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Reliability of shallow foundation design using the standard penetration test

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ABSTRACT: The sources of uncertainty, variability and bias in the performance of the Standard Penetration Test were identified using an extensive literature review and were classified in a manner that should assist the practice in recognizing and reducing them. These uncertainties and additional uncertainties introduced in the design process are then incorporated in a reliability-based evaluation of the design of shallow foundations**.** The results of the reliability analyses show that the factor of safety approach can provide an impression of degree of conservatism that is often unrealistic. At times, foundations with smaller factors of safety have smaller probabilities of failure than foundations with higher factors of safety. The reliability-based approach provides rational design criteria, accounting for all key sources of uncertainty in the foundation engineering process, and thus should be the basis of design.

1 INTRODUCTION

The Standard Penetration Test (SPT) is one of the most popular tools for geotechnical characterization of a site primarily due to its simplicity and economy. A geotechnical problem in which the SPT is particularly popular is the design of shallow foundations. The reliability of the SPT methods in the design of shallow foundations in saturated sands is evaluated. An important part in reliability analysis is the recognition of involved uncertainties. Thus, the uncertainties and variability in the performance of the SPT and in the procedures used for the design of shallow foundations are addressed. The reliability of the factor of safety design procedure is evaluated. The reliability-based approach is appropriate in geotechnical engineering design, because of the uncertainty that is an unavoidable reality for tests and analyses. Reliability methods have been increasingly used in geotechnical engineering, as part of site characterization (e.g. Whitman, 2000), in slope stability problems (e.g. Duncan, 2000), and in foundation engineering design (Phoon et al. 2003). This paper contributes to further incorporation of reliability methods in geotechnical engineering practice.

2 HISTORICAL OVERVIEW OF THE SPT

The Standard Penetration Test was first "standardized" by the American Society for Testing Materials (ASTM) in 1958 (designation D1586-58). It was soon recognized that the test was not a reliable source of information (e.g. Tavenas (1971), Fletcher (1965)). To increase the reliability of the in-situ test, the method was further standardized with the most recent update in 1999 (ASTM D1586-99). This update addresses many of the uncertainties involved and provides guidelines for the performance of the SPT. Further standardization of the method was made to improve the use of the SPT in evaluating the liquefaction potential by the ASTM D6066-96 standard.

3 CLASSIFICATION OF UNCERTAINTY IN THE PERFORMANCE OF THE SPT

There is a large number of uncertainties involved in the performance of SPT. Unfortunately, most of these sources have not been sufficiently quantified.

An extensive literature review was made to evaluate sources of uncertainty in the performance of the SPT, based on the previous work of many researchers (Kulhawy and Mayne (1990), Schmertmann (1975), Barton (1990), ASTM D6066-96, Youd et al. (2001), Kulhawy and Trautmann (1996)). Table 1 summarizes a total of 27 sources of uncertainty and bias, classified in five categories. This classification aims to assist the practicing engineer in taking the necessary measures to minimize the uncertainties in the performance of the test:

- Category A includes sources that depend on the type of soil, with emphasis in sources related to granular materials since the use of the SPT is generally not recommended for cohesive soils.
- Category B lists sources of uncertainty due to the presence of water.
- Category C includes reducible sources related to the equipment and its maintenance.
- Category D includes sources that are reducible if the test procedure is performed carefully.
- Category E lists irreducible sources in the investigation procedure.

Due to the page limitations of this paper, a discussion of the influence of the sources of uncertainty listed in Table 1 is not presented here but can be found in the Geoengineer website: (www.geoengineer.org). A more complete version of Table 1 can also be found there.

4 UNCERTAINTIES ACCOUNTED FOR IN RELIABILITY ANALYSIS

To date, most of the sources of uncertainty listed in Table 1 have not been sufficiently identified. ASTM D1586-99 suggests that for the same apparatus, driller, and soil, the SPT blow-count can be reproduced with a coefficient of variation of about 10%. This is a minimum inherent test error induced even when the ASTM standards are carefully observed and originates from some of the sources listed in Table 1. Kulhawy and Trautmann (1996) reviewed the various sources of uncertainty and suggested that the total uncertainty in the N-value is for the best-case scenario on the order of 14% and for the worst-case scenario about 100%.

The above recommendations suggest that the uncertainty in the SPT blow-count is independent of the number of blows. This is not likely true, but for the purposes of this paper a uniform coefficient of variation is assigned. Two sources of uncertainty in the performance of the SPT test are accounted for in this paper. First, a uniform 10% c.o.v. is assigned in the N-value measured in the field as suggested by ASTM. The second source of uncertainty is the energy that is transmitted from the hammer to the sampler, which is accounted for by the energy correction factor C_E. This has been addressed by ASTM D6066-96 and the NCEER workshop (Youd et al, 2001) through the following equation:

$$N_{60} = N \cdot C_E \tag{1}$$

N is the number of blows measured in the field, and N_{60} is the equivalent number of blows for a hammer energy ratio of 60%. Different energy correction factors C_E are applied depending on the type of hammer used. For a safety hammer C_E is between 0.7 and 1.2 (Youd et al. 2001). ASTM D6066-96 notes that even when the energy is measured in the field, the energy ratio may still vary overall around 10% from the initially measured value.

Table 1: Some sources of uncertainty of the SPT

	Addressed
A. Sources depending on encountered soil	
Vertical Stress	Yes
Mineralogy	No
Coarse gravel or cobbles in soil	No
Horizontal stress	No
Geologically aged sand deposits	No
B. Sources due to presence of water	
Pore pressure generation	No
Moisture-sensitive behavior of geologically aged sands	No
C. Reducible sources related to equipment and its maintenance	
Hammer efficiency	Yes
Borehole diameter	Yes
Sampler	Yes
Rod Length	Yes
Lack of hammer free fall because of ungreased sheaves, new stiff rope for lifting weight	No
Use of bent drill rods	No
Bottom vs. side discharge bits	No
Hammer weight inaccurate	No
Type of drilling equipment	No
D. Reducible sources with careful site investigation procedure	
Inadequate cleaning of hole	No
Inadequate head of water in the borehole	No
Careless measurement of hammer drop	No
Sampler driven above bottom of casing	No
More than two turns on cathead	No
Hammer strikes drill rod collar eccentrically	No
Incomplete release of rope in each drop	No
Tightness of connections	No
Careless blow count	No
E. Irreducible sources in investigation procedure	
Human factor	No
Weather and site conditions	No

These two sources of uncertainty related to the performance of the test are included in the reliability analyses presented. One should recognize that in practice, these sources are the minimum possible sources of uncertainty introduced by the performance of the Standard Penetration Test. If the test is not performed according to the ASTM standards, without careful equipment maintenance or with low quality control in the field, the reliability of the SPT test may decrease, rendering the blow-count practically useless in design.

5 SHALLOW FOUNDATION DESIGN

In foundation engineering, there are two main modes of failure that the engineer needs to design against with safety and economy in mind:

1. Bearing Capacity Failure: caused by the exceedance of the shear strength of soil; this mode of failure is abrupt and catastrophic.
2. Excessive Settlement: defined as the exceedance of a specified maximum acceptable amount of settlement. For typical structures with isolated spread footings, a total foundation settlement of 2.5 cm is a common design value resulting in acceptable differential settlements. Thus, the allowable stress is defined as the stress resulting in 2.5 cm of total settlement. The consequences of this mode of failure are not catastrophic as is the case for the bearing capacity criterion.

In the following, typical design procedures in engineering practice for each failure criterion are presented and used in the reliability analyses.

5.1 *Bearing Capacity*

For a granular, non-cohesive material, the ultimate bearing capacity q_{ult} of a saturated soil having a buoyant unit weight γ_b, under a foundation of width B, founded at a depth D, is often taken as (also known as the Terzaghi Bearing Capacity equation):

$$q_{ult} = \gamma_b \cdot D \cdot N_q + \frac{1}{2} \cdot \gamma_b \cdot B \cdot N_\gamma \qquad (2)$$

N_γ, N_q are coefficients that depend on the effective friction angle of the soil, ϕ'. It is commonly accepted that (Bowles, 1996):

$$N_q = e^{\pi \cdot \tan\phi'} \cdot \tan^2\left(45^o + \frac{1}{2} \cdot \varphi'\right) \qquad (3)$$

However, for calculating N_γ, different equations have been recommended. One of the most popular equations is that of Brinch-Hansen (1970):

$$N_\gamma = 1.5 \cdot \left(N_q - 1\right) \cdot \tan\phi \qquad (4)$$

In this paper, it is assumed that equation 4 provides an unbiased estimate of N_γ and thus equation 2 predicts the actual bearing capacity of the soil.

Because of the difficulties in measuring the effective friction angle of the sand in the laboratory, in-situ index tests such as the Standard Penetration Test, are almost always used to estimate the friction angle (Naval Facilities Engineering Command, 1986). Many researchers provided recommendations correlating the effective friction angle of granular material with the SPT blow-count (e.g. Meyerhof, 1956, Peck et al. 1974, Schmertmann, 1975). Most recently, Hatanaka and Uchida (1996) collected high quality "undisturbed" freezing samples and provided a correlation of the blow-count measured in-situ with the friction angle evaluated in the laboratory. The authors noted that "almost all of the data falls within the range of $\pm 3^o$ "of the best fit line to these data, but did not provide a more quantitative expression of this uncertainty. A regression analysis using their data was performed to evaluate the standard error in the correlation. The resulting equation was also modified to adjust the resulting N-value using the Japanese equipment to the normalized N_{60} value used in the United States (Mayne, 2003). The best fit of the resulting equation was compared against the equation suggested by Hatanaka & Uchida (1996) and there was no difference in the predicted friction angle. The form of equation used in this paper is

$$\phi' = 3.5 \cdot \sqrt{N_{1,60}} + 22.3 \pm \varepsilon \qquad (5)$$

where ε is the standard error from the regression analysis, which has a zero mean and a standard deviation of 2.3.

The design procedure for the bearing capacity criterion used in practice can be summarized in the following steps: the SPT blow-count measured in the field is corrected and normalized to an effective overburden pressure of 1 atmosphere using the Liao and Whitman (1985) recommendation, the deterministic corrections based on Youd et al. (2001), and the energy correction according to equation 1. The Hatanaka and Uchida (1996) correlation (equation 5) is then used to estimate the friction angle from the corrected SPT value $N_{1,60}$. The resulting friction angle is then applied in the Terzaghi equation (equation 2) using equations 3 and 4, and the ultimate bearing capacity is estimated. Recognizing the uncertainties involved, factors of safety are applied to reduce the estimated ultimate bearing capacity from equation 2**.** The bearing capacity allowable design stress is:

$$q_d = \frac{q_{ult}}{FS} \qquad (6)$$

The factor of safety (FS) is a function of the importance of the structure, the consequences of failure, and the uncertainty of the subsurface investigation. The factor of safety approach gives the false impression that when two structures are designed with the same factor of safety the degree of conservatism in the design is the same.

5.2 *Excessive Settlement*

Because of the difficulties in obtaining undisturbed samples in sands to evaluate the compressibility of the soil in the laboratory, the use of in-situ tests are again popular, and various recommendations have been made based on field data. The Burland and Burbidge (1985) procedure involves one of the most comprehensive efforts in this regard. The method was based on a statistical analysis of 200 records of settlement of foundations, tanks, and embankments on sands and gravels. For an allowable settlement of 2.5 cm the allowable stress $q_{2.5}$ (in kPa) is given by the following equation:

$$q_{2.5} = 2540 \cdot \frac{\overline{N}^{1.4}}{B^{0.7} \cdot 10^{T}} \tag{7}$$

where B is the width of foundation in meters, $\overline{N}$ is the average N-value of the SPT over the depth of influence (about one foundation width), and T is a statistically evaluated random variable that has the normal distribution with a mean of 2.23 and a standard deviation of 0.26. The standards at the time the data were collected were ASTM 1586-67, which failed to recognize many of the sources of uncertainty. Thus, it can be reasonably assumed that any uncertainty involved in the SPT blow-count is included in the uncertainty of the T variable.

A simple design equation having a 30% probability of exceeding the settlement of 2.5 cm based on the Burland and Burbidge (1984) approach, which is used in this reliability analysis, is:

$$q_{2.5} = 10.9 \cdot \frac{\overline{N}^{1.4}}{B^{0.7}} \tag{8}$$

6 FORMULATION OF THE RELIABILITY PROBLEM

The idealized component reliability problem can be formulated by considering the safety margin of a structural member defined by the function:

$$g(R,S) = R(\underline{x}) - S(\underline{x}) \tag{9}$$

The g function is called the "limit-state" function (LSF). In this formulation $R(\underline{x})$ is the resistance or capacity of the member and $S(\underline{x})$ is the load acting on the member. Failure occurs when $g(R,S) \leq 0$ and the probability of failure is defined as:

$$p_f = P[g(R,S) \leq 0] \tag{10}$$

Both $R(\underline{x})$ and $S(\underline{x})$ are functions of a vector of some basic random variables $\underline{x} = x_1, x_2, ..., x_n$ that are observable (e.g. blow-count N). Uncertainties in $\underline{x}$ originate in the inherent variability or randomness of each random variable, statistical uncertainty, measurement and human errors, as well as model uncertainties. Addressing these uncertainties accurately is the key to the reliability analysis.

Any civil engineering system can have different modes of failure. This means that different mechanisms lead to failure of the system. Each of these mechanisms is mathematically described by a limit state function and the failure probability is evaluated. A shallow foundation is a two-component series system: bearing capacity and excessive settlement components. The foundation system will "fail" (i.e. not perform satisfactorily) if any of the two criteria is violated.

Various methods have been developed to solve the LSF and evaluate the probability of failure. The popular First- and Second-Order Reliability Methods (FORM and SORM) and the Sequential Conditioning Importance Sampling method (SCIS) are used in this paper. These are some of the solution methods for component and series system reliability problems available by the reliability program CalREL (Liu et al. 1989). Detailed descriptions of these methods are provided in Liu et al. (1989) and are not discussed further in this paper.

7 RELIABILITY ANALYSES

In the following, the limit-state function for each component is developed, and reliability analyses for each component and for the system are performed.

7.1 *Bearing capacity component reliability*

For the formulation of the bearing capacity reliability problem, the capacity $R(\underline{x})$ of the foundation is given by equation 2. The uncertainties in the performance of the test and the variability in the correlation of the blow-count to the friction angle are addressed.

The load $S(\underline{x})$ is equal to the ultimate bearing capacity predicted deterministically by the Terzaghi equation divided by a factor of safety. As it is generally done in practice, these loads are evaluated deterministically without accounting for the uncertainties in the N-value and in the correlations used. Instead, single value best estimates are used. This means that in the reliability analyses performed with CalREL, the load $S(\underline{x})$, is just a constant parameter S evaluated by performing deterministically the calculations presented before. The design load is not uncertain but takes one value, becoming a parameter (Figure 1). An excel spreadsheet that performs a deterministic design of the shallow foundations was developed and the result of these calculations is introduced as a parameter in the reliability analyses defining the "load." This spreadsheet is available at the Geoengineer Website (www.geoengineer.org).

Table 2 summarizes the random variables and the parameters used in the bearing capacity component reliability analyses. For the random variables, the distributions used to describe the uncertainty are presented. Note that all the random variables are in the capacity part of the Limit State Function.

Bearing capacity component reliability analyses were performed to evaluate the effect in the foundation failure probability of different soil conditions (i.e. different blow-counts) and of measuring in the field the energy transmitted to the sampler for designs with different factors of safety. These analyses were performed using the First-Order Reliability Method (FORM) for soil conditions with measured blowcounts that range from 5 to 40. The effective unit weight was considered equal to 9.2kN/m^3 and the foundation depth to width ratio is always 0.5.

Results for a 3 m foundation width using a safety hammer and measuring the energy in the performance of the SPT test are shown in Figure 2. The failure probability is smaller for a foundation design with a factor of safety of 3 than for a foundation design in the same soil with a factor of safety 2. The failure probability when using a factor of safety of 3 instead of 2 is 1.7 to 110 times smaller with the larger decrease corresponding to weak soils.

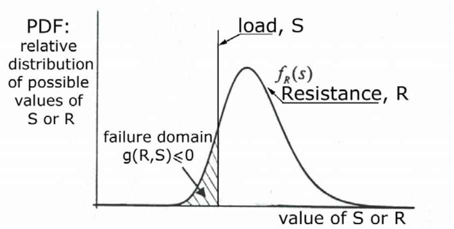

Figure 1: Failure domain in the reliability context, as presented in this paper

Table 2: Parameters, random variables and distributions used in component reliability analysis.

Random Variables	Distribution used to model uncertainty
Blow-count, N	Normal (mean=measured value, coefficient of variation=10%)
Energy correction factor C_E	For measured C_E : Normal (mean=measured value, coefficient of variation=10%) For not measured C_E : Uniform with limits 0.7 to 1.2 for a safety hammer
Standard error ε (equation 5)	Normal (mean=0, standard deviation σ=2.3)
Parameters	
Foundation width (B), Depth to width ratio (D/B), Effective unit weight (γ_b), Load (S)	

For foundation designs with the same factor of safety the probability of failure increases as the blow-count increases. This means that a foundation designed on a strong soil (with high blow-counts) has a much greater probability of failure than a weak soil (low blow-counts) even though the factor of safety in the design is the same. In fact, the probability of failure of a foundation on a strong soil with a blowcount equal to 40 and designed with a factor of safety of 3 is equal to 0.14 while for a soil with a blow-count equal to 5 is $4.8 \cdot 10^{-5}$, a decrease in the order of 2820. In addition, foundations designed on strong soil (blow-count of 40) and with a factor of safety against bearing failure equal to 3 have higher probability of failure than foundations designed with a factor of safety of 2 in an intermediate soil (blow-count of 20).

The reason for this decrease in the reliability of the design as the soil gets stronger can be identified in the mathematical expressions of equations 2, 3 and 4. Assuming a 10% uncertainty in the blow-count number for a soil with a measured blow-count of 5 the mean-σ to mean+σ range is a blowcount of 4.5-5.5, which is an almost insignificant range. For a soil with a blowcount of 40, and the same uncertainty, the mean-σ to mean+σ range is from 36 to 44. This uncertainty is introduced in the correlation of the blowcount with the friction angle and increases more. Thus, the uncertainty in the estimated friction angle is more significant for the strong soil than the weak and is further introduced in the N_γ, N_q coefficients (equations 3 and 4) of the bearing capacity equation 2. The exponential form of the bearing capacity coefficients (Figure 3) results in a significantly larger increase in the uncertainty of the ultimate bearing capacity (the resistance) for the strong soil (large friction angle) than the weak (small friction angle).

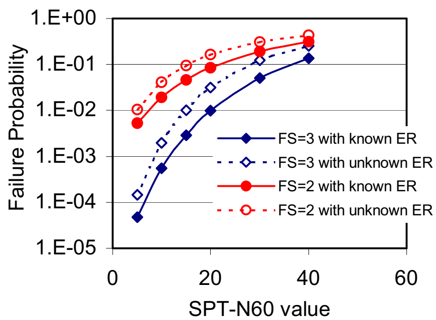

Figure 2: Probability of failure for different soil conditions and factors of safety

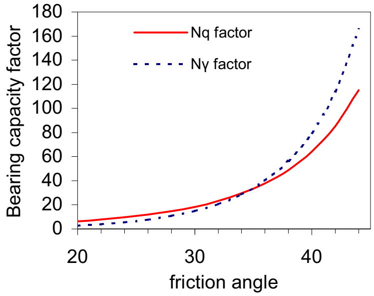

Figure 3: Bearing capacity coefficients as a function of friction angle

The above observations suggest that the current approach in geotechnical design to use factors of safety to account for the existing uncertainty and ignore the uncertainties in the calculations results in inconsistencies in the safety of the foundation design. The factor of safety approach creates a false impression that there is a consistent degree of conservatism in the design. In fact, designs with a factor of safety of 2 can be safer than designs with a factor of safety of 3 depending on site conditions.

Figure 2 illustrates the increase in the probability of failure when the energy transmitted to the sampler is not measured (ER not known), which is typical in foundation design practice. For this case, the estimate of the probability of failure increases by a factor of 1.9-3.6 for a factor of safety of 3 and by a factor of 1.4-2.2 for a factor of safety of 2.

7.2 *Excessive Settlement component reliability*

For the excessive settlement component reliability problem the limit state function is defined again by equation 9. Equation 7 gives the resistance $R(\underline{x})$ and equation 8 the load $S(\underline{x})$. In this case, the only random variable is T. The average blow-count $\overline{N}$ is considered a parameter since, as mentioned, the uncertainty involved in the $\overline{N}$ value is incorporated in the uncertainty of the T random variable. This is a simple problem and the exact solution can be found. The probability of failure was evaluated equal to 30% and remains the same for any foundation width and any blow-count, which is expected as the load $S(\underline{x})$ was on purpose chosen to correspond to a load equal to approximately the mean plus half standard deviation predicted to cause 2.5 cm of settlement by the Burland and Burbidge (1985) design approach which defines the resistance of the foundation.

The probability of failure seems large, as we are used designing with smaller failure probabilities. However, it is not, if one recognizes that the consequences of exceeding this amount of settlement may not be significant. A more complete view of this design recommendation is gained by examining the probability of exceedance of different amounts of settlements when designing for a 30% probability of exceeding 2.5 cm of settlement. This is shown in Figure 4. For example, when we design with a 30% probability of 2.5 cm settlement exceedance, the probability of exceeding 3.8 cm of settlement is only 11.4%. Additionally, there is an implicit factor of safety incorporated in the selection of 2.5 cm of total settlement as the threshold of architectural damage.

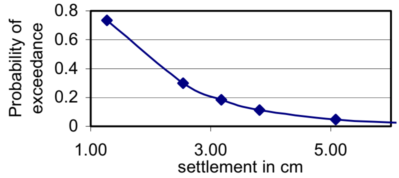

Figure 4: Probability of exceedance of different amount of settlements based on equation 8.

Equation 8 that defines the load for the excessive settlement component provides a consistent design approach resulting in the same failure probability regardless of the soil type and foundation width. As shown previously, this is not the case for the bearing capacity component.

7.3 *System reliability*

A foundation is a series system, because "failure" of the foundation occurs if any of the two components fails. The allowable stress typically used in shallow foundation design is the minimum of the allowable stress evaluated deterministically by the two criteria and is defined mathematically:

$$q_{allow} = \min[q_{2.5}, q_d] \tag{11}$$

The form of equation 8 suggests that the allowable stress for the excessive settlement criterion (or load for the LSF) is reduced as the width of the foundation increases. Also, the allowable stress according to the bearing capacity criterion increases as the foundation width increases (equation 2). Thus, for small foundation widths the bearing capacity criterion dominates (i.e requires smaller loads to be satisfied) whereas for larger foundation widths the settlement criterion dominates. An important information missing in the deterministic analysis is the failure probability not only of the dominating criterion but also of the non-dominating, as explained below.

Reliability analyses of the components and series system were performed using the Second-Order Reliability Method (SORM) and the Sequential Conditioning Importance Sampling Method (SCIS). Two cases were examined: A 0.6 m foundation width, which is common for light residential buildings, and a 1.5 m foundation width, which may be appropriate for light industrial buildings. The results are shown in Figures 5 and 6 respectively.

For the 0.6 m wide foundation, the bearing capacity criterion dominates deterministically. For all soils the probability of exceeding the 2.5 cm settlement is larger than the failure probability according to bearing capacity. This does not affect the deterministic calculations as we design for higher failure probabilities for the settlement criterion. However, the failure probability according to the settlement criterion is comparable to the bearing capacity failure probability and contributes significantly to the system failure probability. Results are shown for two factors of safety against bearing capacity failure and it can be seen that for a factor of safety of 3 against bearing capacity the contribution of the probability of failure according to the settlement criterion in the system failure probability is more significant. For the same factor of safety of 3, the failure probability of the system is varying from $4.87 \cdot 10^{-3}$ to 0.405 depending on the site conditions (blow-count), suggesting again the inconsistencies of the current design approach.

For the 1.5 m foundation width, the settlement criterion controls and the deterministically evaluated load of the system used in the analyses is the $q_{2.5}$ (equation 8). Thus, the results of the reliability analyses are the same either using a bearing capacity factor of safety of 2 or 3. The contribution of the bearing capacity probability of failure in the system failure probability is practically insignificant because of the acceptable high probability of failure for the settlement criterion (30%).

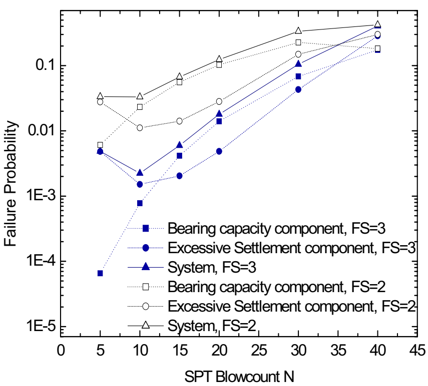

Figure 5: System and component reliability for a foundation of width of 0.6 m and different factors of safety

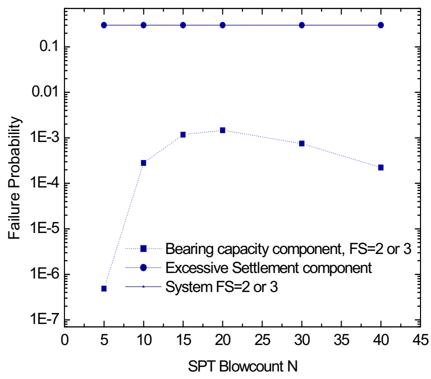

Figure 6: System and component reliability for a foundation of width of 1.5 m.

8 CONCLUSIONS -RECOMMENDATIONS

The SPT can provide useful and reliable data with good maintenance of the equipment and quality control in the performance of the test. Using the same drilling crew and a good engineer on-site are important for the quality of the results.

Table 1 can be useful to identify and quantify the sources of uncertainty and bias in the test. The SPT remains an attractive test, because it is relatively inexpensive and easily implemented while drilling exploratory boreholes. Engineers should focus on making it more reliable. The classification of Table 1 aims to provide a framework for the practicing engineer to recognize the uncertainties of the SPT and take measures to minimize them.

Uniform uncertainty was assumed in the blow-count for the reliability analyses presented. Similar analyses can be performed based on the sources of uncertainty that apply at the specific site. An important problem is that there are insufficient data to adequately quantify each source of uncertainty. The profession should try to evaluate these sources of uncertainty and re-evaluate some others. For example, it is likely that the coefficient of variation in the blow-count depends on the number of blows and thus the ASTM recommendation of 10% reproducibility in the N-value for given soil conditions and drilling crew is not accurate.

Emphasis was given in the bearing capacity component reliability because the design procedure for this failure criterion shows inconsistencies in the design philosophy that also affect the system reliability for small foundation widths. The design philosophy should not only take into consideration the theoretical basis of the mathematical model but also consider the variability and the uncertainties involved in the data that are used as input to this model i.e. the quality of the data. Ignoring the uncertainty in the input can result in unconservative design or at best at an irrational design procedure.

The current practice in shallow foundation design using factors of safety provides the engineer with a false impression of a certain degree of safety in the design. Foundations designed with a factor of safety of 2 may be safer than foundations designed with a factor of safety of 3 in different ground conditions. The reliability-based approach provides a more accurate assessment of the degree of conservatism and rational design criteria. The profession should specify the socially and economically acceptable probabilities of failure in the design.

Measuring the energy transmitted to the sampler can increase the reliability of the design by reducing the failure probability by a factor of 2 to 4.

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