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Tunneling in heterogeneous ground: an update of the PBE code accounting for the uncertainty in estimates of block quantities from site investigations

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Abstract. Hard rock blocks embedded in a soft matrix can be found in many geological units. When tunneling in these heterogeneous formations, many technical problems can be caused by the presence of cobbles and boulders. These risks depend on the excavation method selected, and typically increase as the block content, dimension and frequency increase. Therefore, successful tunneling projects require cobble-boulder properties to be accurately predicted, in order to select the best tunneling method and design the most appropriate cutterhead. A recent and extensive statistically-based methodology was developed to estimate the probability of encountering rock blocks located totally or partially within the tunnel excavation area, resulting in a free executable code, named PBE. A significant limitation of this code is that it requires, among other input parameters, the block content expected within the tunnel zone. This parameter can be estimated from 1D (i.e. borings/scanlines) or 2D (i.e. geological maps, outcrops, photographs) measurements. However, the block quantity inferred from these measurements is generally affected by a high magnitude of error. In this paper, an extension of the PBE is presented, that accounts for the uncertainty in estimates of block quantities from site investigations. The updated version of the executable code is also provided.

1. Introduction

Tunneling in heterogeneous ground composed of hard rock inclusions embedded in a soil-like matrix represents a key challenge for geotechnical engineers. Many risks can arise while excavating through these geomaterials because the cutterhead must break down the strong and abrasive cobbles (from about 7.5 to 30 cm in size) and boulders (from about 0.3 to 9 m) while simultaneously excavating through a soft matrix. However, cutting tools are not always capable of comminuting cobbles and boulders to smaller sizes, especially if they are too large and/or concentrated [1]. Therefore, among other potential consequences, obstructions, face instabilities, extraordinary high strains and stresses on tunnel linings, damage to cutter housings and more rapid wear of cutters can occur [1–5]. These technical problems may cause severe safety risks, considerable delays and huge extra costs.

In order to contain the adverse impact of the cobbles and boulders on tunneling, an appropriate TBM type and an adequate cutterhead design (i.e. opening ratio, shape, cutter type, power, etc.) are necessary [4]. This requires careful geological and subsurface investigations to predict as accurately as possible the cobble and boulder contents, lithology, size and frequency [1,6,7]. A few probabilistic methods have been proposed in the literature to estimate the cobble/boulder volume ratio from large diameter borings, boulder volume surveys, excavations, borehole drillings, geological maps and/or test pits [6,8,9]. The most relevant studies are the statistical approaches proposed by Medley [8] and Napoli et al. [9], which investigate the uncertainty in estimates of the real block quantities of melanges and similar block-in-matrix formations from 1D and 2D measurements, respectively. However, of crucial importance is also the estimation of the proportion of cobbles/boulders of different dimensions that are close to the tunnel perimeter or only partially embedded within the tunnel face (i.e. protruding rock blocks) [1,5,6,10]. In fact, these blocks are much more difficult to cut and more likely to be pushed aside. Consequently, potential risks such as significant settlements, mucking system damage, obstruction or deflection of a TBM shield, excessive torque and thrust demand and significant wear (or breakage) of the cutterhead tools can occur. In this regard, a statistically-based approach, resulting in a free executable code named PBE vers.1.2, has been recently developed to estimate the probability of encountering cobbles and boulders located partially or totally within both the tunnel section and the lateral distance furthest from the centre of the cutterhead [11]. A significant limitation of the PBE code is that it requires, among other input data, the block content expected within the excavation zone. Although this parameter can be inferred from 1D (i.e. borings/scanlines) or 2D (i.e. geological maps, outcrops, photographs) measurements, it has been demonstrated that such estimations can be affected by a high magnitude of error and, therefore, that they should not be used without due regard for the uncertainty [8,9,12].

In this paper, an extension of the PBE code is presented, that accounts for the uncertainty in estimates of block quantities from site investigations. The updated version of the executable code (PBE code vers. 1.3) is also provided.

2. The PBE code

The PBE code is a statistically-based tool for the estimation of the probability of encountering a certain number n of rock inclusions of variable dimensions and locations during the excavation of a circular tunnel in heterogeneous ground.

To this aim, a great number of heterogeneous ground configurations are generated in order to achieve a statistical validity of the results. The configurations, with a control area of dimensions BxH, contain (i) the tunnel section of radius R, (ii) a circular crown of thickness R_ext, for the estimation of cobble-boulder quantities located at the lateral extremities of the tunnel and (iii) the rock blocks, that have a circular shape and variable sizes, from a specified minimum to a maximum value (a and b, respectively, in Table 1), obeying the typical melanges fractal block-size distribution [11,13]. The inclusions are positioned randomly within the control area (Figure 1) and their number depends on the block content, BC, expected. This parameter should be estimated on the basis of geological surveys, site observations and field data, all of which should be as detailed as possible [1,6–9].

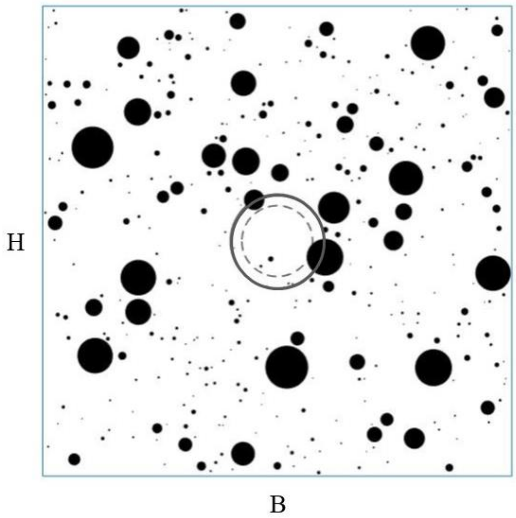

Figure 1. An example of a tunnel configuration in a heterogeneous ground with BC=10%. The size of the control area (with B=H in this example) was set at 10 times greater than the tunnel radius. The tunnel is located in the center of the control area, and is indicated with the continuous circle. The dotted line indicates the inner boundary of the tunnel sub-area, where blocks are more difficult to cut and may cause severe impacts, such as higher tool wear.

The tunnel can be located anywhere within the control area, by assigning its x-y center coordinates, so as to be able to consider underground excavations in different geological units. For example, if the heterogeneous ground is expected to occur only in half of the tunnel section, its center can be positioned on one control area boundary, as shown in Figure 2.

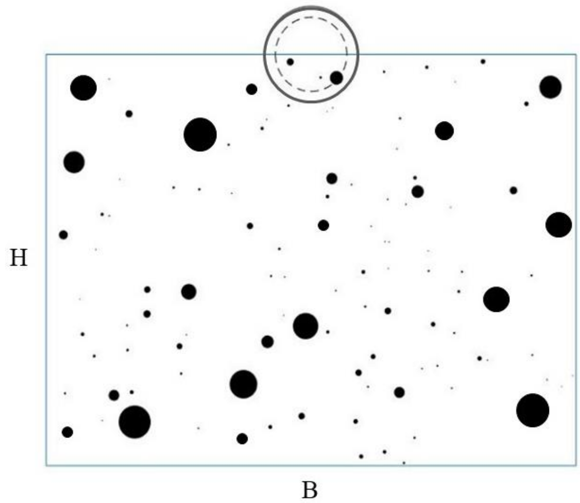

Figure 2. An example of a tunnel only partially located inside the control area, to simulate different geologic units within the tunnel section.

A list of the input parameters required by the PBE code are listed in Table 1, where the default values proposed are also shown.

For each configuration generated, the PBE code computes and returns the number and intersection area of all the blocks that are either entirely or only partially contained within the tunnel section. Then, the code compares each intersection area with a threshold user-defined value, *A_thr1*, corresponding to the smallest block dimension deemed a possible cause of technical problem (e.g. obstruction or tool damage). If the intersection area of a block is smaller than *A_thr1*, the block is not considered problematic and is discarded from the subsequent analyses. On the contrary, if the intersection area is greater than *A_thr1*, an equivalent clast area is computed and stored, which corresponds to the area of the block if it is entirely contained within the tunnel face. Moreover, in order to estimate the probability of encountering cobbles and boulders of different sizes during the tunnel excavation, the code user can define up to six size classes of (equivalent) intersecting rock block areas. The smallest class has the previously defined *A_thr1* as minimum threshold value.

Finally, the probability that a certain number, *n*, of rock blocks (with *n = 0, 1, 2, …, 10, >10*) belonging to a given size class can be encountered during the excavation is finally computed by dividing the number of configurations in which *n* blocks of that size class were found for the total number of simulations performed.

The information provided by the PBE code can be extremely useful for a more rational choice of the tunneling method and a more adequate cutter head design. However, a significant limitation of this code is that it requires the value of the BC expected. Although this parameter can be estimated via 1D or 2D measurements, which provide linear (LBP) and areal (ABP) block proportions, respectively, the block quantity inferred from these measurements is generally fraught with a high magnitude of error [8,9,12].

In this paper, an extension of the PBE is presented, that accounts for the uncertainty in estimates of block quantities from site investigations. Specifically, reference can be made to the works of Medley [8] and Napoli et al. [9], that provide an uncertainty factor, UF, to adjust the estimated block content from 1D and 2D measurements as a function of the amount of sampling. The amount of sampling for 1D and 2D measurements corresponds: (i) to the total length of drilling expressed as multiples (N) of the known length of the largest block (d_{max}), Nd_{max}, and (ii) to the total investigation surface, expressed as multiples (β) of the known area of engineering interest, A_c, respectively (Figure 3). The UF obtained can be used to correct the LBP and ABP estimates, in order to obtain a range of 3D block content which should contain the real volumetric block proportion (VBP) of the heterogeneous formation. For example, for β=3 and for an estimated block content equal to 10%, an UF equal to 0.442 is found from Figure 3b [9]. This UF indicates that the real VBP should be considered to be between VBP_{min}=5.6% and VBP_{max}=14.4% (i.e. VBP = ABP ± UF·ABP = 10 ± 0.442·10).

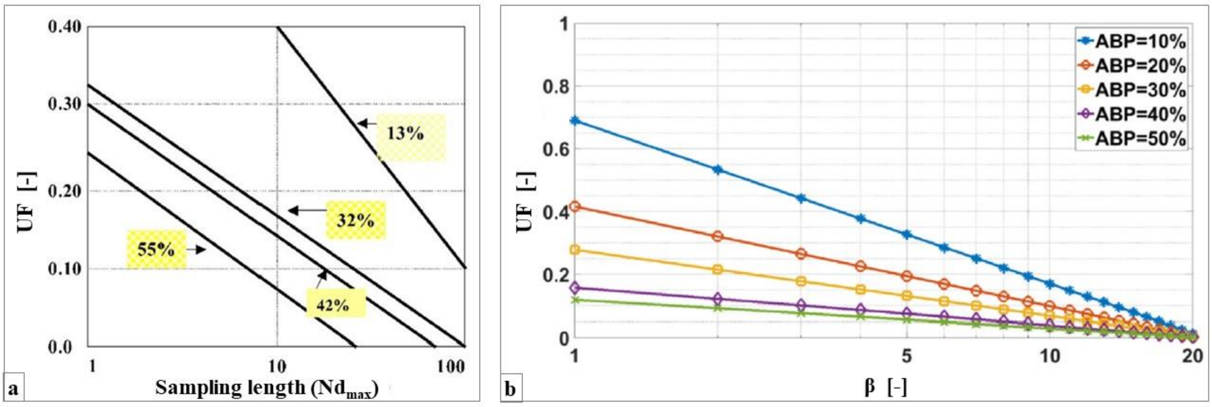

Figure 3. Uncertainty factors, UF: a) uncertainty in the VBP estimate from 1D measurements (LBP), modified from [8]; b) uncertainty in the VBP estimate from areal measurements, as a function of the total investigation surface expressed as multiples, β, of the characteristic engineering area, A_c [9] and block contents measured (ABP).

In the update version 1.3 of the PBE code, the value of the UF, that can be obtained from both 1D and 2D measurements, has been added to the input parameters (UF_BC in Table 1). In this way, the BC

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of the z configurations generated will vary between a VBP_{min} and VBP_{max} value, accounting for the uncertainty in the block quantity estimates.

Table 1. Input parameters of the PBE code. All the default values can be changed by the user code.

Input parameter		Variable	Default value
Length of the control area	[m]	B	32.5
Height of the control area	[m]	H	32.5
Tunnel radius	[m]	R_t	3.25
Circular crown thickness	[m]	R_ext	0.8
Tunnel x-y coordinates	[m]	coord_t	B/2 =16.25 H/2 =16.25
Threshold area class 1 (Equivalent diameter 0.15 m)	[m^2]	A_thr1	0.0177
Threshold area class 2 (Equivalent diameter 0.3 m)	[m^2]	A_thr2	0.0707
Threshold area class 3 (Equivalent diameter 0.5 m)	[m^2]	A_thr3	0.1963
Threshold area class 4 (Equivalent diameter 0.75 m)	[m^2]	A_thr4	0.4418
Threshold area class 5 (Equivalent diameter 1 m)	[m^2]	A_thr5	0.7854
Threshold area class 6 (Equivalent diameter 1.5 m)	[m^2]	A_thr6	1.7663
Block content	[-]	BC	0.10
Block content uncertainty factor	[-]	UF_BC	0.442
Minimum expected clast dimension	[m]	a	0.075
Maximum expected clast dimension	[m]	b	3
Fractal dimension	[-]	D	-1.75
Number of configurations to generate	[-]	z	500

3. An application example

In order to show the validity of the free executable code PBE_vers1.3, the excavation of a circular tunnel in heterogeneous ground was simulated. The default input parameters listed in Table 1 were used. The variability in the BC of the z (i.e. 500) configurations analyzed can be visualized both in a text file and in a JPG image (both named *BC*). Figure 4 shows 3 of the 500 configurations generated for the example considered, and the BC variability. The probability of finding *n* intersecting blocks greater than the threshold value, *A_thr1*, both within the tunnel and at the lateral distance furthest from the centre of the tunnel (i.e. inside the circular crown), is given in Table 2.

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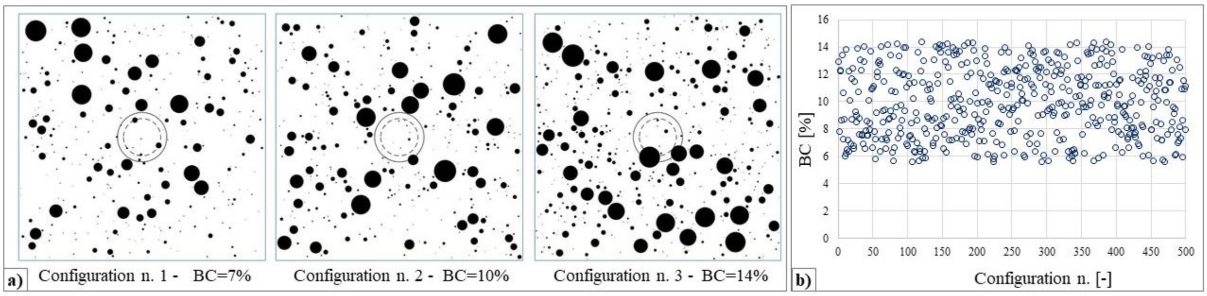

Figure 4. a) Three of the 500 configurations generated as output by the PBE code, vers.1.3. Different block sizes and positions are shown, as well as different BC values; b) BC of the z=500 configurations generated.

Table 2. Probability, P, of encountering *n* blocks (with *n* from 0 to >10) with an intersection area greater than *A_thr1*, equal to 0.0177 m^2 (i.e. equivalent clast diameter = 0.15 m). The results are related to the entire tunnel section (table above) and to the circular crown (table below). These results are contained in the output text file "Probability" provided by the PBE code.

TUNNEL Equivalent clast diameter [m]	P 0blocks [%]	P 1blocks [%]	P 2blocks [%]	P 3blocks [%]	P 4blocks [%]	P 5blocks [%]	P 6blocks [%]	P 7blocks [%]	P 8blocks [%]	P 9blocks [%]	P 10blocks [%]	P >10blocks [%]
0.15-0.30	3.8	14.0	19.4	17.8	15.6	0.2	7	6	1.0	0.8	0.6	0.8
0.30-0.50	19.6	31.6	26.0	15.8	4.2	0.2	0.2	0	0.2	0	0	0
0.50-0.75	35.8	37.2	19.8	6.0	1.2	0	0	0	0	0	0	0
0.75-1.0	56.2	32.0	9.2	2.0	0.6	0	0	0	0	0	0	0
1.0-1.5	53.4	32.4	11.0	2.8	0.4	0	0	0	0	0	0	0
>1.5	53.0	37.0	8.8	1.2	0	0	0	0	0	0	0	0
CIRC. CROWN Equivalent clast diameter [m]	P 0blocks [%]	P 1blocks [%]	P 2blocks [%]	P 3blocks [%]	P 4blocks [%]	P 5blocks [%]	P 6blocks [%]	P 7blocks [%]	P 8blocks [%]	P 9blocks [%]	P 10blocks [%]	P >10blocks [%]
0.15-0.30	16.4	31.6	25.8	12.6	8.8	3.4	1	0.4	0	0	0	0
0.30-0.50	40.2	35.4	18.0	5.0	1.2	0.2	0	0	0	0	0	0
0.50-0.75	53.2	32.4	12.0	2.2	0.2	0	0	0	0	0	0	0
0.75-1.0	65.2	28.4	5.4	1.0	0	0	0	0	0	0	0	0
1.0-1.5	58.0	31.8	9.4	0.8	0	0	0	0	0	0	0	0
>1.5	86.8	12.4	0.8	0	0	0	0	0	0	0	0	0

What stands out in Table 2 is the high probability of encountering 0 blocks (i.e., P_0blocks), especially if greater block dimensions are considered. This result is related to the low BC set (i.e., 10%), which produced a significant number of configurations without blocks inside the tunnel section.

Table 2 also shows that the probability of a single rock block to be encountered during tunnelling (P_1block) is almost always higher than the probability of encountering two (P_2blocks) or more blocks of the same clast size, regardless of the area examined (i.e. the entire tunnel face or a part of it).

Moreover, for a given number n of blocks, with n ≥1, higher probabilities are generally related to the smallest class dimensions. This result reflects the fractal block size distribution used to generate the rock inclusions. Furthermore, in the proposed example, a very low probability of encountering blocks larger than 0.07 m^2 (i.e. equivalent clast diameter greater than 0.3 m) during the tunnel excavation is reached for *n* equal to 4. On the other hand, the results obtained for the circular crown of the tunnel indicate that the probabilities of encountering *n* blocks of a given clast size are generally much lower than those related to the entire tunnel section. Moreover, no configuration has more than 8 blocks in the sub-area furthest from the centre (i.e. $P\_{CIRCULARCROWN\_ n>=8blocks} = 0$) and that the probability of encountering more than 5 blocks is very low, and in case related to cobbles belonging to the two smallest class dimensions only. All this information is essential for assessing the excavation process and tool characteristics.

The executable code also generates other outputs, listed and described in Table 3, as text files or JPG images.

Table 3. Output parameters of the PBE code (vers. 1.3). The output files with the "*" contain the results related to both the entire tunnel section and the circular crown.

Parameter		Output file name
Total number of intersecting blocks (for each configuration)	[-]	Total_IB *
Total intersection area of the blocks (for each configuration)	[m^2]	A_int *
Total number of intersecting blocks greater than the threshold value, A_thr1 (for each configuration)	[-]	N_crit_IB *
Intersection area of all the blocks greater than the threshold value (for each configuration)	[m^2]	A_int_cr *
Probability of finding n intersecting blocks greater than the threshold value during the excavation	[%]	Probability * (Table 2)
Average number of intersecting blocks greater than the threshold value during the excavation	[-]	N_Average *
Graphical representation of the cumulative distribution function F(d)-d of the blocks, where d indicates the block diameter	[-]	CDF
Block content of each configuration	[-]	BC
Graphical representation of the configurations generated	[-]	Configuration 1 up to z (Figure 4)
List of input variables and values assigned	[-]	Info_viewer

4. Conclusions

When tunneling in heterogeneous ground with cobbles and boulders risks of obstruction, cutting tools damage, excessive cutter wear and steering problems, with consequent delays and huge extra costs, can occur. In order to reduce these risks, a proper selection of the tunneling method and an adequate cutterhead design (including cutter types and power) are of utmost importance. To this aim, the prediction of cobble and boulder quantities, sizes and locations along the tunnel is mandatory. In this regard, a recent and extensive statistical study has been developed by Napoli et al. [11] to estimate the probability of encountering a number *n* (with *n* from 0 up to more than 10) of rock blocks during tunnel excavations in heterogeneous ground, which resulted in a free executable code, named PBE. Six class sizes of cobbles and boulders, fully or partially located within the tunnel section or along its perimeter, are taken into account. This information can be extremely useful for making a more rational choice of the tunneling technique and designing a more suitable cutterhead. However, a significant limitation of the PBE code is that it requires, among other input parameters, the block content expected within the excavation zone. Although this parameter can be inferred from different subsurface investigation methods or from in-situ surveys, it has been demonstrated that these estimates are affected by a high magnitude of error and that they should not be used without due regard for its variability.

In this paper, an extension of the PBE is presented, that allows the uncertainty in estimates of block quantities from site investigations to be taken into account. Specifically, reference is made to previous works from the literature that provide an uncertainty factor, UF, to adjust the estimated block content as a function of the amount of sampling. Since the UF corresponds to a coefficient of variation (i.e. a measure of dispersion), it provides a range of block contents which should contain the actual one. This UF value can be inserted in the updated version of the PBE code (vers. 1.3) to generate ground configurations with variable quantities of boulders and cobbles. The updated version of the executable PBE code is also provided.

Supplementary Materials: The code is available online at:
https://data.mendeley.com/datasets/w75kfd8ngf/draft?a=e8f41109-de73-4336-9ab9-699e12719bd1 - DOI: 10.17632/w75kfd8ngf.1

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