Quantification of rock behavior around shallow depth tunnel by Rock Engineering Systems

Man-Kwang Kim, Young-Il Yoo and Jae-Joon Song
(Department of Energy Systems Engineering, Seoul National University)

1. INTRODUCTION

Identifying rock behavior expected in excavating tunnel can assist engineers not only to select tunneling method and support pattern but also to evaluate tunnel stability by numerical analysis adjusted to rock behavior. Rock behavior could be identified by interaction among parameters influencing rock behavior. Many researchers have studied how to identify rock behavior from parameters influencing rock behavior in tunneling. Poschl and Kleberger (2004) described that parameters influencing rock behavior was divided into rock mass properties and circumstantial factors and that rock behavior was identified by combination between them in unsupported stage of tunneling. Martin et al. (2003) illustrated two common modes of failure: stress-driven and gravity-driven based on geological strength index (GSI) value, rock mass strength, and in-situ stress. Goricki et al. (2004) described that rock behavior types were developed from rock mass type and influencing factors such as groundwater, joint orientation, and primary stress conditions and classified the rock behavior into eleven types in the pre-construction stage. Stille and Palmstrom (2007, 2008) have shown that three main ground behaviors, namely gravity driven, stress driven, and water influenced behavior, could be classified by the composition and structure of rock mass, the effect of stresses, ground water, and excavation features and that they might be expressed by a qualitative chart. Goel (2001) reported nine rock behavior types from Himalayan tunneling.

Many researchers have studied how to predict instability and obtain a safety factor on rock behavior in tunneling. Martin et al. (2003) described the instability of spalling behavior in brittle hard rocks through uncertainty analysis using the Monte Carlo Simulation (MCS) method. Sakurai (1997) described the tunnel instability by using critical strain. For squeezing rock behavior, Singh et al. (2007) demonstrated that the extent of squeezing was defined by the ratio of the expected strain and the critical strain and Hoek demonstrated the extent of squeezing was defined by only expected strain. Cai et al. (2004) illustrated brittle failure zone on quantified GSI chart determined by block volume and joint surface condition.

Rock Engineering Systems (RES) could be applied to identifying rock behavior among parameters and obtain their weighting. Hudson (1992) proposed the RES methodology to solve the rock engineering problems using interaction matrix. Benardos and Kaliampakos (2004) reported about the method to assess the hazards by using a vulnerability index, which is computed based on the principles of the RES, and to determine the weight of the eight parameters on tunnel boring machine tunneling. Until now, most of studies to identify rock behavior were qualitative except for some quantitative studies on brittle rock behavior such as spalling and squeezing. However, these studies, however, didn’t consider relative importance and weighting among parameters affecting rock behavior. The purpose of this study is to quantify rock behavior of shallow depth tunnel by the Rock Engineering Systems. Rock behaviors such as cave-in, rock fall, and plastic deformation are identified from rock mass intrinsic parameters (uniaxial compressive strength (UCS), RQD, joint surface condition), rock mass extrinsic parameters (stress, ground water, earthquake), and a design parameter (excavation span). All seven parameters are mutually independent and able to be easily evaluated. We applied the proposed method to the basic design of Seoul Metro Line 9 and quantified the rock behaviors by three rock behavior index (RBI) on fall, cave-in, and plastic deformation.

2. Identification of rock behaviors and their influencing parameters

Three parameter categories dominate rock behavior (Table 1): rock mass intrinsic parameter (uniaxial compressive strength (UCS), RQD, joint surface condition), rock mass extrinsic parameter (stress, ground water, earthquake), and design parameter (excavation span). Rock behavior could be identified by combination among parameters influencing rock behavior. All parameters affecting rock behaviors could not be considered to identify rock behavior due to limitation of geology survey and difficulty in modifying tunnel alignment and tunnel construction method. Because the strength and elastic modulus of intact rock were highly correlated, the strength of intact rock was only considered as intact rock parameter. As it was difficult to obtain information on joint size, joint orientation and joint number of joint set without exposed rock face sampling such as scanline sampling and window sampling, joint condition and RQD obtained from boring were considered as joint parameters. As construction method and blasting damage and excavation shape of construction parameters were generally determined by characteristic of tunnel, excavation size was only regarded as construction parameter. Extrinsic parameters were considered as groundwater, stress, and dynamic condition such as earthquake and blasting. Many researchers have studied rock behavior type and main parameters affecting rock behavior (Table 2).

Table 1. Group of Parameters affecting rock behaviors (from Cai et al., 2004)

Group of parameters		**Individual parameters**
Rock mass inherent parameters	1. Intact rock parameters	Strength of intact rock Rock modulus
	2. Joint parameters	Number of joint sets Joint frequency Joint condition (roughness, infilling) Joint size/length, persistency Joint orientation
	3 Weak zones or faults	Width Orientation Gouge material (modulus and strength)
External parameters		In situ stress Ground water
Construction parameters (excavation parameters)		Excavation size Excavation shape Construction method Blasting damage

In deep tunneling, rock mass strength, ground stress, and RMR were key parameters to identify brittle failure. In shallow depth tunneling, joint condition, ground water, ground stress, and tunnel size could be important parameters to identify gravity driven rock behavior and stress driven rock behavior. From experiences gained by the new Austrian tunneling method (NATM) tunneling in shallow depths, the ground behavior could be identified and determined by the ground conditions. For heavily joint rock condition, *plastic deformation* behavior or *cave-in* behavior was expected. The former indicates that under low confining pressure, shear failure progressively increases and causes plastic displacement and the latter indicates an inward, quick movement of a large volume of rock fragments or pieces. For blocky rock condition, *rock fall* was expected, indicating that the rock blocks move down driven by gravity. *Plastic deformation* was also defined as follows: plastic deformation was the shear displacement of the ground which causes the tunnel periphery to move inward and is initially caused by redistributed stress after excavation. Figure 1 shows rock behavior types expected in shallow depth rock tunnel.

Table 2. Comparison on main parameters on rock behaviors

Researchers	Main parameters	Rock behavior type
Martin et al. (1999)	RMR UCS Ground stress	10 types: stable, rock falls, cave-in, buckling, rupturing, spalling/slabbing, rockburst, plastic behavior, squeezing or swelling, swelling clay
Kaiser et al. (2000)	RMR UCS Ground stress Induced stress	Low mining-induced stress Intermediate mining-induced stress High mining-induced stress
Martin et al. (2003)	GSI UCS Ground stress	Stress-induced plastic yielding Gravity-induced structurally controlled block movement Stress-induced brittle spalling
Goricki et al. (2004)	Rock type Ground water Joint orientation Ground stress Tunnel size, shape	11 types: stable, stable with the potential of discontinuity controlled block fall, shallow shear failure, deep-seated shear failure, rockburst, buckling, shear failure under low confining pressure, ravelling ground, flowing ground, swelling, Heterogeneous rock mass with frequently changing deformation characteristics
Palmstrom & Stille (2007)	Rock type Ground water Joint orientation Ground stress Tunnel size, shape	Gravity-induced (4 types): stable, block falls, cave-in, running ground Stress-induced (6 types): buckling, rupturing from stresses, slabbing, rockburst, plastic behavior, squeezing Groundwater influenced (4 types): raveling from slaking, swelling, flowing ground, water ingress

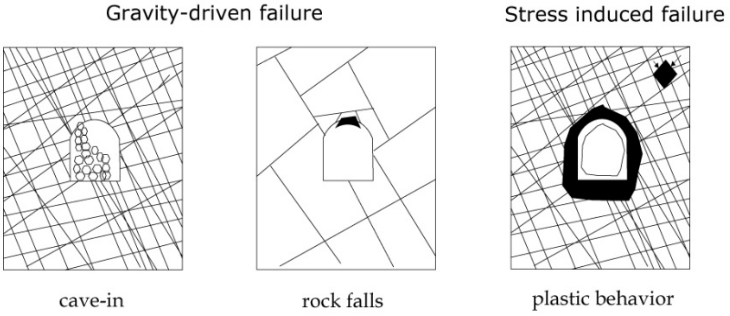

Fig. 1 Rock behavior types in shallow depth rock tunnel

3. Quantification of rock behavior index

3.1 Weighting of parameters according to rock behaviors using Rock Engineering Systems method

Hudson (1992) proposed the Rock Engineering Systems (RES) methodology to solve the rock engineering problems using interaction matrix. The concept of interaction matrix dates from the 1970s (Leopold et al., 1971). It was used to evaluate cause-and-effect relationship between existing (environment/natural) factors and human actions. It was then modified and applied to rock stability problems (Hudson, 1992; Hudson and Harrison, 1992; Mazzoccola and Hudson, 1996), environment problems such as the disposal of spent fuel (Skagius et al., 1997), river catchment pollution (Matthews and Lloyd, 1998) and sewer collapse problems (Davies et al., 1999).

Parameter interactions can be evaluated using a matrix display and are to be read in a clockwise sense, as they might be path independent (Hudson, 1989). To quantify the different importance of the interactions, a coding method is required. Hudson (1992) proposed an Expert semi-quantitative (ESQ) method shown in Table 3.

Table 3. ESQ-coding of the parameters' interaction intensity used in the model (Hudson, 1992)

Coding	Description
0	No interaction
1	Weak interaction
2	Medium interaction
3	Strong interaction
4	Critical interaction

Consider the diagram in Figure 2 which shows the generation of the cause and effect co-ordinates. From the construction of the matrix, it is clear that the row passing through P_i represents the influence of P_i in all the other parameters in the system (i.e. the Cause value). Also, the column through P_i represents the influence of the other parameters (i.e. the Effect value). In the matrix, the sum of coding value being I_{ij} in the system. Thus, the following are evaluated:

$$C_{Pi} = \sum_{j=1}^{n} I_{ij} \tag{1}$$

extent to which the parameter affects the system,

$$E_{Pj} = \sum_{i=1}^{n} I_{ij} \tag{2}$$

extent to which the parameter is affected by the system (Hudson, 1992).

The interactive intensity value of each parameter is denoted as the sum of the C and E values $(C+E)$, which is used as the parameter's weighting factor $W1_i$ according to the following expression:

$$W1_i = \frac{(C_i + E_i)}{(\sum_i C_i + \sum_i E_i)}(\%) \tag{3}$$

Where, C_i is cause of the *i*th parameter, E_i is effect of the *i*th parameter, *i* is number of principal parameters.

$$W2_{ki} = \frac{E_{ki}}{\sum E_{ki}}(\%) \quad (k = 1, 2, 3) \tag{4}$$

Where, E_{ki} is effect of the *i*th parameter.

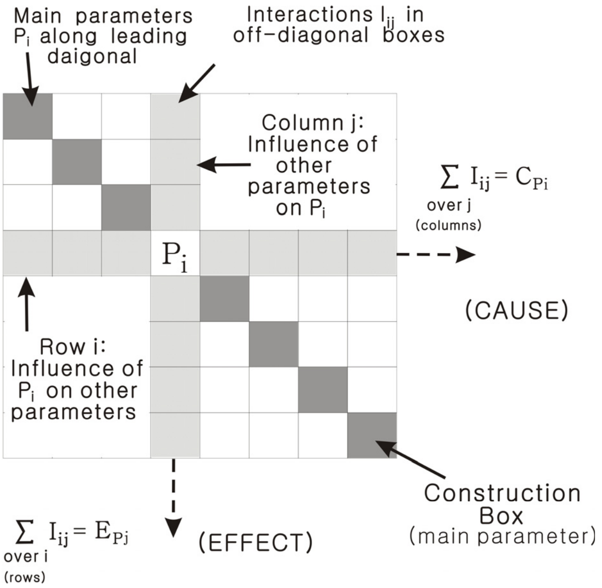

Fig. 2 Summation of coding values in the row and column through each parameter to establish the cause and effect co-ordinates (modified from Hudson, 1992).

To determine the priority of each parameter, twenty five experts' opinions are reflected in this study using questionnaire (Table 4). Figure 3 shows that there is a tendency allowing discrimination between 'less interactive: earthquake' and 'more interactive: SCR and tunnel span' parameters because of $(C+E)$ values.

Table 4. Interaction matrix coding for study area

	E_1	E_2	E_3	E_4	E_5	E_6	E_7	Rock behavior		
C_1	**UCS**	1.2	0.8	1.4	0.3	0.2	1.7	0.9	1.2	2.4
C_2	1.6	**RQD**	2.4	1.2	1.9	0.5	2.2	2.7	3.2	2.1
C_3	1.5	2.1	**SCR**	1.4	2.2	0.8	2.4	3.2	3.2	2.0
C_4	1.6	1.9	1.8	**Stress**	0.7	1.2	2.5	1.4	1.5	3.2
C_5	1.6	1.5	2.4	1.2	**Ground water**	0.3	2.4	2.1	2.6	1.6
C_6	0.2	0.4	0.9	1.4	0.4	**Earth-quake**	1.1	1.6	1.4	0.9
C_7	0.9	0.8	1.2	2.2	1.8	0.4	**Tunnel Span**	2.6	2.2	2.2
								Rock fall	**Cave -in**	**Plastic Deformation**

$$W_{ki} = (W1_i \times W2_i)^{1/2} \tag{5}$$

Table 5 shows principal parameter weighting ($W1_i$) and rock behavior weighting ($W2_{1i}, W2_{2i}, W2_{3i}$) according to the equation (3), (4) and (5). At last, These weightings make the final weighting. Principal parameter's weighting means that the importance among principal parameters influencing instability of shallow depth rock tunnel; rock behavior weighting factor means that the importance among principal parameters which has influence on the rock behavior.

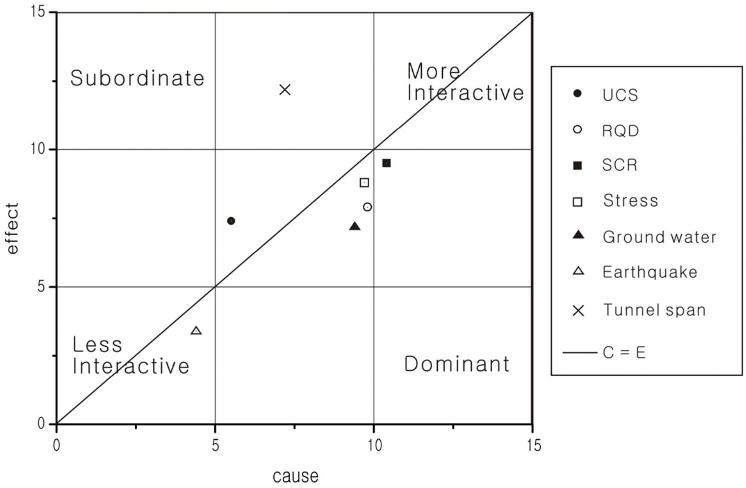

Fig. 3 The cause and effect values for each parameters are the taken x and y coordinates to plot the parameters in a cause versus effect diagram

As shown in Table 5, three parameters (SCR, RQD, Tunnel span) are dominant position in rock fall, four parameters (SCR, RQD, Ground water, Tunnel span) are dominant position in cave-in. Also, three parameters (Stress, SCR, Tunnel span) are dominant position in plastic deformation.

Table 5. Weighting factor and Final weighting factor of the principal parameters

	Principal weighting	Rock behavior weighting			Final weighting		
	$W1_i$	$W2_{1i}$	$W2_{2i}$	$W2_{3i}$	W_{1i} (rock fall)	W_{2i} (cave-in)	W_{3i} (plastic deformation)
UCS	0.12	0.06	0.08	0.17	0.09	0.09	0.14
RQD	0.16	0.18	0.21	0.15	**0.17**	**0.18**	0.15
SCR	0.18	0.22	0.21	0.14	**0.20**	**0.19**	**0.16**
Stress	0.16	0.10	0.10	0.22	0.13	0.13	**0.19**
Ground water	0.15	0.14	0.17	0.11	0.15	**0.16**	0.13
Earthquake	0.07	0.11	0.09	0.06	0.09	0.09	0.07
Tunnel span	0.17	0.18	0.14	0.15	**0.17**	**0.16**	**0.16**

3.2. Calculating rock behavior index (RBI)

Rock behavior index (RBI) could be used as a potential indicator on rock behavior expected in shallow depth rock tunnel. It was expressed as linear combination of the parameter's weighting (W_{ki}, $k=1$: rock fall, $k=2$: cave-in, $k=3$: plastic deformation) and its respective rating (P_i) as shown in Table 6.

$$RBI = (100 - \sum_{i=1}^{n} W_{ki} \frac{P_i}{P_{\max}}) \tag{6}$$

Where, $P_{\max}$ is the maximum value a parameter can take as normalization factor.

The RBI ranges from 0 to 100 (Table 7). In a more explicit manner, five major categories could be classified. If RBI value is more than 60, the possibility of rock behavior can be high.

Table 6. Suggested rating of parameters affecting rock behavior in shallow depth tunnel

Parameters	Description	Classes	Rating				
			0	1	2	3	4
UCS (MPa)	-	P_1	< 25	25-50	50-100	100-250	> 250
RQD (%)	-	P_2	< 20	20-40	40-60	60 - 80	> 80
Joint surface condition	Joint weathering+Joint infilling+JRC	P_3	< 3	3-8	8-12	12 - 15	> 15
Stress condition	Overburden height/Tunnel Span	P_4	< 1.0	1.0-1.5	1.5-2.5	2.5-3.5	> 3.5
Groundwater condition	Ground water level - tunnel crown level (m)	P_5	> 15	10-15	5-10	0-5	< 0
Earthquake	Earthquake intensity	P_6	>0.25g	0.20-0.25g	0.15-0.20g	0.1-0.15g	< 0.10g
Excavation span	Joint spacing /Tunnel span	P_7	< 1/200	1/200-1/100	1/100-1/50	1/50-1/5	> 1/5

Table 7. Rock behavior index (RBI) catagories

Linguistic values: Rock Behavior Index (RBI)	0~20	20~40	40~60	60~80	80~100
Linguistic terms	Very Low Probable	Low Probable	Moderately Probable	High Probable	Very High Probable

4. Case Study

Seoul metro Line 9 will be located in Kangnam-Gu, Seoul. The total length of the case study site of Seoul metro Line 9 is 1.77km with a tunnel length of 1.41km. The tunnel will be excavated by conventional drill and blasting method. Gneiss was mostly distributed in this site and four fracture zones were estimated from boring, geophysical prospecting and geological survey (Figure 4). Most of the tunnel sections were double-lane track sections (PD). Sections connected to the tunnel station were enlarged sections (PW) and 2-arch sections. The overburden height ranged from 16 to 38m. The depth of tunnel excavation was mostly composed of rock masses.

The RES was applied to identify rock behavior. Expected rock behaviors were considered as rock fall, cave-in, and plastic deformation. The seven parameters influencing rock behaviors were regarded as three rock mass intrinsic parameters (intact rock strength, RQD, and joint surface condition), three rock mass extrinsic parameters (ground stress, groundwater, and earthquake), and one excavation parameter (excavation span). Table 8 shows results obtained from suggested rating of parameters affecting rock behavior as shown in Table 6. From estimated RBIs, possibility on rock fall and cave-in was higher than that on plastic deformation in all sections. More detailed analysis should be performed in the sections that have more than 60 RBI value.

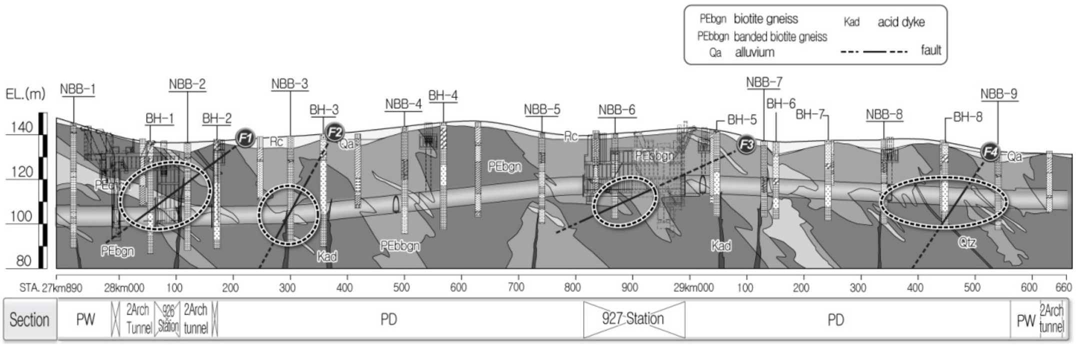

Fig. 4 Geology and tunnel longitudinal section (PD: double lane track section, PW: enlarged section)

Table 8. Suggested rating of parameters and rock behavior index (RBIs) according to support pattern of PD section

support pattern	Section	P1	P2	P3	P4	P5	P6	P7	RBI_1	RBI_2	RBI_3
PD-4	28,172 ~ 28,182	2	0	2	3	2	2	1	60.00	60.25	56.75
PD-5A	28,182 ~ 28,270	3	2	2	3	3	2	1	45.75	45.00	42.50
PD-4	28,270 ~ 28,344	2	0	1	3	4	2	0	61.75	61.00	58.25
PD-5B	28,344 ~ 28,414	1	1	1	3	4	2	1	55.25	54.75	54.00
PD-5A	28,414 ~ 28,445	2	0	1	3	3	2	1	61.25	61.00	57.50
PD-4	28,445 ~ 28,510	2	2	2	3	4	2	1	44.00	43.25	42.75
PD-5A	28,510 ~ 28,560	1	1	2	2	3	2	1	57.25	57.25	58.00
PD-5A	28,999 ~ 29,105	2	0	1	2	3	2	1	64.50	64.25	62.25
PD-5A	29,195 ~ 29,260	3	2	2	2	3	2	2	44.75	44.25	43.25
PD-3B	29,480 29,573	2	1	2	2	2	2	1	59.00	59.00	57.75

5. Conclusion

Rock behavior index (RBI) was suggested identifying the rock behavior in shallow depth tunnel by RES method. To determine the priority of each parameter, 25 experts' questionnaire responses were reflected in this study. Rock behavior types were regarded as rock fall, cave-in, and plastic deformation. Seven parameters influencing on rock behavior were determined: three rock mass intrinsic parameters (UCS, RQD, joint surface condition), three rock mass extrinsic parameters (ground stress, ground water, earthquake), and one excavation parameter (excavation span). We applied this proposed method to basic design of Seoul Metro Line 9 and quantified rock behavior into RBI on fall, cave-in, and plastic deformation. From estimated RBIs, possibility on rock fall and cave-in was higher than that on plastic deformation in all sections.

ACKNOWLEDGEMENT

This research was funded by the Korea Institute of Construction and Transportation Technology Evaluation and Planning under the Ministry of Construction and Transportation in Korea (Grant No. 04-C01).

REFERENCE

1. Benardos A. G. and Kaliampakos D. C., 2004, A methodology for assessing geotechnical hazards for TBM tunneling-illustrated by Athens Metro, Greece, International Journal of Rock Mechanics & Mining Sciences 41, 987-999.
2. Cai M., Kaiser P. K., Uno H., Tasaka Y., and Minami M., 2004, Estimation of rock mass deformation modulus and strength of jointed hard rock masses using the GSI system, International Journal of Rock Mechanics & Mining Sciences 41, 3-19.
3. Davies, J. P., Clarke, B.A., Ockleston, G.O., Whiter, J.T., Cunningham, R.J., 1999. Application of interaction matrices to the problem of sewer collapse. In: Proceedings of the 11th European Sewage and Refuge Symposium, Liquid Wastes Section, Munich, 4-6 May, 11pp
4. Goel R. K., 2001, Status of tunnelling and underground construction activities and technologies in India, Tunnelling and Underground Space Technology 16, 63-75.
5. Goricki A., Schubert W., Riedmueller G., 2004, New developments for the design and construction of tunnels in complex rock masses, International Journal of Rock Mechanics and Mining Sciences Volume 41, Supplement 1, 720-725
6. Hudson, J. A. (1989), "Rock Mechanics Principles in Engineering Practice", CIRIA Ground Engineering Report: Underground Construction.
7. Hudson, J. A. and Harrison, J. P. (1992), "A New Approach to Studying Complete Rock Engineering Problems", Quarterly J. of Engineering Geology, Vol. 25, pp. 93-105
8. Kaiser P. K., Diederichs M. S., Martin C. D., Sharp J., and Steiner W., 2000, Underground works in hard rock tunneling and mining, An international conference on geotechnical and geological engineering.
9. Leopold, L. B., Clarke, F. E., Hanshaw, B. B. and Balsley, J. R. (1971), "A Procedure for Evaluating Environmental Impact", US Geological(USGS) Circular 645 USGS, Government Printing Office, Washington, DC.
10. Martin, C.D., Kaiser, P.K., and McCreath, D.R., 1999, Hoek-Brown parameters for predicting the depth of brittle failure around tunnels. Canadian Geotechnical J., 36(1): 136-151
11. Martin C. D., Kaiser P. K., Christiansson R., 2003, Stress, instability and design of underground excavations, International Journal of Rock Mechanics & Mining Sciences 40, 1027-1047.
12. Matthew, M. and Lloyd, B. J. (1998), "The River Test Catchment Surveillance Project, South Water Utilities Final Research Report" Department of Civil Engineering, University of Surrey, UK, 101pp
13. Mazzoccola, D. F. and Hudson, J. A. (1996), "A Comprehensive Method of Rock Mass Characterization for Indicating Natural Slope Instability", Quarterly J. of Engineering Geology, Vol. 29, pp. 37-56
14. Palmstrom A. & Stille H., 2007, Ground behavior and rock engineering tools for underground excavations, Tunnelling and Underground Space Technology 22, 363-376.
15. Poschl I., and Kleberger J., 2004, Geotechnical risk in rock mass characterization-a concept, Geotechnical risks in rock tunnels, 145-154.
16. Sakuri S., 1997, Lessons learned from field measurements in tunnelling, Tunnelling and Underground Space Technology 12, 453-460.
17. Singh M., Singh B.,Choudhari J., 2007. Critical strain and squeezing of rock mass in tunnels, Tunnelling and Underground Space Technology 22, 343-350.
18. Stille H. & Palmstrom A., 2008, Ground behavior and rock mass composition in underground excavations, Tunnelling and Underground Space Technology 23, 46-64.
19. Skagius, K., Wiborgh, M., Strom, A., Moren, L., 1997, Performance assessment of the geosphere barrier of deep geological repository for spent fuel. The use of interaction matrices for identification, structuring and ranking of features, events and processes. Nuclear Engineering and Design 176, 155-162.doi:10.1016/S0029-5493(96)01333-7