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Spatial modelling for the assessment of geotechnical parameters

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Abstract

Spatial modelling of geotechnical parameters can help engineers tackle the inherent uncertainty related to the subsurface. In the paper, the 3D spatial modelling is used in order to properly assess geotechnical properties and to identify the problems encountered during the construction of the underground hazardous waste repository of the Lavrion Technological and Cultural Park. The input data used originated from the initial borehole investigation and the analysis focused on the main geotechnical properties of UCS and RQD. The SURPAC software package was used for the development of the 3D spatial models of the subsurface, while the final outputs were presented in the form of block models. The analysis showed good correlation with the actual encountered conditions and was able to identify the risk-prone areas having deteriorated geotechnical characteristics - near the entrance area - as well as to assess the strength of the rock pillars.

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Keywords: Geological uncertainty, Geotechnical parameters, Spatial interpolation/modelling methods, Block modelling.

1. Introduction

Underground projects have been providing solutions to efficiently overcome pressing problems of the modern world. Nevertheless, their cost and their successful development is greatly affected by the conditions encountered during the construction period. Issues that involve uncertainty relating to the geotechnical properties of the ground medium pose threat to the successful accomplishment of the project within the initial time and cost targets. In order to tackle the above mentioned shortcomings, it is essential for the engineers to have a clear view of the geotechnical

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properties at the initial design stages so as to tune-up the construction system and achieve a more efficient meeting of the site-specific demands. Nevertheless, at that exact period, the main obstacle to overcome derives from the variations in the geotechnical properties found or the limited data from which the main assumptions of the design should be drawn. Limited sampling, especially in subsurface drilling, further complicates prediction of soil properties. A solution to resolve the above issues is to launch a more detailed geotechnical campaign. This requires additional funding and more time, however the most disturbing concern is that even under this scenario the level of certainty relating to the properties of the ground medium might not be lowered below an acceptable threshold.

The tackling of the problems described can be made through the use of a more sophisticated analysis taking into account the spatial relationship of the modeled geotechnical property [1, 2]. Prediction of the spatial occurrence of soil properties in either an optimal best estimate or within a probabilistic framework is necessary for effective numerical modeling of soils with heterogeneous properties [3]. In this manner basic assumptions can be drawn with ease, while at the same time the identification of questions and matters that need to be resolved can be targeted with more precision.

The present paper performs a systematic analysis of the prevailing conditions in a complex geological environment with the use of spatial modelling. More particularly, the analysis is made in an attempt to and identify the problems encountered during the construction of the underground hazardous waste repository of the Lavrion Technological and Cultural Park (LTCP), which is used as a case example. Thus, the modelling is made so as to assess the ability of the proposed method to proactively identify risk-prone areas in which failures could be experienced. The models developed take as inputs data from the available initial borehole investigation and are focused on the main geotechnical properties of UCS and RQD. The 3D spatial modelling of the subsurface is made through te development of the block models with the use of the SURPAC software package. Through the spatial analysis performed the assessment of the whole construction area is made possible in terms of their vulnerability related to their geotechnical performance. Accordingly, the most critical zones are accurately depicted and identified. Hence, such information could result in the optimization of the design process and could assist in actively reducing the construction risks.

2. Uncertainty in the geotechnical properties of the ground medium

The design and construction of an underground project is a challenging task for the geotechnical engineer. Incorrect classification of the geological formations and prediction of the behavior of rock formations based on inaccurate - incomplete data can easily lead to different situations between expectations and reality. The clause about "differing site conditions - DSC" has attracted a lot of attention as its use was the standard practice to share the risks - and to raise possible claims - between the involved parties [4].

There have been many efforts to classify and categorize uncertainty in its different modes. According to Morgan et al. [5] a total of 6 major uncertainty types can be discerned: i). Statistical variation, the most common form attributed mainly to measurement errors, ii). Subjective judgment and Disagreement, iii). Linguistic imprecision iv). Variability (of a property in time and/or space, v). Inherent randomness and finally vi). Approximation in the models selected to describe the attribute in question. Christian et al. [6] identify the two basic parameters that contribute to the uncertainty of the ground medium's geotechnical properties. The first is due to the dispersion in the measurements (data scattering), which can be attributed to both the actual existing spatial variability and the random errors made during the measurement process; the second is due to the systematic errors derived though the measurement errors /mishaps as well as due to the limited number of measurement taken that cannot compensate for, or smooth out random errors. The same approach is also followed by [7, 8], which classify uncertainty in the aleatory and epistemic categories. Aleatory uncertainty results from the lack of information and shortcomings in the measurement and calculation process of the property in question. Epistemic uncertainty includes the systematic error resulting from factors such as the method of property measurement, the quantity of available data, and modeling errors, calculations etc. Sampling uncertainty is present because the parameters are estimated from a limited set of data, while testing uncertainty is due to imperfections of an instrument or of a method to register a quantity.

Figure 1 illustrates the types of uncertainty in geotechnical soil properties, according to the above mentioned classifications. As for the contribution of the human errors, they can be considered as a third source of uncertainty, or can be incorporated and included in compilations of statistics on aleatory uncertainty [3].

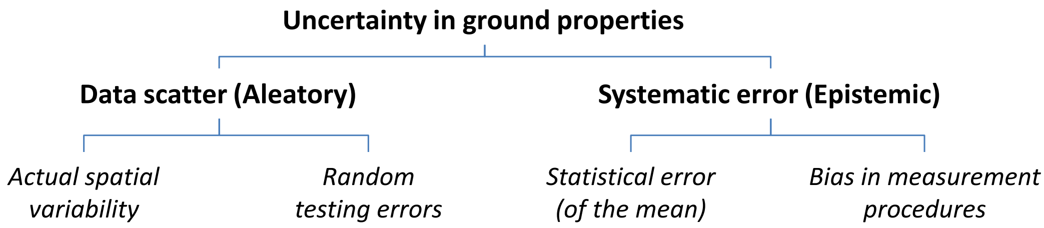

Fig. 1. Categories of sources uncertainty in soil properties (adapted from [6, 7]).

Over the years geotechnical engineers have developed several strategies for dealing with uncertainty. They include: (1) "by ignoring"; (2) "by being conservative"; (3) "by using observational method" or (4) "by quantifying the uncertainty" [8]. The spatial distribution of geotechnical properties in natural soil deposits is difficult to predict deterministically, thus the quantification of uncertainty is usually performed within the framework of probability theory, where soil parameters are modeled as random variables. There are several attempts made [1, 3, 6, 10, 11, 12] either in the form of probabilistic modelling through Monte Carlo simulation or artificial neural networks or with the modelling of the parameters by taking into account its location and interference/influence with the other sampling points, with the use of geostatistics of similar spatial modelling techniques with the use of GIS. In this manner insight on the values of the parameters under investigations can be made available even in points where no investigation has taken place.

3. Problems in the construction of the underground hazardous waste repository in LTCP

The underground hazardous waste repository of LTCP is the first of its kind in Greece and amongst the few underground repositories worldwide [13]. This facility is designed, in relatively low depth, following the principles of the room and pillar mining method. Its storage capacity is approximately 5,000 t, facilitating the storage of the hazardous wastes resulting from the remediation activities undertaken in the LTCP site. The hazardous waste consists mainly of waste having unusually high concentrations of heavy metals and toxic metalloids, such as arsenic, lead, cadmium and zinc.

The LTCP repository is constructed within limestone (Upper Marble of Lavrion), a permeable geologic formation above the water table; thus, key issue in its design was to minimize any possible leakage from the pollutants to the biosphere. This is made possible by firstly adopting a series of support measures, so as to ensure the structural integrity of the site and secondly by installing a series of technical barriers, which in conjunction with the physical barrier system of the host rock, will minimize any pollution risk to the environment. The construction started in 2008 and the repository was delivered in fully operational mode in 2009.

The design was based on a total of 8 boreholes that were drilled to pinpoint the limestone formation strata and to gather information on its geotechnical properties. However, during the construction at the entrance area of the main complex the overlaying strata comprising mainly of graphic schist was revealed at the crown of the excavation, at the level of +16,5 m to +17,0 m. This resulted to local instability phenomena and raised a concern about the structural integrity of the pillars. Figure 2 depicts the area of the graphic schist intrusion where the problems located (ch. E+0 to ch. E+24). It can be seen that the intrusion gradually diminishes and finally vanishes after approximately 25 m from the entrance area. The problems were addressed with a more aggressive support pattern which was installed there, whereas, a monitoring program was introduced to the adjacent pillars to identify any failure initiation.

This failure of the geotechnical investigation campaign to reveal the problematic zone, even if the average distance between the boreholes was about 30-35m, reveals the challenging nature of the ground medium. The pursue of analyzing and decoding the information gained - even from the initial borehole results - so as to provide insight about the conditions anticipated during the construction period is the main driver of the research and methodology presented in the paper. The major assumptions, the methods and finally the results obtained are given in the following sections.

4. Spatial analysis of geotechnical properties

4.1. Main assumptions, data modeled and method of analysis

The analysis was made using the initial results obtained by a total of 9 boreholes that have been drilled as part of the geotechnical investigation campaign (Figure 3). The parameters selected for the investigation were the RQD, the uniaxial compressive strength (UCS), the modulus of elasticity (E) and their analysis was made using the SURPAC software package in order to produce the 3-dimensional block model (Figure 4). At a second stage, the 3D geotechnical mapping would be used to evaluate potential problematic, vulnerable, areas to identify and classify them accordingly.

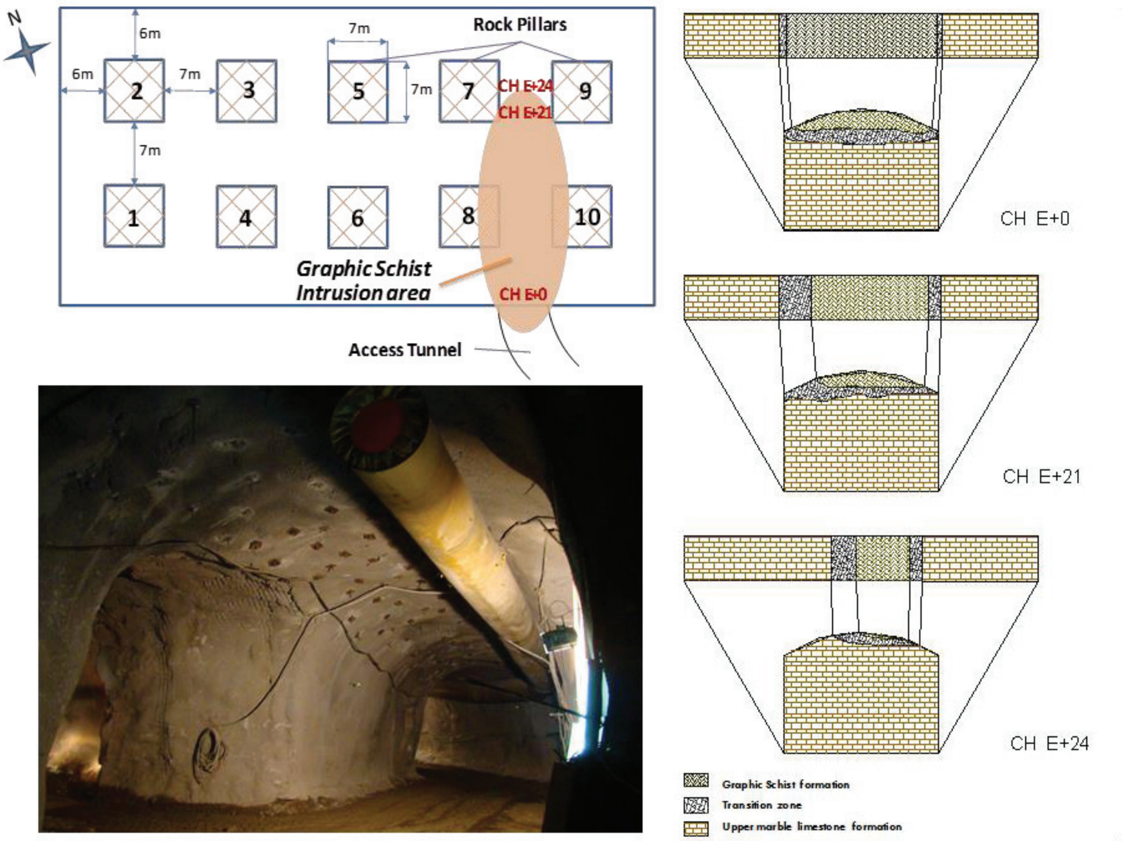

Fig. 2. Details of the graphic schist's intrusion at the repository area and geological mapping of the face. Additionally details of the support measures (bolting) enforced at a denser pattern is shown.

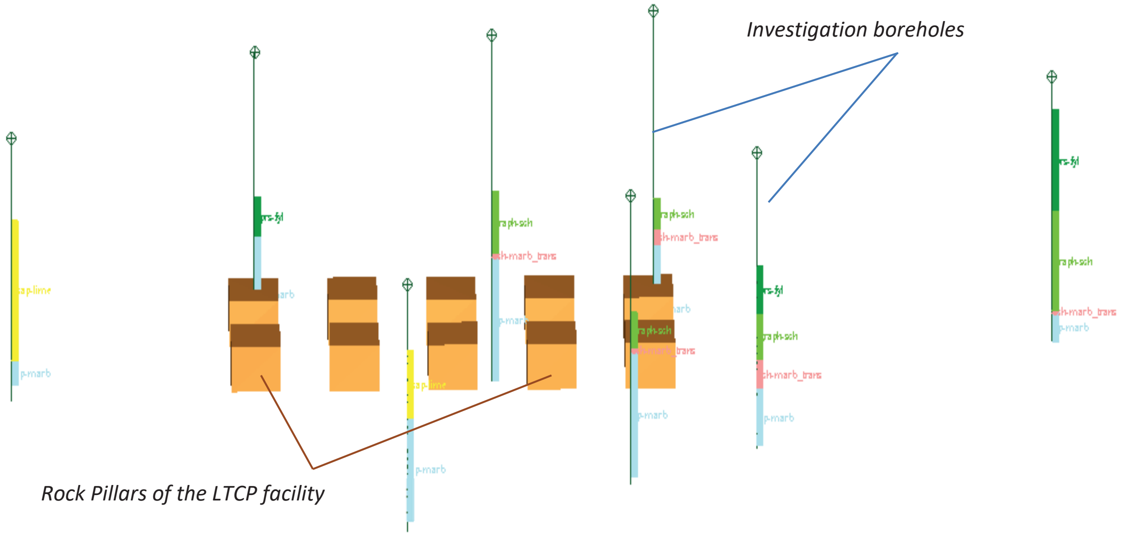

Fig. 3. View of the 9 investigation boreholes with respect to the pillars of the underground repository.

Given the dimensions of the underground repository as well the spacing of the boreholes it was decided to use a block size equal to 3 x 3 x 2 m (L x W x H) so as to have an adequate resolution. Furthermore, the inverse distance weighting (IDW) method was selected for the spatial interpolation of the parameters.

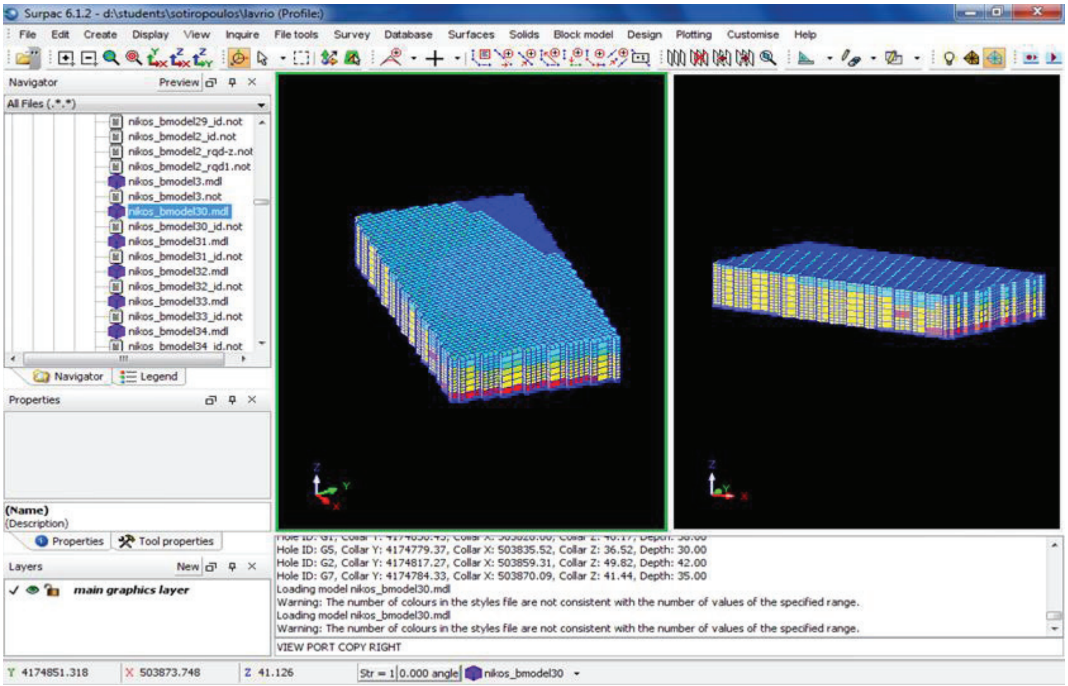

Figure 4. View of the 3d block models that were used for the analysis (RQD).

A total of 31 block model attempts were made in order to try and match the values at various validation points, which have been pre-selected. Such attempts considered a number of parameters to find the optimum sampling pattern. The parameters that were investigated were (in parenthesis the optimum values selected) both the horizontal and the vertical search radius (55m / 2m), the max and min number of samples for the interpolation (3 / 15), the shape of the search ellipsoid (major/semi-major axis:1, bearing:0, dip:0, plunge:0), as well as the composite downhole constraints (0.5m / 75%).

4.2. Results

Some notable results of the analysis performed are given in Figure 5 and 6. In there, the block models of the UCS and the RQD parameters, are presented with a focus given on the most vulnerable areas. Additionally, a number of horizontal sections are illustrated to provide insight and allow for a better understanding of the geotechnical properties at the areas of investigation. It can be seen that in both models there is a relatively vulnerable area at the eastern border of the complex that intrudes the facility and reaches until the area of the access tunnel (entrance area). In terms of UCS the problems seems to be intensified at the level of +19.5m, just above the crown of the tunnel excavation, while for the RQD's case the intensity of the vulnerable area is more clearly identified at the level of +15.5m to +17.5m.

In an attempt to increase the resolution of the analysis it was decided to divide the eastern part of the repository in three analysis areas E1, E2 and E3. The analysis is focusing on the upper part of the pillars and on the roof area as this seems to be the most vulnerable one. More particularly, E1 consists of pillars n.5 and n.6, E2 of pillars n.7 and n.8 and finally E3 of pillars n.9 and n.10. Besides the pillars, all the areas also include the space that each pillar is influencing which roughly reaches until the centre of the room between two adjacent pillars. The results are presented in Figures 7a and 7b, for the case of UCS and RQD, respectively.

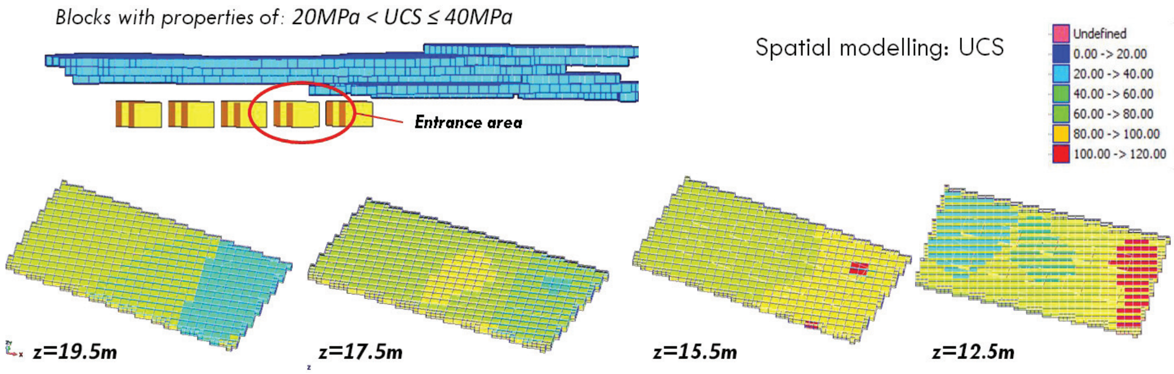

Fig.5. Spatial modelling of the UCS parameter at the area of the LTCP repository (Top: block with UCS values greater than 20MPa, Bottom: horizontal sections depicting the UCS distribution).

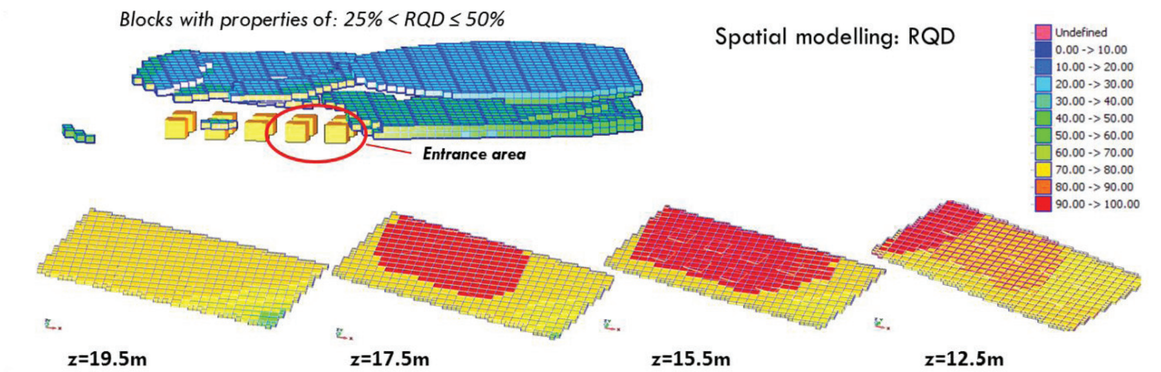

Fig. 6. Spatial modelling of the RQD parameter at the area of the LTCP repository (Top: block with RQD values greater than 25%, Bottom: horizontal sections depicting the RQD distribution).

The spatial analysis in these particular zones concluded in low values of UCS for areas E2 and E3. As far as area E1 is concerned the respective UCS values are generally higher. In addition, the same conclusions are drawn when studying the data deriving from the spatial interpolation of RQD. The most affected area is E3, showing lower quality in its geotechnical characteristics, owing to the intrusion of the graphic schist formation, whereas area E1 displays the higher values among the three.

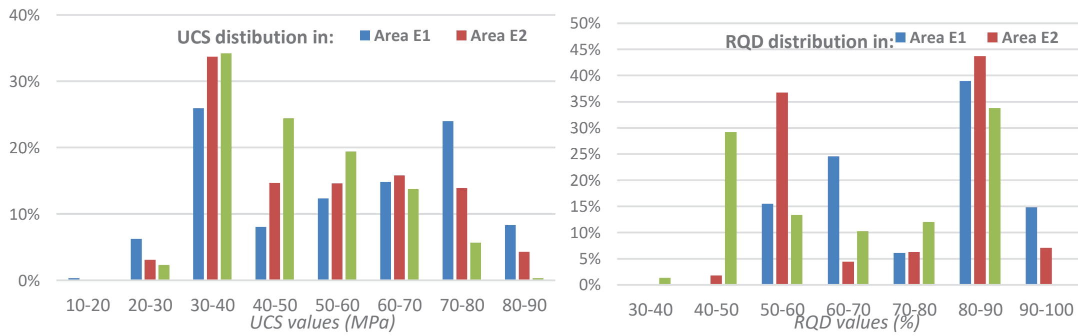

Fig. 7. Distribution of the (a) UCS values and (b) RQD values at the areas under investigation (E1, E2 and E3).

The pillar's geotechnical characteristics can also be assessed and evaluated (Table 5) in terms of the min, max and median values of the modelled RQD and UCS parameters. The most important issue to consider for the pillars are their strength values and hence UCS is the key parameter to monitor. This could allow for a proactive identification of potential vulnerable zones in those important elements of the structure in terms of structural integrity.

Table 1. Analysis of the geotechnical parameters (UCS, RQD) of the rock pillars of the underground facility.

Pillar id (as in Fig. 2)	UCS (MPa)				RQD (%)			
	min_value	max_value	median	st.dev	min_value	max_value	median	st.dev
1	60.79	77.37	69.53	6.48	89.6	95.27	92.75	1.45
2	61.82	76.87	64.81	6.30	90.28	96.85	94.25	2.23
3	59.39	78.55	72.09	7.05	91.77	96.3	94.68	1.61
4	61.45	79.43	71.99	6.71	89.23	96.16	93.25	1.99
5	51.44	82.08	75.48	11.33	93.16	96.72	94.76	1.22
6	55.50	81.69	76.52	9.31	88.81	96.57	93.31	1.85
7	56.55	85.19	76.01	7.05	86.34	95.68	91.44	2.38
8	63.31	84.26	78.01	6.10	87.90	94.23	90.78	1.57
9	57.97	100.97	88.33	16.36	80.00	90.38	83.09	3.84
10	68.39	87.77	85.07	7.28	75.89	87.57	81.33	3.03

In all cases the data derived from the spatial analysis indicate that the pillars are generally in good condition, with the lowest UCS found at 51 MPa and the lowest RQD value to be 75%. It can be seen that the blocks comprising pillar n.5 are displaying the lowest UCS, followed by the values found in pillars n.6 and n.7. Moreover, pillar n.5 is having the lowest median value of 75MPa, while also notable is the great variation that the blocks of pillar n.9 exhibit. Regarding the RQD, the blocks of pillars n.9 and n.10 have both the lowest RQD values and also the highest variance.

The results of the analysis are in good agreement with the ones actually encountered during the construction. The problems were mainly found in area E1, and to a lesser extend to area E2, that needed to adapt the excavation methodology and to leave unexcavated parts that are mainly located in the vicinity of pillar n.9, mainly for precautious reasons. Apart from that the pillars showed no sign of failure or spalling and are still, almost 6 years after the completion of the excavation in very good shape.

5. Conclusions

The increasing utilization of the underground space provides solutions to efficiently overcome pressing problems of the modern world and achieve sustainability goals, especially in the urban areas. The accurate prediction of the risk level for any underground project is very important as any failure in this process results in delays and extra costs.

Underground construction always involves a certain degree of uncertainty regarding the geotechnical conditions of the subsurface. Geological mapping, investigation boreholes and sample testing provide valuable information concerning the geological strata and their mechanical properties at the initial design stages. However, the correlation of this information with the actual encountered conditions during the excavation and construction stages, in many cases, is not satisfactory. To this end, spatial analysis and 3-D geotechnical modelling can be a powerful tool, offering many advantages for engineers as it can be used to identify risk-prone areas - in which failures could be experienced.

In this manner, following the initial investigation campaign, the next step is to use the data to develop the 3-D block model, assess the conditions, discern and classify potential hazardous zones. This can provide valuable insights to properly adapt the construction plan and support design to the geotechnical conditions. The methodology is flexible, operates at a proactive context and therefore can be further calibrated as underground construction proceeds and as it can be constantly fed with actual real-world data.

The present paper outlined the application of such an approach for the underground hazardous waste repository that was constructed in the LTCP in Greece. The analysis and the results stress that spatial analysis offers new possibilities for the use of geotechnical data. In particular, using the RQD, UCS and E as input parameters the analysis highlighted a zone near the entrance of the underground complex where rock mass was poor. The entrance area (eastern part) shows lower values for both RQD and UCS in comparison with the rest of the area. Furthermore, the results suggest that the weak geological formation (graphitic shale) has an EW direction and appears to affect the roof in the region of pillars n.9 and n.10. These are in line with the conditions that were experienced during the construction of the structure. Moreover, the ability to examine smaller areas with increased resolution and the statistical tools from software packages enabled a more detailed perspective for individual pillars of the repository.

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