between block frequencies and sizes is well approximated by a negative power law on a log-log plot (Medley 1994, 2001, 2007a, 2007b; Riedmüller et al. 2001; Medley and Zekkos 2011; Kalender et al. 2016). This law is defined by its exponent, D, which is the fractal dimension.

The property of fractality means that blocks can be found in bimrocks at any scale of observation (Medley 1994; Medley and Rehermann 2004). As a consequence, the smallest and largest block sizes must be defined considering the dimension of the problem at hand, termed the characteristic engineering dimension, L_c, which may variously indicate the height of a landslide, the diameter of a specimen or that of a tunnel (Medley 1994, 2001, 2002, 2007b; Medley and Rehermann 2004; Wakabayashi and Medley 2004; Medley and Zekkos 2011; Kalender et al. 2014).

According to previous findings from the literature, the block size distribution of the bimrock models, generated with the Matlab code, obeys a negative power law (i.e., fractal distribution) with relatively few large blocks and increasing numbers of smaller inclusions.

Since bimrocks usually show values of D between 2.3 and 2.7 (Medley and Lindquist 1995), an average value equal to 2.5 is used in this research, as in (Haneberg 2004). However, significant differences in the results are not expected for different values of D, as shown in Figure 6. The minimum and maximum block dimensions were chosen as suggested by (Medley 1994, 2001), according to the scale of interest selected, limiting blocks to be between about 5%L_c (d_{min}) and 75%L_c (d_{max}) (Medley 1994, 2001).

2.2 The Matlab code

In order to develop the statistical approach proposed in this paper, a Matlab code and a high-performance workstation were used to carry out the analyses.

Five VBP values were considered (i.e., VBP = 10%, 20%, 30%, 40%, 50%) and, for each of them, the procedure described below was followed.

A square-shaped parallelepiped domain enclosing spherical blocks was created to simulate a typical bimrock formation. The dimensions of the parallelepiped were L_c x L_c x $10L_c$, so that its cross-section surface was $A_c=L_c^2$, which is the area of engineering interest.

The diameters of the spheres, d, were extracted randomly from a population distributed according to the cumulative distribution function of Eq. 1 (Napoli et al. 2018):

$$F(d) = \frac{a^{1+D} - d^{1+D}}{a^{1+D} - b^{1+D}} \qquad (Eq. 1)$$

The corresponding probability density function, *f*(*d*), is expressed by Eq. 2, which is the derivative of F(d) and describes a truncated negative power law (i.e. a fractal distribution):

$$f(d) = -\frac{1-D}{a^{1+D} - b^{1+D}} d^D \qquad (Eq. 2)$$

where:

- D is the fractal dimension, set as equal to 1.5;
- a and b are the smallest and largest block dimensions, respectively (i.e., the limits of the block size distribution), which were set as $5\%L_c$ and $75\%L_c$, respectively as per Medley (1994).

The achievement of the required VBP was checked for each bimrock model by computing the ratio between the cumulated volume of all the spheres and the volume of the parallelepiped.

The spheres were located randomly within the parallelepiped, by requiring that neither interpenetration between spheres nor intersections with the edges of the domain occurred. Figure 1 is an example of a virtual bimrock model resulting from these operations, obtained for an actual VBP of 30%. Since a virtual bimrock prism was created, partial blocks larger than $0.75L_c$ (which a real melange may contain) were not considered.

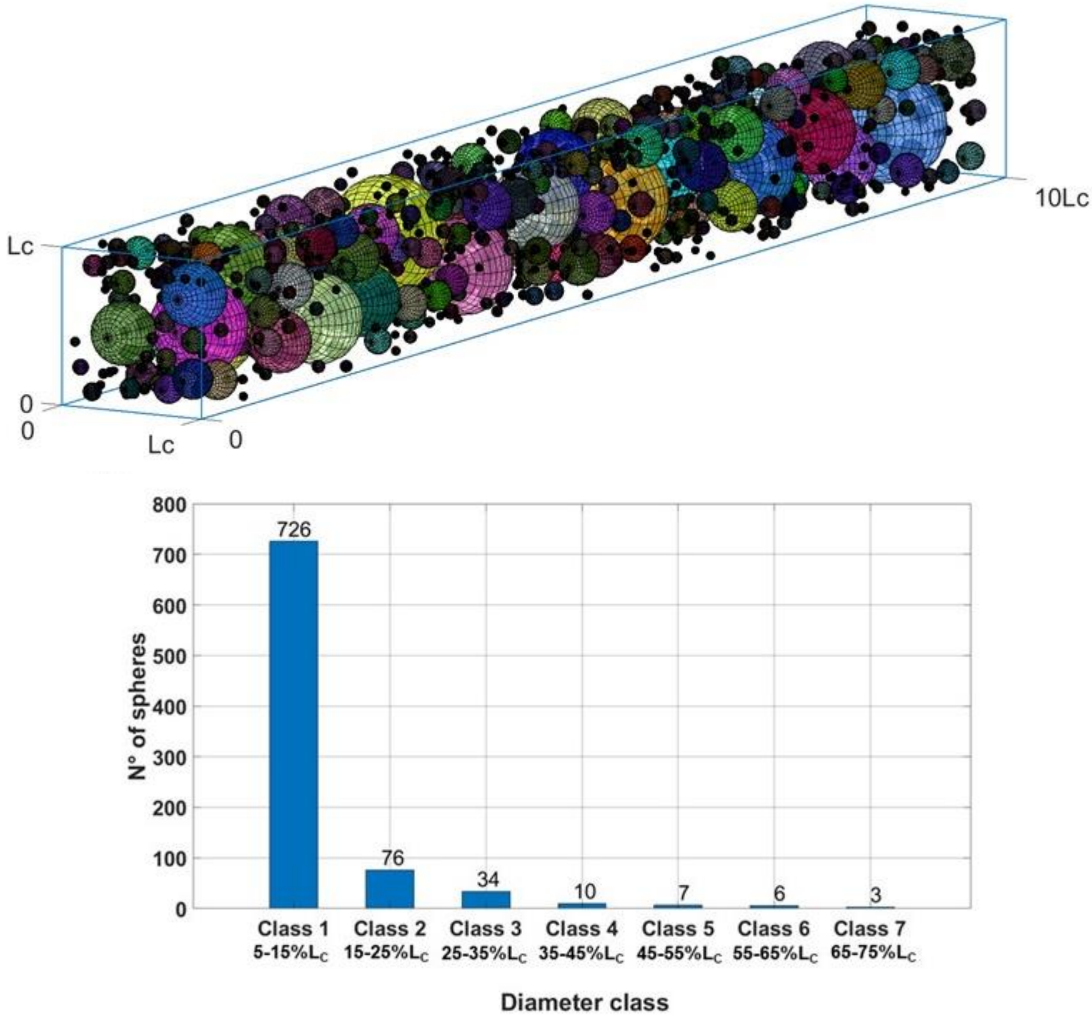

Figure 1: Block sizes, quantities and positions for VBP=30%.

The parallelepiped was then sectioned along its longest dimension with 150 equidistant and parallel planes, representing potential outcrop faces. The number of section planes was defined so as to ensure the statistical validity of the results, but at the same time to avoid section planes too close to each other. In fact, this would have provided duplicate results, compromising the reliability of the results. Assuming the minimum plane spacing to be at least equal to the smallest block dimension (parameter a) 150 section planes were generated for each of the 5 models. The solid circles (discs) obtained from the intersection between the planes and spherical blocks were analysed, by evaluating their (apparent) diameters and areas. The areal block proportion (ABP) of each plane was then computed as the ratio between the total area of circles with diameters greater than $5\%L_c$ and A_c (i.e., the domain cross-section equal to L_c^2). It is worth pointing out that outcrop discs obtained by arbitrary slicing of the spheres by the cross-sections are almost always smaller than the diametrical disks of the parent spherical blocks. As a consequence, the ABPs from cross-sectional areas of the sections only rarely have numerical values equivalent to the true VBP.

Figure 2 shows the circles (i.e. blocks) resulting from the intersection between the spheres contained in a 30% VBP parallelepiped and four section planes. The total of the four planar outcrop faces is four times greater than the area of engineering interest, A_c. From this example, the great variability of the ABP of the different section planes is evident, as well as the discrepancy between the average ABP value (16.25%) and the real VBP (30%). As expected, this result indicates that inferring 3D block proportions from measurements of a few outcrop areas (which yields an insufficiently large total sample area) compared to A_c yields widely erroneous estimates. So, the question then presented is: “How large should the total investigated area be to obtain confidently accurate estimates of VBPs?”.

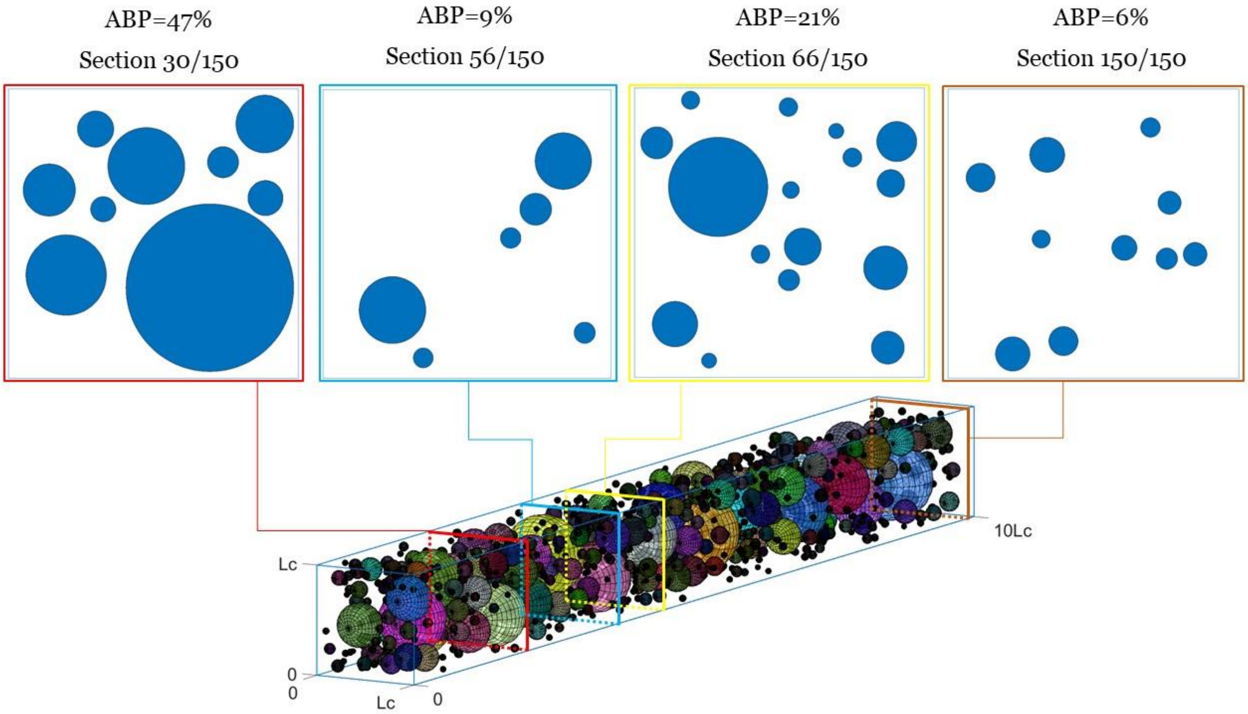

Figure 2: Intersected blocks and ABPs identified on four different planes, representing outcrop surfaces of dimension L_cxL_c. The planes section a 30%VBP parallelepiped.

A statistical processing of the results obtained was performed in order to investigate if and how 2D block measurements can provide more reliable estimates when increasing the total size of the summed outcrop areas is considered.

To this aim, subsets of an increasing number of combined section planes from the population of 150 cross-section slices were analysed. Specifically, an overall investigation surface between $1 \cdot A_c$ (corresponding to a single section plane) and $150 \cdot A_c$ (corresponding to 150 section planes) was examined. To do so, a number of section planes, β, from 1 to 150 were simultaneously considered, statistically combining the results (i.e., ABP values). In other words: β represents the multiplicative coefficient to be applied to the area of engineering interest (i.e., L_c^2, corresponding to the area of a single section plane, A_c) to obtain the equivalent overall total of surfaces investigated.

For each value of the overall survey area, i.e. for each β, a great number of subsets composed by β planes, extracted randomly (Monte Carlo fashion) from the total 150, were generated avoiding duplicates. Then, for each β, the average ABP and the overall standard deviation were determined provided by the planes of all the subsets.

In order to fall within the calculation and storage capacity of the workstation, the maximum number of subsets extracted for each β was limited to 5000. In fact, the number of possible combinations of 150 elements taken β at a time without duplicates (i.e., subsets) is $N = \binom{150}{\beta}$, which is a huge number for only some values of β. Instead, if β is equal to 1 only, $N = \binom{150}{1} = 150$. However, if β increases for example to 10, $N = \binom{150}{10} \cong 1.17 \cdot 10^{15}$ combinations.

Finally, similarly to Medley (1997) with regard to LBP measures, an uncertainty factor (UF) was determined to adjust the initial ABP measured. This factor was calculated, for each β value, as shown in Eq. 3, which is a form of the equation for the Coefficient of Variation (Standard Deviation divided by the Mean):

$$UF_{\beta=i} = \frac{\sigma(ABP_j)\big|_{\beta=i}}{\mathrm{VBP}} \quad ; \quad j = 1, 2, \ldots, j_{max} \qquad (Eq.3)$$

where:

- $i = 1, 2, \ldots, 150$, values of β, representing the number of section planes analysed simultaneously;
- j = number of subsets;
- j_{max} = number of subsets considered for each $\beta = \min\left(\binom{150}{\beta}, 5000\right)$;
- $\sigma(ABP_j)\big|_{\beta=i}$ = standard deviation of the ABP values provided by all the subsets considered for $\beta = i$;
- VBP = real volumetric block proportion of the complex formation simulated.

3. Results and discussion

The average ABPs and overall standard deviations computed for each model bimrock as a function of β (i.e., the investigation area) are shown in Figure 3. These graphs highlight that the ABP values estimated show deviations from the real VBP value, even by taking a great number of β section planes into account. However, the data dispersion decreases as the investigation surface increases. Furthermore, it is possible to observe that the average ABP values trend toward the real VBP for higher β values. These outcomes are consistent with the results found by Medley (1997).

From that, it follows that the error committed by assuming ABP = VBP decreases as the analysed investigation surface increases and, for a sufficiently large outcrop area, it can be considered negligible. In fact, this error cannot be completely eliminated by considering 2D measures to describe a 3D content of blocks: the error could reach a null value only when an infinite number of sections is considered, which corresponds to the transition from 2D measurements to 3D measurements.

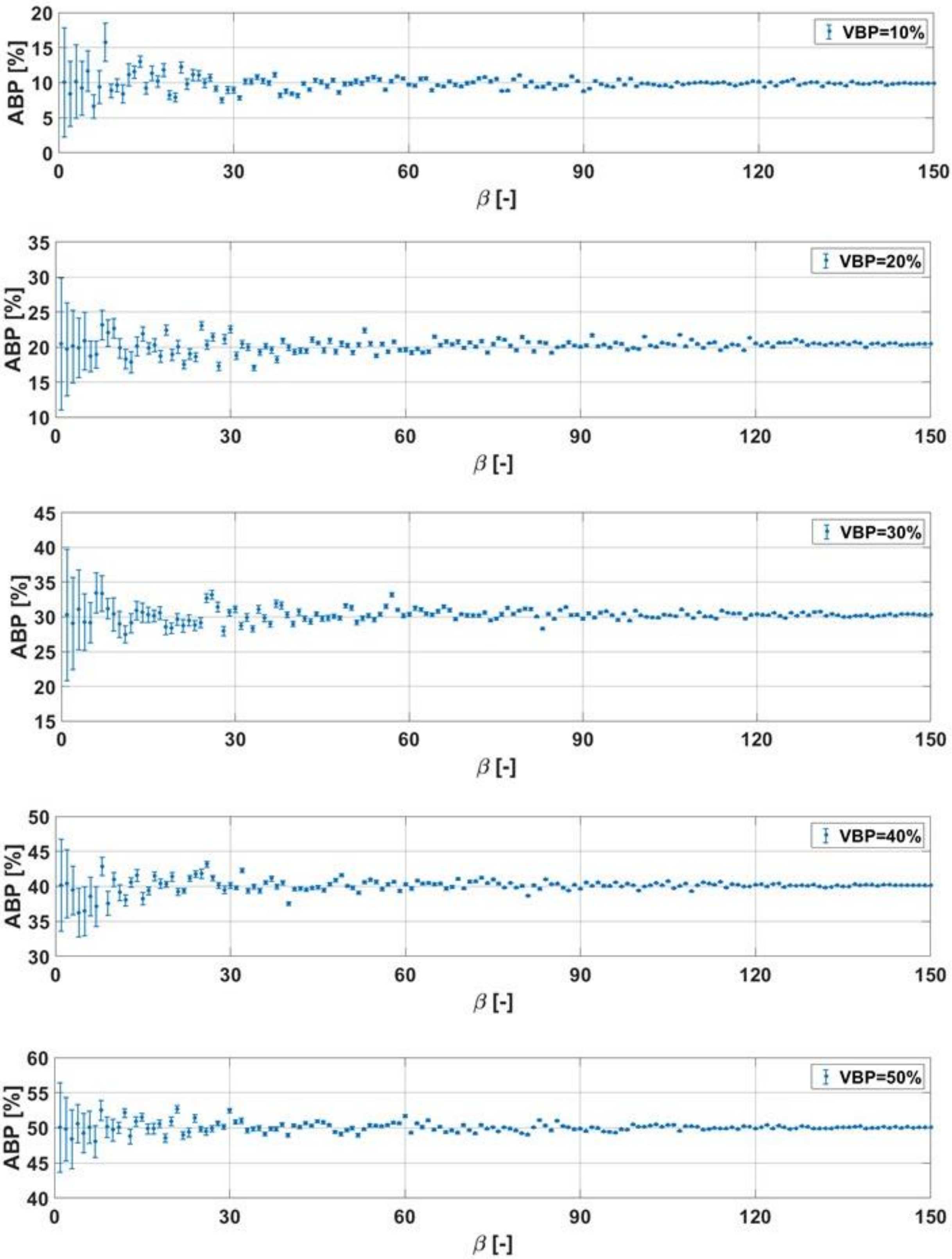

Figure 3: Plot of cumulative ABPs vs the multiplicative coefficient of the area of engineering interest, A_c (total investigation surface). Error bars represent ± 1 standard deviation about the mean of the data derived from randomly combined section planes.

As stated above, the results shown in Figure 3 were used to define a coefficient of variation (UF), COV, associated with the estimate of the VBP, by means of Eq. 3. Hence, to determine the uncertainty factor (UF), the actual VBPs were used instead of the mean in the COV expression of Figure 4, as the mean ABPs converge to the actual VBPs.

The relationship between the uncertainty (i.e., COV) in estimates of VBP, the dimension of the outcrop where 2D measurements are performed and the measured block content (i.e., ABP) is shown in Figure 4. Consistently with Medley (1997), for each VBP considered a decreasing trend of the UF as a function of β is obtained. Moreover, higher VBPs lead to lower biased results. This result is due to greater geometrical probability of block encounters in outcrops with higher VBPs (and thus greater opportunity to measure ABPs). Conversely, lower VBPs lead to less 2D expressions of blocks that, as indicated above, are nearly always smaller than true block diametrical section views.

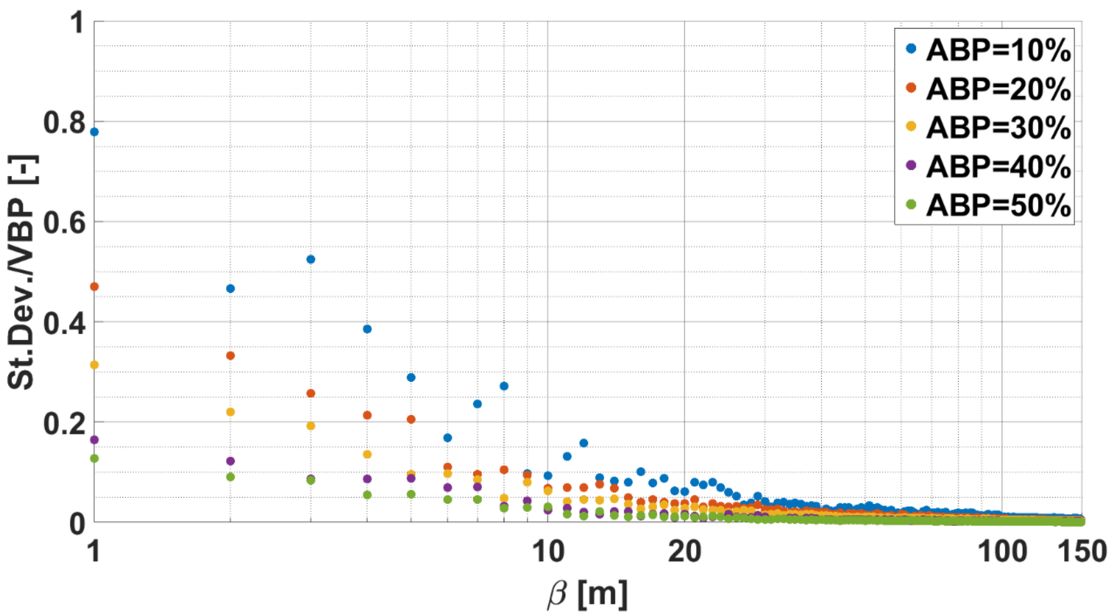

Figure 4: Uncertainty in the VBP estimate from 2D measurements, as a function of the total investigation surface (expressed as multiples, β, of the A_c) and block contents measured (ABP).

In Figure 4 it can be observed that the error in the estimate of the VBP stabilises and tends asymptotically to zero for β greater than about 20, whatever the ABP measured. Since the availability of investigation surfaces corresponding to β values greater than 20 could be difficult to achieve (see Table 1), particular attention was paid to the analysis of the results relating to β values in the range [0; 20].

Table 1: Examples of typical engineering works and related characteristic engineering dimensions, L_c. The size of outcrop surfaces corresponding to βA_c, with β equal to 1 (i.e. engineering characteristic area), 10, 20 and 50, is given by way of example.

		Outcrop surfaces, $\beta \cdot A_c$ [m^2]			
Typical engineering works and functions	Characteristic engineering dimension, L_c [m]	β =1	β =20	β =50	β =150
Microtunnel (e.g., water)	3 (diameter tunnel)	7	141	353	353
Tunnel (e.g., light rail)	6.5 (diameter tunnel)	33	663	1659	1659
Tunnel (e.g., highway)	15 (diameter tunnel)	176	3534	8836	8836
Landslide	30 (high slope)	900	18000	45000	45000

Similarly to Medley's (1997) results, the trend of the UF in relation to β is well approximated by a logarithmic law, which presents as a line on a semi-logarithmic plot (see Figure 5 and Table 2).

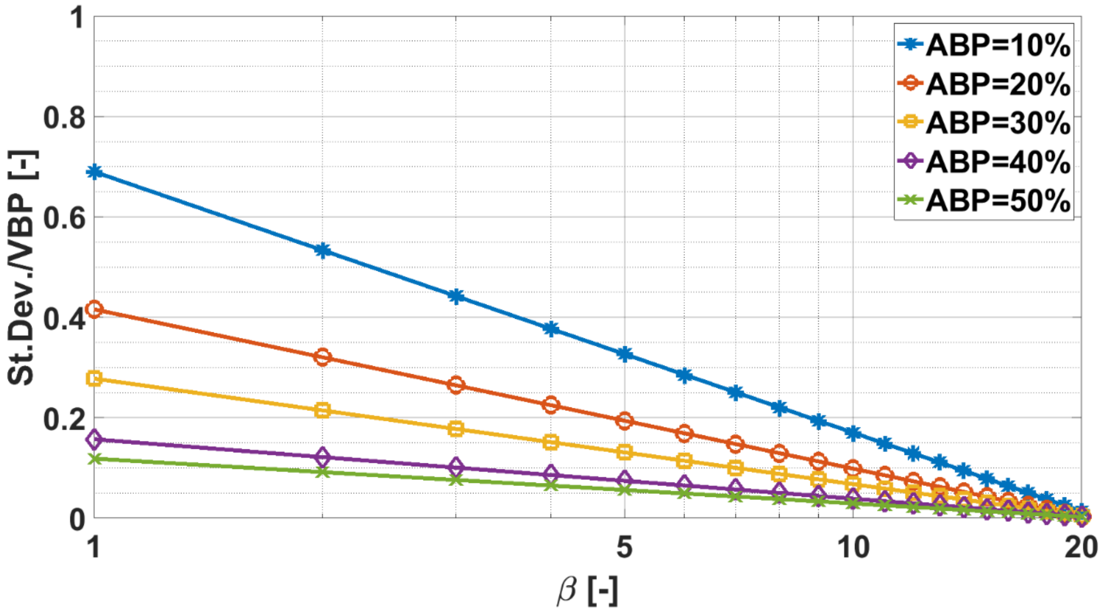

Figure 5: Linear fitting of uncertainty factors (shown in Figure 4), for β values in the range [0; 20], on the semi-logarithmic plot.

Table 2: Specifications of the linear fittings.

VBP [%]	Fitting equation [β=1;20]	R^2 [-]	UF_{min} [-]	UF_{max} [-]
10	UF=-0.226·ln(β)+0.690	0.911	0.014	0.690
20	UF=-0.137·ln(β)+0.416	0.940	0.003	0.416
30	UF=-0.091·ln(β)+0.278	0.937	0.005	0.278
40	UF=-0.051·ln(β)+0.157	0.951	0.003	0.157
50	UF=-0.039·ln(β)+0.119	0.960	0.003	0.119

The lines in Figure 5 can be used in design to correct the ABP estimates in order to obtain a range of VBPs which should contain the actual 3D block quantity.

For example, consider a survey which yields an estimated ABP = 30% (i.e., the yellow line in Figure 5) using an investigation area three times larger than A_c (i.e., β = 3), the UF is equal to 0.178 and the real VBP can be computed as:

$$VBP = ABP \pm UF \cdot ABP = 30 \pm 0.178 \cdot 30 = (25 \div 35)\%$$

In this regard, it is worth to note that, as was the case in (Medley 1997, 2001), an interpolation can be made between the diagonal lines on the graph of Figure 5, in order to obtain the uncertainty factors associated with ABP values other than those considered in this study. However, it would not be correct to extrapolate the results provided by these analyses if the ABPs were greater than 50% or lower than 10%. In fact, it is not possible to predict accurately the trend of the lines in a range different from that analysed here.

Finally, as already suggested by (Medley 1997; Medley and Zekkos 2011), prudent and conservative estimates of the corrected VBP should be made depending on the engineering interest. For example, if the strength parameters of a bimrock are to be determined, the smallest VBP value should be used. On the other hand, if the adjusted VBP will be used to select an excavation method and/or design a cutter head for a tunneling project, the highest VBP should be used. Adopting these guidelines, the design engineer will err on the side of prudence and safety.

3.1 Influence of the fractal dimension

In order to verify the influence of the fractal dimension (D) on the results, the procedure described in the previous sections was repeated. Two further analyses were performed on bimrock models with the same VBP, set as equal to 30%, and (different) block size distributions with fractal dimensions, D, equal to 2.3 and 2.7, respectively. These values correspond to the average upper and lower limits of D found for melanges and similar bimrocks.

As can be seen from the example in Figure 6, the results show very similar trends and there are no significant differences that put into question the validity of the input D value used previously (i.e., D=2.5). In fact, it was observed that the data map on semi-log plot as lines superimposed on each other.

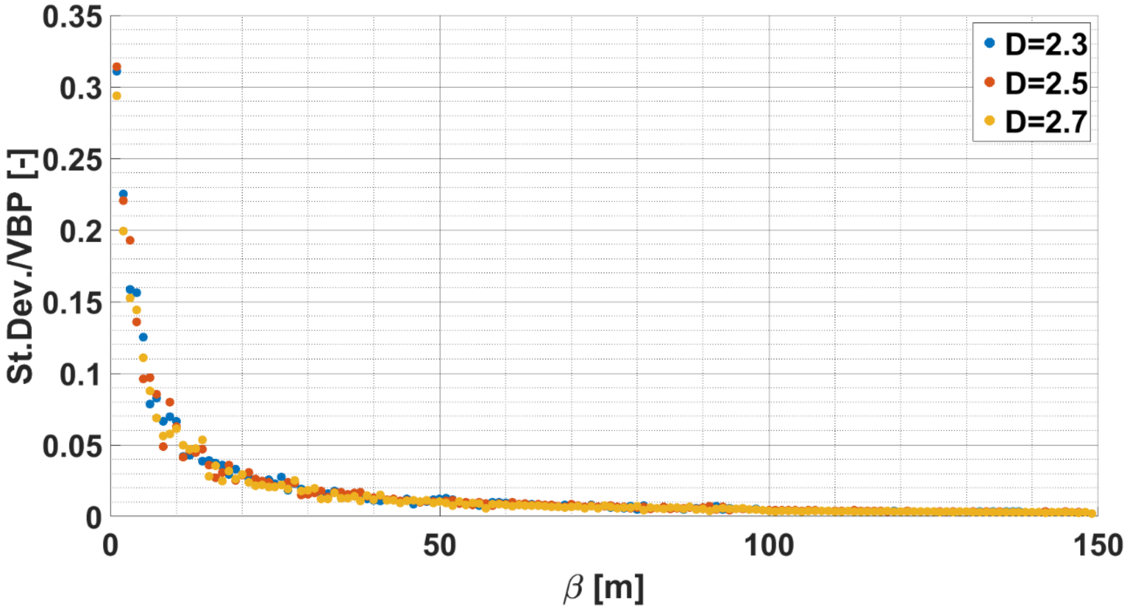

Figure 6. Uncertainty in VBP estimates from 2D measurements, as a function of the total investigation surface of model bimrocks characterized by a VBP equal to 30% and block size distributions with fractal dimensions, D, equal to 2.3 and 2.7. The results with D=2.5 are also illustrated, by way of comparison. All points are almost overlapping.

3.2 Comparison between 1D and 2D measurements and related uncertainties

The results that can be obtained through the procedure proposed in this research were compared to those presented in Medley (2001) related to the use of 1D measurements (i.e. borehole drillings) for the estimation of the VBP. The latter are summarized in Figure 7, where the trendlines of the uncertainty factor are reported as a function of the cumulative sampling length and the block content measured.

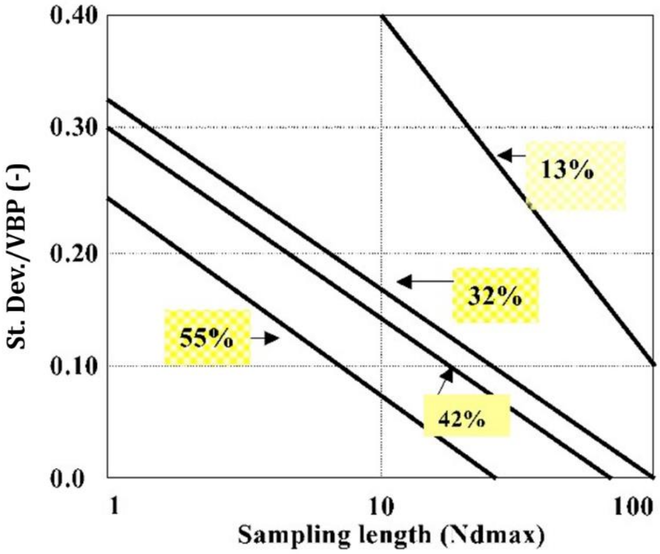

Figure 7: Uncertainty in estimates of VBP from 1D measurements as a function of the total sampling length (expressed as a multiple N of the length of the largest block, d_{max}) and the measured LBP (modified from Medley, 2001).

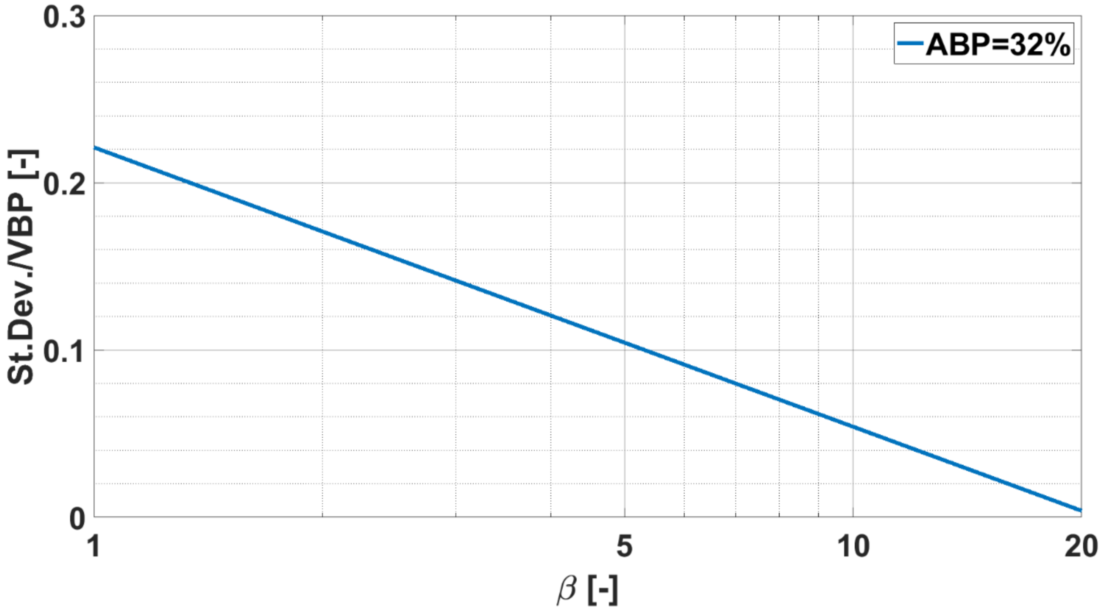

Figure 8: Uncertainty in estimates of VBP from 2D measurements of a bimrock model with VBP=32%, as a function of the total investigation area, expressed as a multiple β of A_c.

In order to perform the comparison, a new bimrock model with a VBP equal to 32% was generated since it corresponds to one of the block contents considered by Medley (2001). The result obtained is shown in Figure 8.

From the graphs of Figure 7 and Figure 8, an uncertainty factor equal to 0.1 is obtained for Nd_{max} = 25.2 (Figure 7) and β = 5.3 (Figure 8). This uncertainty factor is an acceptable value from an engineering point of view.

Considering the characteristic dimension of the problem at hand, L_c, the area of engineering interest and the maximum block size are equal to $A_c=L_c^2$ and $d_{max}=0.75*L_c$,

respectively.
Table 3 shows, for different values of L_c, the investigation surface required to obtain an uncertainty factor equal to 0.1 in the estimate of the VBP from 2D measurements (A_{req}) and the total length of drilling/block intercepts required to obtain the same level of uncertainty if 1D measurements are used (L_{req}).
To compare the results, L* was calculated, where L* is the side of an equivalent square outcrop of size A_{req}. Table 3 shows that 2D measurements may require less effort than 1D measurements (i.e., $L^* < L_{req}$), where the uncertainties are numerically equal (in this case 0.1). For example, for L_c = 30 m, VBP = 32%, N_{dmax} ~25 and UF=0.1, 567 m of drilling are required (e.g. 19 borings 30 m deep), which could be very expensive for core drilling. Alternatively, the 2D approach just needs a total measured area of 69m by 69m, which certainly should require a lot less effort.
These observations suggest that 2D areal measurements could be preferable to 1D linear measurements for VBP estimates, this highlighting the potential of the procedure proposed in this research. In fact, the graph shown in Figure 5 represents a useful design guide that will encourage geopractitioners to secure on-site ABP measurements as well as 1D borehole measurements, to reduce the burden of exploration operations.

Table 3: Investigation surfaces and total perforation lengths required to obtain an UF=0.1, for VBP=32% and different values of L_c (L is the side length of a fictitious square with area equal to A_{req}).*

L_c [m]	**1D measurement approach Nd_{max} = 25.2 for UF = 0.1 and VBP = 32%**		**2D measurement approach β = 5.3 for UF = 0.1 and VBP = 32%**		
	$d_{max} = 0.75 \cdot L_c$ [m]	**$L_{req} = d_{max} . Nd_{max}$ [m]**	$A_c = L_c^2$ [m²]	$A_{req} = \beta \cdot A_c$ [m²]	**$L^* = \sqrt{A_{req}}$ [m]**
5	3.75	**95**	25	133	**12**
10	7.5	**189**	100	530	**23**
15	11.25	**284**	225	1193	**35**
20	15	**378**	400	2121	**46**
30	22.5	**567**	900	4771	**69**

4. Conclusions

The VBP is the most important parameter governing the overall mechanical behaviour of a bimrock or bimsoil. Hence, correct estimation of in-site VBP is of paramount importance. Generally, the only way to measure VBP at site scales is from 1D borings/scanlines (LBPs) or 2D outcrop mapping/photographs (ABPs). But, assuming the LBPs or ABPs are equivalent to the true VBP leads to significant errors which may invalidate the geomechanical characterization of the bimrock or bimsoil under investigation.
The purpose of this paper was to provide a means for assessing the uncertainty error. To this aim, a Matlab code was developed to generate 3D bimrock models with given block

size distributions and different VBPs. Then, a statistical approach was applied to each model to determine the deviation of 2D measurements (ABP) from the real block contents (VBP) as a function of the size of the outcrop area investigated. The deviation was assessed by means of an uncertainty factor, and a graph (Figure 5) was developed as a design aid to adjust on-site ABP measurements to obtain an appropriate estimate of the VBP. The graph can be used, directly or by interpolation, for a range of ABP values and dimensions of the outcrop analysed.

The method was developed with a view to assist geopractitioners with an accessible and straightforward means for accommodating the uncertainty inherent in accurate estimation of true site-scale VBPs. This method represents an extension of previous studies from the literature concerning the uncertainty in estimates of the VBP from 1D measurements and preserves the ease of application of the corrections proposed. A comparison with the results obtained from these studies was performed, highlighting the strength of the procedure developed in this research.

The practical potential of the research presented lies in the fact that working with 2D rather than 1D data can often be more convenient.

In fact, it is generally possible and easier to analyse an outcrop large enough to obtain estimates of the 3D block content that are generally closer to the real VBP than 1D measurements would be, although with a certain degree of error. Moreover, assuming that the ground surface geology is accessible and visible, 2D mapping surveys are usually cheaper to perform than geotechnical exploration drilling programs. Furthermore, the approach developed in this research is based on purely geometric considerations, regardless of the mechanical characteristics of the complex material to be analysed. For this reason, it can be used to estimate the volumetric block proportion of different geological formations with a block-in-matrix fabric.

However, since real bimrocks generally contain non-spherical rock inclusions, the assumption of block sphericity represents a limitation. Hence intended (and necessary) future work should investigate if other block shapes, such as more realistic ellipsoids, yield different results.

Moreover, other potential research areas will be to validate and extend the work of Medley (1997), by performing virtual drilling programs through the computer-derived bimrock models constructed in the research presented in this paper.

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