

# Application of the auxiliary tunnel reinforcement design using the decision making tools based on expert system integrated fuzzy inference rule

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**Abstract:** Specification of reinforcement method was suggested according to the ground condition and tunnelling environment such as adjacent building and surface settlement. Tunnel database consists of 8 different groups of data according to the tunnel construction situations and major problems of ground. A tunnel countermeasure expert system based on client/server system was developed with on-line. The expert system provides proper solution to the each construction sites backing up the information of the tunnelling and ground information through Internet. The effective factors of tunnel construction were shown by the analyzing relationship and partial relationship between face stability and RMR factors. This study will be very helpful to make the most of in-situ data and suggest proper applicability of tunnel reinforcement system escaping from the dependence of some experienced experts for the absent of guide.

## 1. Introduction

Many studies of tunnel and tunnelling safety have been done based on the increasing social interests in underground space since 1990's in Korea. Increasing the construction of tunnel, it is important to define the cause of the abnormal phenomenon and then to carry out the countermeasure against the major cause. Especially, proper countermeasure for the unexpected and difficult excavation is urgently needed in the case of tunnelling site constructed in urban area. Although technological development of tunnel engineering has been accelerated consistently, there has been no clear specification of reinforcement method for the unstable tunnel situation in Korea.

In this study, a lot of types of tunnel failure and their countermeasure methods were surveyed, then the specification of countermeasure was suggested according to the ground condition and tunnelling environment such as adjacent building and surface settlement. A tunnel countermeasure expert system based on client/server system was developed with on-line database. The expert system provides proper solution to the each construction sites backing up the information of the tunnelling and ground information by internet.

This study will be very helpful to make the most of in-situ data and suggest proper applicability of tunnel reinforcement system escaping from the dependence of some experienced experts for the absent of guide.

## 2. Modified Takagi-Sugeno (TS) Fuzzy Model

On actual sites, the engineers often have to begin to cope with the safety problem while the cause is still unknown. However, the selection of counter measure is not easy because there are many unexpected problems and uncertainties of ground. In this study, many types of tunnel failure were surveyed and the detail causes were studied for brief countermeasure. Then, the expert system using fuzzy inference rule was developed (Chikahisa et al.1997).

The record of Tunnel failure and collapse throughout Korea has been established and 21 significant incidents are documented in this study. Especially, subway tunnels including second stage of Seoul subway, road tunnels and express railway tunnels have been analyzed. This data shows that these incidents, particularly in soft ground in urban areas, may, when they occur, result in major consequences not just to those working in the tunnel but to members of the public, the infrastructure and the built environment.

The 10 significant collapses and outlines of the circumstances of the incident were investigated during second stage of Seoul subway, and 11 major collapse incidents among the various tunnel sites were studied since 1993. Among those 21 incidents, 8 sites were surface collapse and large collapses more than 50m<sup>2</sup> were 5 cases. 14 incidents were occurred in urban areas and three in road tunnel and one in express railway tunnel (Kim et al. 2000).

Kim et al. (2000) analyzed the main cause factors of the collapsed tunnel analyzing the relationship between collapsed cases and their ground conditions. Especially, RMR classification items suggested by Bieniawski were considered because it is usually applied in-situ site of Korea. 20 significant incident sites are separated from 52 tunnel failure data and

studied about water inflow, depth, rock type, joint, alteration and so on. Abroad failure tunnels surveyed by Cecil (1963), whose total length is approximately 67km and which contain 14 projects and 97 sections are analyzed as well.

### 3. Expert System for Tunnel Reinforcement

According to the record of tunnel incidents above, proper countermeasure system is urgently needed so that the expert system was studied to predict the safety of tunnel and choose proper tunnel reinforcement method using fuzzy quantification theory and fuzzy inference rule based on tunnel information database (Watada et al. 1982). Using fuzzy theory, fuzzy membership function is composed and tunnel safety level is inferred through the membership function. After the tunnel safety level is graded, proper tunnel reinforcement is selected. This expert system is purposed to help the engineers to make a decision of counter measure against unexpected situation providing proper judgment criteria applying the fuzzy theory. Each observed items and tunnel face mapping data are changed to fuzzy set and tunnel reinforcement applicability has been inferred. To establish the membership function is the most important and difficult part of fuzzy inference system because of the absence of experienced engineers and lack of data. Quantification theory was used for building membership function as an alternative method (Kim et al. 2000). The membership function consists of more objective data through the application of quantification theory, which gives weight value to tunnel quality data. Tunnel safety set to be the independent criterion and the items of tunnel information database set to the subordinate variables and then, the fuzzy inference rule is predicted.

#### Overview Fuzzy inference system

Fuzzy sets were introduced by Zadeh as an approach to handling vagueness or uncertainty and, in particular, linguistic variables. Classical set theory allows for an object to be either a member of the set or excluded from the set. This, in many applications, is unsatisfactory since, for example, if one has the set that describes all males who are tall as those whose height is greater than 5'8" then a 6'0" male is a member of the set. A male whose height is 5'7", however, is not a member of the set. This implies that a man who is "shorter than another tall man is not tall.

By the same token this approach does not differentiate between members. Michael Jordan (6'8") and Bob John (5'11") are both equally members of the set 'tall'. Although this appears at face value to be a trivial example there are many domains where this approach is of little use. Fuzzy sets differ from classical sets in that they allow for an object to be a partial member of a set. So, for example, John may be a member of the set 'tall' to degree 0.8. He is tall to degree 0.8. Fuzzy sets are defined by a membership function. For any fuzzy set A the function represent the membership function for which indicates the degree of membership that x, of the universal set X, belongs to set A and is, usually, expressed as a number between 0 and 1.

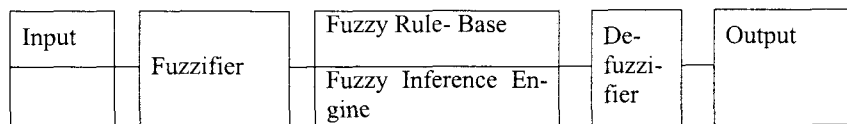


Figure 1. Diagram of fuzzy inference.

Fuzzy theory has been applied to describe ambiguous data in many filed include engineering fields. Fuzzy set is used for fuzzy inference and the process of inference is introduced in Figure 1. After fuzzification of the input data, Fuzzy inference is done based on the fuzzy rule, then output comes through defuzzification of the inference values.

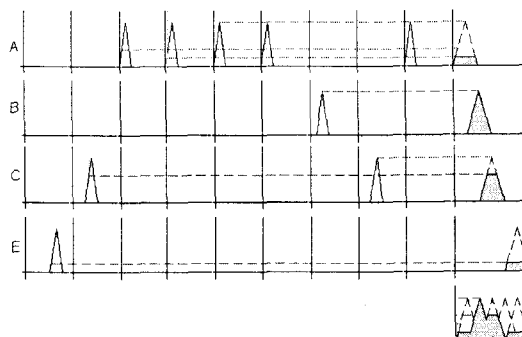


Figure 2. Fuzzy inference processing.

Fuzzy reasoning needs fuzzy rule. If the rule, "IF x is A then y is B" were given, y is to be inferred with the condition of the input information, "x is A". Fuzzy rule is expressed IF-THEN form and consists of pre-condition proposition and post-condition proposition.

### Tunnel face mapping D/B

D/B for this expert system consists of 8 groups whose characteristics of tunnel construction is different. Table 1 shows explanation of each database group such as special ground condition or major concerning of tunneling. The standard of division is based on the major situation of tunneling in Korea.

Table 1. Tunnel face mapping information for D/B.

D/B	Site	No. of face	Length (m)
Under river	River Han	133	460
Fault zone	Pusan subway	330	600
Weathered rock and sand soil	Seoul subway station 6-00	97	200
	Seoul subway station 6-00	60	50
Weathered rock	Seoul subway station 5-00	91	118
Alluvial near river	Seoul subway station 5-00	154	338
Ground Structure	Seoul subway station 5-00	59	106
Underground structure	Seoul subway station 5-00	67	436
Fault zone & Gneiss	Road tunnel	170	450

### Constitution of inference system

This inference system has two main parts. First part decides tunnel information input items based on the tunnel face mapping information data easily obtained in-situ site. In this stage, using fuzzy quantification theory II, fuzzy membership function is composed and tunnel safety level is inferred. After tunnel safety level is predicted in first module, fuzzy inference rule is arranged between safety level and countermeasure method, then proper applicability of tunnel reinforcement is selected from post-module tunnel information database.

Tunnel information database consists of major face mapping items and tunnel safety effect factors such as adjacent building and overburden above tunnel, but in this system, only face mapping data expressed 4 levels was used. Main input data was made of uni-axial strength, RQD, joint spacing, joint condition, joint direction and water inflow included to RMR classification commonly adapted in Korea. First membership function built by correlation coefficient evaluates the safety level of tunnel face in Figure 3. Input module of tunnel reinforcement database showed in Figure 4 has eight items mostly used major collapsed sites and it consists of face shotcrete, ringcut excavation, mechanical excavation, forepoling, L.W grouting, bench shorten, invert and steel pipe grouting. As shown in Figure 5, membership for the applicability of each reinforcement method was built and the grade was calculated by defuzzification using centroid method. Fuzzy inference rule between each group of data and reinforcement methods shows in Table 2.

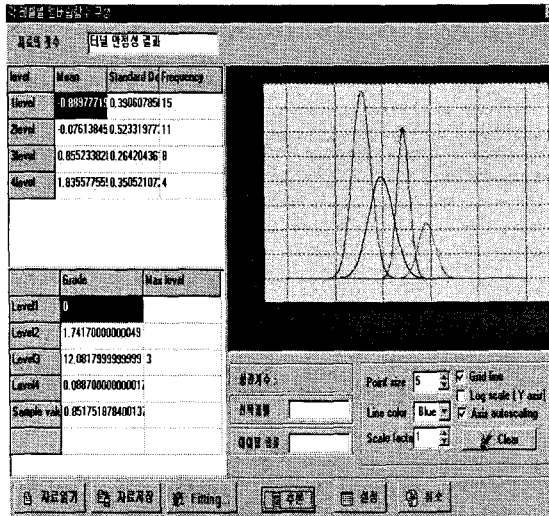


Figure 3. Membership function of safety evaluation of tunnel face

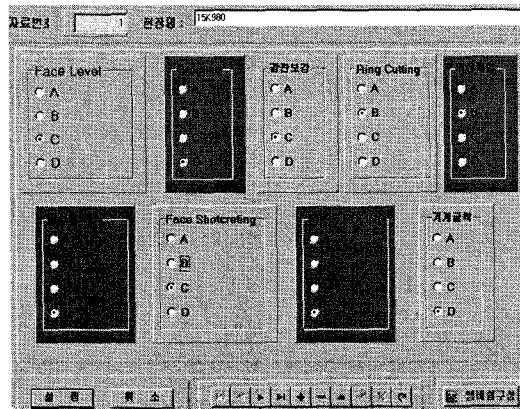


Figure 4. Tunnel Reinforcement database.

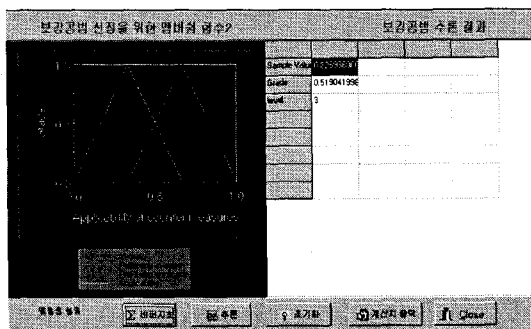


Figure 5. Membership function of reinforcement.

Table 2. Fuzzy inference rule of Seoul subway (Station 5-18).

No. of face	1	2	3	4
First membership grade				
Level A	0.96	0.09	0	0

Level B	0.04	0.91	0.98	0.01
Level C	0	0	0.02	0.99
Level D	0	0	0	0
Fuzzy inference rule				
Face shocrete	0.18	0.63	0.67	0.88
Steel pipe grouting	0.67	0.67	0.67	0.88
Ringcut	0.14	0.33	0.34	0.87
Mechanical excavation	0.14	0.33	0.34	0.87
L.W grouting	0.35	0.74	0.86	0.12
Invert	0.18	0.63	0.67	0.88
Bench shorten	0.18	0.63	0.67	0.88
Forepoling	0.16	0.78	0.89	0.89

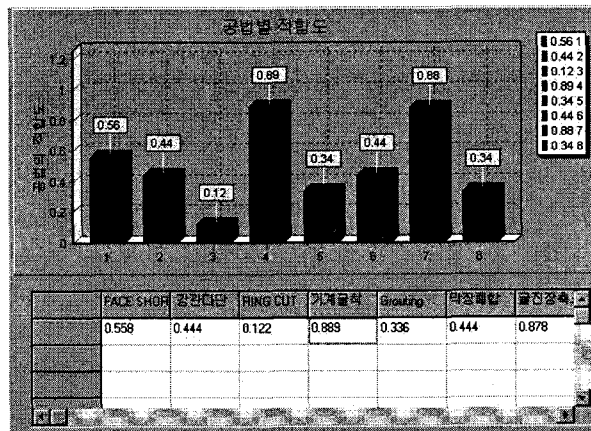


Figure 6. Inference result of reinforcement applicability.

The comparison results between the predicted applicability by reinforcement system and measured data were very similar. In-situ data were obtained in eight tunnel sites as shown in Table 1. There is inference result of eight reinforcement methods used in Seoul subway tunnel in Figure 6. In the case of Seoul subway tunnel under the river Han, 104 sections were used for building database among 133 face mapping data, then the system was tested with other 29 sections. This system will be very helpful to make the most of in-situ data and suggest proper applicability of tunnel reinforcement system escaping from the dependence of some experienced experts for the absent of guide.

### Additional decision-making

After evaluating the applicability of each reinforcement method by fuzzy inference system, user can be provided a simple pattern of selecting methods with more specific data of tunneling such as details of ground condition and occurring problems. Ground condition consists of seven items as shown in Table 3 and the levels were defined according to the opinion of experienced experts and construction results in Korea. Problems of excavation are composed of five items and each problem has countermeasure methods shown in Table 4. The relationship between each problem and its countermeasure is based on the Korea specification and opinions of experts. Table 5 shows the pattern of suggestion method for the given 2 input data.

Table 3. Details of ground condition.

Items	Level
Depth	less than 1.0D
	1.0 - 1.5D
	1.5D - 3D
	More than 3D
Ground Classification	Sediment
	Weathered soil
	Weathered rock
	Soft rock Moderate rock
Fault Zone	Yes
	No
Location of Fault zone	On the face crown
	lower than 0.5D
	0.5 ~ 1.5D higher than 1.5D
Overburden	Calculation
Inflow	Dry
	(10 ~ 25ℓ /min)
	(25 ~ 125ℓ /min) (>125ℓ /min)
Location of Groundwater	Over SL, Below SL

Expert system will provide construction site direct countermeasure method for the unexpected problems via on-line. Selecting similar ground condition among the 8 data group, Proper reinforcement is suggested and similar construction pattern, which was used in other sits, will be very helpful in decision-making.

Table 4. Problems of excavation.

Items	Level	Countermeasure
Overburden	< 1.0 D	Forepoling, Umbrella arch, Ringcut, Jet grouting, Piperroof
	1.0 - 1.5 D	
	1.5 D - 3 D	
	> 3 D	
Inflow	RMR	Chemical grouting
Face stability	Fuzzy level	Face shotcret, invert, ringcut, bench shoten, Face rockbolt
Adjacent Building	On the face crown	Piperroof, forepoling, umbrella arch method, Jet grouting
	< 0.5 D	
	0.5 ~ 1.5 D	
	> 1.5 D	
Surface settlement	Neural network inference	Piperroof, Jet grouting, umbrella arch method, Invert

Table 5. Suggested pattern of reinforcement.

Method	Forepoling
Purpose	Sealing of fault zone and reinforcement of around tunnel face
Design Pattern	L=12 m 2 columns overlap
Others	More than 5 hole into the tunnel face
Warning	If upper alluvial layer comes close to 1 m, reinforcement required

The data used in this study were obtained from the various tunnel construction sites in South Korea. They consisted of laboratory tests and engineering rock mass classification. They are specific gravity, absorption ratio, P and S wave velocities, uniaxial compressive strength, elastic modulus, Poisson's ratio of intact rock, tensile strength, cohesion and friction angle by triaxial compressive test in the laboratory test. They also include RMR and Q values. It is possible to have different influences on rock mass properties even in the same RMR values with the different combinations of six RMR ratings. So separate ratings except for adjustment according to joint orientation were included as input variables for fuzzy model. And output variables were deformation modulus, cohesion and friction angle widely used in numerical analysis. These input and output variables are tabulated in Table 6.

#### Training and validation data

A total number of 107 data obtained from the domestic tunnel construction sites were randomly divided into four sets of 25% of total data. And each set had 26 or 27 records (27+27+27+26=107). The three sets (75%) were used for training of fuzzy model and the other set (25%) was used for validation of it, which meant that there were four possible fuzzy models in each prediction of engineering rock mass property. The reason for doing this was to see how much variation there were in accordance with the distributions of training and validation data. The names of fuzzy models are tabulated in Table 2. Also the data used here was scaled between 0 and 1, which reduced the time for calculation and effect induced by different measured units in each parameter.

Table 6. Input (X) and output (Y) parameters and their ranges for fuzzy model.

	Parameters	Range
X1	Specific gravity	0 - 5
X2	Absorption ratio (%)	0 - 12
X3	P-wave velocity (m/s)	0 - 8000
X4	S-wave velocity (m/s)	0 - 5000
X5	Uniaxial compressive strength (MPa)	0 - 500
X6	Elastic modulus (GPa)	0 - 20
X7	Poisson's ratio	0 - 0.5
X8	Tensile strength (MPa)	0 - 50
X9	Cohesion (MPa)	0 - 50
X10	Friction angle (Deg)	0 - 90
X11	RQD	0 - 100
X12	RMR-1 (uniaxial compressive strength)	0 - 15
X13	RMR-2 (RQD)	0 - 20
X14	RMR-3 (spacing of discontinuities)	0 - 20
X15	RMR-4 (condition of discontinuities)	0 - 30
X16	RMR-5 (ground water)	0 - 15
X17	RMR	0 - 100
X18	Q	0 - 1000
Y1	Deformation modulus (GPa)	0 - 30
Y2	Cohesion (MPa)	0 - 20
Y3	Friction angle (Deg)	0 - 90

### Criteria for the selection of model

Modified TS fuzzy models were trained until they satisfied the criteria as increasing the number of clusters of input data. The indices used for the criteria were RMSE (Root Mean Squared Error) and the rate. Rate is the change of RMSE in each training stage defined by Chen (1998) shown below.

$$RMSE = \sqrt{\frac{1}{n} \sum_{k=1}^n (y_k - \hat{y}_k)^2} \tag{1}$$

$$Rate = \frac{|RMSE - RMSE(0)|}{RMSE} \tag{2}$$

### 4. Inference Results

Based on the tunnel face mapping database, relationship and partial relationship between face stability and RMR factors were analyzed. Partial relationship coefficient means the strength of effectiveness of each factor to face stability when other items are fixed. Relationship coefficient between face stability and RMR items of 8 database groups is shown in Figure 7 and there are various differences among the groups of data according to property of construction situation.

As shown in Figure 8, partial relationship coefficients of 8 data groups between face stability and RMR items are various and it means that major effective factor of face stability is not same in all tunnels. In the same way, the relationship between face stability and the applicability of reinforcement methods was analyzed. Relationship coefficient shows that appropriate reinforcement methods should be considered differently according to the group of data because each database has different property of ground or construction problem. It means that each tunneling face needs different countermeasure method depending on the property of tunneling situation and problem.

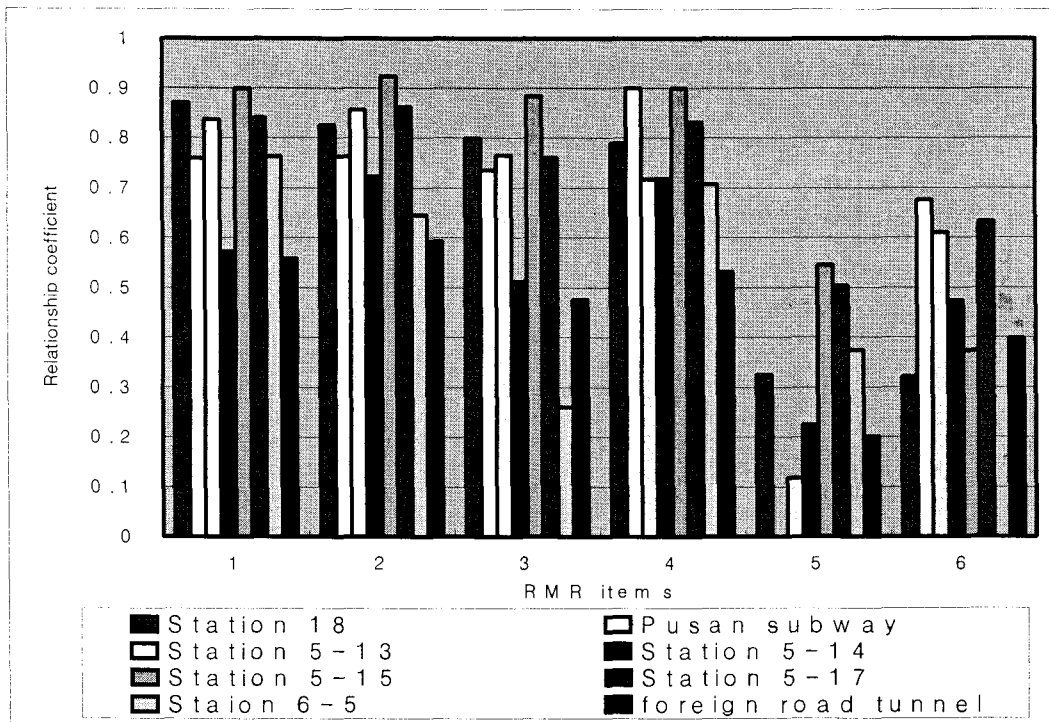


Figure 7. Relationship coefficient between face stability and RMR items.



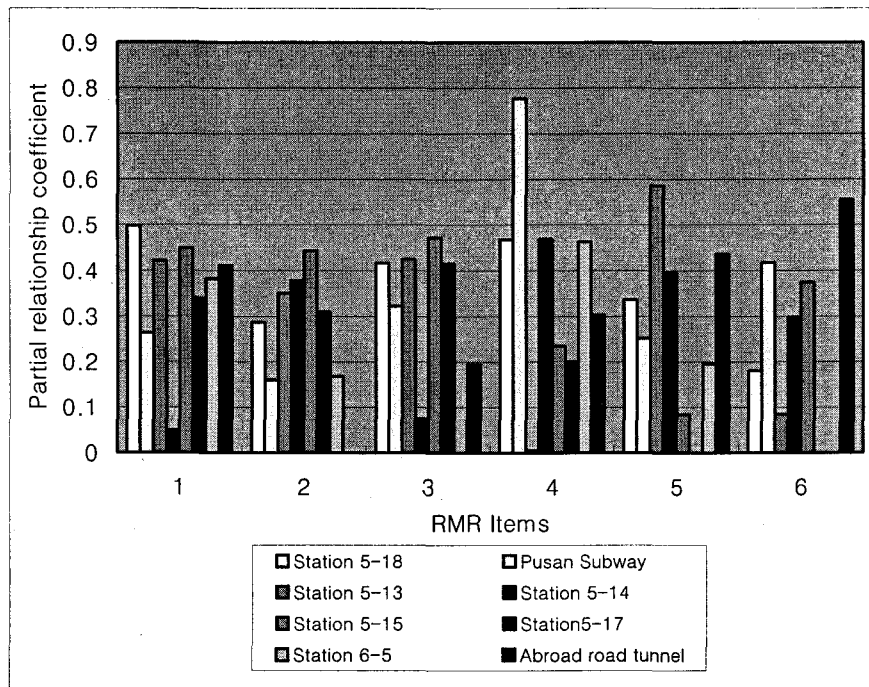


Figure 8. Partial relationship coefficient between face stability and RMR items.

## 5. Conclusions

In this study, after tunnel collapsed incidents were surveyed and the detail causes were analyzed, the expert system for tunnel reinforcement selection was presented. Database is divided to 8 different data group according to the properties of tunneling construction and major problem of excavation because each data group provides different inference results from each particular condition. From this the following suggestions were made for better understanding of the tunnel reinforcement system.

Prototype of the expert system was developed to evaluate of tunnel safety and select proper reinforcement method based on the fuzzy theory after building tunnel information Database.

The expert system developed in this study has been tested on 8 in-situ sites including the river Han subway tunnel considered one of the most difficult construction sites and needed various reinforcement methods. Its applicability has been confirmed by comparison of inferred results and field data.

There are some different among the correlation coefficients between RMR factors, which used as tunnel face observation items, and tunnel safety level according to the in-situ sites. Partial correlation coefficients are various as well. It verified that face mapping items may be considered differently at each site.

## Acknowledgment

This research has been performed as a part of the National Research Laboratory project provided by KMOST (Korea Ministry of Science & Technology) and Samsung Construction Co.. The authors greatly appreciate their financial support.

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