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The integrated prediction system for geological conditions ahead of tunnel faces

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ABSTRACT: It is essential to employ the observational design and construction method to manage tunnel projects efficiently. The original tunnel design is immediately verified or modified based on the in-situ data sequentially obtained in the construction stage. This study proposes an integrated prediction system for geological conditions ahead of tunnel faces, which is composed of long-interval, middle-interval, and short-interval prediction subsystems. The applicability of those subsystems is verified with actual field data.

Subject: Information system, artificial intelligence and other advanced techniques

Keywords: tunnelling, site characterization, rock properties

1 INTRODUCTION

It is essential to employ the observational design and construction method to manage tunnel projects efficiently. The original tunnel design is immediately verified or modified based on the in-situ data sequentially obtained in the construction stage. In the framework of observational design and construction, it is important to predict the geological conditions ahead of tunnel faces with several kinds of data obtained from observation of the face conditions, probe hole drilling, seismic profiling from the face, etc (Shirasagi et al., 2001).

The prediction results are mainly used for the following purposes;

- Master planning
  - Estimation of total construction period and cost of the project
  - Planning a long-term outline of the projects from the viewpoints of quality, process and safe managements
- Detailed planning
  - Judgment of execution of preliminary reinforcement
  - Selection of tunnel support pattern
- Final decision making
  - Confirmation / modification of the detailed plan
  - Determination of tunnel excavation parameters

For each purpose, it is important to perform a specific prediction with the data suited to each purpose. Thus the authors propose the subsystems of long-interval prediction (whole tunnel alignment), meddle-interval prediction (within about 50 m ahead of tunnel faces), and short-interval prediction (within 5 m ahead of tunnel faces).

In order to perform the reliable design and construction, the precision of prediction is required. If the precision of prediction can be grasped, more reasonable decision making can be performed from the viewpoints of risk management. Thus, in this study, geostatistical method is employed to obtain not only the spatial distribution of geological conditions but also the precision of prediction.

The applicability of the proposed subsystems is verified by using actual field data.

2 PREDICTION SUBSYSTEMS

2.1 *Long-interval prediction*

In this subsection, the long-interval prediction method of geological conditions by geostatistical simulation is proposed.

In order to estimate the total construction period and cost of the project, it is required to predict the total distance of each support pattern, which strongly governs construction period and cost, along whole the tunnel alignment. This implies that it is required to predict the spatial distribution of geological conditions along whole the tunnel alignment since the support pattern is determined by referring the geological conditions.

In the beginning of construction stage, we can usually obtain geophysical data and geological data. Geophysical data is obtained from the seismic and/or resistivity survey along whole the tunnel alignment in the investigation stage. In general, geophysical data is not accurate but can be used as soft data which shows data trend (drift). On the other hand, geological data such as rock mass rating, rock strength, TBM driving parameters, etc. is obtained from the observation of tunnel face or wall conditions only along the already excavated tunnel section. In general, geological data is accurate data and can be used as hard data. The proposed method integrates those two kinds of data.

The procedure of the method is as follows;

(1) Classify the tunnel alignment into several sections based on the geophysical data.

(2) Characterize each section by calculating mean and standard deviation of geological data in the already excavated section.
(3) Standardize the data of each section so that the frequency distribution of geological data shows standard normal distribution (the mean value = 0, and standard deviation = 1) to filter the drift of each section.
(4) Simulate many realizations of the standardized geological data with different random number series by geostatistical simulation.
(5) Transform the realizations by inverse standardization to add the drift of each section.

This method is to perform the geostatistical simulation by taking external drift into consideration.

2.2 *Middle-interval prediction*

In this subsection, the middle-interval prediction method of geological conditions by geostatistical estimation is proposed.

It is required to predict the detailed geological conditions within about 50 m ahead of tunnel faces in order to judge the necessity of preliminary reinforcement and to select the tunnel support pattern in the framework of safe, quality, and process management.

In addition to geological data in the already excavated tunnel section, geophysical data obtained from the tunnel front and geological data obtained from the evacuation tunnel could be useful input data for geostatistical interpolation if available.

The procedure of the method is as follows;

Use of geophysical data (Yamamoto et al., 2003)

(1) Examine the correlation between geological data and geophysical data in the already excavated tunnel section.
(2) Transform the geophysical data into the equivalent geological data based on the correlation.

Use of geological data

(1) Examine the correlation between geological data in the evacuation tunnel and geological data in the already excavated tunnel section.
(2) Transform the geological data in the evacuation tunnel into the equivalent geological data based on the correlation.
(3) Predict the geological data ahead of tunnel faces by geostatistical interpolation.

2.3 *Short-interval prediction*

In this subsection, the short-interval prediction method of geological conditions by geostatistical interpolation and simulation is proposed.

It is required to predict the fully detailed geological conditions within about 5 m ahead of tunnel faces in order to confirm or modify the detailed plan and determine the tunnel excavation parameters such as TBM driving parameters, blasting parameters, etc. in the framework of safe, quality, and process management.

If available, in addition to geological data in the already excavated tunnel section, drill logging data obtained from the probe drilling from the tunnel face is used for geostatistical interpolation and simulation.

The procedure of the method is as follows;

(1) Examine the correlation between drill logging data and geological data in the already excavated tunnel section.
(2) Convert the drill logging data into the equivalent geological data based on the correlation.
(3) Predict the geological data ahead of the tunnel face by geostatistical interpolation and simulation.

3 FIELD APPLICATION

In this section, the applicability of the proposed methods is verified through the field application in the motorway tunnel project involving main tunnel and the accompanied evacuation tunnel. This tunnel project has already been completed. The evacuation tunnel (length: 3,692 m, sectional area: 20 m^2) was excavated by a 5.0 m-diameter open-type TBM antecedent to the main tunnel, while the main tunnel (length: 3,660 m, sectional area: 78 m^2) was excavated by drill and blast method. The distance between 2 tunnels is about 30 m. The geology is composed of Cretaceous granites. The maximum overburden depth is approximately 280 m.

3.1 *Long-interval prediction*

Electrical resistivity obtained along the tunnel alignment (3,660 m) is used as the soft data, while geological score, an index to select tunnel support pattern, which is correlated with rock mass rating, obtained along the already excavated tunnel section (500 m) is used as the hard data.

Figure 2 shows the relationship between the class of resistivity and geological score. The trend of the data can be perceived.

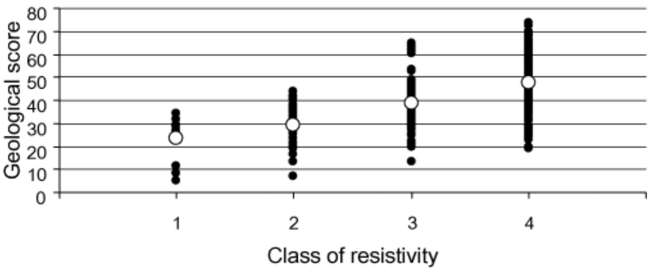


Figure 2. The relationship between the class of resistivity and geological score. The white circle shows mean value. The data is divided into 4 classes according to the magnitude of resistivity as follows; Class 1: under 150 Ωm, Class 2: 150–300 Ωm, Class 3: 300–600 Ωm, Class 4: over 600 Ωm.

Figure 1. The resistivity structure along the main tunnel.

Sequential Indicator Simulation is employed as the geological simulation method. 200 realizations of spatial distribution of resistivity are generated and the total length of each tunnel support pattern is calculated for each realization.

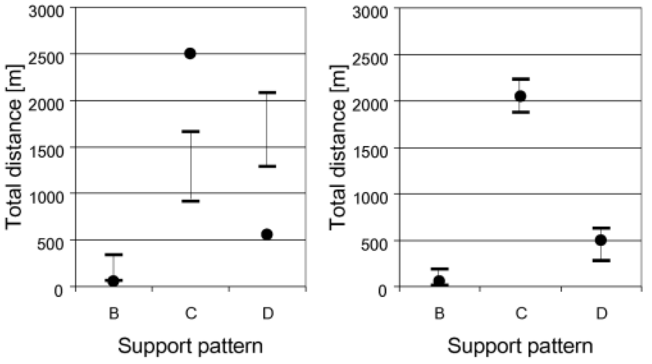
Figure 3 shows the range of the total length of each tunnel support pattern (mean ± 2 * standard deviation) and the actual value (point). Figure 3 (a) shows the case that the data trend is ignored, while Figure 3 (b) shows the case that the data trend is taken into account (the proposed method). From this figure, it is clarified that the proposed method appropriately predicts the actual value and the advantage of the proposed method is verified.

Figure 4 shows the frequency distribution of the expected construction period which is calculated by summing the total length multiplied by advance rate for each support pattern. The proposed method precisely predicts the actual value. This implies that the construction cost can also be predicted by this method precisely.

3.2 *Middle-interval prediction*

Ordinary kriging is employed as the geostatistical estimation method. The geological score obtained along the evacuation tunnel and the already excavated section of the main tunnel is used as the input data.

Figure 5 shows the predicted geological score at 30 m and 5 m ahead of the tunnel face, and the corresponding observed value. The predicted value is well fitted to the observed value.



(a) The trend is not considered (b) The trend is considered

Figure 3. The calculated range of the total length of each tunnel support pattern (line: mean ± 2 * standard deviation) and the corresponding actual value (point). The data trend is not considered in the case (a) while that is considered in the case (b).

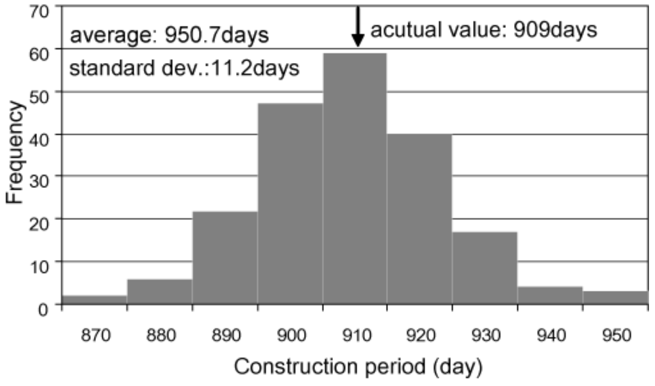


Figure 4. Frequency distribution of the calculated expected construction period (200 realizations).

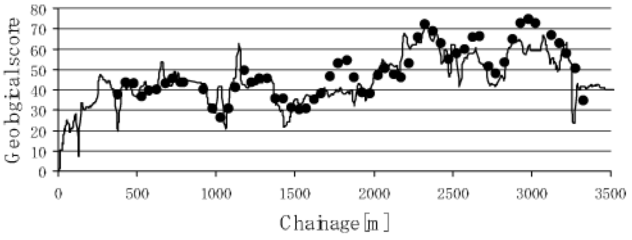
Figure 6 shows the root mean square error (RMSE) of prediction as a function of the distance ahead of the tunnel face. The longer the distance ahead of the tunnel face, the larger the prediction error. What the prediction with higher precision can be obtained is not very important because the magnitude of prediction error changes depending on the distance between the main tunnel and evacuation tunnel or spatial correlation. What the precision can be clarified in the form like Figure 6 is the most important outcome of this method. This allows us to perform risk analysis approach to make engineering decisions such as judgment of execution of preliminary reinforcement, selection of tunnel support pattern, etc.

3.3 *Short-interval prediction*

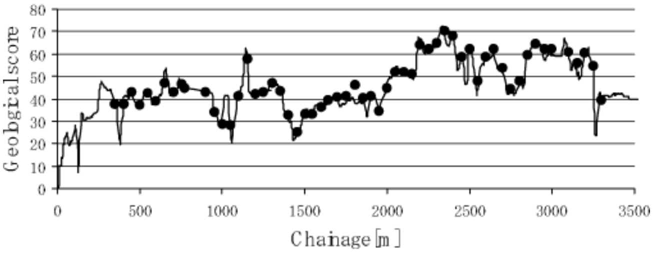
Ordinary Kriging is employed as the geostatistical estimation method as well as the middle-interval prediction. The rock strength index, RSI (Shirasagi et al., 2004) obtained along the already excavated section of the evacuation tunnel and the converted RSI obtained from the drill logging are used as the input data (Mito et al., 2003).

Figure 7 shows the predicted RSI at 5 m and 0.5 m ahead of the face of the evacuation tunnel, and the corresponding observed value. The predicted value is well fitted to the observed value especially in the case of 0.5 m.

Figure 8 shows the RMSE of prediction as a function of the distance ahead of the tunnel face. The longer the distance ahead of the tunnel face, the larger the prediction error. What



(a) 30 m ahead of the tunnel face



(b) 5 m ahead of the tunnel face

Figure 5. The predicted geological score (point) at a specific distance ahead of the tunnel face, and the corresponding observed value (line).

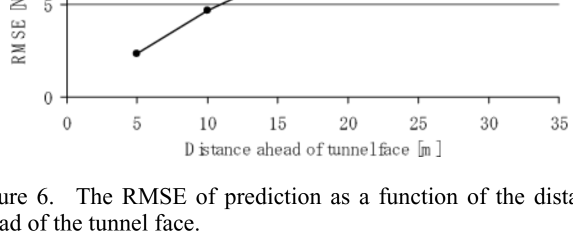
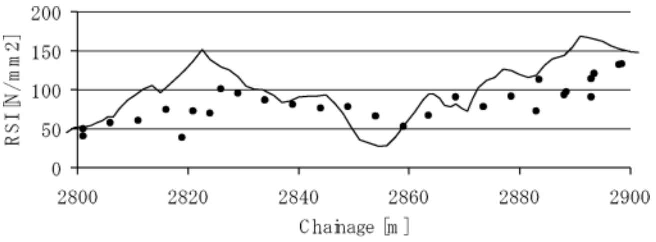
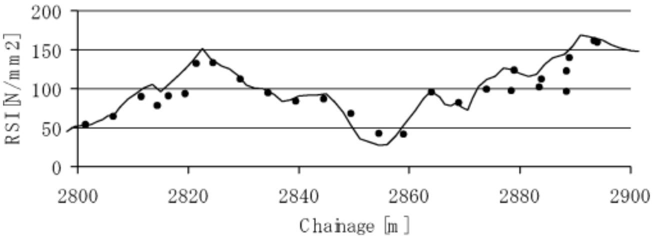


Figure 6. The RMSE of prediction as a function of the distance ahead of the tunnel face.



(a) 5 m ahead of the tunnel face



(b) 0.5 m ahead of the tunnel face

Figure 7. The predicted RSI (point) at a specific distance ahead of the tunnel face, and the corresponding observed value (line).

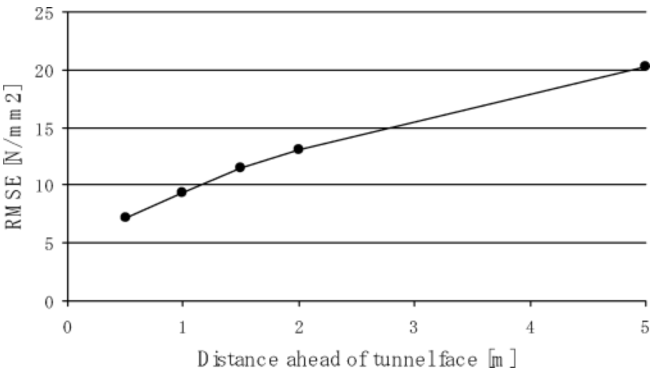


Figure 8. The RMSE of prediction as a function of the distance ahead of the tunnel face.

the precision can be clarified in the form like Figure 8 is the most important outcome of this method as well as the middle interval prediction.

Furthermore, Sequential Indicator Simulation is employed as well as Ordinary Kriging. 30 realizations are generated and the mean value and the range of distribution (mean ± 2 * standard deviation) are calculated. Figure 9 shows the predicted RSI at 0.5 m ahead of the tunnel face, and the corresponding observed value. The precision of prediction is almost the same as that of Ordinary Kriging. The range of distribution differs at each point of the estimation. In general, the range is larger at the interval where the change in value is notable. This fact is a very significant feature of simulation to make a decision carefully.

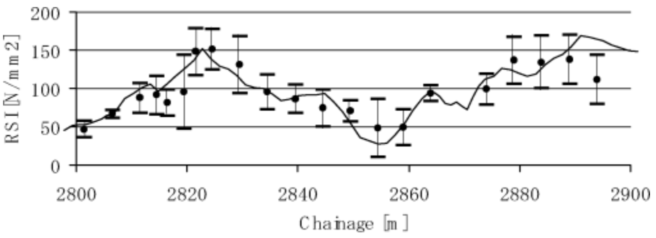


Figure 9. The predicted RSI at 0.5 m ahead of the tunnel face, and the corresponding observed value. The mean value and the range of distribution (mean ± 2 * standard deviation) are plotted as the prediction.

4 CONCLUSION

In this paper, the authors develop the integrated prediction system for geological conditions ahead of a tunnel face. The system is composed of the long-interval, middle interval, and short-interval prediction subsystems for the several engineering purposes in the framework of observational design and construction in the tunnel project. Geostatistical method is employed to obtain not only the spatial distribution of geological conditions but also the precision of prediction. The applicability of the proposed subsystems is verified through the field application.

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