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PREDICTION OF Q_U AND R_U CAPACITIES OF PILE IN CLAYEY SOIL LAYER USING GEOSPATIAL ANALYSIS

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ABSTRACT: The basic purpose of foundation design is to predict ultimate soil bearing (Q_u) and to determine actual load-carrying capacities (R_u) at the final set installation. One specific case study was when the project owner was only allowed to use limited CPT data of the high-cost reason for complete soil investigation. Besides that, the location was not only relatively densely populated, but also the soil investigation work could cause some noise during the implementation of field-testing methods using SPT and Borlogs. CPT has been selected and easy in predicting the Q_u value of a single pile. Two points at one of the configurations of single piles were evaluated randomly by the PDA test in determining the actual load capacity or R_u. In general conclusion, the Q_u was less than R_u values for all existing points of the single pile at the study area. To find out other values of Q_u and R_u in all piles were analyzed by a geospatial analysis. By using isotropic Moran's method, there was a positive autocorrelation in adjacent pile location since I = 0.1767 > I0 = - 0.25. Graphically, the semivariogram also validated Gaussian interpolation models as the best correlation in searching pair; distance; and semivariance values among the single pile. Finally, the ordinary Kriging method was used to plot all points graphically in 3 D based on Moran's and semivariogram of Q_u and R_u data. Thus, this method yields good results of Q_u and R_u for other single piles with an error of around 13.2% at the final set installation between 8.9 to 9.5 m.

Keywords: Bearing capacity; Load-carrying capacity, PPC pile foundation, PDA test

1. INTRODUCTION

Soil investigation work is an expensive and time-consuming process [1; 2]. Geotechnical engineers must work with limited data. It is not often, the project owner is only allowed to use one kind of instrumentation for field tests without taking an undisturbed sample for laboratory tests. And, another environmental case, some residents with a dense population do not want some noise due to soil investigation work.

One case is shown in this paper during the design of the pile foundation system of an office building at Central Jakarta using 30 cm square of precast prestressed concrete (PPC) on soft and thick clay soil. The office building was designed to have 7 floors. Generally, field investigation for deep foundation design only uses cone penetration test (CPT) [3; 4].

CPT data can be used to determine the other soil parameters using some correlations required for deep foundation design, especially in predicting the ultimate soil-bearing capacity of the single pile (Q_u). However, it was not all methods that showed the best capability [5; 6] in predicting (Q_u) single piles installed at a certain point in the study area. One of the methods to evaluate the Q_u value is the Schmertmann method. Schmertmann method (1978) for static loading analysis was selected and considered suitable for the study area. the value of Q_u is obtained from the sum of Q_p and Q_s. Q_p is load carrying capacity of the pile point; Q_s is frictional resistance (skin friction) derived from the soil-pile interface.

Pile Driven Analysis (PDA) test is to measure the actual ultimate load-carrying capacity (R_u) of a single pile and it can be used to evaluate a single pile based on prediction analysis (Q_u). Evaluation of R_u of selected single piles tested from a certain configuration of group piles can be performed randomly, thus some failures and defects of a single pile of all deep foundations systems can be avoided. For this case, two random points of a pile configuration of this project after installation up to the final set were selected to determine R_u.

Geospatial analysis theory has been developed by geostatistical science on geoscience including geotechnical engineering. This method is widely used, for example, Sambah et al [7] described the visualization of possible damage and loss areas that may result from a tsunami attack in the southern coastal area of East Java, Indonesia. Geospatial analysis is a tool to find out the other unknown important data (Q_u and R_u) as well as point position (2-D or 3-D) according to [8; 9].

This paper aims to focus on analyzing the Q_u in static loading and R_u at the final set installation of a single pile according to coordinate points before they were arranged into a configuration of group piles to carry upper structure loads at each point. Since the limitation data of Q_u and R_u, values of both parameters were analyzed by spatial autocorrelation through Moran's I as well as the prediction and interpolation by semivariogram and ordinary Kriging on Q_u and R_u data. Then, it compares other prediction and interpolation models (gaussian, exponential, and spherical). The Moran's I test was used to analyze a spatial autocorrelation for Q_u and R_u. Based on interpolation model evaluations, the best interpolation model was chosen to determine Q_u and R_u values for all coordinates at the study area. Finally, by the mapping of results of predictions Q_u and measurements R_u, it could be evaluated the appropriate ultimate load carrying and bearing capacities for the other coordinate point of the pile.

2. RESEARCH SIGNIFICANCE

Almost all geotechnical engineers work with a limitation of soil and loading test data in designing Q_u and or R_u. The geotechnical engineer always designs the substructure and predicts the single pile using the closest point of soil investigation results or loading test data since the limitation point is provided by the project owner. Geospatial autocorrelation analysis is required to determine the Q_u and R_u for the other point on the existing area, so that it can assess these values accurately and fulfill all requirements in supporting the upper structure. Besides that, all data results can also be applied to modify the equation of the bearing capacity formula.

3. LITERATURE REVIEW

3.1 Pile Bearing Capacity Using CPT Field Test

Since CPT was first discovered, the CPT test has been widely used in predicting the bearing capacity of the pile [5] based on cone resistance (q_c) and sleeve friction (f_S); pore water pressure (u) during soundings [6]; time behind vs original time of pile installation [10]; constitutive model using artificial neural networks (ANN) [11]; etc. All testing procedure was adopted from ASTM D3441 – 16 [12]. Generally, the ultimate bearing capacity (Q_u) is analyzed for a single pile in static loading [13; 14; 15]. This study selected to use the Schmertmann method [16] in analyzing the Q_u of single pile up and suitable for the Jakarta area.

3.2 Pile Load Carrying Capacity Using PDA Test

PDA (Pile Driving Analyzer) test or the dynamic strain testing high strain pile tests (HSDPT) [17] recently is always used as one of the solutions in evaluating load carrying capacity (R_u). [18]. PDA was used in determining short and or long-term ultimate load-carrying capacity (R_u) [19]. The R_u can be evaluated from the manual field reading output directly using CASE and CAPWAP analyses [20]. Normally, the difference in R_u values between CASE and CAPWAP methods were not exceeding 1%.

3.3 Geospatial Analyses

Geospatial analysis is a numerical technique related to analyzing and predicting spatial or temporal variability of values of spatially correlated data and one tool of geostatistical methods to describe the combination of spatial software and analytical methods with terrestrial or geographic datasets [21, 22]. Geospatial analysis is widely applied to geotechnical engineering since engineering for geotechnical design always works with the limitation of both laboratory and field data [23; 24]. This study uses geospatial analysis for autocorrelation through Moran's I as well as the prediction and interpolation by semivariogram and ordinary Kriging on Q_u and R_u data [25, 26; 27] to determine all coordinates in this area.

4. RESEARCH METHOD

4.1 CPT and PDA Data from The Investigation Area

Geographically, the Jakarta Pusat area is located in the center of Jakarta city with 6º 12’ SL and 106º 50’ EL. Geographically, the study area is located in Senen District. The total area of the Senen District is 4.22 km^2. Jakarta is a deposited layer of clayey soil and soil strength can be classified by soft to medium class with the location of bedrock between 345 to 707 m depth [28]. The basic aquifer system was formed by Miocene impermeable sediments which were also cut outside the southern boundary of the basin [29].

CPT data samples were taken from the site plan. The layout of CPT and PDA tests is shown in Fig. 1. The number of CPT tests is 5 (five) sample points (Fig. 2). The ground investigation started from the ground surface below the filling with the variation of thickness between 1.0 to 1.5 m and followed by a medium to stiff silty clay, medium clay, dense to very dense silty sand layers on bedrock layer to the depth of 12.0 m.

4.2 Assessment of Q_u (CPT) and R_u (PDA)

Q_u or total of Q_p and Q_s values were calculated by using the Schmertmann method [16] under static loading conditions only. Parameter R_u was assessed by manual calculation of the CASE methods; and application of the CAPWAP program software. Based on each method above, there is no correlation between Qu and Ru values.

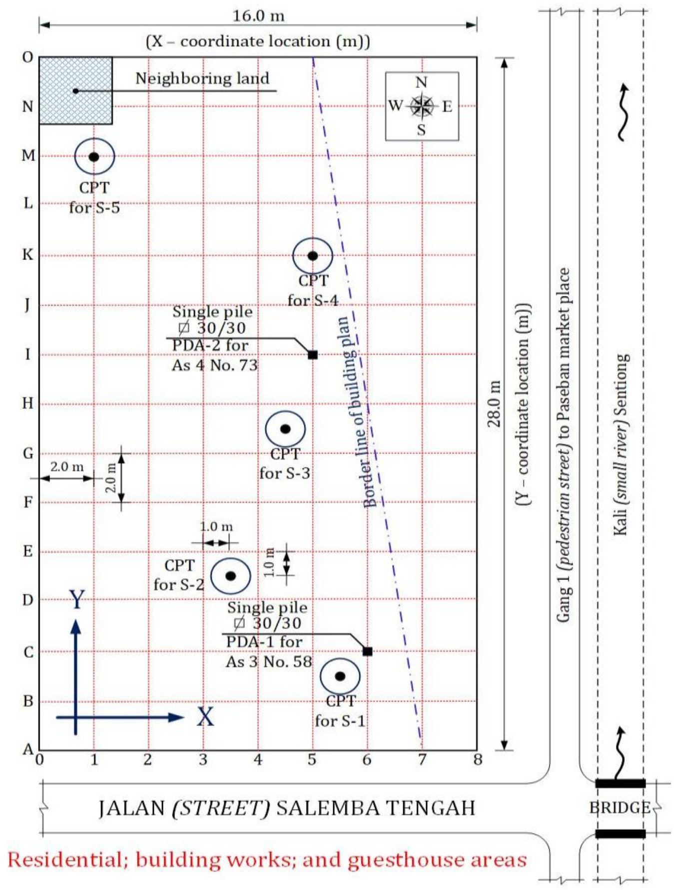
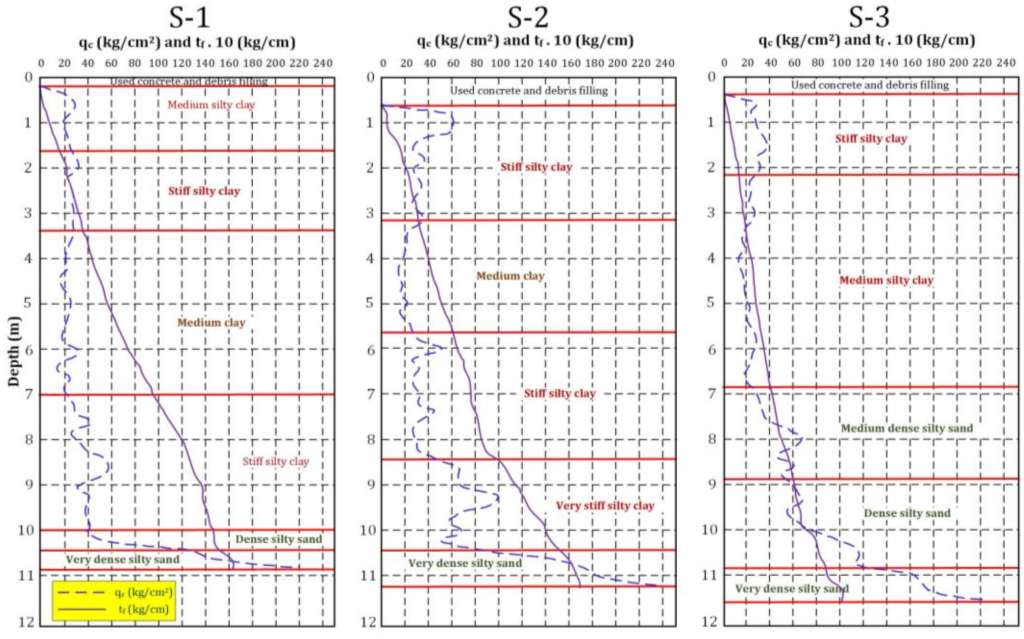
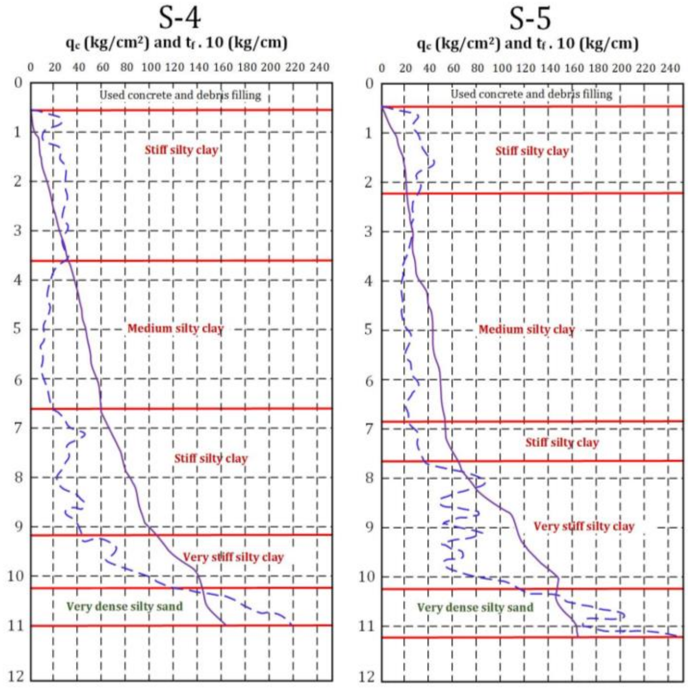


Fig. 1 Layout of CPT and PDA tests in the study area



S-1 S-2 S-3

Fig.2a Soil profile based on CPT data



S-4 S-5

Fig.2b Soil profile based on CPT data

Typical of Q_u from CPT test (S-1 & S-2) result using the Schmertmann method is shown in Fig. 3. The values of Q_u increase with increasing the depth. Average of Q_u of 30 cm PPC for the depth of 9,5 m reach the range of 90,0 to 100,0 tons. PDA test results using the CASE method are 137,0 tons and 166,8 tons, the CAPWAP method is shown in Table. 2, both of R_u values of 137,3 tons and 167,7, respectively

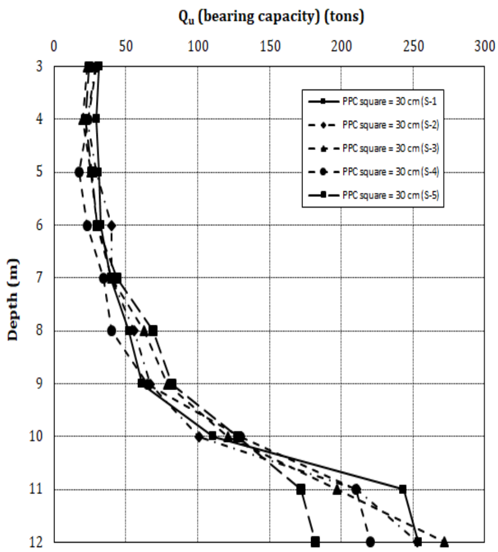


Fig. 3 Typical of Q_u (Schmertmann method) [16] up to final set installation; PPC pile size = 30 cm

5. RESULTS AND DISCUSSION

Estimating of missing data at every point of single needs a model for geospatial analysis. Therefore, this research needs to use spatial autocorrelation analysis in determining the other points unknown of Q_u and R_u values. On Table 1 shows the descriptive analysis of Q_u and R_u values at the final set (9.5 to 10.5 m depth), there were differences significantly.

Table 1. Descriptive analysis of Q_u and R_u (tons) At final set installation and PPC pile size = 30 cm

Descriptive analysis	Q_u (CPT)	R_u (PDA)
Number of data	5	2
Average	118.2	152.0
Median	120.8	152.0
Deviation standard	12.1	20.8
Variance	116.4	432.2
Maximum	129.9	166.7
Minimum	101.2	137.3
Range	28.7	29.4

Table 2. R_u Value based on CASE & CAPWAP methods

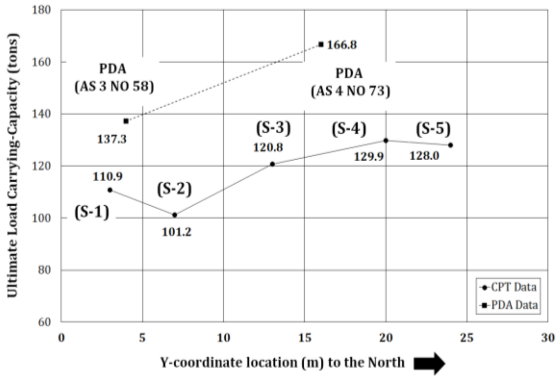
Pile	CASE Method (Tons)	CAPWAP Method (Tons)
AS 3 No. 58/NEAR S-1	137.0	137.0
AS 4 No. 73/NEAR S-3 and S-4	166.8	167.7

5.1 Moran's I method

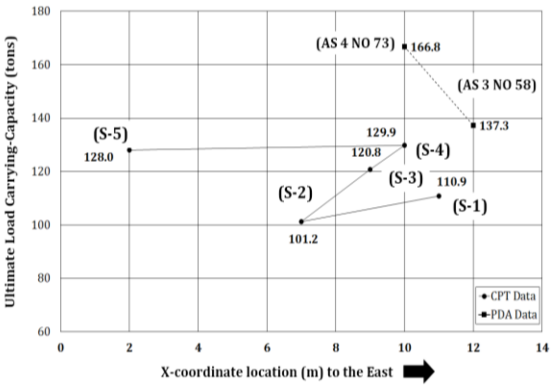
Moran's I is used to test for geospatial autocorrelation. From the isotropic Moran's I analysis is 0.1767 or greater than I_o = -0.25, it shows that there is a positive autocorrelation or clustered pattern that has similar characteristics in adjacent locations. The isotropic condition is also shown in Fig. 4 and 5, the direction from South to North has a certain pattern approaching a gaussian model, where further to the North the values of (Q_u) and (R_u) enlarge. However, from the anisotropic is -0.088 or less than I_o, there is no geospatial autocorrelation and Fig. 4 and Fig. 5 also indicate that there is a poor correlation and has no pattern in the direction from West to East. Thus, it can be concluded that the Q_u and R_u have no similar values or indicate that the data are not in a group according to the isotropic Moran's I.

5.2 Semivariogram Method

The results of the semivariogram are selected and plotted into gaussian, exponential, and spherical models for the prediction of Q_u and actual measurement of R_u values.



a. Variation values of bearing capacity (tons) from South to North



b. Variation values of bearing capacity (tons) from South to North

Fig. 4 2-D pattern of distribution of Q_u and R_u

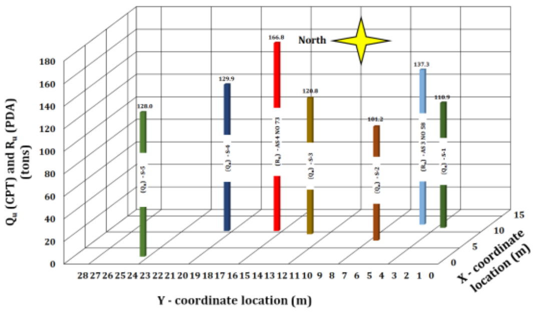


Fig. 5 3-D pattern of distribution of Q_u and R_u

After all points Q_u and or R_u plotted, the lines will show all types of semivariograms according to the theory of gaussian, exponential, and spherical models. Generally, the result of the semivariogram has a sill value of 0.2047, a range of 10.837, and a nugget of 0.0010. This semivariogram shows pair of data, the distance between data, the value of semivariance, and spatial correlation. From the comparison of gaussian, exponential, and spherical models, it can be indicated that the gaussian model semivariogram is more suitable for the other prediction of Q_u data because it approaches the measured data of R_u. Thus also, the other unknown data of Q_u and R_u according to the certain coordinates of the study site can be predicted by gaussian model data value and gives the best correlation with a small error of around 13.2%, despite it having a low coefficient of variability.

5.3 Ordinary Kriging Method

Kriging is one of the prediction and interpolation methods in geostatistics. There are two types, such as ordinary Kriging when there is only one variable; and co-Kriging when there is more than one observed variable. The definition of interpolation, in this case, is a method for generating a prediction surface that is continuous from a group of data samples. Interpolation analysis is necessary because the data is not possible be taken from all the existing locations. The interpolation technique retrieves data in some locations and generates predictive values for other locations.

Prediction and measurement results of the Q_u and R_u by using the ordinary Kriging method are presented in Fig. 6 and 7. The results of ultimate Q_u and R_u using the gaussian model give the smallest Root Mean Square Error (RMSE) value than others. Fig. 6 and 7 show that all locations have almost the same characteristics, Q_u is always smaller than R_u values and both values enlarge to the northward. It can be concluded that the soil in this area has a cohesion parameter that is much better than the data obtained from the results of laboratory testing.

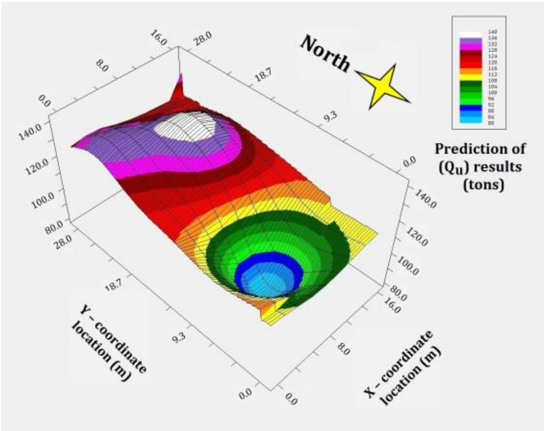


Fig. 6 Prediction results of Q_u (CPT)

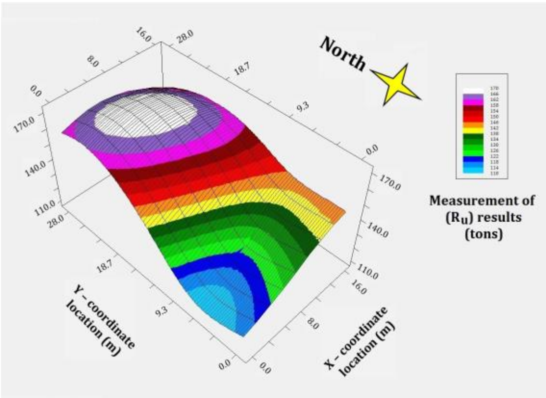


Fig. 7 Measurement results of R_u (PDA)

This study aimed to benefit from Moran's I, semivariogram, and Kriging techniques to assess ultimate soil bearing (Q_u) and load-carrying capacities (R_u) for the study site. However, two primary sources of uncertainty contribute to the variability of in situ test measurements, namely, spatial variability, and measurement error when determining Q_u and R_u, separately. Spatial variability is the natural variation that clayey and sandy soils, and rock layer exhibit, from one location to another, as a result of the myriad and complex processes which form them, and to which they have subsequently been subjected. Uncertainties associated with equipment effects can occur as a result of procedure drift (CPT devices), non-linearities, and out-of-calibration errors related to the electrical transducers and mechanical devices (PDA instruments), which each have different levels of reliability. Procedure and operator effects cause variabilities in measurements as a result of inadequate, or limited, testing standards, noncompliance with these standards, as well as uncertainties as a result of different operators. Both of these effects, equipment, and operator and procedure, are systematic, or biased [12, 17], errors which consistently under-estimate and or over-estimate when determining Q_u, and a measured parameter when assigning R_u.

The Variograms method was prepared at 7 (seven) data consisting of 5 (five) data obtained by Schmertmann method [16] analysis in calculating Q_u based on CPT data and 2 (two) real data or measured by PDA test in determining R_u in hand. Among the semivariogram models analyzed in this study, the largest errors in the determined values of Q_u and R_u relative to the empirical data were observed for the exponential and spherical models and the smallest for the Gaussian model. However, it should be emphasized that the values of the analyzed errors for the individual semivariogram models were almost similar.

Subsequently, the ordinary Kriging method was used to calculate Q_u and R_u values inside the study site. Thereafter, contour maps were prepared for better visualization of this variation. The models were validated using the RMSE parameter calculated at each coordinate, which was found to be a reasonably low coefficient of variability [23; 27]. Besides, the results obtained in real data from direct measurement were compared with the estimated data, for better visualization of the performance of the models. Application of the ordinary Kriging method for interpolation of geospatial distribution of Q_u and R_u yields good results, but the final shape of the spatial distribution is influenced by the selection of the semivariance function model. The study site has a variation of Q_u and R_u. The highest values of Q_u and R_u occurred northward, while the lowest values were found the southward at the study site. The random measurement error associated with a particular test, depends greatly on: (1) the micro-variability of the geotechnical material; (2) the spacing of the samples in the data set; and (3) the stationarity of the data.

It was considered that the results obtained from 5 (five) CPT data and 2 (two) PDA data can be useful for Q_u and R_u in the area for all coordinates. The results of this study can be used to detail engineering design parameters (e.g., the configuration of the pile group, bearing capacity of the pile group, normal and liquefaction stability, pile cap design, etc) related to the ultimate bearing and or load carrying-capacities of single pile inside the study site. From a geotechnical engineering point of view, the bearing capacity equation of the Schmertmann method [16] for a single pile should be modified according to the condition of the OCR (overconsolidated ratio) value, especially for clay soil layers.

Based on the analysis results obtained from Moran's I analysis shows that there is spatial autocorrelation in the ultimate load carrying-capacity Q_u and R_u in the direction from south to north of the study site. The Gaussian model gives better results of prediction and interpolation than exponential and spherical models. The measurement using the PDA test at the study site, it shows that the value (R_u) is always larger than (Q_u). This matter can be understood that the alluvial deposit in the study area has been subjected to initial loading and OCR is possibly larger than 1.0. The OCR > 1.0 values can influence the tip-bearing capacity and skin friction of the pile.

From geology analysis, the pattern of soil strength from South to North as the results from this study is almost similar to some geology references. Where soil strength as the alluvial deposits were expressed by the same pattern of the position of hard layers of soil in the northern region, it was around 10 m to 25 m depth. The southern part consisted of alluvial deposits extending from east to west at 10 km south of the northern coast area. Underneath was an older sediment layer. Thus, this study has verified the previous analysis that the condition of soil strength by the depth of the pile has increased in the north ward, regardless the clay soils have experienced an initial loading and increased the OCR value in the case history. However, but it also must be noted that the final shape of the spatial distribution is dependent on the selection of the semivariance function model and at least have a good correlation between the connected points based on the point position in 2-D and or 3-D in the existing area. Geospatial analysis has advantages and disadvantages that exist in the method [21; 22] including: without considering the time effects on pile bearing capacity; affects the skin friction of the pile on the clayey soil; etc [30]. Geospatial analysis shows a realistic approach and is very helpful in the design of the bearing capacity of a single pile in the study area.

6. CONCLUSIONS

It was considered that the results obtained from 5 (five) CPT data and 2 (two) PDA data can be useful for Q_u and R_u in the area for all coordinates. The results of this study can be used to detail engineering design parameters (e.g., the configuration of pile group, bearing capacity of pile group, etc) related to the ultimate bearing and or load carrying-capacities of single pile inside the site. This method yields good results of Q_u and R_u for other single piles with an error of around 13.2% at the final set installation between 8.9 to 9.5 m.

However, despite the low coefficient of variability and the narrow range of the investigated CPT and PDA values, the prediction and or actual measurement and model variogram confirmed, almost, a pure nugget effect which is an indication of a high level of spatial variability across the site. Whereas, for the investigated data with a small difference between the observation points, a common average process could be adopted for the geotechnical design across the whole site with a high level of confidence. Accordingly, a conclusion could be drawn that, using the Gaussian model gives better results of prediction and interpolation than exponential and spherical models. The measurement using the PDA test at the study site, it shows that the value (Ru) is always larger than (Qu) as per the case presented here.

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