Comparison of cone and minicone penetration resistance for sand at shallow depth

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ABSTRACT: The paper presents a side-by-side comparison of minicone ($2cm^2$) and standard cone ($10cm^2$) soundings conducted in sand test beds to shallow depth. The sand test beds were prepared at a range of relative densities representing loose to dense conditions. This data set provides a unique opportunity to compare the tip resistance profiles with data in the literature and to study possible scale effects. Explanations of the observed behavior are discussed.

1 INTRODUCTION

The CPT is widely used in offshore geotechnical investigations for determining soil parameters in-situ. Numerous correlations linking cone penetration resistance to soil parameters are based on cone penetrometers with a base cone area of either 10 cm^2 or 15 cm^2. The minicone penetration test, which typically uses a cone penetrometer with a base cone area of 1 cm^2 or 2 cm^2, has shown potential in obtaining reliable geotechnical data in offshore pipeline and cable burial assessments at shallow depth. However, since many of the soil parameter correlations were derived from the larger cones, there remains a question as to whether these correlations are applicable for a minicone and in particular at shallow penetration where confining pressures are low. To address this issue, minicone and standard cone soundings were conducted side-by-side in sand test beds to shallow depth at the Naval Facilities Engineering Service Center (NFESC) in Port Hueneme, California. Results of that investigation correlating tip resistance to soil friction angle and relative density have been published elsewhere (Tufenkjian & Yee, 2006; Tufenkjian & Thompson, 2005). This paper focuses on comparing the tip resistance profiles of the minicone and standard cone soundings in sand test beds prepared at a range of relative densities. Scale effects and possible explanations of the observed behavior are discussed.

2 PREVIOUS COMPARISONS OF CONE SIZE EFFECTS IN SANDS

Tip resistance profiles in sand using various cone diameters have been reported in the literature for more than 50 years. Early investigations (before 1980) were mainly focused on the applicability of using cone tip resistance data to model shallow and deep foundation behavior. These investigations relied on field data or tests conducted in test pits and have generally looked at cone and penetrometer diameters greater than or equal to a standard 10 cm^2 cone (diameters of 35.7 mm to 300+ mm). Kerisel (1958) reported that the tip resistance in loose, medium dense, and dense sands decreases as the diameter of the penetrometer increases, with the most pronounced effect in dense sands. Sanglerat (1972) notes that in certain cases for loose sand, small diameter penetrometers have shown point resistances that are smaller than that of larger sized penetrometers. De Beer (e.g. 1963) showed that point resistance was essentially the same for 36 mm and 50.5 mm diameter cones. Schmertmann (1978) noted that based on available field and chamber test data the cones with areas ranging from 5 cm^2 to 40 cm^2 produce about the same CPT data as the standard 10 cm^2 cone in all soils. Inconsistencies in the reported results are not surprising owing to the difficulty of comparing across investigations with vastly different test conditions.

More recent investigations (after about 1980) have relied on field tests but more heavily on results from calibration chamber testing and centrifuge test programs. De Ruiter (1982) reported cone tip resistance differences were insignificant for cones with areas ranging from 5 cm^2 to 15 cm^2. This behavior was also observed by Baldi and O'Neill (1995) for minicones with base areas of 1.0 cm^2 and 3.1 cm^2 in sand from centrifuge testing and by Rahardjo et al. (1995) for a 4.2 cm^2 minicone for silty sand in calibration chamber testing. Puppala et al. (1991) found the resistance of a 1.27 cm^2 minicone to be lower than a 10 cm^2 cone in calibration chamber testing of dense sand (relative density greater than 80%).

As pointed out by Lunne et al. (1997) however, depending on the test setup it is difficult to separate scale effects from boundary effects. Much has been published addressing the possible influence of container boundaries in calibration chamber tests as well as in centrifuge tests (e.g. Parkin and Lunne, 1982; Parkin, 1988; Schnaid and Houlsby, 1991; Foray, 1991; Salgado et. al, 1998; Gui & Bolton, 1998). A discussion of possible boundary effects in this investigation is presented later.

Interestingly, field evidence provided by Peuchen et al. (2005) noted that 1 cm^2 or 2 cm^2 minicones produce a higher cone resistance than a standard CPT in strongly dilatant sands; while the minicones produce lower cone resistance than a CPT in sands with contractive behavior. However, they also noted that insufficient data was available to be definitive.

3 EXPERIMENTAL INVESTIGATION

The cone soundings were conducted in a reinforced concrete trench at the NFESC outdoor laboratory facility in Port Hueneme, California. The dimensions of the trench are 1.7 m (width) by 21 m (length) by 1.5 m (depth). Because of the rigid bottom boundary valid data is limited to about 1 m of penetration.

The primary challenge of testing at this scale is creation of uniform sand test beds that can be prepared repeatedly, efficiently, and at a range of relative densities. A custom-designed sand dispensing system was constructed to air pluviate the sand into the trench as shown on Figure 1. The pluviator was mounted on top of the trench and could traverse the length of the trench and depose sand at controlled drop heights and intensities. Only dry sand test beds were tested. The uniformity of the sand test beds was assessed by using density cans to measure the in-place dry unit weight of the sand at strategic locations during deposition. The coefficient of variation of the density measurements was less than 2%. Sand test beds representing average relative densities (D_r) of loose to dense (15% to 72%) were prepared and tested.

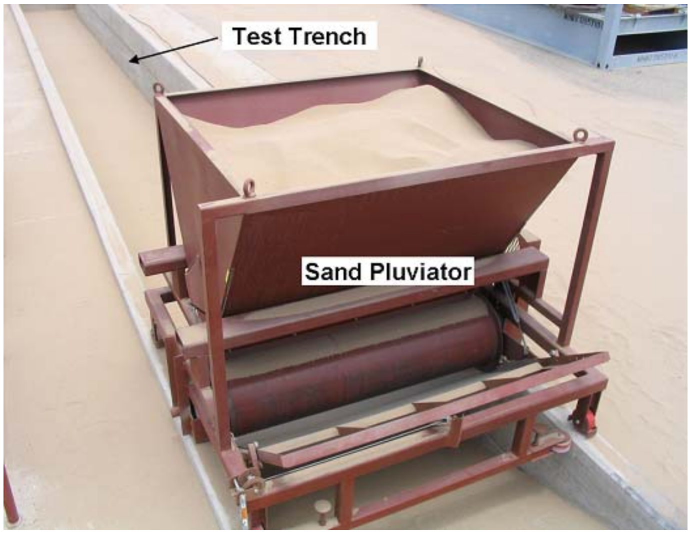

Figure 1. Sand pluviator used to depose sand into test trench.

The sand used in the study is Golden Flint G-50, which has been used by NFESC engineers in other seafloor studies and is typical of sediment found at medium water depth (Girard & Taylor, 1995). It is poorly graded with angular to subangular grains and is predominantly quartz. The pertinent index properties are shown in Table 1. The cone soundings performed in the sand generally showed friction ratios less than 0.5% indicating that the sand is relatively incompressible (Lunne et al. 1997; Robertson & Campanella 1983).

Table 1. Average index properties for Golden Flint G-50 sand.

FC %	C_u	C_c	D_{50} mm	G_s	γ_{dmax} kN/m^3	γ_{dmin} kN/m^3
1.2	1.65	1.06	0.24	2.74	16.79	14.36

The minicone used is a subtraction type with a tip area of 2 cm^2 and friction sleeve area of 30 cm^2. The cone is designed with an equal end area friction sleeve and a tip end area ratio of 0.82. The cone apex angle is 60 degrees. The cone is attached to a continuous stainless steel coil that is straightened as it goes through a set of rollers in the thrust unit and is re-coiled as the cone is retracted. This type of unit and setup is similar to others reported in the literature and has been used for many years in both onshore and offshore investigations (e.g. Young et al. 1988; Power and Geise, 1995; Tumay et al. 1998). The standard cone used was a 10cm^2 compression cone with a 60 degree cone apex angle and a friction sleeve area of 150 cm^2.

The cones were pushed into the prepared sand test bed using the hydraulic feed system of a limited access drill rig that was positioned alongside the test trench. All soundings were performed in general accordance with ASTM D5778-95 (2002). The cones were advanced at a relatively constant rate of 2 cm/sec. Tip resistance and sleeve friction were recorded at depth intervals of about 2.5 cm. In order to ensure the cone electronics were operating properly, baseline readings of temperature shift and zero load offset was taken prior to and at the end of each sounding. The same operator using the same data acquisition system was used for all of the soundings.

Cone soundings were performed along the longitudinal centerline of the loose, medium dense, and dense test beds and were spaced at intervals of at least 30 cone diameters to avoid the effects of adjacent tests. Standard cones were located adjacent to two minicone locations. Usually, 10 to 12 minicones and 5 to 6 standard cones were performed in each test bed. The width ratio of the test setup (computed as the width of the trench divided by the cone diameter) was 47 for the standard cone and 105 for the minicone.

4 TEST RESULTS

The minicone and standard cone tip resistance profiles for loose (D_r = 15%), medium dense (D_r = 48%), and dense (D_r = 72%) sand test beds are shown on Figure 2. The tip resistance profiles shown are the mean values.

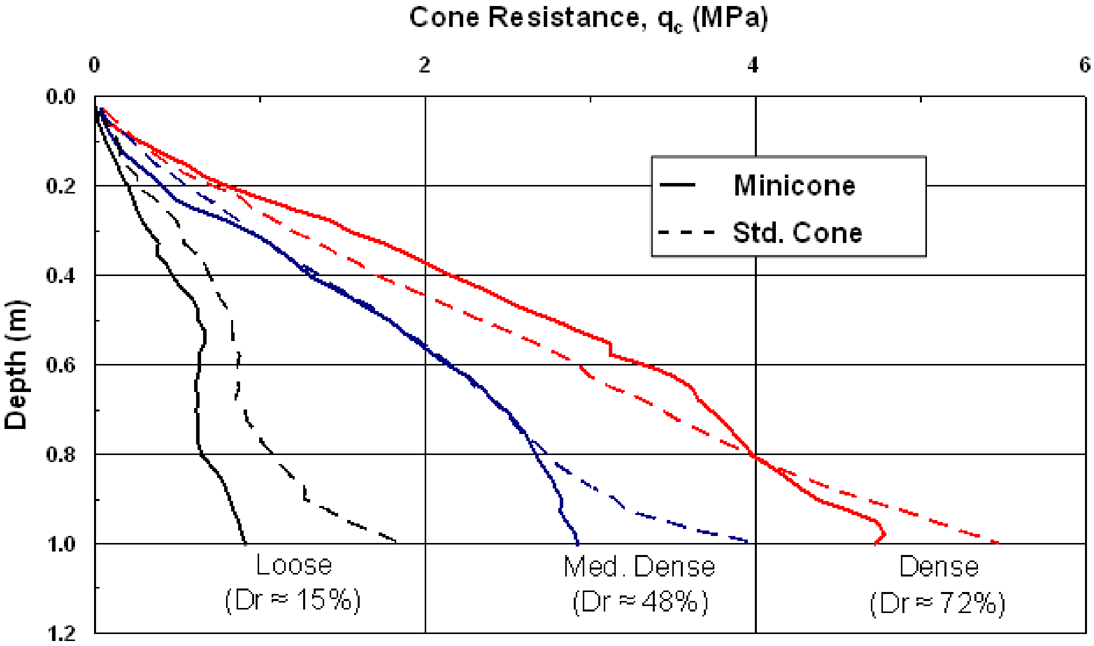

Figure 2. Comparison between minicone and standard cone soil resistance profiles for loose, medium dense, and dense sand test beds.

As expected, the initial tip resistance for both the standard cone and minicone increase with depth in a linear to slightly parabolic shape. Beyond a certain depth, the rate of increase sometimes slowed or in the case of the loose sand test bed remained more or less constant. This transition depth has sometimes been referred to in the literature as the "critical depth" (e.g. De Beer, 1974; Mitchell & Lunne, 1978; Puech & Foray, 2002; Schmertman, 1978) and is thought to perhaps be the transition of the soil failure mechanism from shear to compression (i.e. shallow versus deep foundation mechanism) in the vicinity of the cone tip. Also as expected, the overall cone tip resistance values increase as the relative density of the sand test bed increases. The overall magnitudes of tip resistance for the loose, medium dense, and dense test beds are comparable to laboratory and in-situ cone resistance values in sands at shallow penetration reported by Puech and Foray (2002).

However, comparing the minicone and standard cone tip resistance side-by-side reveals an interesting trend. For the loose test bed, the minicone resistance is clearly less (by about 30 to 40%) than the standard cone resistance over the depth of penetration. For the medium dense test bed, they are practically the same over a large part of the penetration. At about 0.8 m depth the two begin to deviate with the standard cone showing a faster rate of increase. This increase is most likely due to the standard cone sensing the rigid bottom boundary sooner than the minicone. For the dense test bed the minicone resistance is greater (by about 20 to 30%) than the standard cone over the majority of the penetration up until about 0.8 m depth. Beyond about 0.8 m the standard cone resistance becomes larger than the minicone and is again most likely due to the standard cone sensing the bottom boundary.

This phenomenon is further illustrated on Figure 3, which shows the ratio of minicone tip resistance divided by the standard cone tip resistance with depth. Values less than unity indicate that the minicone tip resistance is less than the standard cone resistance. Values greater than unity indicate the minicone tip resistance is greater than the standard cone tip resistance.

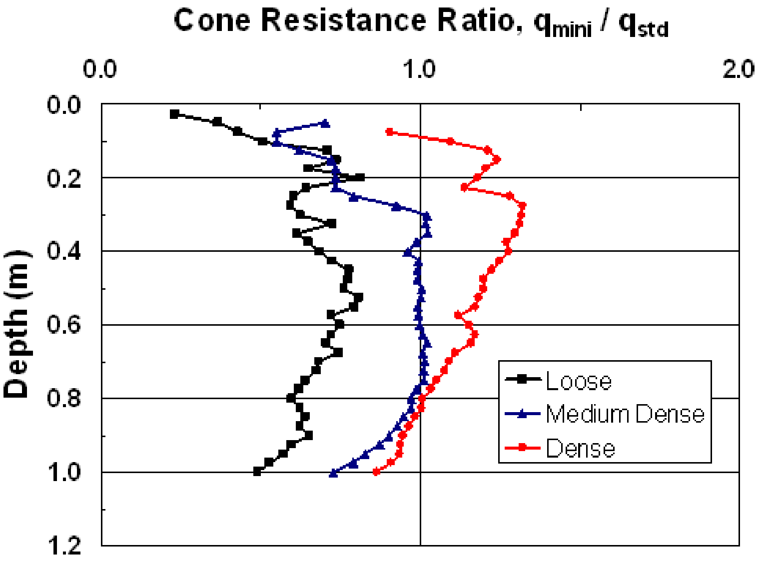

Figure 3. Ratio of minicone resistance to standard cone resistance for loose, medium dense, and dense sand test beds.

If one assumes that loose sand is contractive and dense sand is dilative, then this trend is consistent with those reported by Peuchen et al. (2005) who noted that the minicone produces lower cone resistance than a standard cone in sands with contractive behavior, while the minicone produces a higher cone resistance than a standard cone in strongly dilatant sands. However, this does not account for the effect of confining pressure on contractive or dilative behavior during drained shear. It is well known that at low confining pressures, such as those in the test beds, even loose soils will dilate when sheared. In fact, drained triaxial tests on the test sand showed dilatant behavior for loose sand specimens at comparable confining pressures as those in the test trench. In this sense, the observed behavior would contradict the results by Peuchen.

Perhaps the cone-tip resistance values for the medium dense sand test bed represent an intermediate “critical” density where the minicone and standard cone values are practically the same. The data shown here indicates a possible scale effect between the minicone and standard cone and the observed behavior is dependent upon the sand's relative density and confining pressure.

5 POSSIBLE EXPLANATIONS OF OBSERVED BEHAVIOR

The side-by-side comparisons of the minicone and standard cone tip resistance profiles show a possible scale effect and a dependency upon relative density and confining pressure. However, is it really a cone size scale effect? Or might it be due to other factors? Aside from the cone size scale effect, some other possible "scale" effects include the grain size effect and boundary effects.

The so-called grain size effect has been shown to alter the tip resistance values in sands if the mean soil grain size is large compared to the cone diameter. Bolton et. al. (1993) and Gui et. al. (1998) studied these effects in the centrifuge and concluded that grain size effects are not relevant as long as the cone diameter to mean grain size ratio is greater than 20. Puechen et. al. (2005) also noted that the minicone signature may be different from the standard cone if the cone diameter to mean grain size is less than 10. In this investigation, the ratios of cone diameter to mean grain size were 67 for the minicone and 149 for the standard cone. Therefore, the grain size effect is not expected to influence the tip resistance values.

Much has been written about sidewall boundary effects in both centrifuge and calibration chamber investigations. The sidewall boundary effects are usually evaluated by the chamber ratio, which is defined as the diameter of the chamber divided by the diameter of the cone. Generally, in loose sands (relative density less than 30%) a chamber ratio greater than about 20 is believed to have little influence on the tip resistance (Parkin and Lunne, 1982; Parkin, 1988). In dense sands however (relative density of 80% to 90%), there is evidence of at least some boundary effect even with diameter ratios as high as 60. In these types of soils, Parkin and Lunne suggest a diameter ratio of at least 50 for normally consolidated sand. The boundary effect is particularly evident for dense soils at low confining pressures.

As mentioned previously, the chamber ratio (or width ratio in this case) for this investigation was 47 for the standard cone and 105 for the minicone. The ratio for the minicone was likely large enough to have minimized any sidewall boundary effects in the loose, medium dense, and dense sand test beds. Likewise, the ratio for the standard cone was probably large enough to minimize sidewall boundary effects in the loose and medium dense stand test beds. However, it is unclear as to what effect there may have been in the dense sand test bed. The effect of the rigid sidewall in proximity to the standard cone in the dense test bed would most likely lead to an increase in tip resistance with penetration depth. The tip resistance profile for the standard cone shown on Figure 2 however shows a lower resistance than the minicone. Given this information it is unclear what if any effects may have been manifested by the sidewall boundary for the dense sand test bed.

As mentioned earlier, the profiles shown on Figure 2 have been truncated before the cone reached the bottom of the test trench. The effect of the rigid bottom boundary was to sharply increase the tip resistance when the cone came within close proximity to the bottom of the trench. Schmertamnn (1978) suggested that it takes between 5 to 10 cone diameters to sense a boundary interface in sands, while Gui et. al. (1998) reports that in sands it takes a "few" cone diameters for a cone to detect a hard boundary. Lunne et. al. (1997) suggests the sphere of influence over which the cone can sense an interface is about 2 to 3 cone diameters for soft materials and up to 10 to 20 cone diameters for stiff materials. Assuming an intermediate value of 10 cone diameters, the standard cone and the minicone would not sense the bottom boundary until after about 0.9 m and 1 m depth, respectively. These depths would therefore not affect the upper part of penetration where the observations have been made. As a matter of fact, 10 cone diameters or beyond 0.9 m depth, would help explain why the standard cone tip resistance deviates and becomes larger than the minicone in the medium dense and dense test beds as shown on Figure 2.

6 CONCLUSIONS

This paper presented the observations and results of side-by-side minicone (2 cm^2) and standard cone (10 cm^2) penetration soundings to shallow depth in controlled test beds consisting of loose, medium dense, and dense sands. The tip resistance profiles showed that in loose sand, the minicone produced a lower penetration resistance (30% to 40%) than the standard cone. In medium dense sand, the tip resistance profiles were practically the same. In the dense sand, the minicone produced a higher penetration resistance (20% to 30%) than the standard cone. These observations show a dependency on density state which could not be explained by boundary or grain size effects and are believed to be a possible scale effect between the different cone sizes.

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