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Estimation of geomechanical parameters of tunnel route using geostatistical methods

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Abstract. Geomechanical parameters are important factors for engineering projects during design, construction and support stages of tunnel and dam projects. Geostatistical estimation methods are known as one of the most significant approach at estimation of Geomechanical parameters. In this study, Azad dam headrace tunnel is chosen to estimate Geomechanical parameters such as Rock Quality Designation (RQD) and uniaxial compressive strength (UCS) by ordinary kriging as a geostatistical method. Also Rock Mass Rating (RMR) distribution is presented along the tunnel.
Main aim in employment of geostatistical methods is estimation of points that unsampled by sampled points.To estimation of parameters, initially data are transformed to Gaussian distribution, next structural data analysis is completed, and then ordinary kriging is applied. At end, specified distribution maps for each parameter are presented.
Results from the geostatistical estimation method and actual data have been compared. Results show that, the estimated parameters with this method are very close to the actual parameters. Regarding to the reduction of costs and time consuming, this method can use to geomechanical estimation.

Keywords: geostatistics; geomechanical parameters; tunnelling; ordinary kriging

1. Introduction

A rock mass consists of two components: intact rock and discontinuities, each of which has a significant effect on the geomechanical parameters of rockmass. Therefore, reliable estimates of rock mass strength and deformability are very important in rock mass characterization (Yoon *et al.* 2015). Investigation into the geotechnical properties of geological formations along a tunnel route is crucially important because of the economical and safety aspects of high budget tunnel projects. Excavation and support systems for underground openings are designed based on geotechnical properties. These parameters can be obtained directly from laboratory tests that require many high quality samples. Samples of rock subject to laboratory tests are usually acquired through exploratory boreholes. However, in many projects, due to the influence of some factors such as topography, the number and location of boreholes are not in accordance with the mechanical requirements of the project.

Rock mechanics tests performed on cores, despite high precision, due to high costs, core demolition (caving), and present information only in the interval which the core is existent, incapable to providing continuous reports of geomechanical behavior of drilled column (Christaras 2014). In this situation, the core test not used alone, and often indirect and calculation methods using for measurement. The use of geostatistical methods can play a significant role in reducing errors and costs of exploration. The expected benefit from these applications is to obtain the distribution of data for each point in the study area in order to estimate the magnitude of parameters for construction and geotechnical properties. Ozturk and Nasuf (2002) applied kriging to estimate rock quality designation index (RQD), compressive strength (CS), Schmidt hammer hardness (SHH) and net cutting rate (NCR) in some parts of the sewerage system in Istanbul, Turkey. Result of this research was the spatial relationship between the used parameters, with a considerable resemblance between the real and estimated values of the parameters. In addition, geostatistic used successfully to estimate rock mass rating (RMR) from borehole and MT resistivity data (Oh *et al.*, 2004).

Stavropoulou *et al.* (2007) investigated the possibility of reproducing spatial variability of the surrounding rock qualities by kriging. They developed three-dimensional integration of geological datasets, creating a geostatistical and numerical simulation that framed an industry-wide geotechnical design trend. Based on this research, use of geostatistical simulations as input parameters in numerical modeling could provide for more efficient appraisal of rock mass behavior and minimize the need for engineering judgment.

Jeon *et al.* (2009) applied ordinary and indicator kriging and sequential indicator simulation to estimate RMR around the tunnel. The results in this study also support the use of geostatistics to estimate geotechnical properties as ReVs. Oh (2012) proposed the integration of seismic velocity and resistivity data for the evaluation of rock quality based on geostatistical methods. This study illustrates how to investigate geophysical surveys with geostatistics for the

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estimation of RQD. Ozturk and Simdi (2014) applied kriging and cokriging to estimate RQD, Geological Strength Index (GSI), rock mass elastic modulus (Er), elasticity modulus of intact rock (Em), uniaxial compressive strength (UCS) and daily advance rate (AR) in Istanbul subway. The main difference relates to consider the relationship between some parameters and the use of cokriging. The results showed that use of correlated data set with cokriging can be useful to repair insufficient data whiles geostatistical estimation accuracy increases. Doostmohammadi *et al.* (2014) using the software SGEMS modeling geostatistical uniaxial compressive strength along the axis of the Behesht-abad tunnel in central Iran. The validation Process in this study show high accuracy of geostatistical and near the predicted and actual values. In addition, the combined estimation simulation geostatistical and engineering judgment lead to better understand the pros and cons geotechnical investigations in different parts of the tunnel (Woo 2015).

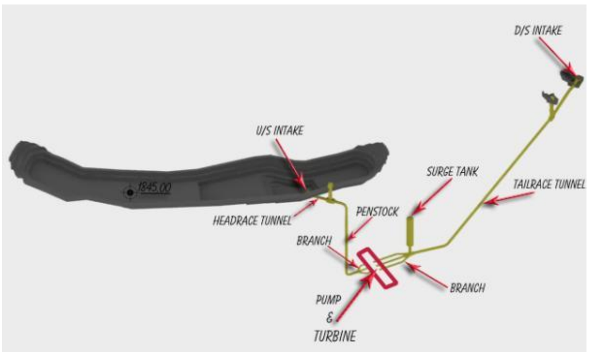


Fig. 1 Schematic layout of Azad PSPP structures

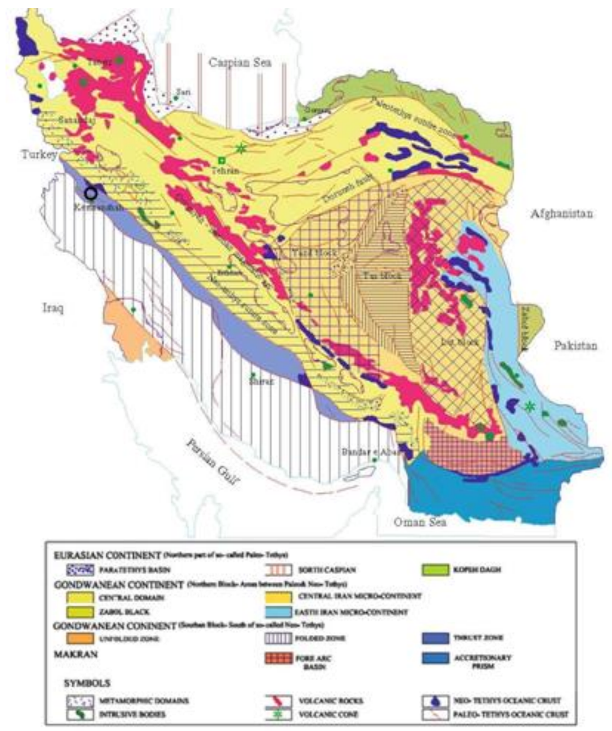


Fig. 2 location of Azad PSPP at geological map of Iran(black circle) (Aghanabati 2004)

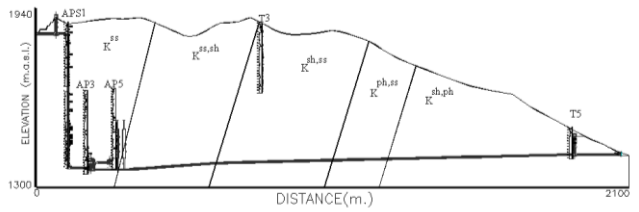


Fig. 3 Geological section along the axis of the tunnel

Table 1 Variations of actual values of RQD

RQD	Unit
55- 45	Kshph
50- 40	Klish
55- 45	Kphss
60- 50	Kshss
85- 75	Ksssh
90- 80	Kss

Table 2 Average of actual values of UCS

UCS (SAT)	Unit
82.85	sandstone
19.38	Schist and philit

2. Geology

The Azad pumped storage power plant (PSPP) project has designed to store hydraulic potentiality using pumping system under low load conditions of the power supply network and then generate electricity by turbine and generator under peak load conditions of the network. The Azad PSPP is composed of two reservoirs and a power plant. The lower reservoir is the Azad dam reservoir, and upper reservoir is made from an excavation at 1,900 m elevation (Fig. 1).

The Azad tunnel is under drilling in order to convey water from Azad dam reservoir pumped storage power plant. The area under tunneling is located in Sannandaj-Sirjan zone of the geological divisions of Iran. (Fig. 2)This formation consists of a series of asymmetric folding and faults and has gone through mild to high metamorphisms. The lithology of this area consists of metamprphed formation. The formation consists of metamorphic shale and sandstone units. Main geological units in the tunnel are units of slightly metamorphosed sandstone (Kss), metamorphosed sandstone and schist (Kss, sh), schist-slightly metamorphosed sandstone (Ksh, ss), philit-metamorphosed sandstone (Kph, ss), schist and philit (Ksh, ph), shale and limestone shale (Kli, sh), and young alluvial Trusts (Qt). (Fig. 3) The tables 1 and 2 show the values of the geomechanical properties of the various units.

The geomechanical parameter of each units are described in the Tables 1 and 2.

3. Methodology

The aim of the geostatistical methodology is to estimate the variable value at unsampled locations. Base of the geostatistical methodology is existence spatial structure. The variogram is more important tool for recognition this structure and also spatial correlation between data. The variogram is defined as the average of squares of difference of the two variables that their distance is h. An experimental variogram function can be determined as follows

$$\gamma\ (h) = (1/2n)\ \Sigma[\ p(x) - p(x+h)]^2 \qquad (1)$$

where n is the number of pairs that their distance is h; and $p(x)$ is valueof the variable at locacation x, $p(x+h)$ isvalue of the variable at location $x+h$**.**

Kriging is a form of weighted average estimator. The weights are assigned on the basis of a model fitted to a function, such as the semivariogram, which represents spatial structure in the variable of interest (Lloyd and Atkinson, 2001, Aalianvari *et al*. 2013). Ordinary kriging (OK) is known as the most frequently used form of kriging. Based on the ordinary kriging algorithm, the value of variable p atunsampled location x_0 could be estimated as follows

$$p(x_0) = \sum w_i\ p(x_i) \qquad (2)$$

where p(xi) isthe measured value at location $x_i$and w_i is the weight of i^{th} sample.The weights $w_i$are obtained by minimizing the estimation variance as follows

$$Min\ \ \sigma_e^{\ 2} = 2[\sum \bar{\gamma}(x_0, x_i)] - \sum\sum w_i w_j \bar{\gamma}(x_i, x_j)$$
$$s.t: \sum w_i = 1$$

where $\sum \bar{\gamma}(x_0, x_i)$ is the weighted average of semivariogram values between the whole set of information points and the point being estimated, $\sum\sum w_i w_j \bar{\gamma}(x_i, x_j)$ is the weighted average of semivariogram values between all possible paired points.A problem with two unknown parameters in the above equation can be solved using the kriging matrix given in Eq. (3).

$$\begin{bmatrix} \bar{\gamma}(x_1,x_1) & \bar{\gamma}(x_1,x_2) & ... & \bar{\gamma}(x_1,x_n) & 1 \\ \bar{\gamma}(x_2,x_1) & \bar{\gamma}(x_2,x_2) & ... & \bar{\gamma}(x_2,x_n) & 1 \\ ... & ... & ... & ... & ... \\ \bar{\gamma}(x_n,x_1) & \bar{\gamma}(x_n,x_2) & ... & \bar{\gamma}(x_n,x_n) & 1 \\ 1 & 1 & ... & 1 & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ ... \\ w_n \\ \mu \end{bmatrix} = \begin{bmatrix} \bar{\gamma}(x_0,x_1) \\ \bar{\gamma}(x_0,x_2) \\ ... \\ \bar{\gamma}(x_0,x_n) \\ 1 \end{bmatrix} \qquad (3)$$

where μ is the Lagrange parameter. The required data for this kriging matrix can be determined from the theoretical semivariogram.

4. Geostatistical application

In order to estimation of geomechanical parameters using geostatistical methods, the required including coordinates, position, length and depth of holes, also azimuth and dip of holes, have been collected from the exploratory drilling (Fig. 3).

For ordinary kriging estimation, dataset should follow normal distribution. In this study, distribution of data isn't normal, so the data must be normalized. The important

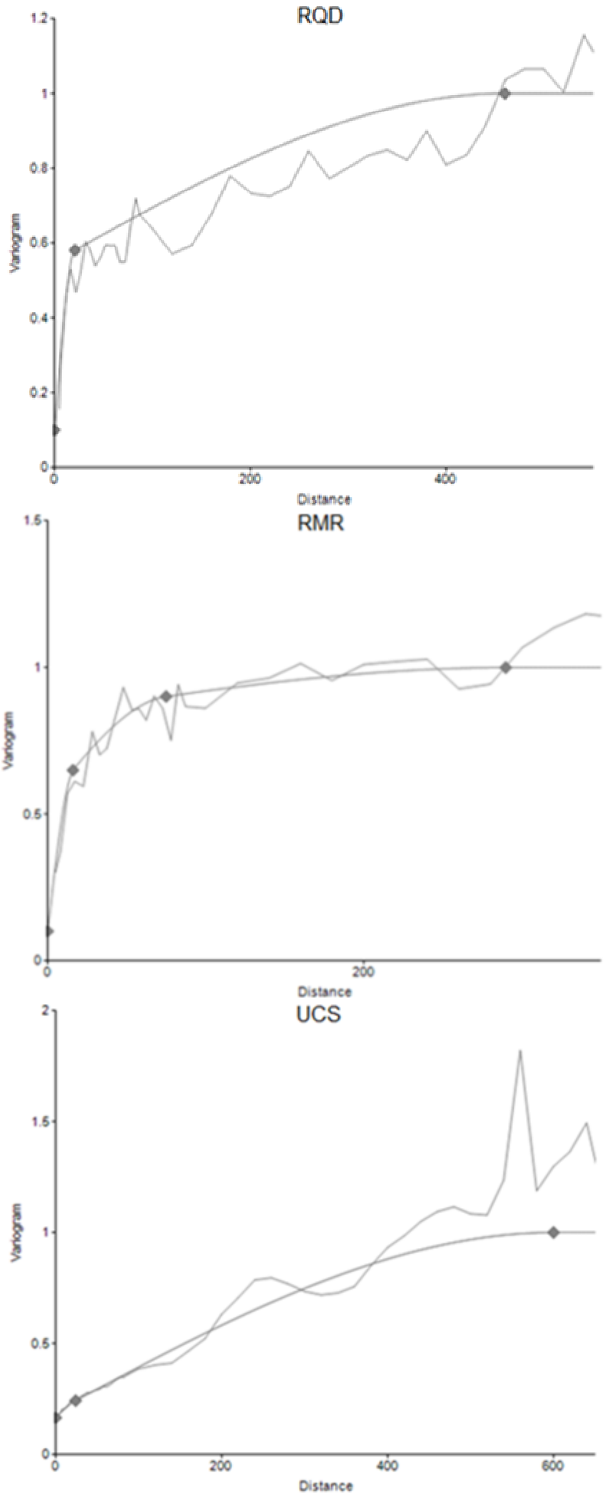


Fig. 4 Experimental Log variograms and fitted models for RQD, RMR and UCS parameters

Table 4 Fitted variogram modelparameters and the r^2 resulted from cross validation

ReV	Varigram parameters				
	Model	C0	C0+C	A0	r^2
RQD	Spherical	0.100	1	460	0.828
UCS	Spherical	0.165	1	600	0.909
RMR	Spherical	0.100	1	290	0.869

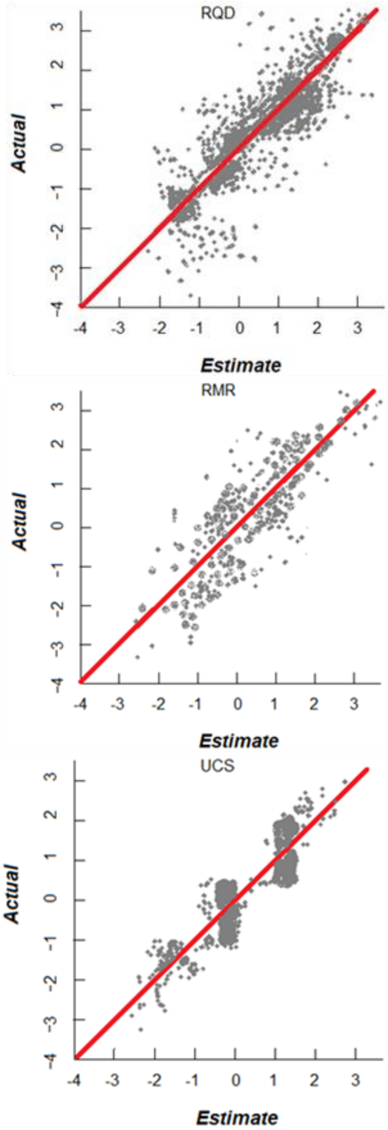


Fig. 5 Comparison of actual and estimated magnitudes

point here is back transformingestimation result to primary data distributionafter kriging. The next step is varipgrhpy. In this step, the experimental variogram calculation, anisotropy study and model fitting should be done. The experimental log-variogram of geomechanical parameters and fitted models are shown in Fig. 4. The variogram model parameters are listen in table 1. Due to limited data, fitting the proper models to directional experimental variograms isnot possible, thereforestudying the anisotropy is impossible.The cross-validation method is used for validation of the results. The results of the cross-validation process are shown in Fig. 5 and the r^2 statistics are inserted in Table 4. The high values of r^2 show the proper fitting of estimated values to the real values.

5. Estimation of geomechanical properties in Azad dam by ordinary kriging

After structural analysisst, ordinary log-kriginghas been used to estimation process. The estimation process needing

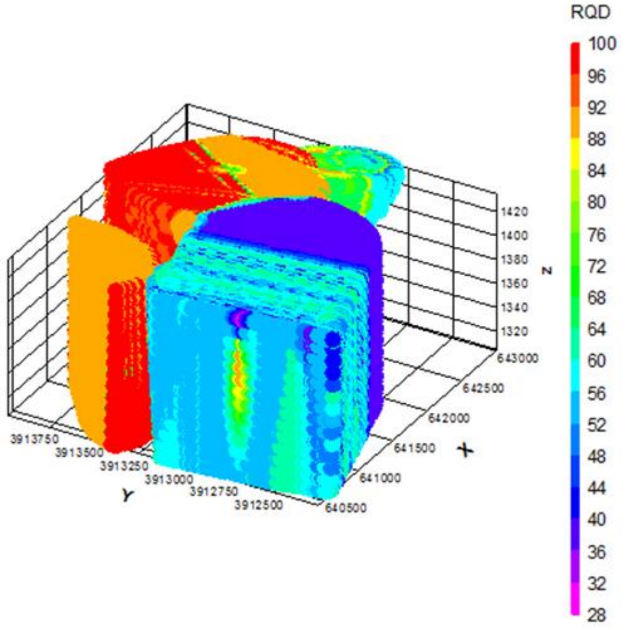
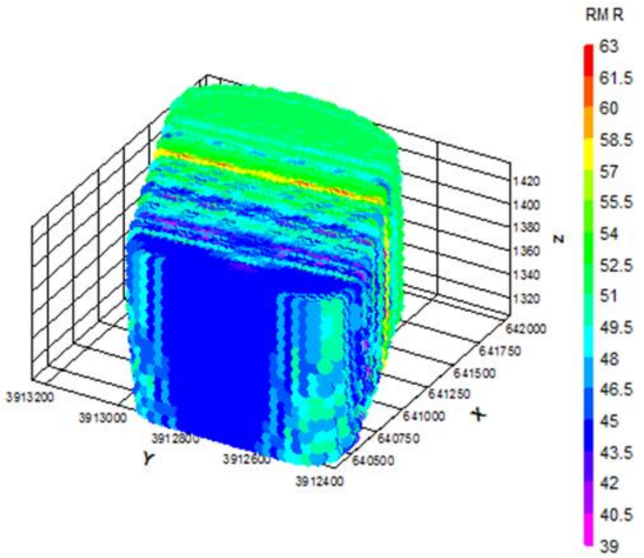
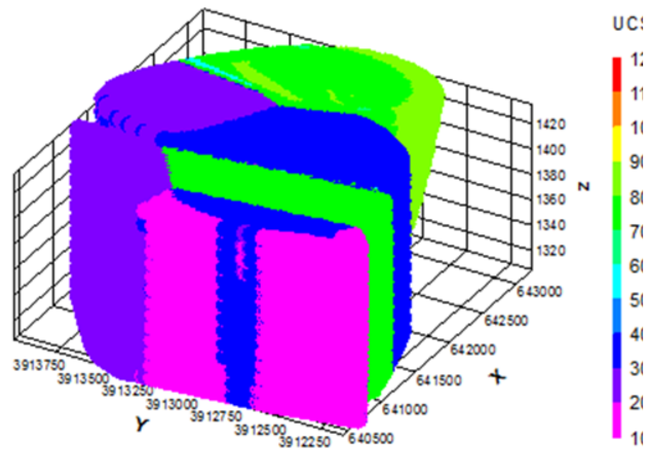


Fig. 6 Distribution map for RQD at 3D space



(a)



(b)

Fig. 7 (a) Distribution map for RMR at 3D space and (b) Distribution map for UCS at 3D space

Table 5 Variations of estimated values of RQD

RQD	Unit
55- 65	Kshph
45- 55	Klish
55- 45	Kphss
55- 45	Kshss
55- 45	Ksssh
90- 80	Kss

Table 6 Variations of estimated values of UCS

UCS (SAT)	Unit
75- 100	sandstone
5- 25	Schist and philit

Table 7 Statistical study for actual values of parameters

ReV	min	max	mean	variance
RQD	26.547	100.000	64.884	440.503
UCS	5.432	122.619	45.677	519.967
RMR	38.926	63.260	49.403	11.207

Table 8 Statistical study for estimated values of parameters

variable	min	max	mean	variance
RQD	0.000	100.000	61.6762	800.035
UCS	1.800	131.80	43.1187	40.533
RMR	27.000	67.50	48.2823	758.018

several steps that each requires enough attention. The study area is divided into 658860 blocks with a size of 20 m×20 m×10 m. Next, the value of geomechanical parameters has been estimated in the block model and estimated values has been back-transformed to their primary distribution. Finally kriging maps determinated, in three dimension, for each parameters. Distributions are given in Figs. 6-8 for RQD, RMR and UCS, respectively. Variability of each parameter toward the depth is justifiable by lithology variation and decrease of joints density in more depths. Preparation of kriging maps for the study area remind that distribution of variables can't be achieved by classical methods and these maps can be used to interpret the geomechanical properties of the rock mass.

In order to compare the results of estimation by ordinary kriging method provided Tables 5 and 6 to determine the estimated values and the validity of the used method. In general, taking into account the results of distribution maps, the quality of the rock mass in different parts of the tunnel is stated as follows

Table 6 indicates mean of estimated compressive strength of the various units in the saturation condition. With good approximation, estimated values can be near to real values for RQD and UCS. RMR also at the purpose section has an average of 48 related to real data and the results of the estimated value of this parameter is between 40-55 which indicates the efficiency of the used method. Tables 7 and 8 show the statistic properties both real and estimated values.

6. Conclusions

In this study, Azad dam headrace tunnel is chosen to show usability and importance of geostatistical methods for high budget tunnel projects. Geostatistical methods used to determine rock quality index (RQD) and geomechanical rock mass classification (RMR) as rock mass parameters and uniaxial compressive strength (UCS) as a parameter of rock material. The requirement data were collected from previous studies that core sampling obtained from 24 boreholes. After conversion of variables to the normal data, distributions of RQD, RMR and UCS, was determined by semivariogram functions and utilization kriging as a geostatistics method. It is therefore possible to estimate each variable for points that unsampled in the study area. Maps of the distribution of all the variables were collected to understand the relationship of each variable based on their magnitudes and location in a graph. The quality of Geostatistical models that specified in this study was investigated by scattering the estimated values of the variable determined using geostatistical model with the actual values. The results show that most of the estimated values of the geotechnical parameters are highly relevant to the actual values.

The match between the distribution of the estimated parameters and geological position of area, results of estimates are acceptable. This study shows that kriging maps can be used to determine the value of a variable in unsampling locations. Variogram function is applicable to find the efficacy range, which is useful for geotechnical planning of the boreholes location. This type of estimate will be useful to extrapolate for the same places and the creation of a mechanism to analyze geotechnical and construction data for the tunnel projects. Describe the spatial distribution of geomechanical properties in correlate regions with tunnel and sidelong foundations, uses in many fields of applied geology, including: Locate boreholes, design of drilling, support of underground spaces and opening, stability analysis and etc.

References

Aalianvari, A. (2014), “Optimum depth of grout curtain around pumped storage power cavern based on geological conditions”, *Bull. Eng. Geol. Environ.*, **73**(3), 775-780

Aalianvari, A., Tehrani, M.M. and Soltanimohammadi, S. (2013), “Application of geostatistical methods to estimation of water flow from upper reservoir of Azad pumped storage power plant”, *Arab. J. Geosci.*, **6**(7), 2571-2579.

Barton, N. (1983), “Application of Q-system and index tests to estimate shear strength and deformability of rock masses”, *Proceedings of the International Symposium on Engineering Geology and Underground Construction*, Lisbon, Portugal.

Bieniawski, Z.T. (1978), “Determining rock mass deformability: experience from case histories”, *J. Rock Mech. Min. Sci. Geomech. Abstr.*, **15**(5), 237-247.

Chilès, J.P. and Delfiner, P. (1999), Geostatistics: Modeling Spatial Uncertainty, Wiley, New York, U.S.A.

Christaras, B. and Chatziangelou, M. (2014), “Blastability quality system (BQS) for using it, in bedrock excavation”, *Struct*. *Eng*. *Mech*., **51**(5), 823-845.

Deutsch, C.V. and Journel, A.G. (1997), *Geostatistical Software Library and User's Guide*, Oxford University Press, New York, U.S.A.

Doostmohammadi, M., Jafari, A. and Asghari, O. (2014), “Geostatistical modeling of uniaxial compressive strength along the axis of the Behesht-Abad tunnel in Central Iran”, *Bull*. *Eng*. *Geol*. *Environ*., **74**(3), 789-802.

Exadaktylos, G. and Stavropoulou, M. (2008), “A specific upscaling theory of rock mass parameters exhibiting spatial variability: Analytical relations and computational scheme”, *J*. *Rock Mech*. *Min*. *Sci*., **45**(7), 1102-1125

Exadaktylos, G., Liolios, P. and Barakos, G. (2007), “Some new developments on the representation and standardization of rock mechanics data: from the laboratory to the full scale project”, , *Proceedings of the 11th International Congress on Rock Mechanics*, Lisbon, Portugal, July.

Gurocak, Z. and Kilic, R. (2005), “Effect of weathering on the geomechanical properties of the Miocene basalts in Malatya, Eastern Turkey”, *Bull*. *Eng*. *Geol*. *Environ*., **64**(4), 373-381.

Hejazi, Y., Dias, D. and Kastner, R. (2008), “Impact of constitutive models on the numerical analysis of underground constructions”, *Acta Geotech*, **3**(4), 251-258.

Jeon, S., Hong, C. and You, K. (2009), *Design of Tunnel Supporting System Using Geostatistical Methods*, in *Geotechnical Aspects of Underground Construction in Soft Ground*, 781-784.

Öztürk, C.A. and Nasuf, E. (2002), “Geostatistical assessment of rock zones for tunneling”, *Tunn*. *Undergr*. *Sp*. *Technol*., **17**(3), 275-285.

Woo, J., Kim, D. and Na, W.B. (2015), “Application of numerical simulation of submersed rock-berm structure under anchor collision for structural health monitoring of submarine power cables”, *Smart Struct*. *Syst*., **15**(2), 299-314.

Yoon, S., Lee, S.R., Kim, Y.T. and Go, G.H. (2015), “Estimation of saturated hydraulic conductivity of Korean weathered granite soils using a regression analysis”, *Geomech*. *Eng*., **9**(1), 101-113.

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