Use of Reliability-Based Approach to Determine Geotechnical Parameters of Soil Site

Gurpreet S. Bhatia and G. Prabhakar

Abstract Proper geotechnical investigation plays an important role in suitably addressing the geotechnical challenges faced during construction stages. However, improper investigations lead to shocking results both financially and technically. Some of the most important geotechnical investigation tests like the Standard Penetration Test (SPT), Pressure Meter Test (PMT), etc. which are very much important in determining the foundation parameters, require too much manual intervention. These factors govern the workmanship of geotechnical investigation and the results we obtain from them. This leads to uncertainty in the results of these investigations. Generally, a number of tests are conducted below a particular structure and their average results are used for the design of foundations or other underground utilities. Against the backdrop of the fact that there are no stringent guidelines on the extent of geotechnical investigations to be carried out below critical structures like defense facilities, nuclear facilities, etc., this method of averaging may lead to obnoxious results. The greatest drawback of this approach is that we are not using sufficient data to characterize the soil profile of any particular area. In case some more investigations are done in that area, the results may change drastically. In this paper reliability-based approach is used to estimate the parameters obtained from SPT and PMT. The probabilistic approach is used to estimate the 95 percentile values of parameters that become input for the design of underground structures or utilities. As uncertainty exists in the evaluation of these parameters due to improper investigations, it is appropriate to evaluate these parameters based on the probabilistic approach using the best fit probabilistic distribution curve. This approach helps in the conservative estimation of geotechnical parameters below any structure with minimal failure probability.

Keywords Standard penetration test · Pressure meter test · 95 percentile values

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1 Introduction

The biggest element of technical and financial risk in any Infrastructure project lies majorly in sub-strata. An inadequate or inappropriate geotechnical investigation often leads to structural failures. Due to the absence of stringent guidelines on the extent of geotechnical investigations to be carried out below critical facilities, it often leads to inadequacy of investigations that are required to appropriately map the strata available below these structures. This inadequacy in geotechnical investigations leads to a lack of knowledge about the sub-strata which further leads to faulty designs. AERB Safety Guide No (2008) illustrates the Geotechnical Aspects and Safety of Foundation for Buildings and Structures important to the safety of Nuclear Power Plants. The cost incurred at geotechnical investigations is very low, somewhere around 0.01–0.2% only when compared to the overall Project cost (Jaksa et al. 2003). This insufficient coverage often leads to uncertainties, which results in unforeseen costs and delays during the construction stage.

A reliability-based approach is required to estimate geotechnical parameters due to the large uncertainties associated with the estimation of these parameters. It is highly difficult to predict the behavior of soil due to spatial variations and the presence of local irregularities in strata even in the relatively smaller area (Lacasse and Nadim 1998). This aspect is more predominant in alluvial soils as the formation of different layers has taken place with time and every layer may behave differently leading to more uncertainties in understanding the actual soil behavior. The reliability approach provides the geotechnical engineers an edge to deal with the inherent risks associated with the investigation data and helps them to reduce the failure probability during design. This approach takes into account every data obtained and provides a value that has a specific probability of occurring based on the entire collected data under consideration. In case some very low or high value is encountered in a particular zone, then this technique will take that value also into account in the estimation of a specific percentile value unless that value is ignored, considering it an outlier.

This paper aims to establish the procedure for determining the geotechnical parameters from the conventional investigation methods using a reliability approach. These parameters can then be used for design purposes with higher confidence level as some amount of uncertainties associated with them will get eliminated. The focus will be to derive parameters from the two most important field tests in geotechnical engineering, i.e., SPT and PMT. Parameters obtained from these tests can then be utilized to design the structures with a reduced level of failure probability.

2 Geotechnical Investigation to Determine Field Parameters

One of the most important field tests that is widely used worldwide to determine soil properties is the Standard Penetration Test (SPT) (IS 2131 1981). SPT provides data that can be used as input to determine various soil properties like liquefaction potential, bearing capacity (IS 6403 1981), relative density, angle of shearing resistance, etc. Conduction of SPT at the site requires skilled manpower. There is too much manual intervention in the method generally being adopted to determine SPT values at the site. Due to the absence of skilled workmanship and too much manual intervention, there are possibilities that the data obtained may have a large number of uncertainties and may not represent the actual soil behavior. In order to minimize the human/machine error as far as possible, all tests were performed by the same operator/technician using the same equipment. All equipment and accessories were calibrated at regular intervals to avoid any error arising out of the use of faulty equipment. All Standard penetration tests were performed using safety type SPT hammer and no in-situ hammer efficiency was measured for the type of hammer used. However, it may be noted, that by using automatic trip SPT hammers and by performing hammer efficiency at the site, many uncertainties and errors associated with measuring site data can be minimized further.

Similarly, the pressure meter test is also one of the important tests that provide information on the Modulus of Elasticity of soil which is very much essential in designing sub-structures and estimating settlements of soil. As compared to SPT, the pressure meter test is even more complex to conduct and not everyone has the required skills to conduct this test. Generally, the Menard-type pressure meter is used for the estimation of the modulus of elasticity of soils as per the guidelines given in ASTM-D 4719-20 (ASTM D4719 - 20 en Standard Test Methods for Prebored Pressuremeter Testing in Soils 1.1) or ISO 22476-4 (2012). One of the most critical parts in the conduction of a pressure meter test is the preparation of the test pocket. With the presence of a water table and loose soil this process becomes even more complex. In case there are some issues with pocket preparation, even the most skilled person will not be able to conduct the test in a proper manner. This will eventually add uncertainties in the field results and may not provide a true resemblance of actual soil properties. As far as possible, the results of the pressure meter test which seems to represent ambiguous data due to reasons attributable to improper pocket preparation, test pocket failure, loosening of soil while drilling, etc. have been ignored and re-test was performed at slightly lower depth to re-assess data of specific depth for that particular borehole.

The probabilistic analysis will be carried out on the available field data from these tests in order to determine the 95 percentile values of these parameters. Higher percentile values indicate a higher confidence level with which this parameter has been obtained from the available raw data (Haldar and Mahadevan 2000). Data from geotechnical investigations carried out in approximately 300 m $\times$ 300 m area in the Northern region of India has been used to conduct these studies. A total of 20 boreholes were drilled to conduct both SPT and PMT. These two tests were performed in the same borehole at different depths. SPT was conducted at an interval of 3 m along the depth of the borehole while PMT was conducted at an interval of approximately 5 m. Results obtained from these tests show that there is large variability in the results. Generally, the averaging technique is used to design foundations based on SPT data. SPT results from different boreholes at particular depths are averaged and results are then used for further design calculations. In case some values are greater than 50% of the average value, then those results are neglected in calculating the average. This same methodology has been adopted to estimate 95 percentile values from the test results of SPT. In the case of PMT, all field values have been considered and no value has been neglected or capped for estimating 95 percentile values. However, there is very high variability in the results of PMT mainly due to the fact that it captures the soil property of small pocket very precisely. There are certain uncertainties associated with the results of PMT mainly due to the testing method and condition of the test pocket in which the test was conducted.

Figure 1 shows the depth-wise distribution of PMT values as obtained from a field test using the Menard Pressure meter apparatus. Figure 2 shows depth-wise distribution of SPT values obtained in different boreholes. From both figures, it can be observed that there is too much variability in the obtained field data.

The disadvantage of the averaging technique is that we are not taking into consideration the variability of data appropriately. This method may not provide the most conservative results which might be suitable for designing any critical facilities. Similarly, if minimum value is considered to design critical facilities in a conservative way, it might also lead to erroneous results. Taking a minimum value for calculation is not recommended because this minimum value is coming from the data available based on limited geotechnical studies. In case some more investigations are carried out in a similar area, there is a fairly high probability that this minimum value will

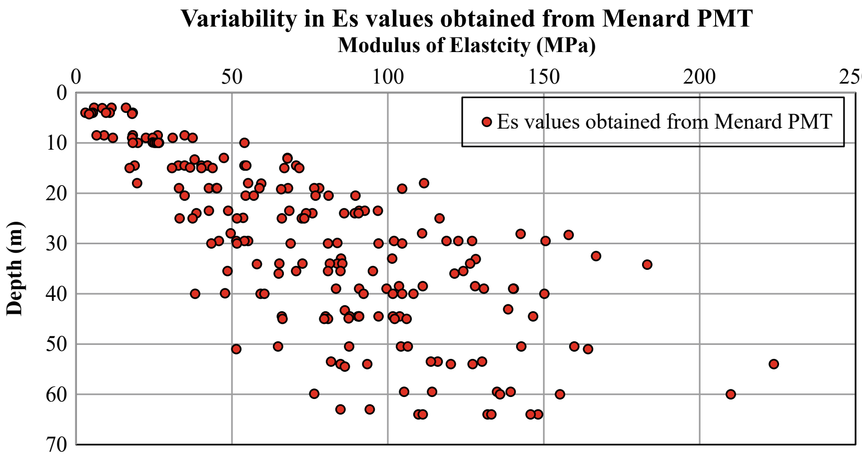

Fig. 1 Variability in values of Static Modulus of Elasticity along the depth of boreholes

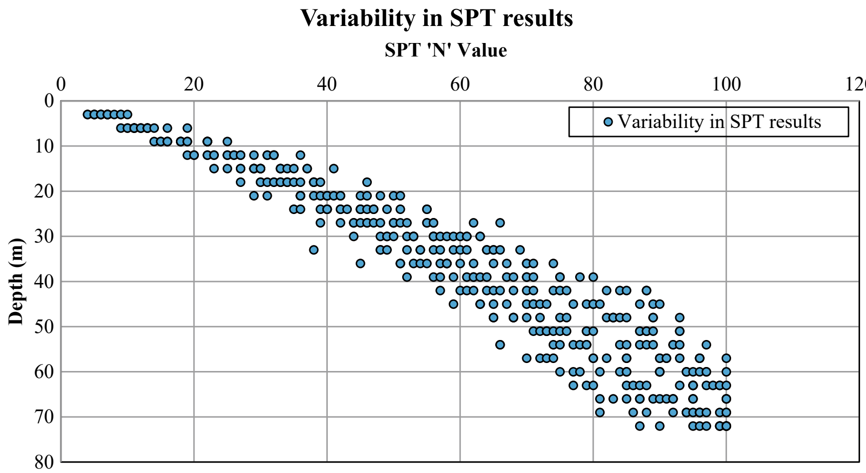

Fig. 2 Variability in SPT values along the depth of boreholes

get changed, and then we have to again re-design everything considering the new value. In order to avert such situations, the probabilistic approach is considered to be more effective in the determination of design parameters from field data. Obtaining 95 percentile values of these parameters will give substantial confidence that even if some more investigations are carried out there is only a 5% probability that we will get values lower than already obtained values using the probabilistic approach.

3 Assessment of 95 Percentile Values

The approach will be to identify the best fit function which represents this data at each depth. Data from available 20 boreholes are analyzed at each depth and different probabilistic distribution curves (like normal, lognormal, and gamma) are used to find the best suitable curve for each parameter at each depth under consideration. In order to find out the 95 percentile value of data from these distributions, it is first required to plot the PDF and CDF of the random data using all the probability distribution functions. In case random data satisfies all the probability functions, it is then required to choose the best function among the available functions that best suits the randomness of data. Comparing probability functions with each other can be done by performing statistical tests like the Chi-square test, Kolmogorov–Smirnov test, or Anderson–Darling test.

In this paper, the K–S test has been used to identify the best probabilistic function out of the available functions for raw data at each depth (Haldar and Mahadevan 2000). The K–S test can be applied on the small number of data effectively as compared to the Chi-square test. Moreover, the advantage of the K–S test is that it is not necessary to divide the data into intervals; thus the error or judgment associated with the number or size of the interval can be avoided.

The K–S test compares the observed cumulative frequency and the CDF of an assumed theoretical distribution. The first step is to arrange the data at a particular depth in increasing/ascending order of their absolute value. Then the maximum difference between the two cumulative distribution functions of the ordered data can be estimated as

$$Dn = \max|Fx(x_i) - Sn(x_i)| \tag{1}$$

where $Fx(x)$ is the theoretical CDF of the assumed distribution at the ith observation of the ordered samples x_i, and $Sn(x_i)$ is the corresponding stepwise CDF of the observed ordered samples. $Sn(x_i)$ can be estimated as

$$Sn = \left\{ \begin{array}{l} 0, x < x_i \\ \frac{m}{n}, x_m \leq x \leq x_{m+1} \\ 1, x \geq x_n \end{array} \right\} \tag{2}$$

Mathematically, Dn is a random variable and its distribution depends on the sample size n. The CDF of Dn can be related to the significance level α as

$$P\left(Dn \leq D_n^{\alpha}\right) = 1 - \alpha \tag{3}$$

And the D_n^{α} values at various significance levels can be obtained from a standard mathematical table. Thus, according to K–S test, if the maximum difference Dn is less than or equal to the tabulated value of D_n^{α}, the assumed distribution is acceptable at the significance level α.

The probability density (PDF) of the normal distribution is expressed as

$$fX(x) = \frac{1}{\sigma_x \sqrt{2\pi}} \exp\left| -\frac{1}{2}\left(\frac{x - \mu_x}{\sigma_x}\right)^2 \right|, -\infty < x < +\infty \tag{4}$$

The corresponding CDF can be expressed as

$$FX(x) = \int_{-\infty}^{x} \frac{1}{\sigma_x \sqrt{2\pi}} \exp\left| -\frac{1}{2}\left(\frac{x - \mu_x}{\sigma_x}\right)^2 \right| \mathrm{d}x \tag{5}$$

where μ_x is the mean or expectation of the distribution; σ_x is the standard deviation; σ^2 is variance.

Probability Density function (PDF) of the Lognormal Distribution can be calculated as

$$fX(x) = \frac{1}{\sqrt{2\pi}\zeta_x x}\exp\left[-\frac{1}{2}\left(\frac{\ln x - \lambda_x}{\zeta_x}\right)^2\right], 0 \le x \le \infty \tag{6}$$

where λ_x and ςx are two parameters of the lognormal distribution. The lognormal variable has values ranging from 0 to ∞. Two parameters of the lognormal distribution can be calculated from the information on the two parameters of the normal distribution, the mean (μ_x) and the standard deviation (σ_x) of the sample population. It can be estimated as

$$\lambda x = E(\ln x) = \ln\mu x - \frac{1}{2}\zeta_x{}^2 \tag{7}$$

$$\zeta_x{}^2 = \mathrm{Var}(\ln X) = \ln\left|1 + \left(\frac{\sigma_x}{\mu_x}\right)^2\right| = \ln(1 + \zeta_x{}^2) \tag{8}$$

PDF of the Gamma distribution can be calculated as

$$f(x) = \frac{\left(\frac{x-\mu}{\beta}\right)^{\gamma-1}\exp - \left(\frac{x-\mu}{\beta}\right)}{\beta\Gamma(\gamma)} x \ge \mu; \gamma, \beta > 0 \tag{9}$$

where γ is the shape parameter, μ is the location parameter; β is the scale parameter, and Γ is the gamma function having the formula

$$\Gamma(a) = \int_0^\infty t^{a-1}e^{-t}\mathrm{d}t \tag{10}$$

CDF of the gamma function can be calculated as

$$F(x) = \frac{\Gamma_x(\gamma)}{\Gamma(\gamma)} x \ge 0; \gamma > 0 \tag{11}$$

where Γ is the Gamma function defined above and $\mathit{\Gamma} x(a)$ is the incomplete gamma function. The incomplete gamma function has the formula

$$\Gamma x(a) = \int_0^x t^{a-1}e^{-t}\mathrm{d}t \tag{12}$$

There are several computational methods for the K–S test. In this study, K–S test static version is used. First, sort the data. Then establish the assumed distribution and estimate its parameters. Then obtain both the theoretical (assumed CDF) distribution (FX) as well as empirical (Sn) at each data point. Since K–S is a distance test, it is required to find the maximum distance $|Fx - Sn|$ between the theoretical and empirical distribution. Its two basic functions are described as

$$FX(em) = PX(X \leq em) = \mathrm{CDF}(em) \tag{13}$$

FX(*em*) is the assumed cumulative distribution function evaluated at *em* and *Sn*(*em*) is the empirical distribution function obtained by the proportion of the data smaller than *em* in the data set of size *n*.

$$Sn(em) = i/n;\ i = 1, 2, \ldots n. \tag{14}$$

Then, define $D+ = Sn - FX$ and $D- = FX - \mathrm{Sn\text{-}1}$ for every data point *em*. The K–S static is

$$D = \text{maximum of all} D + \text{ and } D - (\geq 0);\ \text{for } em = 1, 2 \ldots n. \tag{15}$$

The K–S logic is, if the maximum departure between the assumed CDF and empirical distributions is small, then the assumed CDF will likely to be correct. But if the discrepancy is "large" then the assumed *FX* is likely not the underlying data distribution.

For a 95 percentile level and 20 sample points, $Dn\alpha$ is calculated from the standard table for the K–S test.

This assessment was done for each depth of the data set of SPT and PMT individually. From the assessment, 95 percentile values are obtained for SPT and PMT at each depth. As a comparative study, apart from 95 percentile values of parameters, 50 percentile and 98 percentile values were also obtained and plotted on the same curve.

95 percentile values of these parameters have been obtained at each depth at which the investigation was carried out and the same has been compared with average values in Figs. 3 and 4 for SPT and PMT, respectively.

From Figs. 3 to 4 it can be observed that higher percentile values give more conservative results as failure probability decreases with an increase in percentile values.

As can be seen from Fig. 4, there are too many variations in the values of Static Modulus of Elasticity as compared to the results of SPT obtained from different percentiles. This is mainly due to the fact that results of PMT obtained from field tests already had inherent variations with too much difference between the minimum and maximum values at similar depths in different boreholes. This variation resulted in lower values of PMT as obtained from different percentiles as compared to the average value. This shows the impact of the reliability technique in the estimation of certain parameter which contains too much variability.

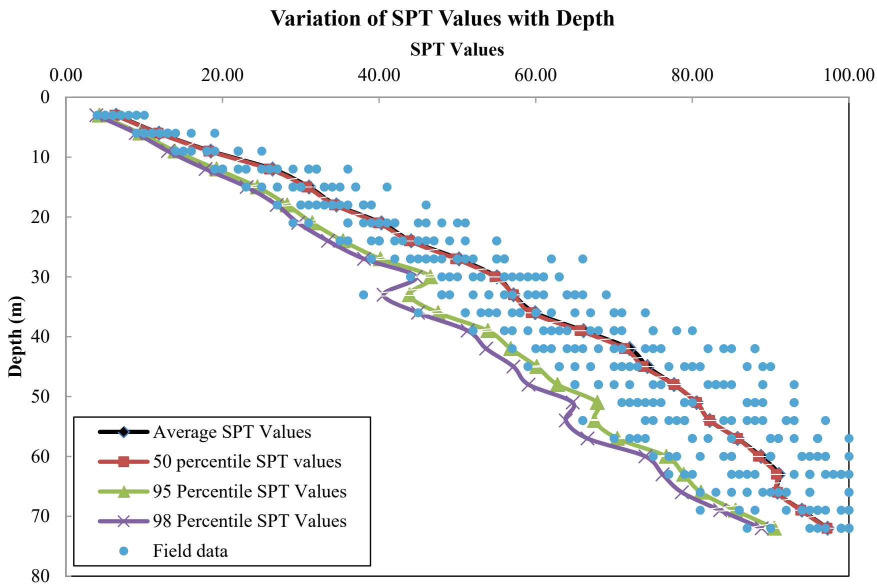

Fig. 3 Variation in SPT values along the depth obtained using different percentile values

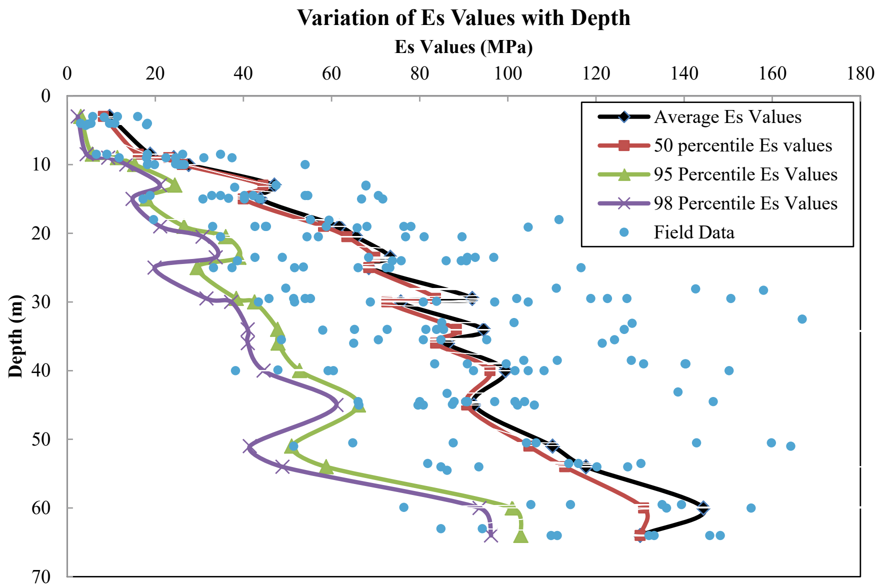

Fig. 4 Variation in Es values along the depth obtained using different percentile values

4 Conclusion

Standard penetration test (SPT) and Pressure meter test (PMT) were conducted in 20 boreholes up to a maximum depth of around 80 m from the existing ground level. As the conduction of these tests requires too much manual intervention, some uncertainties are always associated with the results of these tests. The conventional method is to average the results of field values at a particular depth from different boreholes and use the same for further design purposes. However, the biggest drawback associated with this technique is that it does not take into account the data variability appropriately. There are chances that in case some more investigations are carried out than these values may change drastically. To minimize human/machine error as far as possible, all tests were performed by the same operator/technician using the same equipment.

The reliability-based approach was used as a final check to determine 95 percentile values of parameters at different depths using the best probabilistic function based on available data. K–S test was used to determine the best probabilistic function out of three functions, i.e., normal, lognormal, and gamma. From the results, it can be observed that 95 percentile values give conservative results as compared to the average values of parameters. 50 percentile values give results almost similar to average values. Using 95 percentile values for design purpose helps in reducing the failure probability drastically and also reduces the uncertainties associated with obtaining these values during the investigation. Values obtained using different percentiles provide many conservative results as compared to average values especially for the data which contain too much variability. This helps in dealing with the uncertainties that may arise in case some additional investigations are carried out in the vicinity of area where investigations have already been carried out earlier.

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