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Interpretation and development of top-surface grid in subsurface ground profile using Inverse Distance Weighting (IDW) method for twin tunnel project in Kenny Hill Formation

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Abstract: Constrained soil investigation works in tunnel construction projects brings inevitable uncertainties in capturing the exact subsurface profile. This uncertainty leads to misinterpretation of tunnel analysis, which can later cause unreliable prediction of settlements trough in tunnel analysis. The initial stage of interpretation of the subsurface soil profile is generating reliable top-surface grid profile. Increasing the number of boreholes can provide more information for modelling the grid profile. The profile is conventionally developed using borehole information and survey plan, which are interpreted manually and sometimes can be erroneous. This situation proves that the lack of method for data interpretation should be supported with another approach such as Inverse Distance Weighting (IDW). IDW is categorized as a type of deterministic method for multivariate interpolation with a known scattered set of points. The assign values for unknown points will be determined by a weighted average of the values available at the known points. IDW interpolation influenced by weight decreases as the distance increases from the interpolated point. This study focused on the development of top-surface grid for Klang Valley Mass Rapid Transit (KVMRT) project using data from borehole investigation and survey plan along the tunnel alignment. Reduced level of boreholes and information from survey plans that were completed for this project were analyzed. Based on the study results, the Model 2 assigned with exponent 5 for IDW analysis is more preferable for subsurface ground modelling in tunnel analysis for this particular project.

Keywords: Top-surface grid, subsurface soil profile, Inverse Distance Weighting method, Kenny Hill Formation

INTRODUCTION

Subsurface characterization process provides important input during preliminary and detailed analysis of tunnels construction (Chapman *et al.*, 2010). During preparation of the subsurface investigation, engineers normally realize that factors of the unforeseen costs and failures are normally associated with construction and is geotechnical in nature. On the other hand, the potential hazards at the construction site should be taken into account while investigating the basic geotechnical information to observe the geologic material and its deformation under the action of forces introduced by the unloading and loading processes. Geotechnical characterization of a project site for engineering applications is indispensable in engineering geology and geotechnical engineering, and there are many unavoidable variabilities and uncertainties during characterization of a project site (Wang *et al.*, 2016). Since geological material is natural and is always complex, it leads to various geotechnical uncertainties. McMahon (1985) identified three main types of ‘geotechnical uncertainty’, which he described as the ‘risk’ of encountering an unknown geological condition, the ‘risk’ of using the wrong geotechnical design criteria, and the ‘risk’ of bias and/or variation in the design parameters being greater than estimated. Subsurface investigation is required and carried out prior to commencement of a construction project including tunneling projects. Conventional method such as borehole exploration is frequently used as soil investigation method in tunnel construction projects.

Tunnel excavation will induce soil stress and perturbance around the opening of the tunnel and displacement will also occur. Therefore, soil and rock characterization including strata (subsurface profile) obtained from preliminary site investigation should be established for safety and optimal tunnel designs. The interpretation of subsurface profile used during the design stage is vital to meet the requirement of tolerance settlement trough during tunnel construction. To counteract any misinterpretation of subsurface soil profile due to insufficient data, models incorporated with spatial interpolation must be proposed. However, development of top-surface grid model is more important as a first step of tunnel analysis. This is due to the fact that the overburden above the tunnel must be considered and taken into account to produce a reliable result.

SITE CHARACTERIZATION

The site characterization was conducted in the Klang Valley Mass Rapid Transit (KVMRT) project area. This twin tunnel project is located within the Kenny Hill Formation that consists of homogenous residual soil and weathered sedimentary rock, specifically known as meta-sedimentary rock formation (Tan, 2006). It is composed of interbedded sandstone, siltstone and shale of Upper Silurian-Devonian age. The mass rapid transit project is to encourage economic

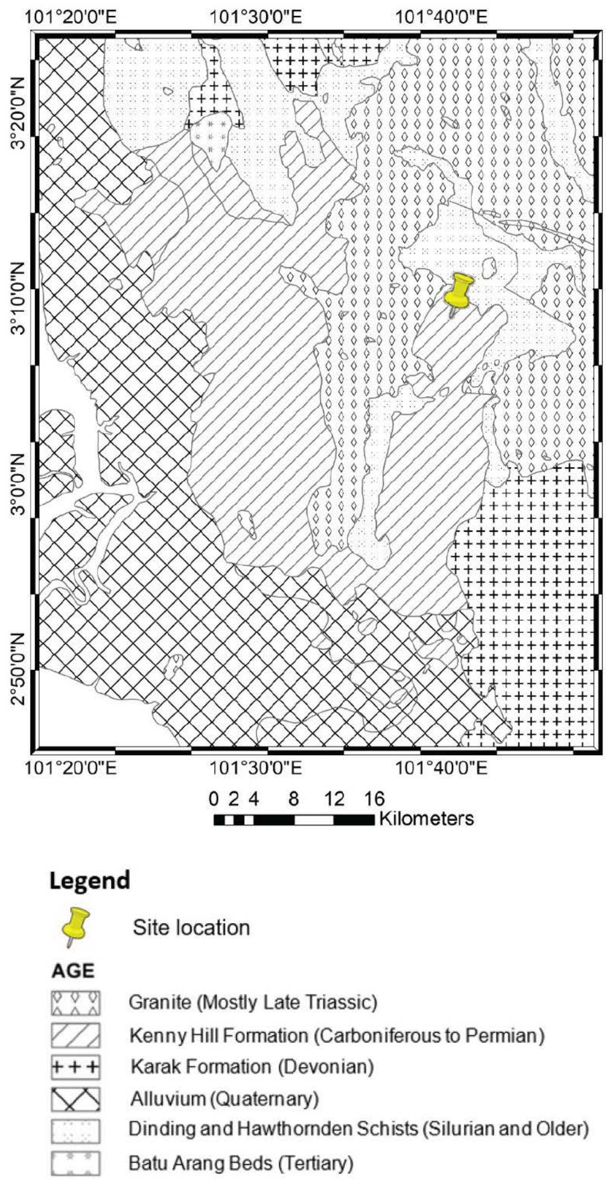

Figure 1: Distribution of Kenny Hill Formation in Geological Map of Selangor (redrawn from Geological Map of Peninsular Malaysia [l:300,000]).

growth and increase mobility for urban citizen by using efficient public transportation. It was involved in several phases, such as planning and execution. The design process is part of the execution task to determine tunnel specifications in construction. The inevitable risks that potentially rise during this stage are considered. Technique, selection of tunnel lining and method of construction will be addressed at this stage. However, the interpretation of subsurface soil profile, which forms the basis in tunnel design should be reliable and represent the site conditions. Therefore, the first stage in tunnel analysis is to predict or interpolate top-surface grid model before performing subsurface modelling. The subsurface modelling will then be based on Standard Penetration Test (SPT) N-blows or RQD for the detail design and tunnel analysis.

About 223 boreholes were drilled along the tunnel alignment. Spatial interpolation was utilized to predict the unknown point which is related to its lithology and soil stratification. Rockwork software was used as a tool to analyse the subsurface profile. During the first stage, the top-surface model should be determined. The top-surface is considered reliable if the interpolation using IDW produces similar results with the borehole reduced level. This interpolation stage is known as the preliminary stage in developing a subsurface ground model. The required information including site location contour (obtained from survey plan), coordinate of boreholes and borehole depths and elevations are important inputs to be assigned in the Rockwork software. The area of tunnel construction was divided into five (5) zones based on soil lithology similarities. However, due to modelling limitation, several zones were further divided into smaller sections. Zone 1 consists of two sections, Section A and Section B. Zone 2 and 4 have 3 sections each, Sections A, B and C. Whereas, Zones 3 and 5 were modelled without sections due to being small in area. This methodology was aimed to develop model appropriately using proper project dimensions and avoid larger outlier interpolations. It can also generate the models and compute faster than zone without small section. The related area of modelling is most important to be analysed and interpolated.

INTERPOLATION METHOD

Interpolation or algorithm is a method that is commonly adopted in computer modelling in simulating top-surface grid profiles. Through interpolation, absence of data in any specific location can be estimated to the closest data point from the nearest borehole that was drilled during site investigation. This task if performed manually may be tedious, particularly for the larger areas. Spatial analysis is the use of statistical assumption and techniques to improve the interpretation of spatially referenced data using interpolation methods. Spatial interpolation corresponds to measuring the same parameter at different locations and using these to estimate for the data at unsampled points (Bamisaiye, 2018). Spatial interpolation enhances the visualization of the pattern and continuity in a variety of spatial data. This is due to the ability of interpolation methods to create continuous surfaces from scattered observations by estimating the depth of occurrence of lithology and structures at un-sampled points (in-between borehole) based on the premises that close observations are likely to have similar values than those that are far apart (Tobler, 1970). Thus, it can be summarized as a method to measure the values of surrounding data for the prediction location, and each data at certain points which is to be predicted is more influenced by the local data and diminishes with distance.

Selection of interpolation method

Inverse distance weighting (IDW) and Kriging methods are prominent interpolation methods. According to Rasmunsen-Rhodes & Mayers (1993), the IDW method is applicable for datasets of small size for that the modelled semi-variograms are very difficult to fit. It provides a measure of uncertainty of the estimates that is directly related to the values being estimated, in contrast to kriging standard deviation which is based on the modelled semi-variogram (Adisoma & Hester, 1996). Kravchenko (2003) found that kriging with known variogram parameters performed significantly better than IDW for most of the case studies; however, it was very less accurate than IDW when a reliable sample variogram could not be obtained because of either an insufficient number of data points or too large a distance between the data points. Kriging had a higher accuracy if the spatial structure of altitude was strong. Compared with other methods, most notably kriging, the IDW method is simpler to programme and does not require pre-modelling or subjective assumptions in selecting a semi-variogram model (Henley, 1981).

The general premise of this method is that the attribute values of any given pair of points are related to each other, but their similarity is inversely related to the distance between the two locations. However, many studies, especially in the spatial interaction literature, have revealed that the decline in spatial relationship between any two locations is not simply proportional to distance (Fotheringham & O'Kelly, 1989). As a result, a power or exponential function modifying the distance weight is often used to model spatial interaction between places. In applying the IDW method, such a function is often considered when predicting the unknown attribute values at certain locations (Lu & Wong, 2008). The general formula of IDW interpolation is the following (Johnston *et al*., 2001):

$$w(x,y) = \sum_{i=1}^{N} \lambda_i w_i, \lambda_i = \frac{\left(\frac{1}{d_i}\right)^p}{\sum_{k=1}^{N}\left(\frac{1}{d_k}\right)^p} \qquad (1)$$

where w(x,y) is the predicted value at location (x,y), N is the number of nearest known points surrounding (x,y), λ_i are the weights assigned to each known point value w_i at location (x_i,y_i), d_i are the Euclidean distances between each (x_i,y_i) and (x,y), and P is the exponent, which influences the weighting of w_i on w. Figure 2 shows the fundamental of IDW to generate nodes from a known data point.

Bekele *et al*. (2003) used inverse-distance weights of powers 1, 2, and 3 to map soil potassium. Lloyd (2005) used a power of 2, a frequently used value, to interpolate precipitation.

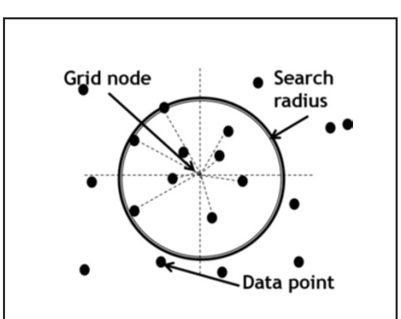

Figure 2: A radius is generated for each grid node from which data points are selected to be used in the calculation.

METHODOLOGY

Top-surface grid modelling

Rockwork consists of Map/Grid-Based Map. This utility is to provide a grid model to generate top-surface grid that is important before modelling the subsurface ground profile. The first procedure is to assign the XYZ data obtained from the survey plan and borehole reduced levels into utilities worksheet. This can be performed by importing the database from Microsoft Excel. At the next stage, a 3-dimensional map surface will be developed to represent the grid model. This grid model is known as top-surface grid and is being used for subsurface soil modelling in tunnel analysis. Rockwork has a function of IDW method that is the most common gridding method that emphasis on the exponent value. Power function (exponent) was provided by IDW method as a user-selection. This study will concentrate on this exponent function adopted in IDW approach to develop the top-surface grid before modelling the subsurface soil profile in the Kenny Hill Formation, particularly for this twin tunnel construction.

This study was carried out using two models for top-surface grid determination. Model 1 utilized IDW method with exponent 2 and Model 2 which adopted exponent 5. The gridding is more localized for the higher exponent since the distant has less influence on the value assigned to each grid node. This method has advantages in terms of the highest grid value will be less than the maximum data point, and the lowest grid value will be greater than the minimum data point.

Validation of top-surface grid model

The validation of output model should be investigated by previewing the output model with the coordinates and reduced levels obtained from the survey plan. This should not rely on the theoretical of IDW method only. Justification of the output model is most important to represent the actual site condition. This method does not provide prediction standard error, thus justifying of this model can be variable. The validation of the output model is necessary to ensure

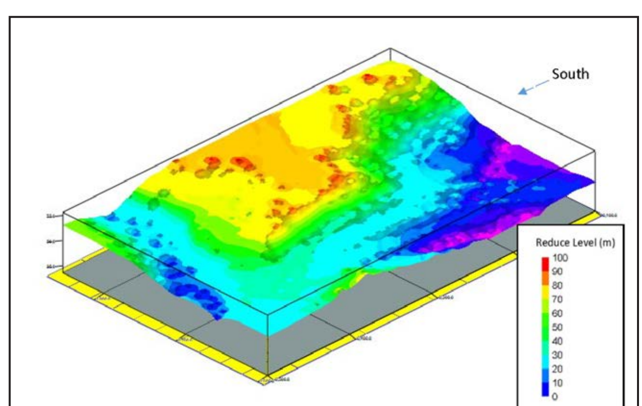

Figure 3: Model 1 (exponent value is 2).

its compatibility with the heterogeneous data sets. The computational method will be considered as successful if minimum error variances are obtained for probable surface.

RESULTS AND DISCUSSIONS

According to Figure 3, Model 1 was generated using IDW method and the value assigned to a grid node is considered as a weighted average from the data distributing neighbours. This method was specified accordingly to the inverse distance from the grid node. The selected exponent for the Model 1 is 2. In this approach, the greater exponent value will result in a 'localized' gridding rather than a 'global' gridding. The reason for this condition is stated in Equation 1. The value of each data point is weighted according to the inverse distance which are from the grid node and considering the *p* power. In this case, Model 1 is more global for gridding process.

Model 2 as shown in Figure 4, was proposed with higher exponent value (exponent value equal to 5). This adjustment was made to produce the best-fit model and to represent exact given data point to reflect actual site condition. The result shown in Model 2 gridding is more localized. The reduced level for the unknown data point was interpreted based on its surrounding data and greater distance has less influence on the analyses compared to the exponent value of 2. The advantage of IDW method is that a smooth and continuous grid can be obtained. Its extrapolation data was designed not to be analysed beyond the given data range; the highest grid value less than the maximum data point and the lowest grid value is greater than the minimum data point. Raising distance factor in denominator to exponent 5, the value distant of data point will exert less influence than nearby points on the value assigned to a grid node. By proposing two models with different exponent values, the most reliable model was obtained in this research.

Relying on this isotropic view to justify the best fit model is insufficient. Top-surface grid for each model should be supported with other information including South-view. South-view will display results of IDW computation at each data point. Advanced display is required as a guideline for IDW interpolation at any data point. Therefore, this procedure was enhanced by utilization of 3D-Points function. This tool visualizes the control points in 3D view. Figure 5 below show the 3D point for given data in this respective area.

This function is used to facilitate the validation process. Results from the 3D-Points can be appended to top-surface grid model. Figure 6(a) and 6(b) show that the models appended with 3D-Points have a good agreement between reduced level generated from IDW method. This top-surface

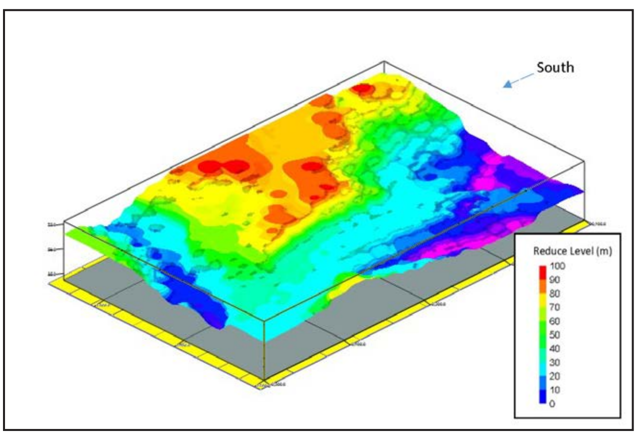

Figure 4: Model 2 (exponent value is 5).

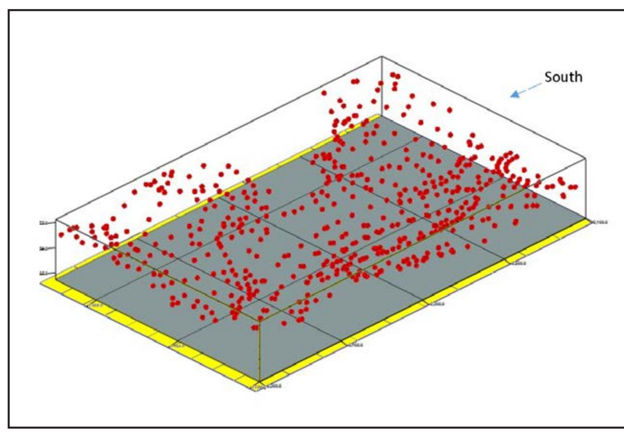

Figure 5: 3D-Point for given data point.

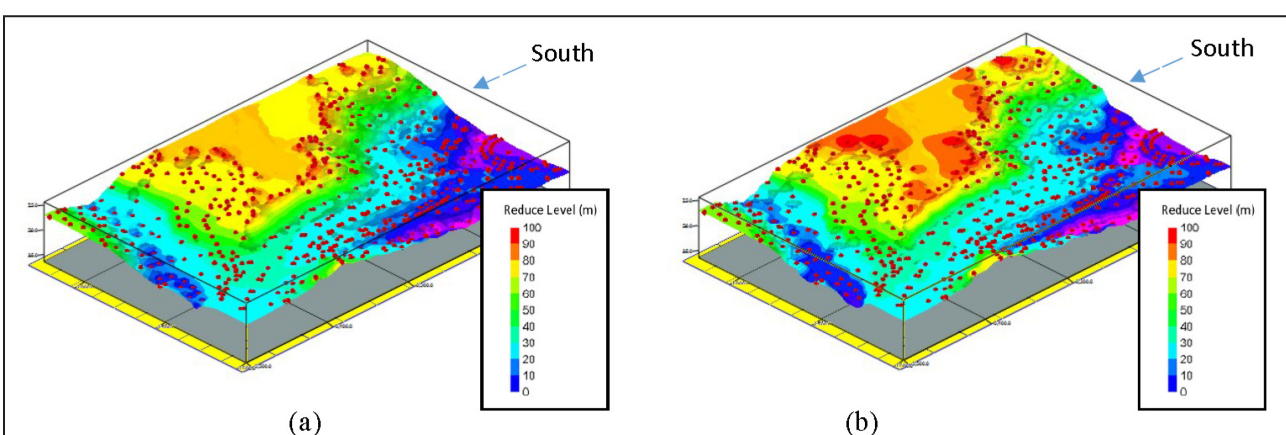

Figure 6: Top-surface grid model a) Model 1 (exponent value is 2) appended with 3D-Points b) Model 2 (exponent value is 5) appended with 3D-Points.

grid will be compared with the exact data point from the survey plan.

However, the results for both models are approximately similar with the appended 3D-Points. This can be distinguished by South-view to optimal the verification process. The significant tool in Rockwork that can assist this prediction is Vertical Exaggeration and set to be 10.

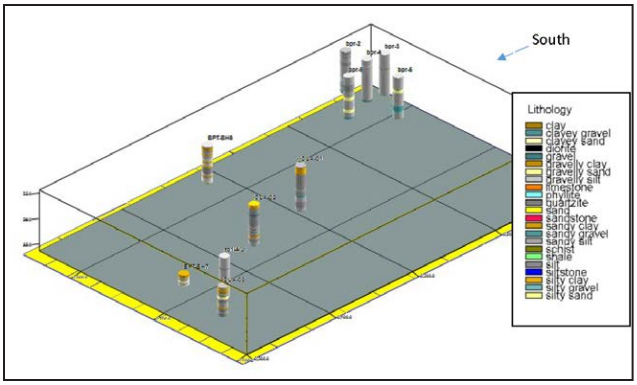

Figure 7: Borehole locations.

Accurate prediction of IDW method for both models are presented effectively in South-view. Another important aspect that must be considered before predicting the top-surface grid model and the validation process is the borehole locations, as shown in Figure 7.

Borehole location is relatively important for model validation. Point data which is sparsely distributed for this section should be controlled by borehole locations and borehole reduce level. This stage is imperative since data from borehole will be further extracted and referred to during the design stage. Accuracy of model in interpolating the borehole locations and reduce level should be emphasised.

South-view presented for Model 1 (Figure 8(a)) in comparison to Model 2 (Figure 8(b)) shows more variables in terms of borehole reduce level. It can be identified that Model 2 is the more preferable model because it is likely to offer better predictions of borehole reduce level.

The IDW logarithm which created grid models in highly anomalous data is shown in Figure 9. Model 1 with selection exponent 2 is graphically more detached from the 3D-Points

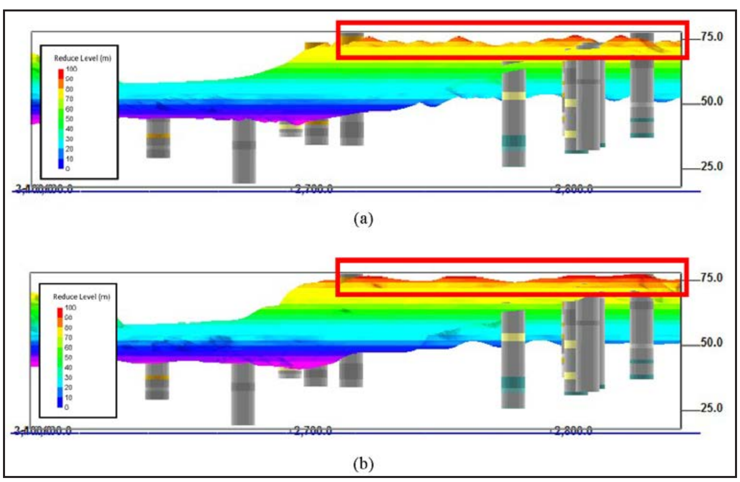

Figure 8: South-view for (a) Model 1 (exponent value is 2) South-view appended with borehole locations and elevations (b) Model 2 (exponent value is 5) South-view appended with borehole locations and elevations.

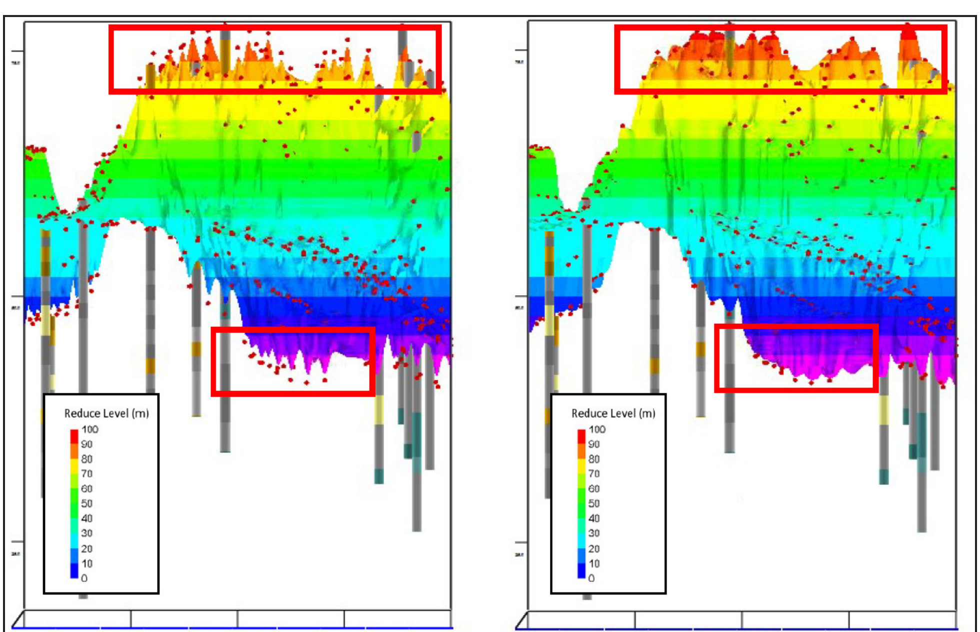

Figure 9: South-view a) Model 1 (exponent value is 2) appended with 3D-Points b) Model 2 (exponent value is 5) appended with 3D-Points.

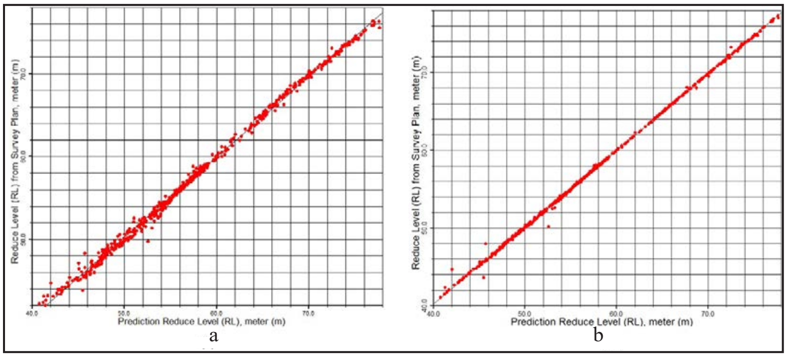

Figure 10: Graph of Reduce Level (RL) from Survey Plan versus Prediction Reduce Level (RL) for a) Model 1 (exponent value is 2) b) Model 2 (exponent value is 5).

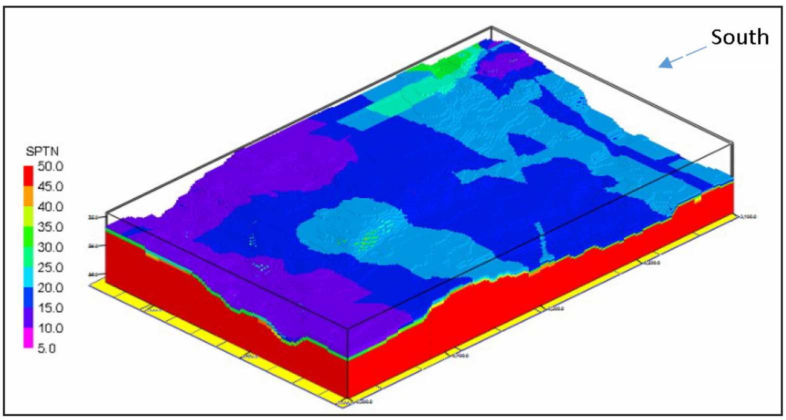

Figure 11: Subsurface soil profile for SPT-N developed using IDW and top-surface Model 2.

as compared to Model 2. This establishes that Model 2 is the best fitted model to represent this area.

The alternative technique is to plot a graph from the IDW spatial interpolation results that is applicable for both models. This graph is incorporating with the correlation between prediction of data point and measured data point from survey plan. From the Figure 10, Model 2 demonstrates more consistent graph and linear in representing the reasonably accurate prediction of data point value and data point obtained from survey plan.

According to Figure 11, Model 2 top-surface grid was adopted in further analysis of SPT-N ground model. As a conclusion, it is more reliable to adopt Model 2 as top-surface grid to represent subsurface soil profile compared to Model 1 top-surface grid for this area.

CONCLUSIONS

The several methods discussed above are interrelated and provide continuity to the subsurface ground model by producing top-surface grid model to fit as desired degree of exactness in the first stage of the modelling process to simulate real on-site conditions. As a conclusion, the best interpolation method is the method that gives the closest approximation to known data for all study areas. In this research, the proposed IDW method which consists of exponent value of 5 is statistically reliable and highly suggested for further tunnel analysis study.

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