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Prediction of Rock Mass along Tunnels by Geostatistics

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Abstract

A study is made on the applicability and limitation of geostatistical methods in predicting rock mass quality along tunnel alignments based on investigation drillhole data. Two projects were used as the case study: - Lam Ta Khong Pumped Storage Project for a simple geologic setting and Klong Tha Dan Dam Project for a complex geologic setting. The study showed that the estimated rock mass quality and distribution was reasonably comparable with the field observation value for the case of Lam Ta Khong project but it was not the case for Klong Tha Dan Dam site.

Keywords: *geostatistics, tunnel, drillhole, geologic settings*

1. Introduction

For tunnel construction, geological and geotechnical investigation is of vital importance. The degree of accuracy in predicting, evaluating, and interpreting the quality of rock mass along the tunnel alignment is a key for successful project execution. For long and deep tunnels, the extent of geotechnical investigation in terms of boreholes or geophysical probing possible during the preconstruction stage is normally limited. They can only be carried out at some localized points leaving areas in a majority of tunnel alignment un-sampled, thus the conditions need to be interpreted from data at the sampled points. This may lead to large uncertainty and major geological risk in the construction stage, particularly when the site involves a complex geological setting. Interpretation on the ground conditions for the whole tunnel alignment may be made by means of deterministic judgment by experienced engineering geologists or a statistical treatment. For the latter, investigation data are quantified by mathematic methods. Classical statistical tools (i.e., Monte Carlo simulation method or others) are generally applied to estimate variables based on an assumption that all samples of a population are normally distributed and independent. However, engineering data, such as rock properties, often have a spatial correlation. The fact that data values from locations that are closer to one another tend to be more similar than those from locations far apart, therefore, the geostatistics technique can be used a tool to capture the descriptive information on a phenomenon from sparse, often biased, and often expensive sample data (Zhang, 2007). It incorporates both the statistical distribution of sample data and the spatial correlation between sample data. Moreover, the geostatistics approach provides an unbiased and minimizes variation in data values estimation. The prominent point of geostatistics is uncertainty quantification. The important tool in geostatistics is the variogram that expresses the dissimilarity of a given parameter between different locations. It is commonly used to describe the spatial property of a domain. Kringing technique that is an interpolation method in geostatistics, is focused on estimation of values at unknown points by existing values. Application of the geostatistics to tunnel investigation were reported by Chiles and Delfiner (1999); Oh *et al*. (2004); Ozturk and Nasuf (2002); etc. Mostly, data from drillholes supplemented by seismic probing data were used as inputs for analysis and prediction.

In this study, the geostatistical approach is applied to assess rock mass conditions of two tunnel projects in Thailand excavated in different geologic settings on the basis of drillhole data only. Commonly, geological and geotechnical investigation programs of mountain tunnel projects in this region mainly involve borehole drilling and surface geology mapping. Rarely, deep geophysical probing data along the tunnel alignments are available. Thus, this study concentrates on the applicability of the geostatistical prediction on the basis of drillhole data only.

The first case is of tunnels of Lam Ta Khong Pumped Storage Project excavated in a simple geological setting of near horizontally bedded sedimentary rocks. The second case is of tunnels of Khlong Tha Dan dam project which is situated in a complex geological setting of volcanic rocks in proximity of a regional fault zone. In the first case, sample data were obtained

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from vertical drillholes made in horizontally bedded sedimentary rock formations whereas for the second case they were collected from drillholes orientated more or less parallel to main joint sets of unconformed volcanic rocks. Faults and folds were observed as main geological structures at the site. Rock mass quality along the tunnel alignment was interpreted based on borehole data and surface mapping. It is then compared with the actual mapping of tunnel faces during excavation so that applicability and limitation of the geostatistics method-for tunnel investigation in the geological settings of the two cases could be evaluated. This study involved steps of work as follows:

- Classification of rock mass conditions along drillholes based on core log data, core photos and laboratory test results. The Rock Mass Rating (RMR) was used as the index.
- Statistical analysis of RMR to examine the distribution of data and the statistical parameters. The mean, median and mode were calculated to determine reliability of the data. Next, the variance, standard deviation and the interquartile range were calculated. The coefficient of variation and coefficient of skewness were calculated to check symmetry of data distribution.
- Geostatistics analysis to determine the relationship of spatial correlation and predict values at un-sampled points at regular grids along the alignment by the variogram analysis and kriging technique.
- Comparison of the estimated RMR values along the alignment and the actual field observation during the construction.

2. Case Projects

2.1 Lam Ta Khong Pumped Storage Project

Lam Ta Khong Pumped Storage Project was located on the southwestern rim of the Khorat Plateau in Northeast Thailand (Fig. 1a). It was the first underground powerhouse project built in the country. Underground works consisted of a large cavern (25 m wide, 48 m high and 175 m long) and associated tunnels and shafts for a combined length of 10 km. The maximum depth of excavation was over 400 m below the ground surface. The civil construction started in November 1995 and took 4 years to complete.

The project site was located on an escarpment of Lam Ta Khong valley, on the rim of the existing reservoir of Lam Ta Khong dam which was used as a lower pond of the project (Fig. 1a). The topography of area was a valley bordered by flat-top mountains of gentle hill slopes produced by the near horizontal beds of sedimentary rocks of Triassic age (Fig. 2a), with absence of major faults in the vicinity. Rock formations consisted of Phu Kradung and Phra Wihan formations. The former was mainly siltstone, fine-grained sandstone and partly conglomerates and the latter consisted of coarse-grained sandstone, claystone, alternation of fine-grained sandstone and siltstone.

2.2 Khlong Tha Dan Dam Project

Khlong Tha Dan Dam Project was the largest roller compacted concrete (RCC) dam of the country located 150 km east of Bangkok at the foot of mountains of Khao Yai National Park (Fig. 1b). It consisted of two main RCC dam bodies (RCC-B and RCC-S, separated by a middle rock spur) and a 60-m-high earth embankment saddle dam (Fig. 1b). The RCC dams have maximum height of 93 m and the combined length of 2600 m. Five small-size tunnels were built as a part of the rock foundation treatment scheme. Tunnels were excavated in the abutments and central spur with a maximum cover of 65 m. The tunnel construction started in March 2000 and was completed in May 2002.

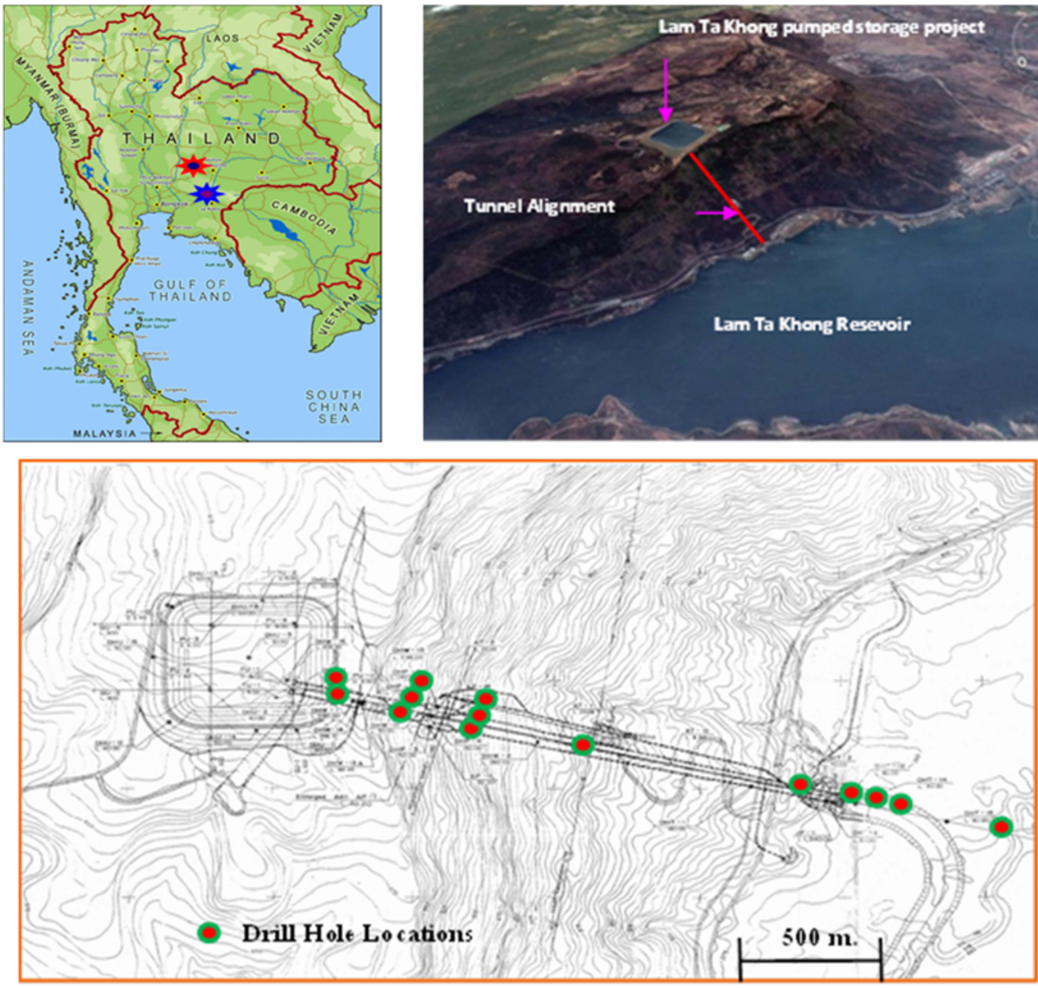
The dam site was located in a volcanic rock belt of Permo-Triassic age near the rim of the Khorat Plateau (Fig. 2b). Major geologic structures of the region resulted from tectonic relaxation or extension in late Triassic that was followed by the early to Middle Triassic collision between Shan-Thai and Indo-china micro-plates. Permo-Triassic volcanic rocks were predominant in the entire project area and primarily consisted of rhyolite, andesite, tuff, agglomerates and few basalt dikes. All were hard with compressive strength in the range of 75-150 MPa. Rock mass was slightly to moderately jointed. Zones of closely jointed rock and minor faults existed sparsely in the right half of the RCC-B. Predominant joint set was in steeply dipping orientation and striked in NW direction, which was parallel to the strike of the main fault of the region as well as to that of most minor faults found in the dam foundation area. They cut obliquely across the tunnel alignment. Generally, joints were slightly rough and tight, often with calcite, quartz and chlorite infills. Minor faults with breccia and clay gouge infills also existed at few locations. In areas of rhyolite which covered the left half of RCC-B and the entire RCC-S, rock mass was mostly massive and widely jointed. Near horizontal exfoliation surfaces were also common in the rhyolite.

Except for TBR-D1 tunnel in the right abutment of RCC-B dam, rocks encountered in the tunnels were mostly rhyolite. Tuff was the prime rock type encountered in TBR-D1 tunnel. Majority of discontinuities were oriented obliquely with or normal to the tunnel axes dipping steeply (60°-90°). Gently dipping joint sets (15°-40°) striking in various directions were also observed. Very few minor faults and shear zones were encountered in the tunnel excavation. Few of them were with thin clay gouge infills. Rock mass was dry for most parts of the tunnel. Few localized ground water infiltrations in fault areas were found.

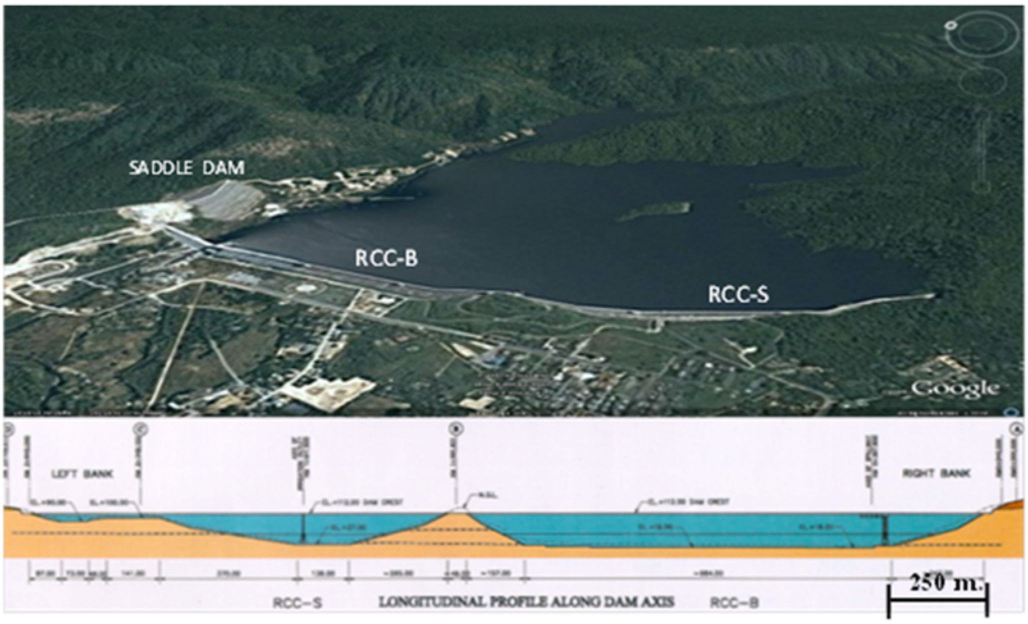
3. Prediction Results

3.1 Lam Ta Khong Tunnels

Core logs data of 14 drill holes made prior to construction were used to determine the characteristics of rock mass quality in term of RMRs along depths of the drill holes at various horizontal locations so that the statistical properties and variograms were determined for prediction of rock mass quality at un-sampled areas by means of the geostatistic analysis. The flow chart of tasks and steps employed in the study is shown in Figure 3. The geostatistc analysis was applied to determine the relationship of spatial correlation – variograms, which was used as the basis to



(a)



(b)

Fig. 1. Location Map of the Two Case Projects: (a) Lam Ta Khong Pumped Storage Project, (b) Klong Tha Dan Dam Project

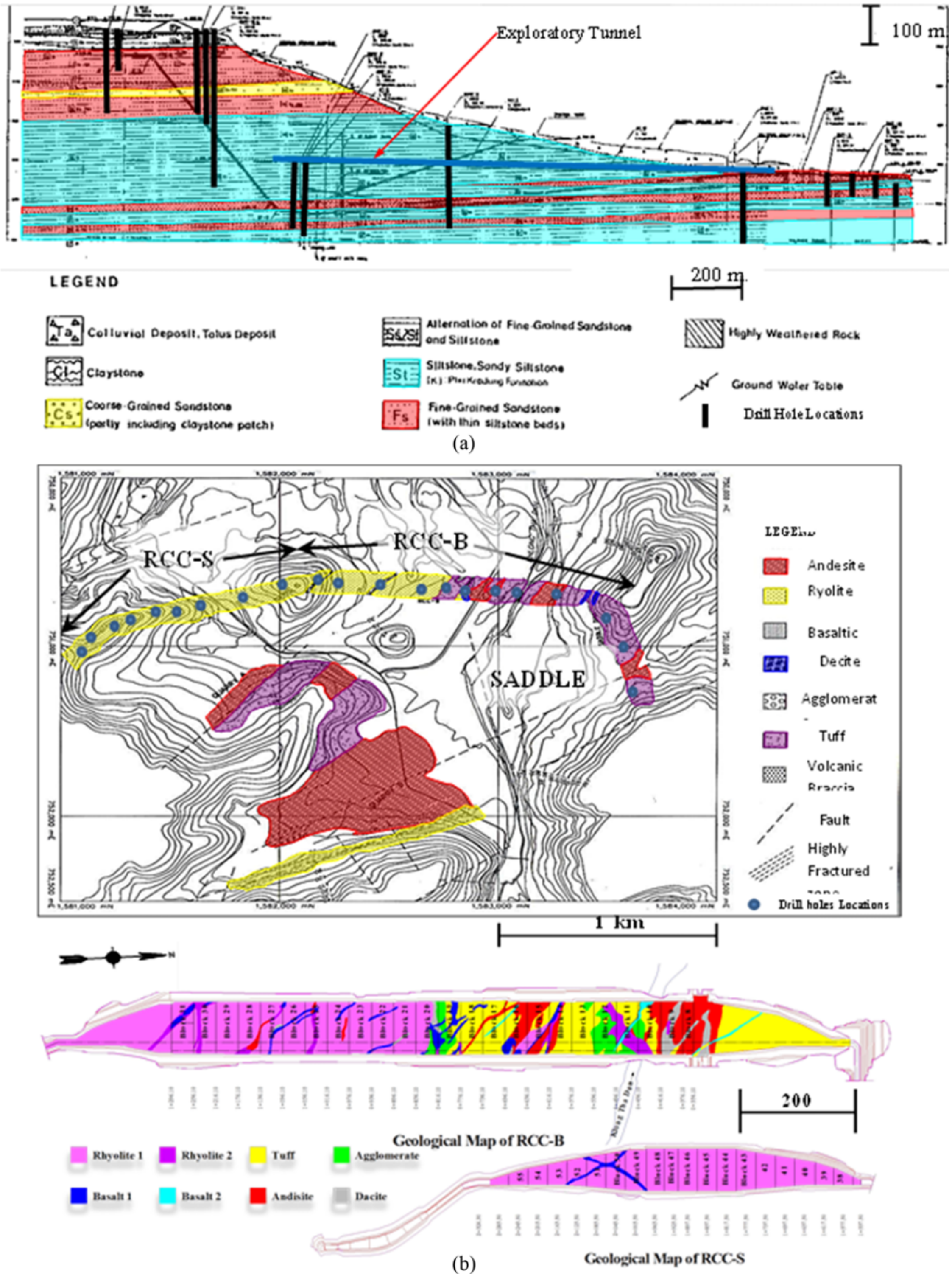


Fig. 2. (a) Geology and Drill Hole Locations of Lam Ta Khong Pumped Storage Project, (b) Geology Map and Drill Hole Locations of Klong Ta Dan Project

predict values at un-sample points of a regular spaced grid by kriging. Then, the results of geostatistic analysis were used to predict possible rock mass conditions along tunnel alignments. Finally, the predicted RMR values along the tunnel alignment by this method was compared with the field observation data from tunnel mapping during construction. Because there were two tunnels of the project with full RMR observation data, i.e. the exploratory tunnel and the access to the powerhouse tunnel, the RMRs determined from drillhole core logs were firstly verified with the RMRs of the actual rock mass mapped along the 1.3-

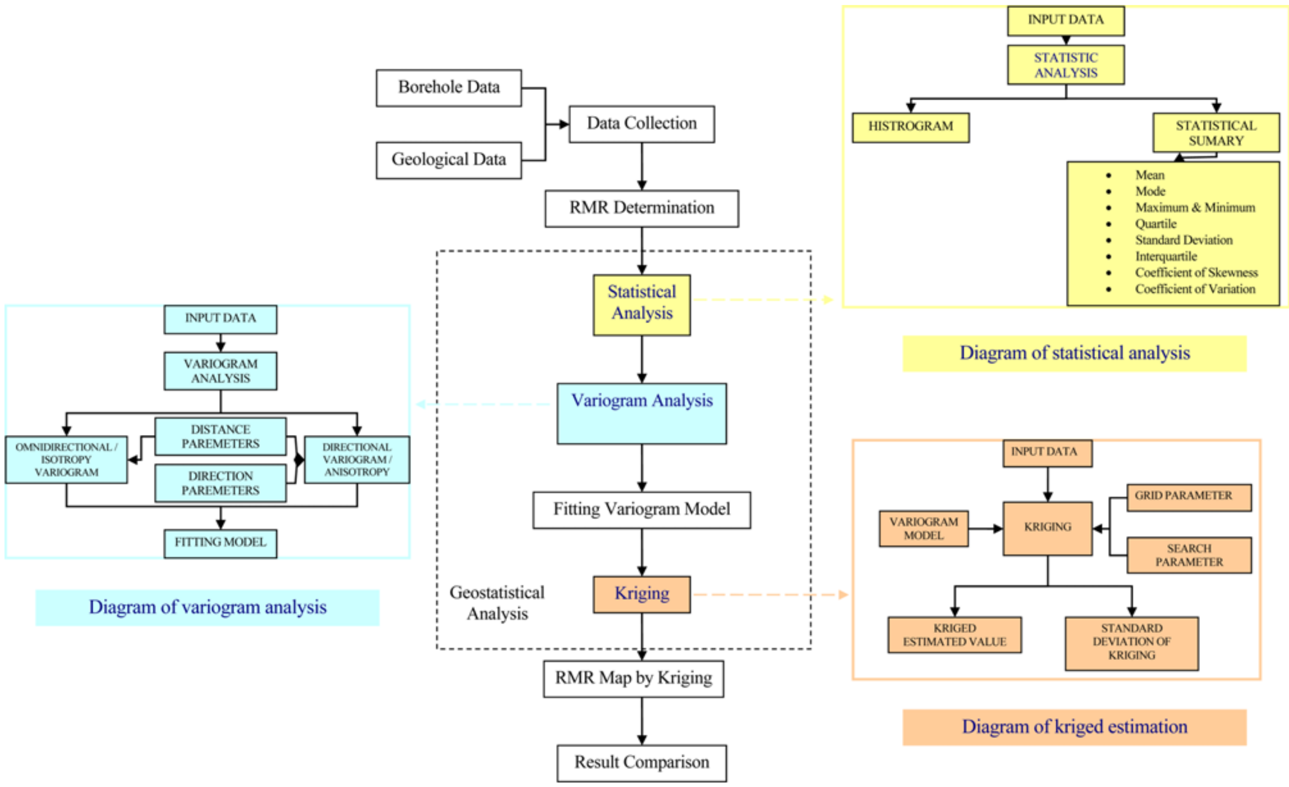


Fig. 3. Flowchart Diagram of Geostatistics Study

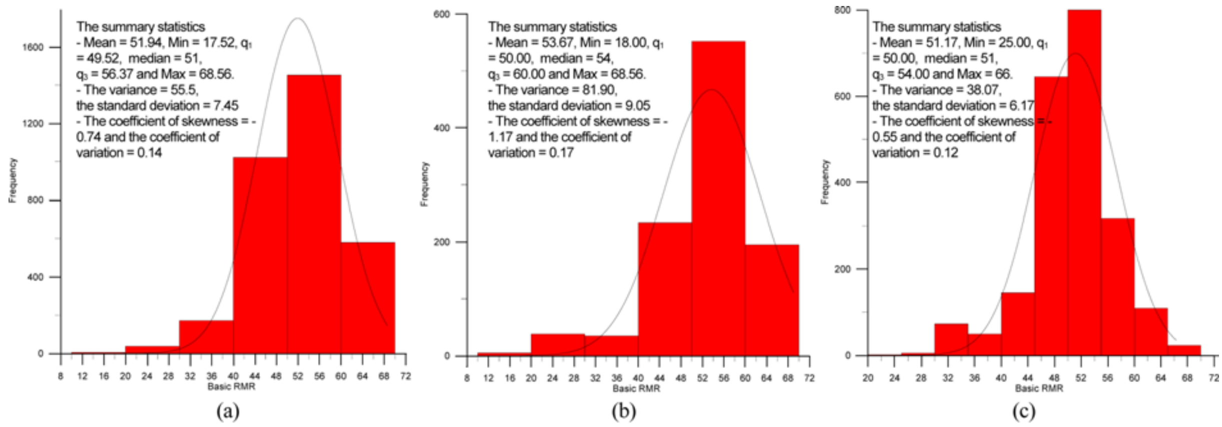


Fig. 4. Histogram and Statistical Characteristics of RMR: (a) Combined Rock Formations, (b) Phra Wihan Formation, (c) Phu Kradung Formation

km-long exploratory tunnels that were reported by Tran (1994). Then the derived geostatistic parameters were used in prediction of rock mass quality in the Access Tunnel to the Powerhouse which ran parallel to the Exploratory Tunnel but was located 50 m deeper.

Two rock formations existed at the site, i.e. Phra Wihan and Phu Kradung formations. The histogram and statistical characteristics of RMR for the formations showed similar results which were reasonably of the normal distribution (Fig. 4). Therefore, the RMR data was used for the geostatistic analysis. The variogram analysis and modeling were applied to determine spatial correlation of the RMR data. At first the omnidirectional variogram analysis of the combined data points of the two rock formations was performed. The derived variogram showed a trend structure but with a peculiar oscillation in long lag distances that did not comply with the expected variaogram characteristics (Fig. 5a). Then anisotropy variogram analyses for vertical and horizontal directions were performed which resulted in a better outcome on the spatial relations of RMR for this near horizontally bedded rock mass. Moreover, the resulted variograms of the data were even better when the analyses were made separately for the two rock formations that possessed two distinct types of sedimentary rocks, i.e. the competent sandstones in the Phra Wihan and the less competent siltstones in the Phu Kadung,the Phra Wihan and

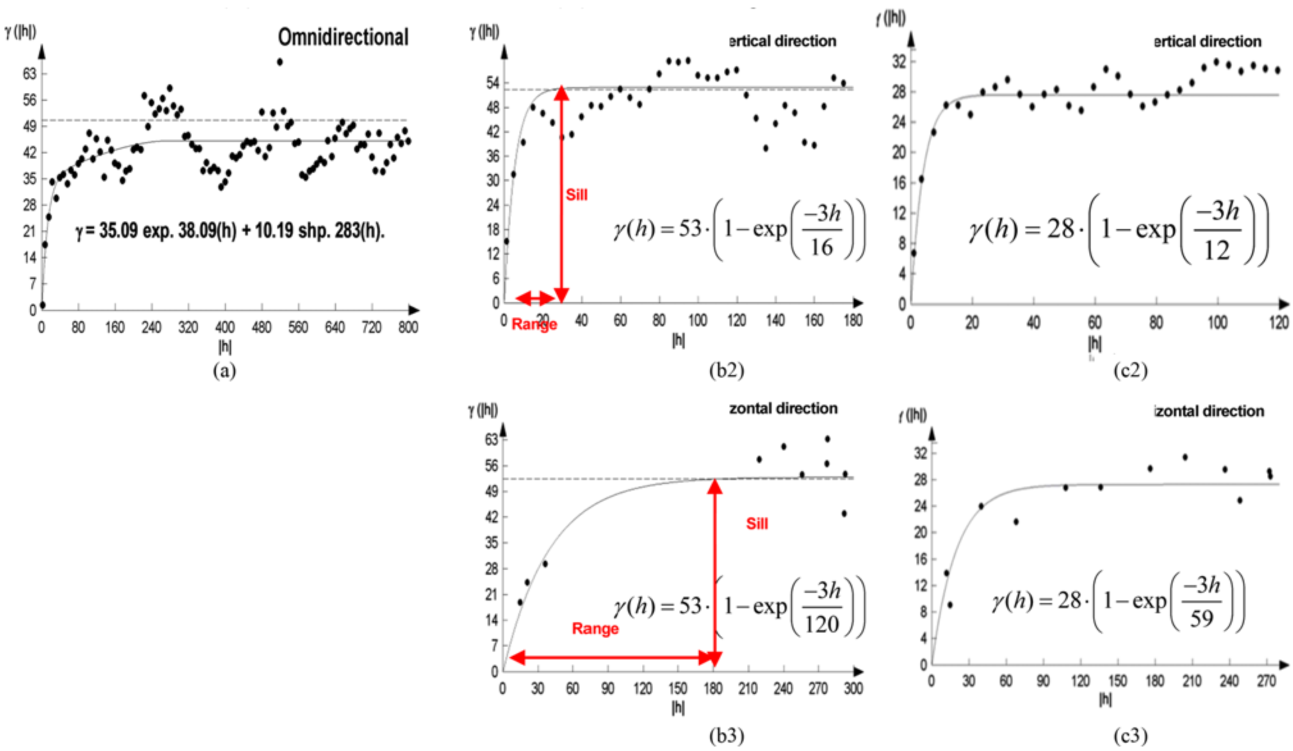


Fig. 5. Variograms of the Sampled Data Points and Fitting Model Equations: (a) Omnidirectional of Combined Rock Formations, (b) Anisotropy of Phra Wihan Formation, (c) Anisotropy of Phu Kradung Formation

the Phu Kradung formations (Figs. 5b and 5c). The parameters of the anisotropy variogram models best fitting the data were determined for the geostistic analyses with an aid of GSLIB software (Deutsch and Journel, 1992.). For Phra Wihan formation, there were some erratic results in horizontal variogram for lag distance of 45 m to225 m, probably owing to non-availability of sampled data points in this spacing range of drillholes. The result was better for Phu Kradung formation because of a larger number of boreholes and deeper length of drillholes through the formation. The spatial correlation of the data is determined by interval of the range value (indicated in Fig. 5b). The higher the range value is, the better the correlation of the data pairs.

The ordinary kriging or the best linear unbiased estimator was used to interpolate RMR values at each grid points. It used the linear weighted combination of the available data method and the mean was constant over the entire domain, i.e. constant for nearby data values in the local neighborhood of each estimation point. The kriging parameters such as the search radius of major direction, the search radius of minor direction, and the maximum number of data points for kriging were verified to find the reliability of kriging estimation. The kriged estimation result of rock mass quality, RMR, of Lam Ta Khong Pumped Storage Project site is shown in Figure 6 from which the estimated RMR values along the two tunnels were determined (Fig. 7). The optimistic estimation (mean value + 1 standard deviation) and the pessimistic estimation (mean value – 1 standard deviation) defined according to Hasegawa and Ohtsu (2007) are also shown in the figure.

According to the geostatistic estimation shown in Fig. 6, the RMR values were between 20 and 70 (poor to good quality

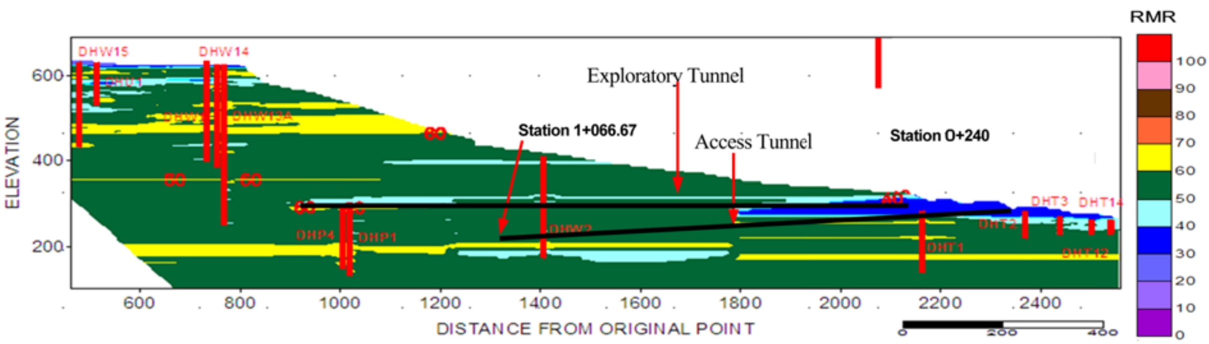


Fig. 6. Kriging Estimation of RMR Values for Rock Mass for Lam Ta Khong Project Site based on the Anisotropy Variogram Model

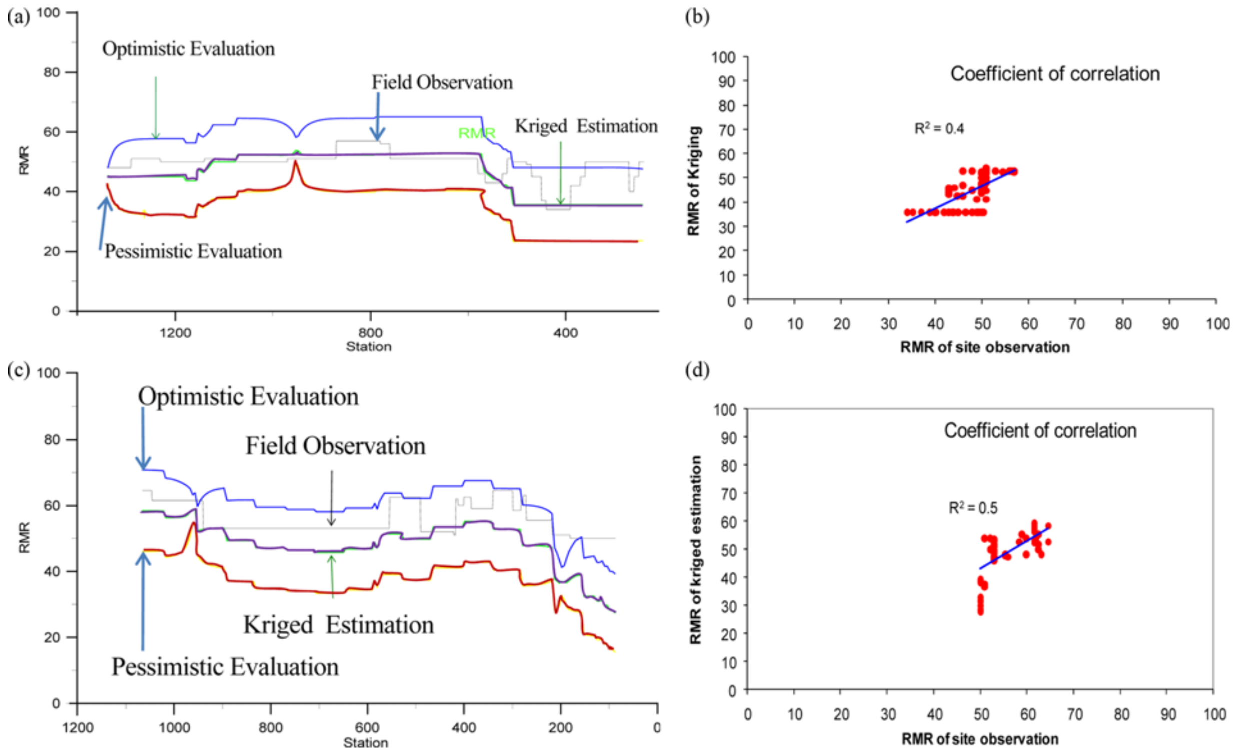


Fig. 7. Comparison of the RMR Values by Kriging Estimation and Field Observation along Tunnel: (a) Exploratory Tunnel from Station 0+240 to Station1+340, (b) Access Tunnel to Powerhouse from Station 0+870 to 1+067, (c) and (d) Comparisons between Estimated and Observed RMRs

rock). The means of RMR estimation of Pha Wihan and Phu Kradung formations were 51 and 50, respectively, which were not so different from the drillhole values of 54. Good rocks existed in sandstone. Poor rocks existed at shallow depths near the surface.

The prediction by kriging estimation was compared with field observation data available from excavation of the exploratory tunnel and access tunnel to powerhouse of the project (Nitaramorn, 1997; Sriwisead, 1996; Tran, 1994). Kriging estimation showed similar RMRs to field observation data at locations of the two tunnel excavations as shown in Fig. 7. For exploratory tunnel, RMR of field observation showed 8% of poor rock class and the rest 92% of fair rock while the RMR estimated by kriging was 72% of good rock and 28% of poor rock. Prediction of poorer rock quality was obtained at chainage 0+240 to 0+380, probably owing to absence of borehole data in the nearby vicinity. Moreover, observed data values in that area of shallow cover depth showed low RMR.

In access tunnel to powerhouse, Sriwisead (1996) obtained field map along 846 m length of the tunnel that showed rock classes as 73% of fair rock and 27% of good rock. Kriging estimated 80% of fair rock and 20% of poor rock which was reasonably close to the actual. Most of the prediction from the kriging indicated similar RMR to field observation. However, in some portions such as station 0+200 to 0+410 and station 1+360 to 1+390 the RMR values were somewhat under predicted. However, the trend of both data points and kriging estimation points showed the similar trend of correlation along tunnel alignments.

3.2 Klong Tha Dan Dam Tunnels

RMR values of volcanic rock mass at Klong Tha Dan Dam evaluated from 21 core logs data were in range of 40-90 and the average of 77. Rock mass quality is mainly good to very good (RMR 61-80). Fair rock (RMR 41 to 60) is founded at shallow depths in the abutments. The histogram was moderately asymmetric as indicated by the difference between mean and median of the data (Fig. 8a). The coefficient of skewness is not close to zero (-1.21).

The variation in data set was quite high because minimum and maximum data set were so different. The variograms showed a fluctuation of data pairs in lag distances and less correlation between data pairs which were shown by low range values (Figs. 8b, 8c, 8d). The kriging estimation was conducted separately for two dam body sections, RCC-B and RCC-S. The grid definition was 5 m × 5 m of grid size and one number of grid discretion. Fig. 9 show the results. Rock mass quality is mainly good to very good (RMR 61-80). Fair rock (RMR 41 to 60) is founded at shallow depths in the abutments. The comparison can be seen from Fig. 9 on the kriegging estimated RMR values of rock masses in the foundations of the two dam bodies and the RMR values along the drillholes that were made mostly in the vertical direction. Few drillholes were made in inclined orientations at an angle of 30 degrees from vertical in an attempt to better intersect the predominant steeply dipping discontinuities in the rock

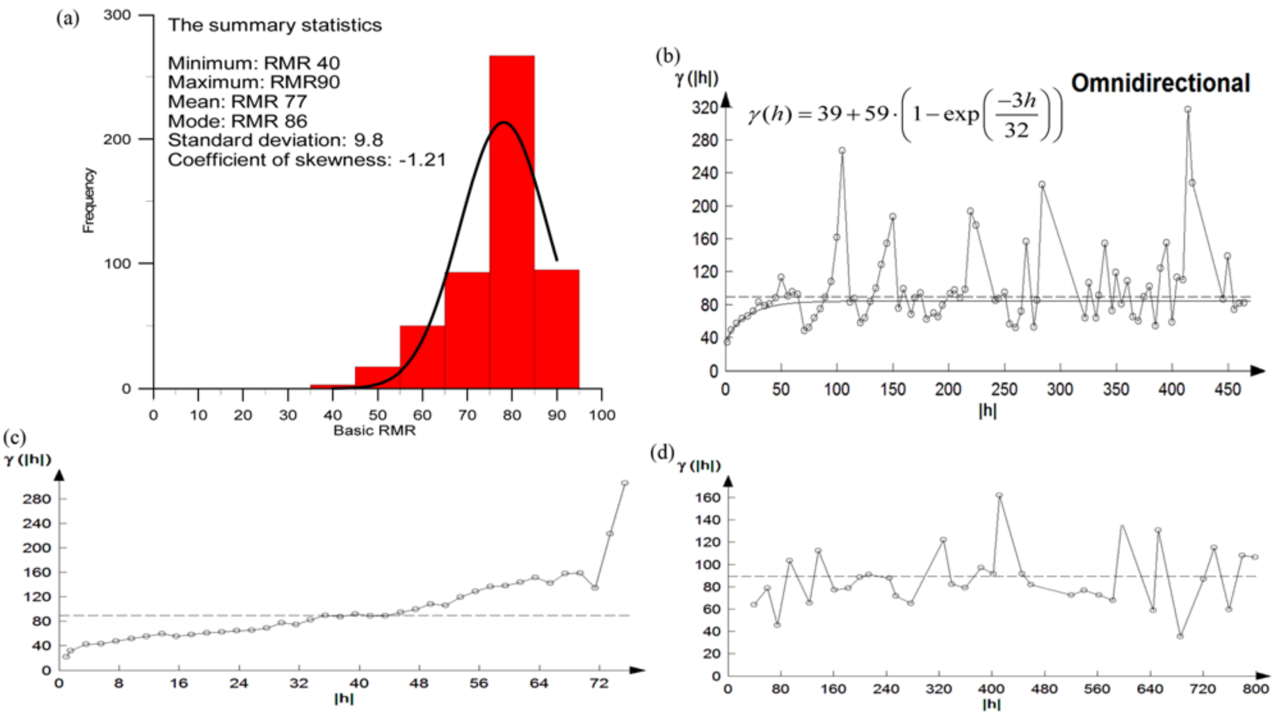


Fig. 8. Histogram and Variogram of RMRs of Klong Tha Dan Dam Project: (a) Histogram and Statistical Characteristics, (b), (c), and (d) Variogram in Different Directions

foundation.

The RMR values from kriging estimation are compared with RMR values obtained from excavation of tunnels in the abutment and the central spur, i.e. tunnels TSL D2, and TSB D3 tunnels (Fig. 9). It can be seen that RMRs from the field observation were consistently lower than the Kriging prediction at all locations along both tunnels (Figs. 10a, and 10c). This discrepancy might be attributed the fact that the determination of RMR at the tunnel faces during excavation was made earlier by a different party from the one who did mapping of rock cores. More importantly,

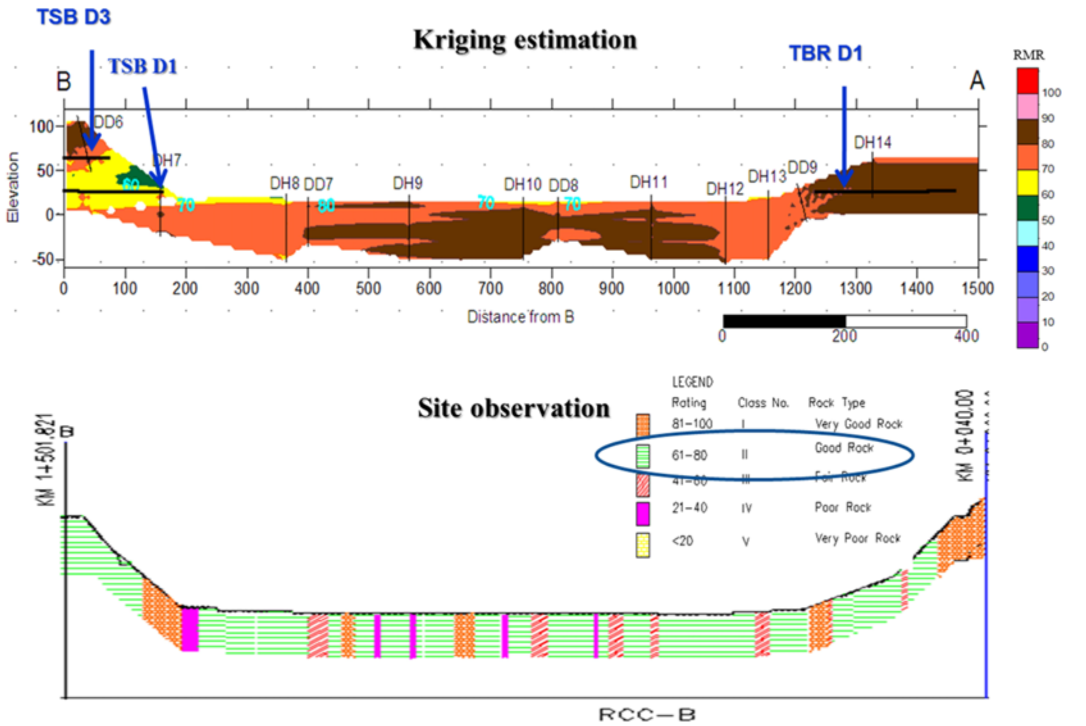


Fig. 9. RMR by Kriging Estimation and RMR by Site Observation of Klong Tha Dan Dam Project

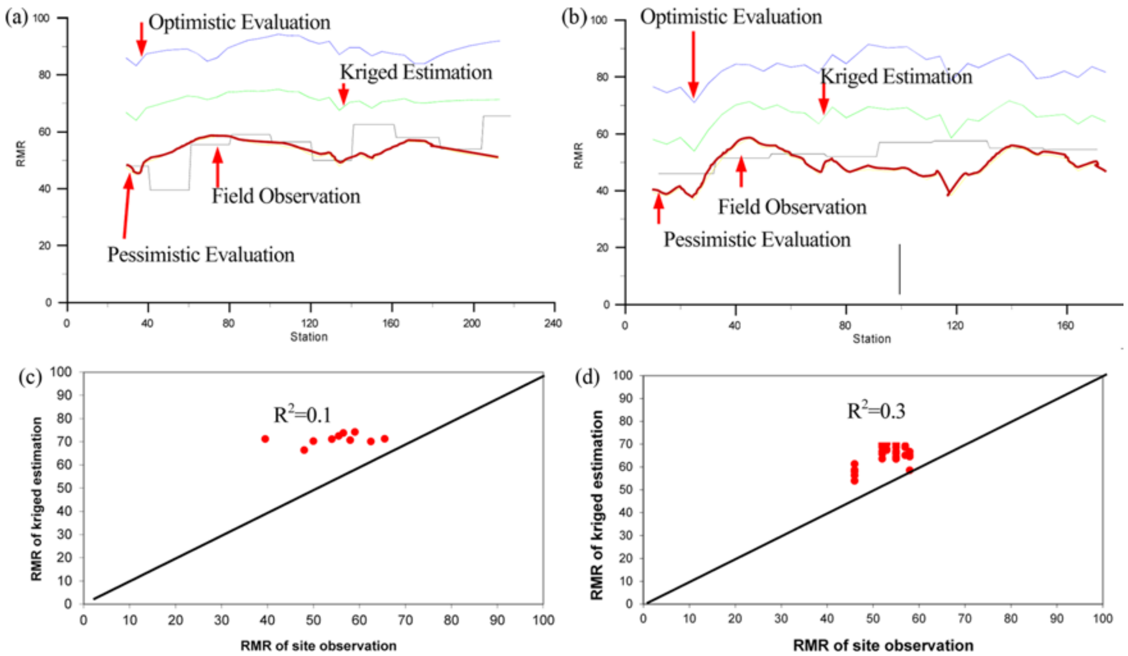


Fig. 10. (a) and (c) Comparison RMR between Site Observation and Kriged Estimation of TSL D2 and TSB D3, respectively, (b) and (d) Plotting between RMR of Site Observation and RMR of Kriging Estimation for TSL D2 and TSB D3, respectively

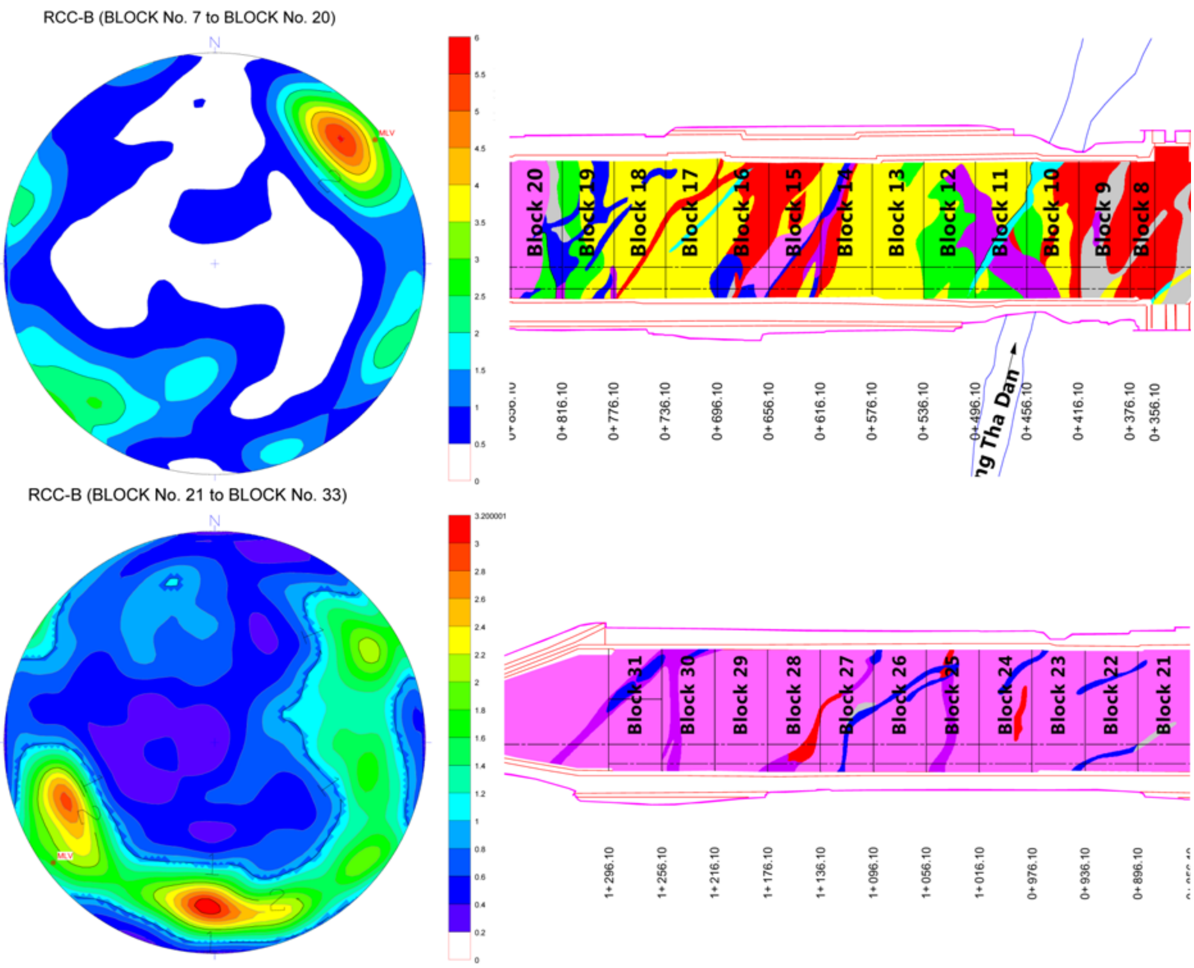


Fig. 11. The Pole Plot of Stereographic Projection of Discontinuities of Rock Mass of Klong Tha Dan Dam Project

the effect of blast induced fractures of in tunnel walls in this hard rock blasting could lead to a bias in the mapping of tunnel wall. Such an observation was also reported by Fookes (1997).

The geostatistical estimation results showed that the field observed values of hard rocks of the Tha Dan Dam tunnels were reasonably comparable with the pessimistic values of Kriging estimation (i.e. mean value less standard deviation), rather than the mean values. This is to say that if the determined field RMR values were to be increased by 15 points (1 standard deviation) for the entire length of the tunnel, they would be similar to the krieging estimated values.

In addition, the predicted distribution of RMR values of the rock mass along the tunnel length showed patterns that were dissimilar to the observed ones. The rather poor comparison may be due to the fact that the kriging estimation was based upon core log data of drillholes which were oriented sub-parallel to orientation of major discontinuities. Moreover, the pole plot of stereographic projection showed that more than 86% of the joints were dipping between 45-90 degree (Fig. 11). That meant rock mass of this area is much more effected by vertical or sub-vertical joint sets.

Therefore, the drillhole data naturally did not well represent the distribution of rock mass quality in the direction sub-perpendicular to the steeply dipping discontinuity. The alignment of the tunnels were approximately in the N-S directions (Fig. 2B) and the strikes of predominant steeply dipping discontinuities sets were in the N 45°-80° W (Fig. 11). In overall, it may be said that the poor prediction on the rock mass quality along the tunnel length by the geostatistical approach based on the drillhole data of the Tha Dan Dam Project might be attributed to various factors which included biases from blast induced fractures in the hard rock excavation and the different parties used in RMR rating of rock core samples and tunnel wall and face, the effect of predominant steeply dipping discontinuities and the predominant vertical orientation of the exploration drillholes, and finally the complex nature of the geologic structures of the rock mass influenced by a nearby major fault system.

4. Conclusions

From the study of applicability of the geostatistical approach in assessing rock mass quality condition along two tunnel projects in Thailand, main conclusions can be made as follows:

- Geologic setting plays an important role on applicability of the geostistical method. It affects the variogram pattern of the sampled data points and then the predicted rock mass quality and distribution.
- The variogram analysis indicated anisotropic variation in rock mass properties (RMR) in horizontal and vertical directions of sedimentary rocks at Lam Ta Khong. On the other hand, rock mass condition of Klong Tha Dan Dam showed poor spatial correlation-variograms for use in the Krige extrapolation.
- Low variation in variogram was found for Lam Ta Khong Pumped Storage Project which showed the smoother and clearer variogram pattern than that of Klong Tha Dan Project. The former site had a simple geologic setting whereas the latter was in a complex setting and the drillholes were made sub-parallel to the orientation of major discontinuities (faults and shears). Therefore, knowledge of geologic setting, which controls the rock mass characteristics and condition, need to be considered for successful variogram analysis.
- The ordinary kriging estimated reasonably well the RMR values for purpose of geo-prediction for tunnel construction in case of simple geology setting such as that of Lam Ta Khong Pumped Storage Project.
- The kriging estimation is unsatisfactory for case of Klong Tha Dan Dam Project of which the geologic settling is complex and borehole data did not truly represent the anisotropic variability of the rock mass quality owing to the predominantly preferred oriented geologic structures of steeply dipping nature sub-perpendicular to the tunnel excavation direction.
- For application of geostatistic analysis to a complex geologic setting site, investigation data from vertical and near-vertical drillholes are not sufficient. A supplemental investigation such as probing by a geophysical mean along the tunnel alignment seems essential.

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