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CPT based settlement prediction of shallow footings on granular soils

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ABSTRACT: Van Oord DMC executed a large land reclamation project, where requirements had to be met concerning the settlement of shallow foundations to be placed on the sand fill. CPT based settlement predictions performed in the design phase had to be verified with zone load testing. After completing the project, all measurement data were analysed to gain insight into the accuracy of existing correlations between CPT data and settlement of a sand fill. The correlations by De Beer & Martens (1957), Schmertmann (1978), Peck et al. (1996) and Robertson (1990) were considered. From the total number of zone load tests, 43 test were selected which allowed for comparison of the results with the predictions using the mentioned correlations. It was concluded that the CPT to stiffness correlation of Robertson combined with the analytical model of Schmertmann corresponds very well with the measurements, consistently showing only small deviations from the measured settlement.

1 INTRODUCTION

Large land reclamation projects commonly have requirements for the settlement of shallow foundations to be placed on the sand fill. The standard method of verification of these requirements for hydraulic fill is estimating the settlement using CPT's. Because of the large variation in the results of the existing correlations between foundation stiffness and cone resistance found in literature, it is often necessary to verify the quality of the predictions by means of costly zone load testing.

2 PROJECT DESCRIPTION

2.1 *General description*

Van Oord DMC have executed a large land reclamation project in Kuwait. Purpose of the project was to construct an approximately 12 km^2 sand platform to function as a foundation for future construction. The thickness of the platform was on average 4 m, with a maximum of 6.5 m. The platform was constructed partly on an existing layer of silty clay (sabkha) and partly on existing sandy deposits. One of the performance requirements for the platform was to limit the maximum settlement of shallow footings placed directly on the sand fill. To achieve this requirement, several techniques of ground improvement were executed: dynamic replacement of the existing sabkha and dynamic compaction complemented by high energy impact compaction of the fill material throughout the site. The dynamic replacement resulted in the creation of sand columns through the sabkha layer to the bearing strata below. The purpose of these columns, with the reclamation as load spreading platform, was to limit the deformations of the sabkha layer by transferring the majority of the reclamation and future foundations loads to the bearing strata.

2.2 *Ground improvement quality control*

One of the quality control methods for the ground improvement works was the execution of CPT's. The site was divided into large sub-areas, which in turn where subdivided in control boxes of 50 m by 50 m. In each of these control boxes CPT's were performed. The purpose of the CPT's was to identify the control boxes with the largest expected settlement under the design foundation load. In those boxes zone load tests (ZLT's) where then performed to verify that the actual foundation settlement would not exceed the required maximum value.

To determine the locations for the ZLT's, the CPT to soil stiffness correlation according to Robertson (1990) combined with the settlement prediction method of Schmertmann et al. (1978) was applied. Using this method the settlement of the shallow footing was predicted for each control box and used as a basis for selecting the ZLT location for each sub-area. Due to the size of the site thousands of CPT's and dozens of ZLT's were executed over the course of the project providing a large amount of data.

The ground water level at the site was elevated due to the hydraulic filling method. The phreatic water level at the moment of executing the CPT's and ZLT's was typically 1 m to 2 m below the surface level of the fill.

2.3 *Fill material*

A limited amount of particle size distribution tests was performed at the fill area. The sand of the fill is coarse to very coarse (average D50 of 0.40 mm), poorly graded and contains a fine content of approximately 3% after placement. Field density tests showed that the material of the top layer was compacted to a dry density of on average 1720 mT/m^3, a relative density D_r of 75% to 80% (relative compaction 95.5%).

Several other parameters of the fill material used for the construction of the platform were investigated. In Figure 1 a soil behaviour types (SBTn) chart (Robertson 1990) shows the distribution of the individual CPT measurement of normalized cone resistance and sleeve friction.

As is common in the Middle-East, the fill material consists partly of calcareous sand. The carbonate content of the material was investigated and found to vary over the site. On average a carbonate content of 20% was found. At specific locations it was measured to be 70% to 80%. The sandy material in the original ground profile of the site is not

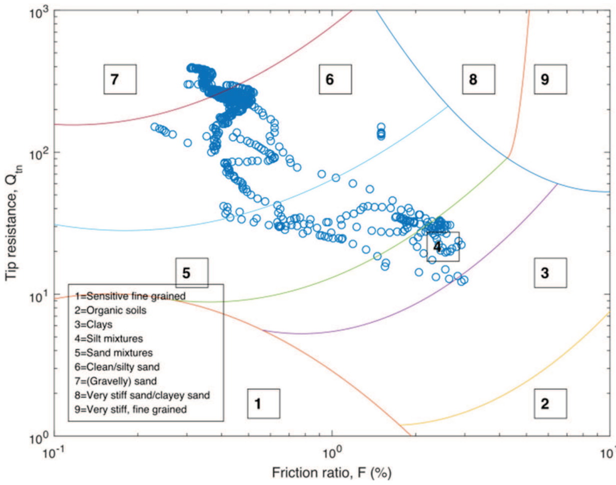

Figure 1. SBTn chart ZLT DD145.

calcareous. The carbonate content is of importance for the analyses as the results of high stress testing methods like cone penetration testing are influenced by crushing of the particles.

3 CPT BASED SETTLEMENT PREDICTION

Execution of CPT's is a cost effective way to gather information on the present soil type and behaviour. Besides a good insight into the strength of the soil, CPT results also give indications of the material stiffness. For granular soils, various analytical and empirical correlations exist between CPT measurements, stiffness properties and the expected settlement of a shallow foundation on the soil. A selection of these correlations is mentioned below.

3.1 *Analytical and empirical models*

De Beer & Martens (1957) developed an expression to predict settlement of a shallow footing based on the stress increase due to loading and the stiffness of distinguished soil layers based on a linear relation with the cone resistance. The method was intended to provide a safe upper limit of the expected settlement. Equations (1) and (2) were derived.

$$s = 2.3 \cdot \frac{H}{C} \cdot \log_{10}\left(\frac{\sigma_0' + \Delta\sigma}{\sigma_0'}\right) \tag{1}$$

$$C = 1.5 \cdot \frac{q_c}{\sigma_0'} \tag{2}$$

where s = settlement; H = thickness of the layer considered; C = compressibility coefficient; s'_0 = effective vertical stress at considered depth; Δs = pressure increase due to loading; and q_c = cone resistance.

The improved Schmertmann (1978) method uses the strain influence factor I_z, which can be derived from the strain influence diagram and depends on the geometry of the footing. The stiffness of the soil is modelled using the secant Young's modulus, obtained from a linear relation with the cone resistance. The expected settlement can be obtained with equations 3–5.

$$s = q_b \cdot B \cdot \int_0^z \frac{I_z}{E_s} dz \tag{3}$$

$$E_{s,i} = 2.5 \cdot \overline{q_{c,i}} \quad \text{for circular/square foundation} \tag{4}$$

$$E_{s,i} = 3.5 \cdot \overline{q_{c,i}} \quad \text{for strip foundation} \tag{5}$$

where s = settlement; q_b = unit load acting on the base; B = footing width; I_z = strain influence factor

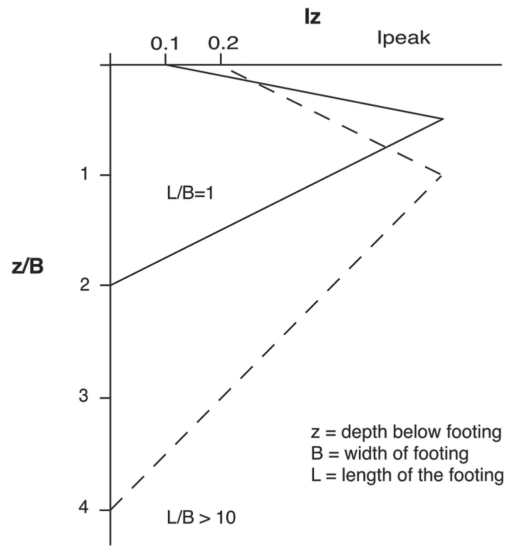

Figure 2a. Influence diagram Schmertmann (1978).

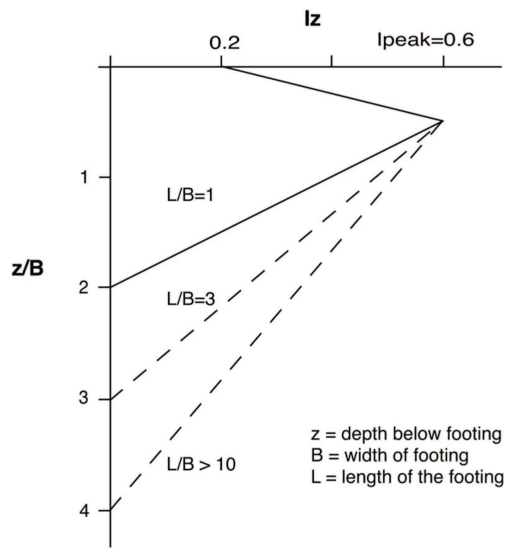

Figure 2b. Influence diagram Peck et al. (1996).

at depth z; E_s = secant Young's modulus at depth z; and q_c = cone resistance. The strain influence diagram is shown in Figure 2a.

Both De Beer and Martens and Schmertmann based their stress distribution calculation on the equation of Boussinesq (1883) and Newmark (1942).

Peck et al. (1996) proposed a modification of the Schmertmann method. They presented a different influence diagram where the depth and size of the peak of the influence I_{peak} is independent of the foundation geometry, in combination with adjusted expressions for the Young's modulus as a function of the cone resistance. Also a distinction is made between direct elastic settlement and time dependent deformation (creep). The equations 6–8 proposed for settlement calculations are slightly different from those by Schmertmann (1978).

$$s = q_b \cdot \sum_{i=1}^{n} \frac{I_z \cdot \Delta z}{E_{s,i}} \tag{6}$$

$$E_{s,i} = 3.5 \cdot q_c \tag{7}$$

$$E_{s,i} = 3.5 \cdot q_c \cdot \left(1 + \log_{10} \frac{L}{B}\right) \leq 3.5 \cdot q_c \cdot 1.4$$

$$\text{for rectangular foundation} \tag{8}$$

where q_c = weighted average cone resistance; L = is the length of the footing; and B = width of the footing. The strain influence diagram is shown in Figure 2b.

Several more recent publications are available presenting an adjusted strain influence diagram with a more general formulation to suit all footing geometries (Mayne & Poulos 1999) or multiple interacting footings (Lee et al. 2007). Das & Sivakugan (2007) give an overview of the existing methods for settlement calculation based on CPT's and SPT's.

3.2 *CPT to stiffness correlation*

The above mentioned methods for prediction of footing settlement include a rough estimation of the material stiffness. Robertson (1990) suggested a more inclusive method making use of normalized and dimensionless CPT parameters. Based on this a distinction can be made between soil behaviour types using the SBTn chart. Equation 9 was proposed for the stiffness modulus based on the soil behaviour type index, the cone resistance and the stress state.

$$E' = 0.015 \cdot 10^{(0.55 I_c + 1.68)} \cdot (q_t - \sigma_{v0}) \tag{9}$$

where E' = Young's modulus; I_c = soil behaviour type index; q_t = corrected net cone resistance; and s_{v0} = in situ total vertical stress. This stiffness is based on combination with the aforementioned strain influence diagram of Schmertmann (1978).

The methods and correlations mentioned are generally only suitable for uncemented normally consolidated cohesionless sandy soils. Stress state parameters like consolidation state and reloading stiffness are not explicitly incorporated.

From experience it is know that the settlement that results from these correlations can vary, also depending on the specific site conditions. Because of the extensive amount of measurement data generated at the project, an evaluation of the CPT based settlement prediction methods can be performed.

4 ZONE LOAD TESTS

4.1 *General*

Van Oord DMC executed a large number of zone load tests to verify the settlement predictions.

A zone load test comprised the incremental loading of a square concrete footing of 3 m by 3 m by 0.6 m up to a load of 250 kPa. A test took three days and the settlements of the footing were measured as a function of time and load.

4.2 *Set up*

The set up of a ZLT is illustrated in Figures 3 and 4 and is designed after the experiences in current practice (Briaud & Gibbens 1999). The load on the footing is transferred from the concrete support blocks to the footing in between by extending a hydraulic jack. Reference beams with measurement devices were installed and supported at reasonable distance from the loading zone. On the footing, four measurement locations were evenly distributed over the surface and the average measured settlement was used as input for the verification of the maximum settlement.

Each load step comprised 20% of the maximum load of 250 kPa and was held for 2 hours. The maximum load was maintained for 48 hours.

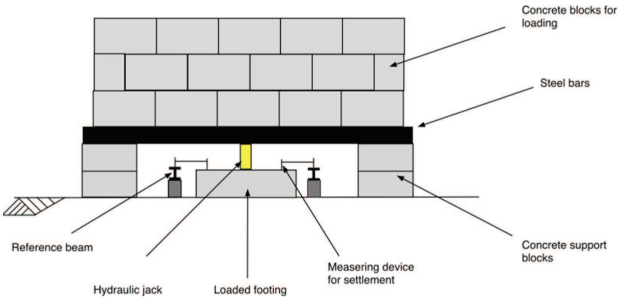

Figure 3. Schematic ZLT set up.

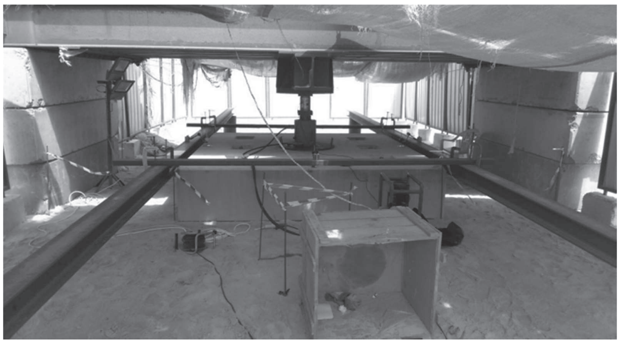

Figure 4. Close up photograph ZLT.

4.3 *Results*

An example of the resulting time displacement curve is presented in Figure 5. In the measured settlements a time dependent behaviour is observed.

5 ACCURACY OF EXISTING CORRELATIONS

To gain more insight in the accuracy of the existing correlations between CPT data and settlement of the sand fill under loading, all the measurement data were analysed after completing the project. From the total number of zone load test results, 43 zone load tests were selected which allowed for comparison of the predictions. In these tests, the sand body had a minimum thickness of 5 m above existing soft soil layers of silt or sabkha. The presence of silt or sabkha at the lower part of the foundation influence depth is expected to have minor impact on the foundation settlement, considering these layers were already treated by dynamic replacement (see section 2.1) and are relatively stiff.

5.1 *Processing of the CPT data*

At the location of every ZLT five CPT's were performed prior to testing. Unless significant variation was observed in the measurements indicating

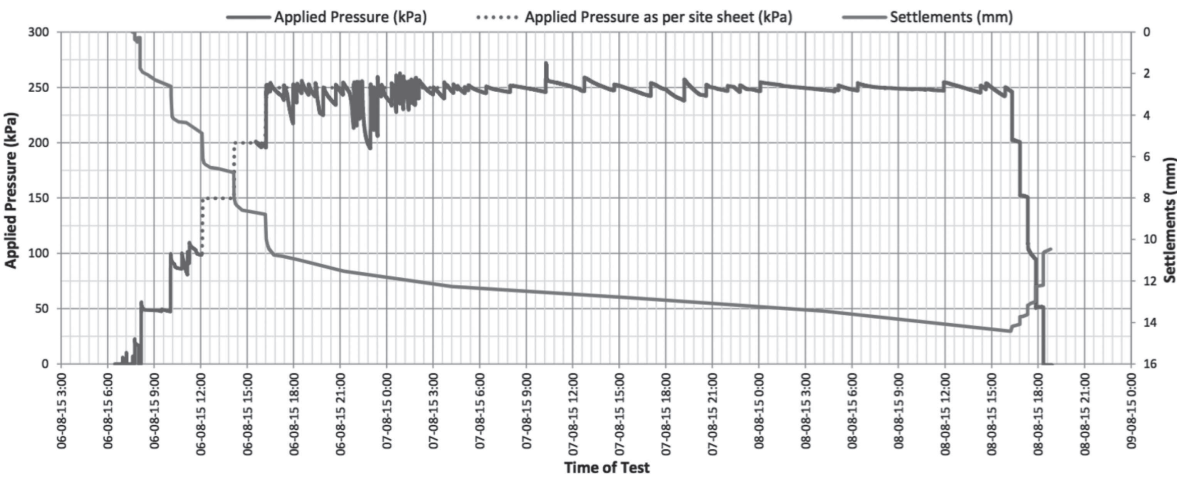

Figure 5. Output ZLT DD145.

high soil variability, the average resulting cone resistance and friction ratio were used for processing. The cone resistance and friction ratio were normalized and introduced in the SBTn chart of Robertson. Based on the resulting soil types, the soil layers were automatically defined, with a minimum soil layer thickness of 0.25 m. The process is illustrated in Figures 6 and 7. With this soil profile and corresponding CPT data the settlement calculations were performed using the available correlations.

5.2 *Comparison of results*

The predicted settlement based on the CPT data via the correlations and the actually measured settlement were compared to establish the error that occurs when using the correlations for settlement prediction. Only the measured direct settlement is used for comparison. The long term part of the measurements was excluded as the correlations in principle concern direct elastic deformation.

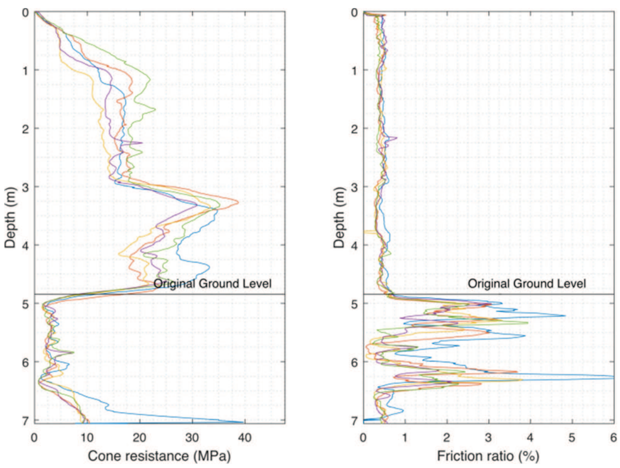

Figure 6. CPT data at ZLT DD145.

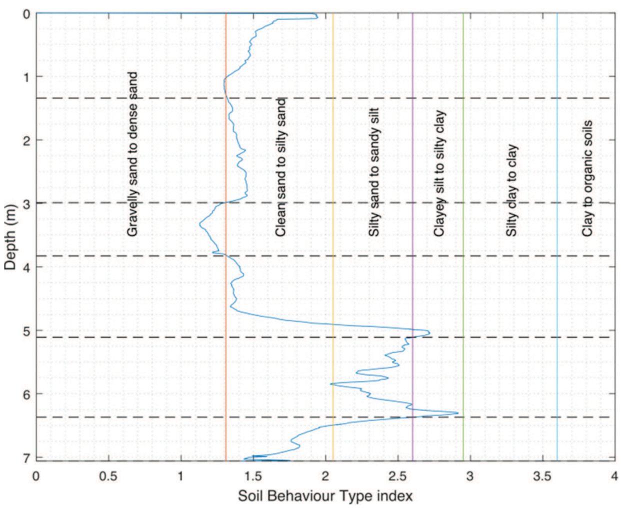

Figure 7. Layering based on CPT's at DD145.

At first, a distinction is made between locations with (1) only sand, (2) sand and silt, and (3) sand, silt and sabkha. The results per group are compared with the overall results. Another distinction in location concerns the thickness of the fill layer. At locations where the thickness of the applied fill is small, the in-situ sand determines a large part of the stiffness to be measured instead of the calcareous sand fill. From the data available no difference was observed between the errors encountered for the distinct situations. Based on these conclusions, the 43 zone load tests are treated as a uniform group.

It was investigated if the encountered error could be described as normally distributed. This was generally the case. The resulting means and standard deviations of the error per prediction method are given in Table 1.

5.3 *Conclusions*

After combining the zone load test measurements with the predictions based on the corresponding CPT's, it was evaluated which existing correlation best fitted the measurements. It was concluded that from the considered methods the CPT to stiffness correlation of Robertson, based on the analytical model of Schmertmann for stress distribution, corresponds very well with the measurements, consistently showing only small deviations from the measured settlement.

5.4 *Uncertainties and imperfections*

The ZLT's showed an increasing settlement while the load was kept constant. Such time dependent behaviour of the material can be caused by consolidation effects or by creep.

The permeability of the fill material is expected to be such that no or very little excess pore water pressure will occur during loading. Therefore it is not expected that consolidation of the sand is an important factor. In the cases that a silt or sabkha layer was present underneath the fill layer, loading can cause consolidation of these layers. However,

Table 1. Error in settlement calculated with analytical methods compared to ZLT measurements.

	Error	
Method	Mean (%)	Standard deviation (%)
De Beer and Martens	28	16
Schmertmann	42	13
Peck et al.	–2	23
Robertson	0	20

the compression of this layer is very limited due to the executed dynamic replacement and would not explain the fact that also at locations without such layers the time dependent behaviour was observed.

The time dependent behaviour can be caused by creep of the calcareous sand. Although no relation was found between the carbonate content present at specific ZLT's locations and the error between the predictions methods and the actual settlement measurements, this cannot be disregarded because of the limited amount of related soil investigation. The behaviour of crushable particles can be of significant influence on the CPT data. In the analyses for this project no shell correction factor was applied.

To verify the uncertainties mentioned above, additional testing is advised for future loading tests, execution of plate load test with variable plate dimensions, concerning the pore water pressures, and measurements of the distribution of the occurring strain over depth.

Finally, it is mentioned that the set up of the ZLT's is of influence on the test results. Although the tests were executed as carefully as possible, the environmental and practical limitations of the situation can affect the measurements. For example, the distance between the supports and the actual footing was relatively small; 1.5 m. Consequently, a stress increase was created in the influence zone of the footing before loading and measurement was started. As the sand will not behave fully elastic, the measured response of the footing can be stiffer during loading than generally to be expected and the total settlement of the footing at maximum load is reduced. The difference is calculated to be in the order of 10% to 15%.

6 CONCLUSIONS

For a specific project, the comparison of CPT based settlement prediction methods with the measurement results of zone load tests (ZLT's) showed that the CPT to stiffness correlation of Robertson combined with the analytical model of Schmertmann corresponds very well with the settlements taking place during zone load testing. The predicted settlement consistently shows only small deviations from the measured settlement. As the correlations give a reasonably reliable estimation of the expected settlement, the number of ZLT's to be performed in future projects to verify settlement requirements can be reduced.

Distinction is made between three types of soil layering at the site and also test locations with predominantly original silica sand deposits and locations with a thick calcareous sand fill with variable carbonate content. No abnormality between the errors of the predictions for the several situations is observed.

The fact that the fill material was calcareous sand does not appear to have influenced the accuracy of the predictions. No correction factor is applied on the CPT results to correct for the presence of the carbonate content in this project. In other cases this is probably necessary.

In the considered models long term deformation is not included. During the ZLT's time dependent settlements were observed. These settlements most likely result from creep of the sand and might be influenced by the carbonate content. To gain more insight in the cause of long term deformation for similar projects additional testing is advised including investigation of the carbonate content that is present and pore water pressure measurements occurring during loading.

REFERENCES

Boussinesq, J. 1883. Application des potentials a l'etude de l' equilibre et du mouvement des solides elastiques. Paris: Gauthier-Villars.

Briaud, J.L. & Gibbens, R. 1999. Behaviour of five large spread footings in sand. Journal of geotechnical and geoenvironmental engineering 125(9): 787–796.

Das, B. & Sivakugan, N. 2007. Settlement of shallow foundations on granular soil – an overview. *International journal of geotechnical engineering* 1(1): 19–29.

De Beer, A. & Martens, E. 1957. Method of computation an upper limit for the influence of heterogeneity of sand layers on the settlement of bridges. *4th International conference on soil mechanics and foundation engineering; Proceedings*: 275–282.

Lee, J. et al. 2007. Strain influence diagrams for settlement estimation of both isolated and multiple footings in sand. *Journal of geotechnical and geoenvironmental engineering* 134(4): 417–427.

Mayne, P. & Poulos, H.G. 1999. Approximate displacement influence factors for elastic shallow foundations. *Journal of geotechnical and geoenvironmental engineering* 125(6): 453–460.

Newmark, N.M. 1942. *Influence charts for computation of stresses in elastic foundations*. Technical report; University of Illinois Bull.

Peck, R.B. et al. 1996. *Soil Mechanics in Engineering Practice*; *3rd edition*. New York: John Wiley and sons.

Robertson, P.K. 1990. Soil classification using the cone penetration test. *Canadian geotechnical journal* 27(1): 151–158.

Robertson, P.K. 2009. Interpretation of cone penetration tests - a unified approach. *Canadian geotechnical journal* 46(11): 1337–1355.

Schmertmann, J.H. et al. 1978. Improved strain influence factor diagrams. *Journal of geotechnical engineering division* 104(8): 1131–1135.