Influence of Soil variability in SPT data for predicting the Bearing Capacity of Piles

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Abstract. Standard Penetration Test (SPT) is one of the most commonly adopted methodology to determine the soil profile at any particular site for calculating the bearing capacity of the pile foundations. Soil variability is inevitable. In this regard, the present study focusses on the statistical process of characterizing the same based on the SPT data. This data was obtained from 20 boreholes at a site in Kolkata, which is proposed to adopt pile foundation for its upcoming structures. The vertical variability is characterised by a probability density function. The statistics of vertical variability comprising of mean and standard deviation are calculated and the scale of fluctuation using the random field theory are obtained. The range of scale of fluctuation is found to be in good agreement with the globally accepted literature. This variability has been incorporated in predicting the bearing capacity of the piles for the proposed site using different correlations given by Meyerhof (1956), Aoki and De'Alencar (1975) and Decourt (1995).

Keywords: SPT, Bearing Capacity, Soil variability, Probability density function, Scale of fluctuation.

1 Introduction

Foundations are the substructures which distribute the load from the superstructures to the underlying soil or to the bedrock as per the design. Foundations are generally classified as shallow and deep. Pile foundations, categorised under deep foundations are commonly used for the massive structures, opted when the underlying soil is weak and prone to excessive settlement. Standard Penetration Test is one of the widely followed methodologies for the soil investigations as well as in determining the bearing capacity of the pile foundations. Many researchers, after the experimental evaluations, developed specific empirical correlations for calculating the ultimate bearing capacity for different kinds of piles. Among them, Meyerhof (1956), Aoki and De'Alencar (1975) and Decourt (1995) have been utilised in this study. In general, the methodologies restrict the parameters as deterministic entities. However, various researchers such as Vanmarcke [1], Phoon [2], Haldar [3] indicated that the response variability of the foundations considering soil variability is appropriate.

1.1 Uncertainty application

Uncertainties prevail in any natural process, which is undesirable. Soil is no more an inferior material in this regard. Soil, being a geological material, is packed with the uncertainties in its parameters, which is inevitable. Uncertainties are of three kinds; Inherent uncertainty, arises by the natural conditions and cannot be left out; Measurement uncertainty arises with the usage of equipment for the investigations; Model uncertainty arises due the mathematical models and equations involved in the analysis. In the present study, a stochastic model has been deployed to quantify the inherent uncertainty lying with the primary parameter engaged with the bearing capacity calculation, i.e. SPT – N value.

1.2 Stochastic modelling

The stochastic modelling has been deployed with the help of one-dimensional random field characterised by probability density function, comprising mean, standard deviation and the scale of fluctuation which denotes the measure of the soil property in a statistical manner using the in situ data. The present study focuses only on the vertical variability of the SPT – N considered in the study, and the data is analysed using the random field theory. Vanmarcke [1] suggested that the fit of the theoretical correlation model could determine the statistical measure in the vertical variation of the property, i.e. the scale of fluctuation to the sample autocorrelation function (Bouayad [4]). Few autocorrelation models, such as exponential, squared exponential, second-order Markovian and cosine exponential functions are available in the literature and utilised in this study (Table-1).

1.3 Monte-Carlo simulation

The Monte-Carlo simulation technique is the process of allowing all the uncertainties with the input parameters to the considered mechanism or the system of analysis. Regarding the stochastic uncertainty analysis, Monte-Carlo simulation, which is a very diversely applied technique in the engineering applications, has been implemented here. With the help of this simulation, the uncertainty involved with the SPT – N are considered in determining the bearing capacity of piles.

This study presents the methodology on incorporating the vertical soil variability in SPT – N for determining the bearing capacity of the pile foundation in the sandy soil.

2 Case Study

The SPT data was collected from a site located at Kolkata. It was planned to have a kind of high rise structure in that site. So, pile foundation has opted. SPT was performed for the soil investigations at that site, and twenty borehole data are considered for the analysis. The profiles are displayed in the fig.1. In most of the boreholes, it was observed that the soil in the top 5m approximately of depth is almost a kind of fill up material; after that, the soil is classified as silty sand.

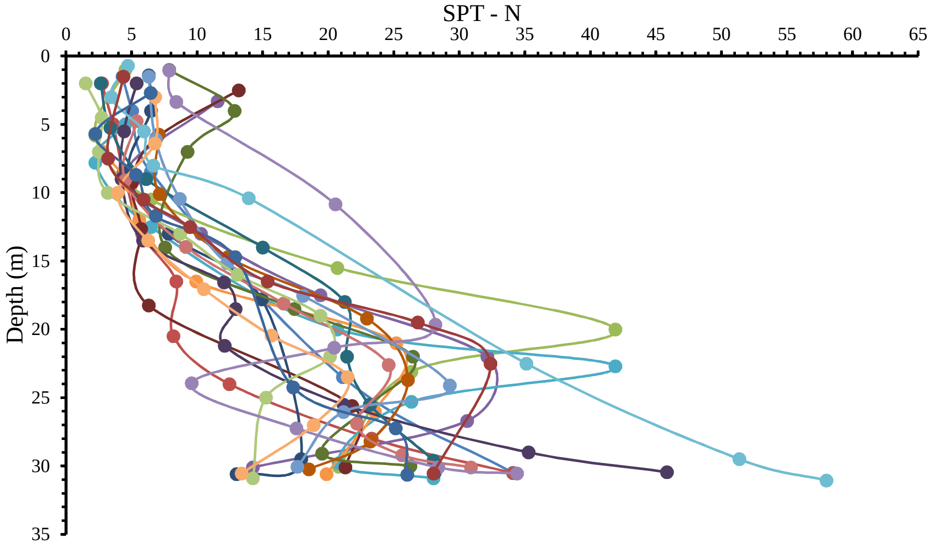

Fig. 1. SPT profiles for twenty borehole data

As suggested by Vanmarcke [1], for the application of random field theory, the data needs to be stationary. To determine the scale of fluctuation or the deviation, the following steps need to be carried out for each SPT profile.

- Using the ordinary least squares method, trend function needs to be evaluated and deducted from the measured to obtain the stationarity.
- The residuals need to be considered for the random field application, and the auto-correlation samples are generated.
- Since the study is concerned with only vertical variability, one-dimensional correlation models are required to make to fit with the samples.
- The scale of fluctuation is calculated for the best-fitted model, i.e. when the coefficient of determination will become closer to unity.

To illustrate the above methodology as well for the bearing capacity calculations, a typical SPT profile of borehole-5 has been considered for the study, and it has been explained in the following sections.

3 Example illustration

The illustration is done in two parts. First one relates to the measurement of the scale of fluctuation, and the other relates to the uncertainty analysis in bearing capacity calculation using different correlations.

3.1 Determination of scale of fluctuation

The SPT data was collected for borehole-5 was shown in the fig.2. Along with the profile, the polynomial trend of second degree has been displayed. To obtain the stationarity, the trend has been deducted from the measured data. The de-trended profile was shown in the fig.3.

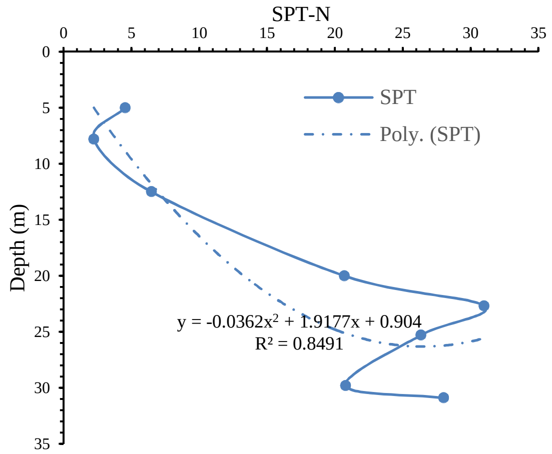

Fig. 2. SPT profile for the borehole-5

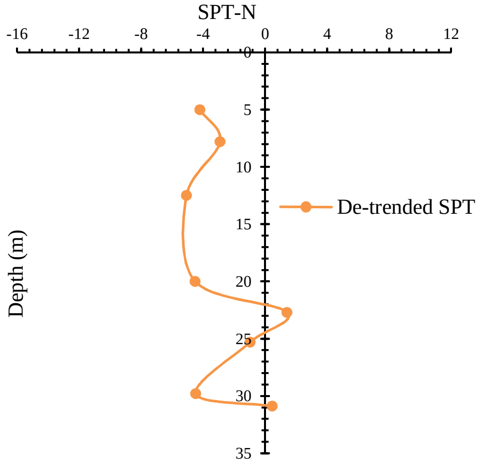

Fig. 3. De-trended SPT profile for the borehole-5

The residuals obtained after the de-trending has been considered for the random field application. Random field theory was applied by the use of shifts in the data mathematically, and the autocorrelation samples have been found. As the information is limited, and so, the present study is concerned only with the direction of availability of the data, i.e. vertical direction. The obtained samples were fitted with the available one-dimensional autocorrelation models to find the scale of fluctuation. The statistical fits are displayed in the table-1. Various correlation models such as exponential, square exponential, second-order Markovian and cosine exponential models have been considered for the study. Fits are displayed in the fig.4. It is found that the samples are best fitted with the cosine exponential correlation model with a coefficient of determination as 0.9282, which is close to 1.0. The correlation length is calculated as 1.9262m. According to Phoon [2], the vertical scale of fluctuation is 0.6-5m. So, it can be said that the obtained scale of fluctuation for borehole-5 is within the prescribed range by Phoon [2].

Table 1. Fit of one-dimensional correlation models

Autocorrelation Model	Correlation Function	Correlation constants	Correlation Length, dv (m)	R^2
Exponential	$y =$ [illegible]	[illegible].639	2/[illegible] 1.2203	0.7639
Squared exponential	$y =$ [illegible]	[illegible].473	[illegible] = 2.6108	0.7871
Second order Markovian	$y =$ [illegible]	[illegible].874	4/[illegible] 2.1345	0.7782
Cosine exponential	$y =$ [illegible]	[illegible].023; [illegible].3961	[illegible] 1.9262	0.9282

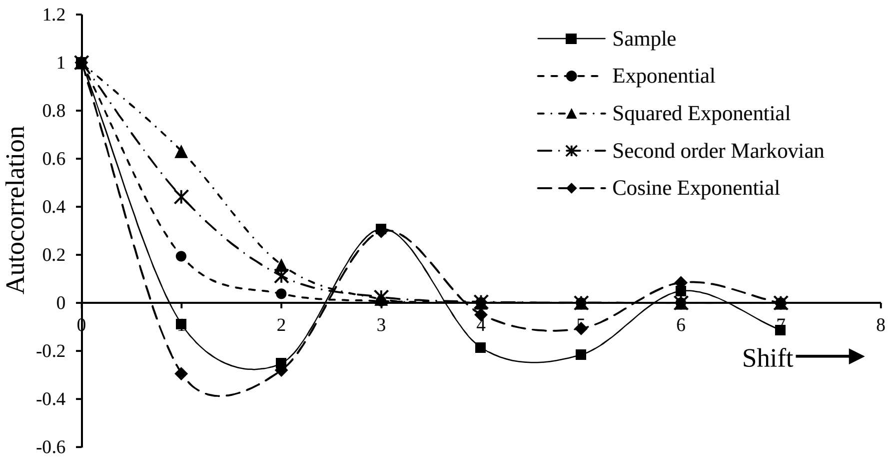

Fig. 4. Fitting for autocorrelation models

The scale of fluctuation will be different for all the boreholes. So, the above-mentioned procedure needs to be followed for all the boreholes to obtain a specific scale of fluctuations. The variation in the SPT – N values of all the 20 boreholes are displayed in the fig.5. By using the above stochastic modelling, considering cosine exponential correlation fit, the coefficient of determination, i.e. the statistical measure of the error and the scale of fluctuation for all the boreholes was calculated and detailed in the table-2.

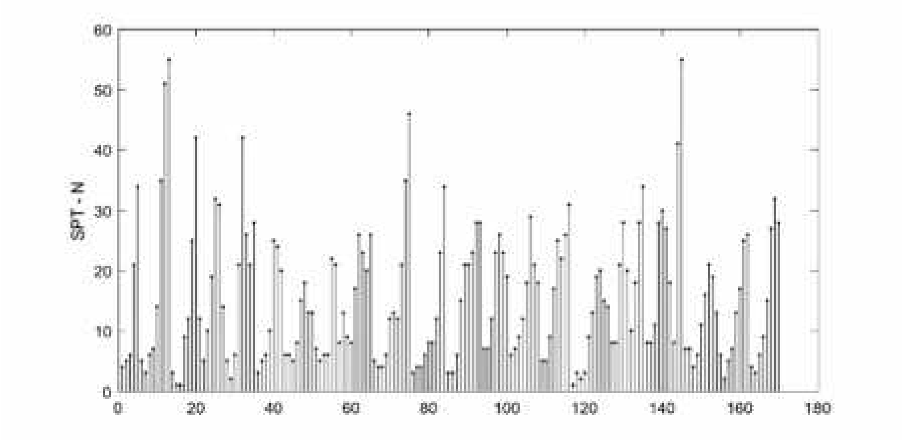

Fig. 5. SPT values of all the boreholes

Table 2. Scale of fluctuation obtained with cosine exponential model for 20 SPTs

Bore hole	R^2	Scale of Fluctuation
1	0.9935	1.8226
2	0.9890	1.7907
3	0.9802	1.7724
4	0.9978	1.8918
5	0.9282	1.9262
6	0.9979	1.8653
7	0.9932	1.8116
8	0.9658	1.6745
9	0.9844	1.8026
10	0.9402	1.6915
11	0.9935	0.9155
12	0.9939	1.8779
13	0.9966	1.8350
14	0.9933	1.8313
15	0.9959	1.8819
16	0.9296	1.6453
17	0.8945	1.8861
18	0.9957	1.8090
19	0.9989	1.8608
20	0.9993	1.8764

3.2 Determination of bearing capacity of piles

To determine the bearing capacity, assumed pile parameters and the coefficient of variation for the example problem are given in the table-3. Three different correlations generated by Meyerhof (1956), also mentioned in IS 2911 [5], Aoki and

De'Alencar (1975) and Decourt (1995) are used in the study [6-8]. They are shown in the table-4.

Table 3. Pile and Statistical parameters considered in the study

Parameter	Range
Diameter of Pile (m)	0.6, 0.8, 1.0
Length of Pile, Lp (m)	21 – 25
Coefficient of variation of N (%)	25, 35, 50

Table 4. Correlations utilised for bearing capacity calculation

Method	Ultimate Capacity (MPa) ([illegible] = [illegible] + [illegible]) Base resistance ([illegible])	Shaft resistance ([illegible])	Remarks
Meyerhof (1956)	$4N_bA_b$	$N_sA_s/50$	-
Aoki and De'Alencar (1975)	$\left(\frac{k}{1.75}\right)N_b$	$\left(\frac{\alpha k}{3.5}\right)N_s$	[illegible] 4, [illegible]
Decourt (1995)	kN_b [illegible]	2.8 [illegible] 10)	[illegible] 0.325; [illegible] 0.5 – 0.6

N_b	=	N value at the pile base
N_s	=	Average N of the embedded depth
A_b	=	Area of the pile base
A_s	=	Surface area of the pile

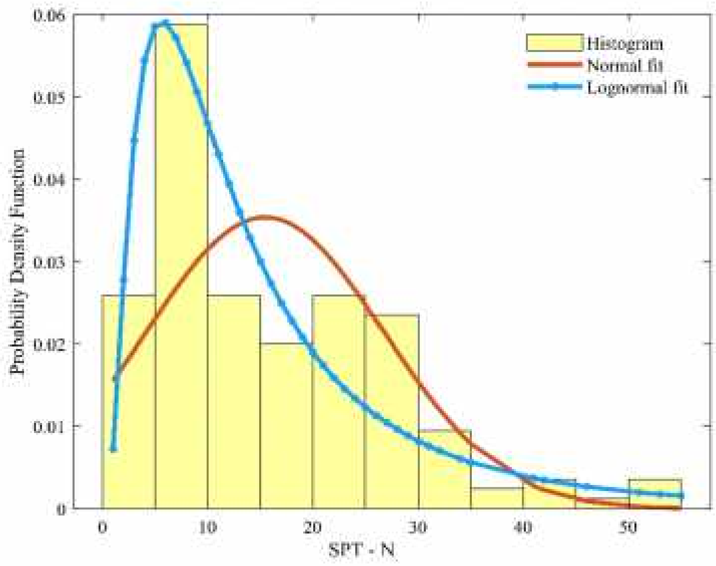

Fig. 6. Histogram and probabilistic distributional fit of SPT – N values

As mentioned earlier, SPT – N is considered as the random variable in the present study. The term "coefficient of variation" which is defined as the ratio of the standard deviation to mean of the samples is one of the important factor in the stochastic uncertainty analysis. According to Phoon [2], coefficient of variation for N is 25-50%. In general, it can be determined by making the probability distribution fit. Based on the available literature, normal and lognormal distributions are considered in the study. The plots of histogram and probability distributions are shown in the fig.6. The SPT – N values from all the boreholes are found to be best fitted in the lognormal distribution with the mean of 2.4258 and the standard deviation as 0.8416, and the resulting coefficient of variation of N is 0.3469, can be rounded up to 0.35. The errors in the lognormal fit are 0.4% in the mean and 0% in the standard deviation, which shows that their magnitudes are acceptable. As mentioned in the previous sections, Monte-Carlo simulation has been implemented for the stochastic uncertainty analysis. The analysis was done as per the parameters are shown in the table-3.

4 Results and discussion

Based on the literature, the plots are generated with the parameter dv/Lp as the abscissa and ultimate bearing capacity as the ordinate. Three different correlations, as mentioned in the previous sections are considered in the generation of plots.

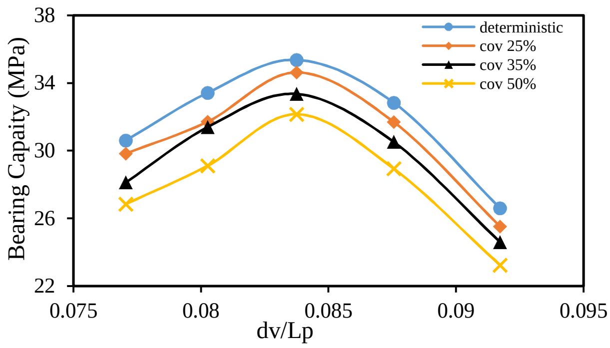

Fig. 7. Bearing capacity variation for pile diameter of 0.6m using Meyerhof 1956

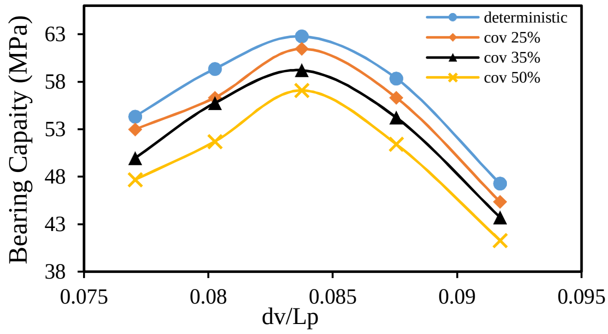

Fig. 8. Bearing capacity variation for pile diameter of 0.8m using Meyerhof 1956

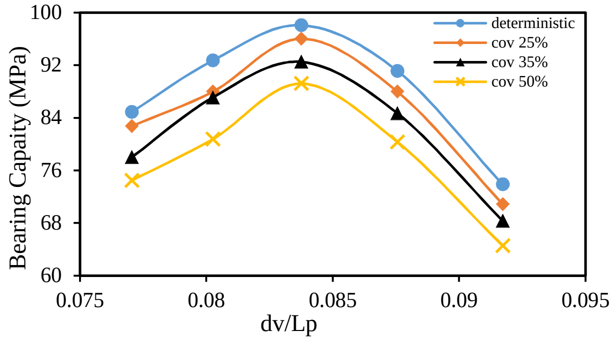

Fig. 9. Bearing capacity variation for pile diameter of 1.0 m using Meyerhof 1956

As the Meyerhof's relationship is the function of the diameter of the pile and the SPT – N, three different plots (fig. 7 – 9) are generated. Aoki and De'Alencar (1975) and Decourt (1995) are the functions of SPT - N only and so, only one for each has been generated.

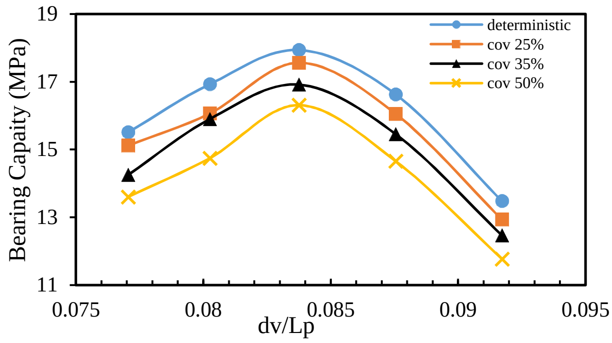

Fig. 10. Bearing capacity variation using Aoki and De'Alencar 1975

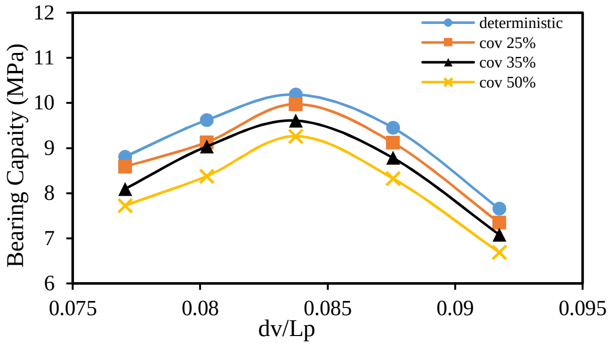

Fig. 11. Bearing capacity variation using Decourt 1995

The lowest magnitude of bearing capacity has been observed when the coefficient of variation reaches higher to the maximum i.e. 50%. Considerable variation in the capacity can be seen with the consideration of coefficient of variation of 35% relatable to the problem of concern. The same has been observed in all the plots. So, with the inclusion of variability in SPT – N, it can be seen that the capacity of the piles decreases.

5 Concluding remarks

SPT data for twenty boreholes have been collected for a site which is planned to adopt pile foundation for the upcoming structure. Due to complexity constraint, the analysis has been briefly explained for the borehole-5 only. As the present study focusses on the measurement of the scale of fluctuation, random field theory has been implemented for a given site and a given borehole. The above procedure has been performed for all the boreholes, and the individual scale of fluctuations are calculated. The measurements are in the range of 0.91 m to 1.89 m, which is in good agreement as prescribed in the well acceptable literature. The bearing capacity has been calculated using different correlations. Meyerhof's correlation resulted in higher capacity when compared to others. For the coeffiecient of variation of 35%, pile capacities are significantly varying. For the other two coefficient of variations, pile capacities have been observed to be in decreasing trend. Using the stochastic modelling presented in this study, the pile capacity variations can be investigated for other boreholes too. The present study shows the necessity of consideration of uncertainties in the analysis for more safer design.

6 References

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