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Settlement predictions of footings on sands using probabilistic analysis

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ABSTRACT

The design of footings on sands is often controlled by settlement rather than bearing capacity. Therefore, settlement predictions are essential in the design of shallow foundations. However, predicted settlements of footings are highly dependent on the chosen elastic modulus and the used method. This paper presents the use of probabilistic analysis to evaluate the variability of predicted settlements of footings on sands, focusing on the load curve (predicted settlements) characterization. Three methodologies, the first- and second-order second-moment (FOSM and SOSM), and Monte Carlo simulation (MCS), for calculating the mean and variance of the estimated settlements through Schmertmann (1970)'s equation, are presented and discussed. The soil beneath the footing is treated as an uncorrelated layered material, so the total settlement and variance are found by adding up the increments of the layers. The deformability modulus (E_{Si}) is considered as the only independent random variable. As an example of application, a hypothetical case of a typical subsoil in the state of Espirito Santo, southeast of Brazil, is evaluated. The results indicate that there is a significant similarity between the SOSM and MCS methods, while the FOSM method underestimates the results due to the non-consideration of the high-order terms in Taylor's series. The contribution of the knowledge of the uncertainties in settlement prediction can provide a safer design.

1. Introduction

Probabilistic or reliability analysis provides a mean of evaluating the combined effects of uncertainties and a way of distinguishing conditions with high or low uncertainties (Duncan, 1999). In geotechnical design, it has become increasingly popular in the last decade (Sivakugan and Johnson, 2004), since the geotechnical analysis based on conventional deterministic approaches, using safety factors, is highly dependent on the models and input parameters.

However, most common studies in probabilistic analysis published in the literature discuss the ultimate limit state (ULS), representing the failure probability of a foundation (bearing capacity criterion), even considering that the settlement criterion is often more critical in the design of shallow foundations, especially for foundation with the width greater than 1 m (Schmertmann, 1970; Rezania and Javadi, 2007) or 1.5 m (Das and Sivakugan, 2007).

Several publications have shown that the predicted settlements of footings on sands are highly dependent on the methods used (Tan and Duncan, 1991; Sivakugan and Johnson, 2004). Fig. 1 shows a comparison of settlement predictions, made by 11 methods based on standard penetration test (SPT) results, with measured settlements. Tan and Duncan (1991) concluded that, through the high variability obtained, there is a tradeoff between accuracy and reliability.

Moreover, the settlement predictions are also influenced by the subsoil spatial variability due to a combination of different geological, environmental and physico-chemical processes (Phoon and Kulhawy, 1999).

This paper presents the use of probabilistic analysis to evaluate the settlements of footings on sands, focusing on the load effect curve (predicted settlements) characterization. Three methodologies, the first- and second-order second-moment (FOSM and SOSM), and Monte Carlo simulation (MCS), for calculating the mean and variance of the estimated settlements through Schmertmann (1970)'s equation, are presented and discussed. As an example of application, a hypothetical case in the state of Espirito Santo, southeast of Brazil, is evaluated.

2. Probabilistic analysis

It is intuitive to believe that the predicted settlement values (total and differential) of foundation are influenced by the

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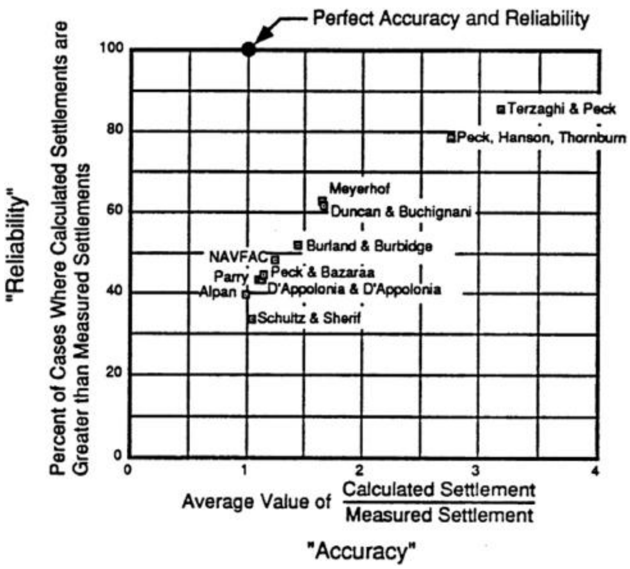

Fig. 1. Relation between accuracy and reliability of settlement predictions made by 11 methods based on SPT results (Tan and Duncan, 1991).

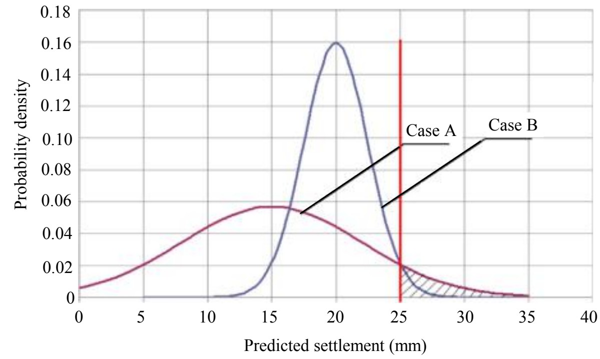

Fig. 2. Example of comparative analysis for two cases (A and B) of predicted settlement with different variability degrees.

variability of adopted soil parameters, which affect the reliability of further design decisions (Fenton et al., 1996). Fig. 2 demonstrates the examples of two different settlement prediction cases. The predicted mean values of the settlement are 15 mm and 20 mm for cases A and B, respectively. In a traditional deterministic analysis, the prediction made for case A would be considered safer (lower comparative value). However, when considering the variability of the predictions, represented by the dispersion of the probability density curves, it is clearly observed that the probability of the predicted settlement for the case that exceeds a preset limit value of 25 mm (the shaded area below the curve) is larger for case A than that for case B, which indicates that the case B is more reliable.

Generally, the failure probability of a foundation, p_{E}, at its serviceability limit state (SLS) is a function of the relative position and scatter degree of the density curves of the load effect $\rho(x)$, representing the variability of the predicted settlements, and the resistance $\rho_{\lim}(x)$, representing the variability of the limiting settlement, as shown in Fig. 3:

$$p_{\mathrm{E}} = \int_0^{\infty} \rho(x)\rho_{\lim}(x)\mathrm{d}x \tag{1}$$

The settlement predictions of footings on sands are usually made by traditional methods (e.g. Schmertmann, 1970; Schmertmann et al., 1978; Burland and Burbidge, 1985; Berardi and Lancellotta, 1991). Limiting settlements evaluation can be made by using observational, empirical, structural or numerical modeling methods (Negulescu and Foerster, 2010).

The present paper focuses on the load effect curve (predicted settlement) characterization, assuming that the variability of the resistance curve (limiting settlement) is null for simplification. In other words, it is considered constant for some specific deterministic values, as the examples discussed in Fig. 1. Thus, the probability of occurrence of limiting settlements, p_{E}, becomes

$$p_{\mathrm{E}}(\rho \geq \rho_{\lim}) = \int_{\rho_{\lim}}^{\infty} \rho(x)\mathrm{d}x \tag{2}$$

The integrals of Eqs. (1) and (2) are commonly solved by using analytical approximations (or reliability methods). Here, three methodologies, i.e. FOSM, SOSM, and MCS, for calculating the mean and variance of the predicted settlements through Schmertmann (1970)'s equation are briefly presented and discussed as a simple and practical way to characterize the settlement solicitation curve for a case of a single footing on sandy soil.

3. Methodologies

Schmertmann (1970)'s equation is briefly presented in Eq. (3) as it is one of the most popular methods for settlement predictions, commonly discussed in geotechnical engineering text books. It is a simple semi-empirical equation, based on the theory of elasticity and supported by model tests and finite element analysis, to predict the settlement of a footing on granular soil. The soil is proposed to be divided into sublayers, which are considered to be elastic, homogeneous and isotropic, with constant deformability modulus, $E_{\mathrm{S}i}$. A simplified strain influence factor, I_z, was introduced and its distribution with depth was defined. Such a factor is basically dependent on the ratio of the depth to the foundation width (z/B) and can be evaluated by graphical or equational forms. The maximum soil strain occurs at a depth $z = B/2$ under the footing embedment depth, D_{f}, and decreases linearly until the depth equals $2B$, where the strain can be ignored. No distinction is made between square or strip footings.

$$\rho = C_1 C_2 \sigma^* \sum_{i=1}^{N} \left(\frac{I_{zi} \Delta_{zi}}{E_{\mathrm{S}i}} \right) \tag{3}$$

where $\sigma^* = \sigma - q$ is the net footing pressure, σ is the applied footing pressure, q is the pressure due to soil mass at the depth D_{f},

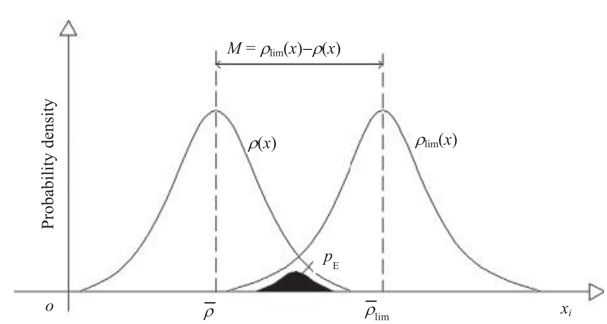

Fig. 3. Reliability analysis of a foundation at the SLS: Solicitation (predicted settlement) and resistance (limit settlement) probability density curves.

Δ_{zi} is the thickness of each sublayer, C_1 is a factor that accounts for the correction of embedment, and C_2 is a time correction due to creep effects.

The factor I_z can be evaluated by the following equation:

$$I_z = \begin{cases} 1.2(z/B) & (z \leq B/2) \\ 0.4(2-z/B) & (B/2 < z \leq 2B) \end{cases} \tag{4}$$

The proposed probabilistic methods take the Schmertmann's equation and its main assumptions (i.e. the soil beneath the footing is treated as a layered material and the total settlement is found by superposing the settlement of each layer). So, the total settlement predicted (ρ) is given by

$$\rho = \sum_{i=1}^{N} \rho_i \tag{5}$$

where N is the total number of sublayers.

If the increment (ρ_i) is statistically independent, the settlement variance $V(\rho)$ can be calculated as the sum of the variance increments of the sublayers, $V(\rho_i)$:

$$V(\rho) = \sum_{i=1}^{N} V(\rho_i) \tag{6}$$

The deformability modulus (E_{Si}) is considered to vary with soil sublayers and it is analyzed as the only independent random variable. The predicted settlement variability is considered to be completely characterized by its first two moments (mean and variance), and the calculations of which are described in the following section using the three proposed methods.

3.1. The FOSM and SOSM methods

Consider the given form of the performance function of the independent random variables $x_1, x_2, x_3, \ldots, x_i$, such as $G(\boldsymbol{X}) = G(x_1, x_2, x_3, \ldots, x_i)$. Developing the function $G(\boldsymbol{X})$ about its mean and mean of the random independent variable x_i, using the Taylor's expansion series, gives (Baecher and Christian, 2003):

$$G(\boldsymbol{X}) = G(\overline{\boldsymbol{X}}) + \frac{1}{1!}\frac{\partial G}{\partial \boldsymbol{x}}(\boldsymbol{X}-\overline{\boldsymbol{X}}) + \frac{1}{2!}\frac{\partial^2 G}{\partial \boldsymbol{x}^2}(\boldsymbol{X}-\overline{\boldsymbol{X}})^2 + \frac{1}{3!}\frac{\partial^3 G}{\partial \boldsymbol{x}^3}(\boldsymbol{X}-\overline{\boldsymbol{X}})^3 + \cdots \tag{7}$$

The mean ($E(\rho)$) and variance ($V(\rho)$) of the predicted settlement can be obtained from Eq. (7) considering the Schmertmann's method as the performance function and assuming the parameter E_{Si} as the unique random variable. For the FOSM method, the mean and variance of settlement can be obtained by the following expressions:

$$E(\rho) = \rho = C_1 C_2 \sigma^* \sum_{i=1}^{N} \left(\frac{I_{zi}\Delta_{zi}}{\overline{E}_{Si}} \right) \tag{8}$$

$$V(\rho) = \left[C_1 C_2 \sigma^* \sum_{i=1}^{N} \left(\frac{I_{zi}\Delta_{zi}}{\overline{E}_{Si}^2} \right) \right]^2 V(E_{Si}) \tag{9}$$

For the SOSM method, the mean and variance of settlement are

$$E(\rho) = C_1 C_2 \sigma^* \sum_{i=1}^{N} \left(\frac{I_{zi}\Delta_{zi}}{\overline{E}_{Si}} \right) + C_1 C_2 \sigma^* \sum_{i=1}^{N} \left[\frac{I_{zi}\Delta_{zi}}{\overline{E}_{Si}^3} V(E_{Si}) \right] \tag{10}$$

$$V(\rho) = \left[C_1 C_2 \sigma^* \sum_{i=1}^{N} \left(\frac{I_{zi}\Delta_{zi}}{\overline{E}_{Si}^2} \right) \right]^2 V(E_{Si}) + 2\left[C_1 C_2 \sigma^* \sum_{i=1}^{N} \left(\frac{I_{zi}\Delta_{zi}}{\overline{E}_{Si}^3} \right) \right]^2 [V(E_{Si})]^2 \tag{11}$$

The first terms at the right side of Eqs. (10) and (11) correspond exactly to the mean and variance, respectively, calculated by the FOSM method, while the second terms represent the additional terms considered in the Taylor's series expansion. This simple observation shows that the FOSM method underestimates the results of mean and variance as the importance of the second term of the performance function considered increases.

With the calculated values of settlement mean, variance and standard deviation (root square of variance) in hand, the probabilistic analysis can be made by setting a probability distribution to represent the predicted settlement and specifying the deterministic values to the limiting settlement.

Here, the lognormal distribution is proposed for being a strictly positive distribution, while having a simple relationship with the normal distribution (Bredja et al., 2000; Fenton and Griffiths, 2002; Goldsworthy, 2006). According to Failmezger (2001), the probability analysis for settlement focuses on the right side of the distribution function, and because of its left skewness, the lognormal distribution gives a higher probability of success (unconservative) than beta or normal distribution.

An isolated footing is assumed and analyzed by the methods. Nevertheless, if two non-correlated footings are evaluated, differential settlement can be obtained by

$$E(\Delta\rho) = E(\rho_1) - E(\rho_2) \tag{12}$$

$$V(\Delta\rho) = V(\rho_1) + V(\rho_2) \tag{13}$$

where $E(\rho_1)$, $V(\rho_1)$ and $E(\rho_2)$, $V(\rho_2)$ are the mean and variance of predicted settlements of the two footings, respectively.

3.2. The MCS method

The MCS method consists basically of the simulation of all random variables and the resolution of the performance function for all those generated values. Here again, the deformability modulus is the only random variable. The method requires to define a domain of possible inputs. For simplification, 1000 simulations of modulus are proposed for each sublayer using lognormal distribution. The simulation can be done by using random number generator algorithms for Microsoft Excel.

The main steps used in this method can be summarized as follows:

(1) Analysis of the mean and variance of q_{ci} results for each sublayer.
(2) Estimation of the mean and variance of E_{Si}.
(3) Simulation of E_{Si} (using the mean, variance and lognormal distribution).
(4) Calculations of the mean and variance increments of settlement for each sublayer.
(5) Calculations of the mean and variance of total settlement.
(6) Probabilistic settlement analysis using the lognormal distribution and limiting settlement value(s).

3.3. Evaluation of the uncertainties in the random variable E_{Si}

In reliability analysis, independent random variables are influenced by the uncertainties and they must be appropriately quantified. In the methodologies considered in this study, only one random variable (E_{Si}) was adopted for each sublayer. The uncertainties in E_{Si} can be analyzed by assigning values to E_{Si} variance ($V(E_{Si})$), or by analyzing the sources of uncertainties according to E_{Si} estimations. Considering that the modulus E_{Si} is estimated according to the cone tip bearing resistance (q_{ci}), obtained from the cone penetration test (CPT) results, as suggested by Schmertmann (1970), three sources of uncertainties are suggested:

(1) The uncertainties due to field measurements of q_{ci} – in other words, the sum of inherent soil variability and equipment's measuring errors from CPT test. This variance is named $V_1(E_{Si})$.
(2) The uncertainties due to transformation models – due to the empirical correlations used to transform the field measurement results (q_{ci}) into required design parameters (E_{Si}). This variance is named $V_2(E_{Si})$.
(3) Statistical uncertainties – due to limited sampling or insufficient representative sampling data in the field. This variance is named $V_3(E_{Si})$.

The sources of uncertainties represented by $V_1(E_{Si})$ and $V_2(E_{Si})$ are explicit in the E_{Si}-q_{ci} correlations. The typical form of those correlations is

$$E_{Si} = \alpha q_{ci} \tag{14}$$

It is observed in Eq. (14) that two variables can contribute to the uncertainties in E_{Si} estimations, which are q_{ci} and α. They represent the uncertainties $V_1(E_S)$ and $V_2(E_S)$ as assumed before. The FOSM method is applied to Eq. (14) to quantify those sources of uncertainties. Then, $V_1(E_S)$ and $V_2(E_S)$ can be given as

$$V_1(E_{Si}) = \alpha^2_{\text{average}} V(q_{ci}) \tag{15}$$

$$V_2(E_{Si}) = q^2_{\text{ci}_{\text{average}}} V(\alpha) \tag{16}$$

where $V(q_{ci})$ is the sampling variance, calculated using q_{ci} results, of the i-th sublayer; α_{average} is the average α value of the chosen correlations; $V(\alpha)$ is the variance of α values, which is supposed to be equally likely. To evaluate $V_2(E_{Si})$, two or more empirical correlations are needed or, in other cases, it equals zero.

The third source of uncertainties is due to the representative of sampling data. Assuming that this source of uncertainties is a function of only the amount of sampling (size of sample), it can be calculated using the following equation proposed by Goldsworthy (2006):

$$V_3(E_{Si}) = \frac{V_1(E_{Si})}{n} \tag{17}$$

where n is the number of data obtained from CPT.

Thus, the equation to account for all sources of uncertainties due to variance of E_{Si} of the i-th sublayer is

$$V(E_{Si}) = V_1(E_{Si}) + V_2(E_{Si}) + V_3(E_{Si}) \tag{18}$$

3.4. Complementary results

The FOSM is a simple and useful reliability analysis method, but it is more suitable for single degree (linear) performance functions, as the cases of most bearing capacity equations. However, for settlement predictions, because of the inverse relations between the settlement and elastic modulus, a loss of convergence is expected for high variability of the independent random variable, where the SOSM or MCS method is more applicable.

Comparative analyses have shown that the FOSM method underestimates the results for the cases where the coefficient of variation of the deformability modulus $COV(E_S) > 30\%$, reaching up to 50% error when $COV(E_S) = 100\%$, due to the non-consideration of the higher-order terms of Taylor's series. The SOSM and MCS methods seem to converge, approximately, to the same results for all $COV(E_S)$ values.

It has been also observed that the depth where the major variance contribution occurs is highly dependent on E_{Si} values, with strong influence of the distribution factor I_z. So, the significance of settlement variance ($V(\rho_i)$) of the i-th sublayer in total settlement variance ($V(\rho)$) increases as the mean value of E_{Si} decreases and the sublayer is more close to the depth where I_z is the maximum.

As a simplified method, it is important to state some advantages and limitations of the FOSM method. The advantages are:

(1) Easy application through electronic spreadsheets, without need of finite element or advanced calculation software.
(2) It is very helpful for giving guidance on the sensitivity of design results (Griffiths et al., 2002), outcome from Schmertmann (1970)'s equation, to the variations of deformability modulus.
(3) It is possible to verify the distribution and contribution of settlement variances in the sublayers.
(4) Despite the non-consideration of spatial correlations or scale of fluctuation of deformability modulus, the use of Taylor's series is not against safety, as observed previously by Gimenes and Hachich (1992).

The main limitations rely on the assumption of a single and isolated footing (i.e. there are no interactions among strain bulbs of adjacent footings and no soil-structure interaction effects), and the consideration of the elasticity modulus as the only random variable (which is necessary in a complete SLS analysis of a foundation to account for the variability of other important parameters such as geometry and load of footings, which were considered constant in the present study).

On the use of the proposed methods, it is recommended that the sublayer thickness should be considered as small as possible, so the influence of tendencies in vertical variability is minimal (Campanella et al., 1987). For example, in mechanical CPT with 0.2 m interval data, it is indicated that the sublayer thickness is set to 0.2 m, so the vertical variability is already taken into account in the subsoil stratification and is not necessary to detrend the data (since the sublayers are treated to be independent of each other). In this case, the evaluated uncertainties in E_{Si} come only from horizontal variability of the sublayers.

4. Illustrative example of application

An example of application of the SOSM method is presented here. A footing with the size of 2 m × 2 m and the buried-depth of 1 m below the ground surface is assumed and analyzed, on which a load of 1600 kN is centrally applied (Fig. 4). The subsoil stratum, with shallow stratum composed of 4 m of clean sand with varied relative density, is a typical soil formation from the coast of the city of Vitoria, in the state of Espirito Santo, southeast of Brazil, which is influenced by the transgression/regression marine phenomena that occurred in Quaternaries' period.

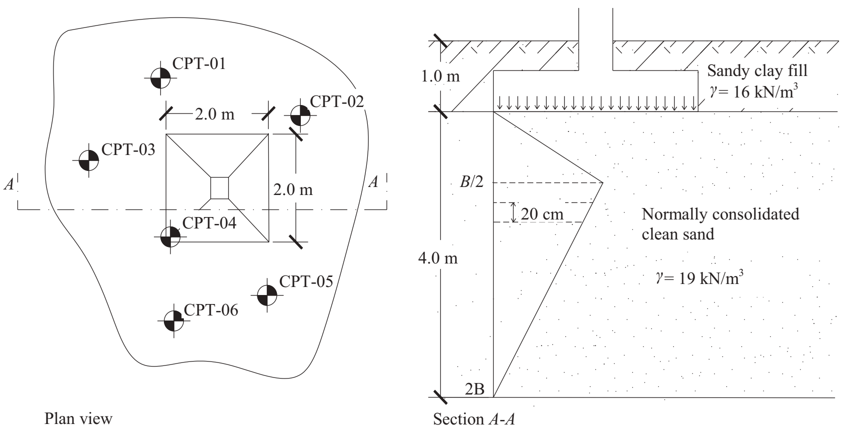

Fig. 4. Subsoil stratum adopted for the example of application.

The results of 6 mechanical CPTs (CPT01, CPT02, CPT03, CPT04, CPT05, CPT06), with 0.2 m limit interval data, are hypothetically assumed to be available in the region, which is represented by the shown subsoil stratum. For Schmertmann (1970)'s equation, the sublayer thickness was set to 0.2 m, therefore, 20 sublayers were used in the calculation. To account for soil variability in this region, CPT data are analyzed firstly. For each sublayer, the mean (q_{ci}) and variance ($V(q_{ci})$) values are calculated and presented in Table 1.

After that, the deformability modulus is estimated for each sublayer through the adopted empirical correlation(s). Here, it is assumed that only one correlation is used, which is given by Schmertmann (1970)'s equation:

$$E_{Si} = 2q_{ci} \tag{19}$$

The transformation must be done using mean values of q_{ci}. The next step is to calculate $V(E_{Si})$. As only one empirical correlation is adopted, $V(\alpha) = 0$ and then $V_2(E_{Si})$ becomes automatically null. Subsequently, the settlement mean and variance contributions of each sublayer are evaluated. Table 1 shows the main results for the given example. Variances are given in square units. The mean and variance of the predicted settlement are then obtained by the sum of the increments of each sublayer, as listed at the bottom of Table 1. So the predicted settlement can now be represented as $\rho = (20 \pm 2)$ mm.

Table 1
Evaluation of CPT results, uncertainties in E_{Si}, and application of the SOSM method.

Sublayer	CPT data (MPa)		Modulus evaluation (MPa)		Settlement evaluation (mm)		Variance contribution, $V(\rho)$ (%)
	q_{ci}	$V(q_{ci})$	E_{Si}	$V(E_{Si})$	ρ_i	$V(\rho_i)$	
1	10	10.3	20.1	48.2	0.252	0.007	0.2
2	9.6	9.9	19.2	46	0.791	0.077	2
3	9.7	9.9	19.4	46	1.308	0.207	5.4
4	9.2	9.4	18.4	44.1	1.937	0.481	12.5
5	8.9	9.3	17.9	43.3	2.576	0.884	22.9
6	9.4	9.6	18.8	44.7	2.607	0.845	21.9
7	9.7	9.8	19.3	45.7	2.358	0.672	17.4
8	11.9	12.1	23.8	56.4	1.737	0.297	7.7
9	13.3	13.5	26.6	63	1.414	0.176	4.6
10	15.4	15.5	30.8	72.2	1.104	0.092	2.4
11	18.1	18	36.2	83.8	0.839	0.045	1.2
12	21.5	21.6	42.9	100.8	0.628	0.022	0.6
13	24.2	24.7	48.4	115.3	0.489	0.012	0.3
14	24.8	25.8	49.7	120.5	0.413	0.008	0.2
15	21.8	22.6	43.7	105.5	0.4	0.009	0.2
16	20.4	21	40.7	97.9	0.352	0.007	0.2
17	19.2	19.8	38.5	92.3	0.291	0.005	0.1
18	16.1	16.3	32.3	76.1	0.25	0.005	0.1
19	15.9	16	31.7	74.5	0.153	0.002	0
20	15.9	16	31.8	74.5	0.051	0	0
Sum	–	–	–	–	19.95	3.86	100
$\sigma(\rho)$	–	–	–	–	–	1.96	–
COV (%)	–	–	–	–	–	9.84	–

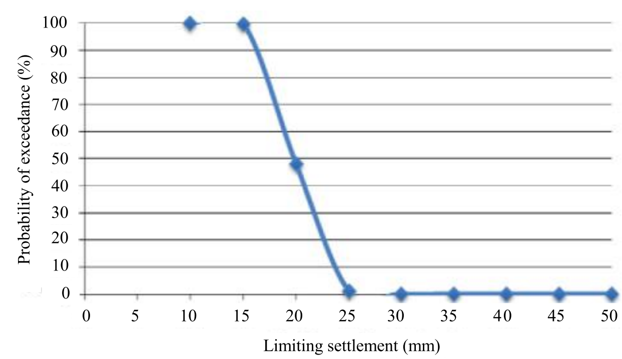

Fig. 5. Probability of exceedance for different values of limiting settlement, considering the footing and subsoil of the proposed example.

For the complete characterization of the solicitation curve (predicted settlement), lognormal distribution was used. Fig. 5 shows the results of the probability that the predicted settlement exceeds different values of limiting settlements in a range of 10–50 mm. For example, the probability of the predicted settlement that exceeds 25 mm is about 1.1%. For predicted settlement exceeding 40 mm, $P(\rho \geq 40 \text{ mm}) \approx 0$.

The analysis of the sources of uncertainties indicates that about 80% of the settlement variance comes from the uncertainties induced by inherent soil variability and measuring errors. It is important to emphasize that the uncertainties due to transformation model was not evaluated in the example.

5. Conclusions

Three simplified methods have been proposed and briefly discussed for probabilistic analysis of settlements of footings on sands, focusing on the load curve variability (predicted settlements) characterization. Using those methods, the mean and variance of estimated settlements were calculated based on Schmertmann (1970)'s equation. The deformability modulus (E_{Si}) was considered to vary with the soil sublayers and it was analyzed as the only independent random variable. As an example of application to determine the footing settlement using CPT data, a hypothetical case in a typical subsoil of the city of Vitoria in the state of Espirito Santo, southeast of Brazil, was evaluated. Simulations indicate that there is a significant similarity between SOSM and MCS methods, while the FOSM method underestimates the results due to the non-consideration of the high-order terms of Taylor's series. Despite the presented limitations of the proposed methods, it can be assumed as a first approximation for evaluating the uncertainties (especially in deformability modulus) in the SLS analysis of a foundation. The association between probabilistic analysis and settlement predictions can become an interesting tool for geotechnical engineering in understanding the soil variability and related uncertainties, which can provide a safer design.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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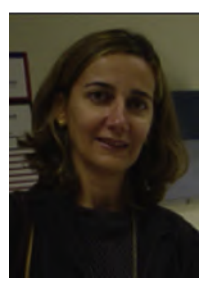

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