Cone resistance profiles for laboratory tests in sand

M. Senders
Woodside Energy Limited, Perth, WA, Australia

ABSTRACT: This paper describes an approach that can be used to convert a cone resistance profile measured in the laboratory with a certain diameter in clean silica sand into a cone resistance profile that would be measured with a cone with another diameter in the same clean silica sand. This conversion assumes that the cone profile will reach a steady state condition after a certain penetration depth, which depends on cone diameter, \( d_{cone} \), stress level, \( \sigma' \), and relative density, \( D_r \), of the sand. The proposed line of thinking is used to generate a formula which predicts the cone resistance as a function of these parameters and depth, \( z \).

1 INTRODUCTION

The cone resistance, \( q_c \), is the penetration resistance of a 60° conical tip. Standard field cones have a total projected tip area of 1000 mm\(^2\) penetrating the soil at a speed of 20 mm/s (ASTM, 2004). In many laboratory tests the use of these 1000 mm\(^2\) cones is limited due to the relative small size of the soil sample in combination with the expected influence the surface effect has upon the measured cone resistance (Puech and Foray, 2002). In these situations typically a smaller size cone is used, although this is in many cases still relative large. For example, a typical cone penetration test in UWA’s beam centrifuge, performed with a 7 mm diameter cone at 100 g, relates to a 700 mm cone which is about 20 times larger than the standard cone (Senders, 2008). There is therefore a need to convert measurements made with a certain cone diameter into expected measurements made with another size cone.

2 LITERATURE

2.1 Deep failure (Steady state)

The classical bearing capacity approach predicts that the cone resistance, \( q_c \), in sand increases linearly with effective stress level, \( \sigma' \). However, experience has shown that
the cone resistance increases less than linearly with increasing stress (Jamiolkowski et al., 1988; Lunne et al., 1997). Rather than following the classical bearing capacity approach, researchers have tried to establish relationships between effective stress, relative density and cone resistance. Most of the proposed prediction methods have a similar format, expressed as:

\[ q_e = C_1 \sigma'_e C_2 e^{C_3 D_r} \]

where \( D_r \) is the relative density expressed as a decimal, and the coefficients \( C_1, C_2 \) and \( C_3 \) are adjustable parameters, which can be adjusted to reflect differences in soil compressibility (Lunne et al., 1997).

One of the most widely used relationships is based on research on Ticino sand and published in Jamiolkowski et al. (1988):

\[ q_{e, Jami} = C_1 \sigma'_e C_2 e^{C_3 D_r} = 205 (\sigma'_m)^{0.51} e^{2.93 D_r}, \]

with

\[ \sigma'_m = \frac{\sigma'_e (1 + 2 K_0)}{3} \]

The parameter \( K_0 \) represents the coefficient of lateral earth pressure. This relationship is based upon earlier suggestions by a number of researchers (Schmertmann, 1978; Lunne and Christofferson, 1983; Baldi et al., 1986).

2.2 Transition from shallow to deep failure

The transition from shallow to deep failure is captured in depth factors used to calculate the capacity of shallow foundations. These factors are described in design codes like DnV (1992) and API (2000), and depend on the relative displacement, \( d/z \).

Puech and Foray (2002) recognised the influence on the measured cone resistance of the change from a shallow to a deep failure mechanism. An experimental database was compiled from a series of calibration chamber tests (at zero confining stress) and data from shallow offshore cone tests. It was found that there are two penetration phases during a cone penetration test, one where the soil moves upward at the free surface next to the cone rods (shallow failure mechanism) and one where the soil stops moving upwards at the free surface next to the cone rods (deep failure mechanism). Furthermore it was found that the transition depth between the two penetration phases increases with the relative density of the sand and that the first penetration phase tends to reduce and disappear in loose to very loose sand.
3 CENTRIFUGE TESTS

3.1 Bolton et al., 1999

The influence of the change in failure mechanism on the cone resistance can also be seen in data presented by Bolton et al. (1999). They compared centrifuge test results from five different European geotechnical centrifuges and used different strong-boxes, different cone diameters and different g-levels. Fontainebleau sand was used in all tests, which is a uniform silica sand, consisting of rounded particles with an average mean particle size, $D_{50}$, of 0.22 mm and average maximum and minimum dry densities of 16.49 and 13.88 kN/m$^3$, respectively (Bolton et al., 1999).

Figure 1 (presented further on in the paper) shows measured cone resistances in a sand measured at 70 g in five different geotechnical centrifuges in both dimensional axes and normalised axes. The reported values of relative density, $D_r$, varied between 0.81 and 0.84 (Bolton et al., 1999). The cone diameters, $d_{cone}$, varied between 10 mm and 12 mm. Figure 1a reveals that this small difference in cone diameter has no influence on the measurements. Figure 1b shows that at a penetration of approximately $11.5d_{cone}$, the normalised cone resistance reaches its maximum value. The measurements taken at a shallower relative depth are believed to be related to failure where the free surface effects play a role. The measurements beyond this relative depth are believed to relate to the deep failure (e.g. steady state).

Figure 2 (presented further on in the paper) presents cone resistance measurements taken with a 11.3 mm cone diameter at different g-levels. The relative density, $D_r$, during these tests was reported to be 0.96. It can be seen that: a) The cone resistance increases with depth and increasing g-level; b) The normalised cone resistance initially increases rapidly with normalised depth, reaches a maximum and thereafter slowly decreases with normalised depth; c) The peak of the normalised cone resistance occurs at lower normalised depths for higher g-levels; and d) The normalised cone resistance drops with increasing g-level.

3.2 UWA centrifuge tests (Senders, 2008)

Senders (2008) presented several cone penetration tests with a 7 mm cone diameter which were performed in the UWA beam centrifuge at 100 g. The sand used during the tests had a (dry) unit weight of 17.8 kN/m$^3$, which for the used wet sand conditions indicates that the relative density, $D_r$, must have had a value of 1.

One of the measured cone resistance profiles can be seen in Figure 3 together with a steady state prediction according to Equation 2, for a $K_0$-value of 0.8 and a $D_r$ value of 0.75. It can be seen that this measured cone resistance profile only reaches the predicted cone resistance at a depth of approximately 90 mm. Where the measurements are normalised as displayed in Figure 3b, it can be seen that this point is defined as the point where the maximum value of $(q_c-\sigma_v)/\sigma_v$ is reached.
4. GENERAL CONE RESISTANCE PROFILES

4.1 Concept and parameters

Based upon the observations described before, the following four steps are recommended to be taken in cases where cone resistance measurements are available and a conversion needs to be made to obtain an estimate of the cone resistance which would be measured with a different cone diameter:

1. Plot the measured data as cone resistance, \( q_c \), versus depth, \( z \), and normalised cone resistance, \( (q_c-\sigma_v')/\sigma_v' \), versus normalised depth, \( z/D \);

2. Spot the peak of the normalised cone resistance and regard this as where the steady state starts.

3. Try to create a steady state profile on the \( q_c \) versus \( z \) graph for the complete length, based upon the data below where steady state starts. Take into account that the relationship between steady state cone resistance and depth follows a power law (e.g. Equation 2);

4. Use the initial part of the \( (q_c-\sigma_v')/\sigma_v' \) versus \( z/D \) graph to predict the build up of cone resistance in the shallow part for the new cone diameter.

This line of thinking can be used to generate a general formula, which can be used to predict a cone resistance profile for any given soil condition and cone diameter for clean silica sand.

4.2 Formula

To combine all the previous findings, the creation of a new formula is proposed comprising two separate components, which must be multiplied together: a) a formula that describes the steady state profile; and b) a formula that has values starting at 0 and increasing to 1, which determines where the shallow penetration changes in the steady state penetration.

Since the formula proposed by Jamiolkowski et al. (1988) is already relatively simple, it was decided to use a similar format. Using dimensional analysis, the following simple formula is proposed:

\[
q_c(z) = C_1 \left( \frac{\sigma_m}{p_a} \right)^{-C_2} e^{2.93D} \sigma_m'
\]

with

\[
p_a = 100kPa
\]

\[(3)\]
By curve fitting the available data from Senders (2008) to this formula and assuming that $K_0$ has a typical value of 0.8, the values for $C_1$ and $C_2$ were found to be 22.5 and 0.5 respectively. If required, these values can be slightly adjusted as proposed by Lunne et al. (1997) to describe different soils more accurately.

The second formula needs to go from 0 to 1, and should account for the influence of the shallow failure mechanism on the cone resistance. As found in measurements and indicated by Puech and Foray (2002), the development of cone resistance at shallow penetration not only depends on the penetration, $z$, but also on the width of the penetrating object, $d_{con}$, the relative density of the soil, $D_r$, and the stress condition, $\sigma_m'$. It is proposed to use a formula in the form of:

\[
f(z) = 1 - e^{\left(\frac{z}{d_\text{con}} C_3 \frac{\sigma_m'}{D_r C_4} \right)^{C_5}}
\]  

(4)

The coefficients $C_3$ through $C_5$ fine tune the location of the normalised penetration at which the maximum normalised cone resistance occurs.

Note that Equation 4 by itself does not determine at which depth the deep failure mechanism starts. This depends on the multiplication of Equations 3 and 4. In the right graphs of Figures 1 through 3 it can be seen that normalised cone resistance increases linearly for all $z/d_{con}$. Therefore the coefficients $C_2$ and $C_5$ must be very similar and in this case be in the order of 0.5.

By combining all previous observations and fitting the proposed formula to the available data, the following new prediction method is proposed:

\[
q_c(z) = 22.5 \left(\frac{\sigma_m'}{P_a}\right)^{-0.5} e^{2.93D_r} \sigma_m' \left(1 - e^{\left(\frac{z}{d_\text{con}} \frac{0.095 \sigma_m'}{D_r P_a}\right)^{0.5}}\right)
\]  

(5)

5 COMPARISON WITH MEASUREMENTS

5.1 Bolton et al., 1999

Figure 1 shows the cone resistance measurements presented in Bolton et al. (1999) at 70-g in different centrifuge facilities as described in Section 3.1 (grey) together with the predictions using Equation 5 for a sand with a relative density of 82% with two cone diameters of 0.010 and 0.012 m (black).
It can be seen that the prediction compares reasonably well with the measurements. Furthermore it is apparent that according to the proposed prediction method the influence of the varying cone diameter is smaller than the bandwidth of the measured data. This could explain why the influence of the cone diameter on the results was not identified by Bolton et al. (1999).

To visualise what the effect would be in cases where a prototype cone would have been used in these tests, a prediction is included in Figure 1 for a cone with a diameter of 36 mm (red). From the prediction it is obvious that the results would have changed significantly. Unfortunately no data is available to check this.

Figure 2 shows the cone resistance measurements of Bolton et al. (1999) for various g-levels as described in Section 3.1 (grey) together with the predictions using Equation 5 (black). It can be seen that the predictions follow the trends of the measurements, and that the values agree well up to 0.2 m penetration, certainly for the higher g-levels. This shallow penetration is the most important data for laboratory (or centrifuge) testing, since most tests will be performed within this depth. Beyond this penetration depth the predictions and measurements start to diverge, although the differences in percentage remain small. A realistic reason for the deviation is the fact that the data gathered beyond 0.2 m penetration might be influenced by the bottom of the strongbox. However, the main reason for this comparison was to check whether the influence of stress level is correctly encapsulated in the new prediction method. It can be concluded that this is the case.
A better fit between measurements and predictions is established by varying the value of $D_r$ and changing the coefficients $C_1$ and $C_2$ from the prediction formula. To maintain uniformity in all comparisons a decision was made not to do this and present only the predictions made with the exact formula as presented in Equation 5.

5.2 UWA centrifuge tests (Senders, 2008)

The last check is made on the cone resistance profile as described in Senders 2008. Figure 3 shows the measured (normalised) cone resistance (grey) and predictions with the proposed formula assuming a relative density, $D_r$, of 0.9 (black). It can be seen that the measurements and the predictions compare very well with each other.
6 CONCLUSIONS

In this paper a method has been presented to convert a cone resistance profile measured in the laboratory with a certain cone diameter in clean uniform sand into a cone resistance profile valid for another cone diameter. The method used for this conversion led to the creation of a formula, which can be used to generate a general cone resistance profile taking into account the width of the penetrating object, the stress conditions and the relative density of the sand.

7 REFERENCES


DNV (1992) “Foundations”, Classification Notes No 30.4


