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Shallow penetration resistance of a minicone in sand

La résistance de pénétration d'un minicone en sable de faible profondeur

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ABSTRACT
The minicone penetration test has shown promise in obtaining reliable geotechnical information within the upper two meters of the seafloor. Standard cones have well established correlations that relate measured cone parameters to soil strength at confining pressures simulating deeper penetration. However, these have not been extensively verified at shallow penetration depths. This paper presents the experimental results of an ongoing investigation to study the penetration resistance of a mincone in sand at shallow penetration.

RÉSUMÉ
L'essai de pénétration du minicone a été prometteur dans l'obtention de résultats géotechniques fiables dans les deux mètres supérieurs du sol marin. Les cônes standardisés ont des corrélations bien documentées, dans lesquelles les paramètres mesurés des cones ont un rapport directe avec la force du sol pressurisée à certaines limites, tout en simulant une pénétration plus profonde. Cependant, celles-ci n'ont pas été vérifiées profondément dans les pénétrations de faible profondeur. Ce rapport relate les résultats expérimentaux d'une recherche courante sur la résistance de pénétration d'un minicone en sable de faible profondeur.

1 INTRODUCTION

The United States Navy frequently installs shallow data/communication cables buried one to two meters beneath the seafloor. Proper geotechnical characterization of the near surface seafloor soils along the cable route is therefore critically important in planning a successful installation. The most common method used to explore seafloor soils is the cone penetration test (CPT) using a standard cone penetrometer (10 cm^2 or 15 cm^2) or more recently a minicone penetrometer (2 cm^2).

The minicone has shown promise in obtaining accurate and reliable geotechnical information within the upper one to three meters of the seafloor (Power and Geise, 1995). The primary advantage of a minicone system over a conventional one is the reduction in downward thrust needed to advance the penetrometer into the seafloor, which is especially critical in an underwater environment where simplicity of equipment is advantageous. However, calibration information is needed to correlate the measured cone parameters to soil stratigraphy and strength properties. Standard cone sizes have well-established correlations for identifying soil types and strength parameters. However, these correlations are primarily based on calibration chamber testing at confining pressures that simulate much deeper penetration depths and have been generally unreliable for soil depths less than about 2 m.

The purpose of this research study is to investigate the penetration resistance of a minicone in sand at shallow penetration depths with the goal of providing experimental information to correlate measured cone parameters with sand strength properties. This paper presents the preliminary experimental results of the cone tip resistance in a full-scale test bed at shallow penetration depths. The paper focuses on creation and measurement of the uniformity of the sand test beds, interpretation of the tip resistance profile with depth, comparison with published shallow penetration sounding data, and assessment of possible boundary effects. All tests were conducted in dry sand.

2 TEST EQUIPMENT AND PROCEDURES

2.1 *Test Bed*

The tests were conducted in a below-grade reinforced concrete test trench located at the Naval Facilities Engineering Service Center in Port Hueneme, California. The trench is rectangular in section and has dimensions of 1.7 m (width) by 21 m (length). The trench bottom slopes at about 1% to a sump at one end. The maximum depth of the trench is 1.5 m.

Creation of uniform sand test beds of this size presented several challenges. The volume of soil needed to fill the trench (on the order of 55 metric tons) required a semi-automated and efficient delivery system that was capable of placing sand at uniform densities repetitively. Several concepts were considered but in the end an air-pluviated streamout feed system was custom designed and built as shown on Figure 1.

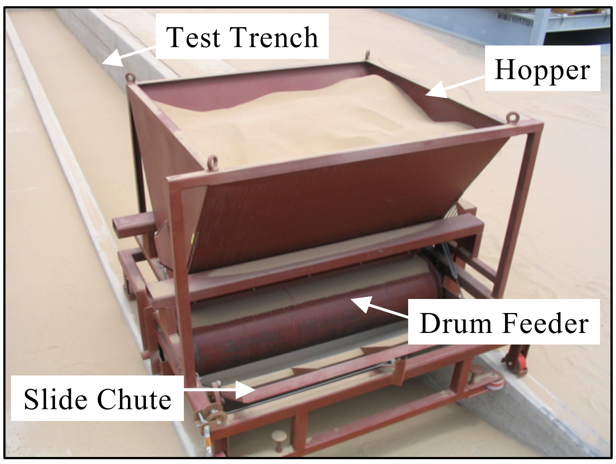

Figure 1. Main Components of Sand Spreader

The main components of the sand spreader are the steel frame, hopper, electric motor, adjustable gate valve, rotary drum feeder, and slide chute. The hopper capacity is roughly 1.5 m^3 and was loaded using a front-end loader. The sand spreader was mounted on two electrically driven load bearing wheels which tracked along the top of the trench. Four guide and four balance wheels provided additional stability. The rotary drum feeder discharges the sand from the hopper by its rotation. Soil flow ceases when the drum is stopped. It is driven by a chain and sprocket connected to a drive wheel gear. The speed of the drum could be varied by changing out the gearing but was maintained constant for this study.

When activated, the sand spreader traversed the length of the trench and deposited the sand along the full width of the trench. The deposition intensity of this sand "curtain" could be controlled by adjusting the gate valve opening. The gate valve could be incrementally adjusted from fully closed (no sand flow) to a wide open position of about 50 mm.

The vertical drop height of the sand could be controlled by a retractable slide chute. The chute could be retracted by an amount equal to the thickness of the layer deposited in the trench to maintain a uniform drop height. The chute could also be inclined to control the acceleration of the sand down the chute. Depending upon the density desired, the trench took anywhere from about 10 to 30 hours to fill to a depth of 1.5 m.

With experience, it was determined that the predominant factor controlling sand density was the deposition intensity which could be controlled by the adjustable gate valve. Critical to the experimental program was the ability of the sand spreader system to deposit the sand uniformly (constant density), repetitively, and at a wide range of relative densities. To date, relative densities up to about 70% have routinely been achieved.

Uniformity of the test beds was monitored by measuring the dry density of the deposited sand using density cans or a Selig-type density scoop (Selig, 1962). Both the density can and density scoop have shown to be accurate and precise methods in determining the in-situ density of dry sands (Trautmann et al., 1985; Weiler and Kulhawy, 1979). In general, with the procedures used to deposit the sand in this study, the density cans were the preferred means of measuring the dry density. Density measurements were typically taken at about 200 mm vertical lifts spaced at 2 m to 2.5 m horizontally along the length of the trench. Approximately 30 to 35 density measurements were made per sand test bed.

Table 1 shows typical density variations for a loose sand test bed. As can be seen the variability is small. In order to demonstrate repeatability with the system, Figure 2 illustrates the mean cone tip resistance with penetration depth for two identically placed loose sand test beds. As shown, the tip resistance profile for the two test beds is nearly the same.

Table 1: Summary of Density Test Results in a Test Bed

Test Bed	No. of Tests	Mean γ_d kN/m^3	Standard Deviation kN/m^3	Coefficient of Variation %
Loose	30	14.94	0.16	1.1

After filling the test trench, mini and standard cone penetrometers were pushed into the sand test bed at predetermined locations. Cones were advanced until reaching the bottom of the test bed. In order to minimize the effect of adjacent tests, the soundings were spaced at center to center distances of at least 30 cone diameters and in between locations where density tests were conducted. For comparison purposes, sounding locations were selected such that one standard cone was located adjacent to two minicone locations. Eleven minicones and six standard cones were performed for each test bed.

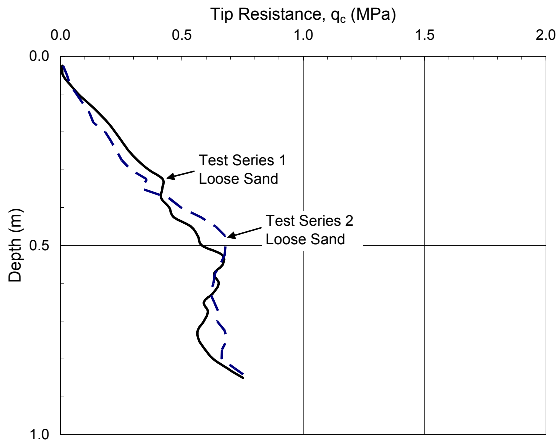

Figure 2. Tip Resistance Profiles in two identically prepared test beds

2.2 *Test Soil*

The soil used in the tests is a commercially available quartz sand called Golden Flint G-50. It is poorly graded, angular to subangular, and typical of sediment found at medium water depth (Girard and Taylor, 1995). The pertinent index properties of the sand are outlined in Table 2.

Table 2: Index Properties of Test Sand

Fines %	C_c	C_u	D_{50} mm	G_s	γ_{dmin} kN/m^3	γ_{dmax} kN/m^3
0.9	1.07	1.71	0.23	2.74	14.61	17.20

3 CONE PENETROMETERS

The minicone used in this study is a commercially available subtraction type cone 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 minicone was pushed into the sand test bed using a hydraulic thrust unit attached to the front of a limited access drill rig positioned adjacent to the trench. 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 recoiled as the cone is retracted. Similar units have been used by other investigators (Tumay et al., 1998; Titi et al., 2000).

The standard cone used was a 10 cm^2 compression cone with a 60 degree cone apex angle. The friction sleeve area is 150 cm^2 and is designed with an equal end area ratio of 0.85. The cone was pushed into the sand test bed using the hydraulic feed system of the limited access drill rig.

All soundings were performed in general accordance with ASTM D5778-95. The cones were advanced at a relatively constant rate of 2 cm/sec. The cones recorded tip resistance and sleeve friction at depth intervals of about 2.5 cm. In order to ensure the cone electronics were operating properly, a complete set of baseline reading of temperature shift and zero load offset was taken prior to each sounding.

4 CONE PENETRATION TEST RESULTS

To date, a total of 51 cone penetration soundings have been performed in three prepared test beds including 33 minicones and 18 standard cones. Test beds representing loose and medium dense sand have been tested and the results analyzed.

Figure 3 illustrates the mean tip resistance profiles from the minicone soundings in the loose sand. The mean values were computed from 22 soundings. The shape of the curve provides two important observations:

1. The tip resistance values initially increases in a parabolic manner.
2. Beyond a certain depth, the tip resistance values remain essentially constant.

Similar cone tip resistance behavior in homogeneous sand has been documented in the literature as far back as the 1950's (e.g. Kerisel, 1958) and more recently by Puech and Foray (2002). The depth at which the tip resistance reaches a "constant" value (q_{cmax}) has been referenced as the critical depth (d_{crit}) (e.g. De Beer, 1974; Mitchell and Lunne, 1978; Sanglerat, 1972; Schmertman, 1978) and is thought to represent the transition of the soil failure mechanism from shear to compression in the vicinity of the cone tip. The reason for the constant resistance below the critical depth is thought to be due to soil arching near the cone tip (Durgonoglu and Mitchell, 1975; Folque 1975; Mitchell and Lunne, 1978). This pattern of penetration resistance behavior is not unique to soil and has also been observed in metals (Sanglerat, 1972).

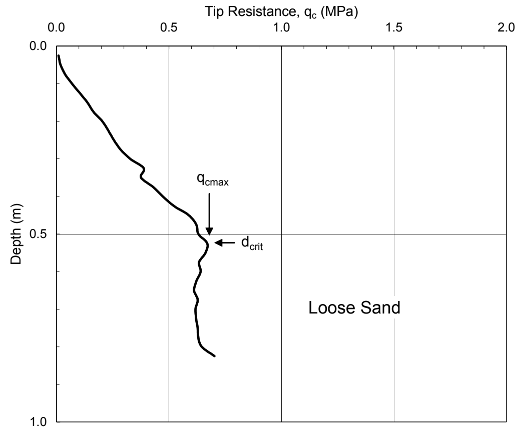

Figure 3. Tip resistance profile in loose sand for shallow penetration

Figure 4 shows a comparison of the mean minicone tip resistance profiles in loose and medium dense sand. The tip resistance profile for medium dense sand is similar in shape to the loose sand, however, the d_{crit} is reached at deeper penetration and the value of q_{cmax} is larger.

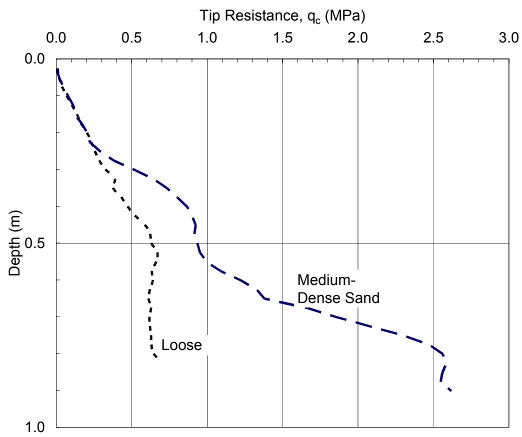

Figure 4. Tip resistance profile in loose and medium-dense sand

4.1 *Comparison with Published Data*

For a given sand, the value of q_{cmax} in loose to medium dense sands is believed to be controlled primarily by the soil density (Puech and Foray, 2002; Sanglerat, 1972). In dense to very dense sands the effect of the cone diameter may have more influence (Sanglerat, 1972). Likewise, the critical depth is believed to be primarily a function of soil density (Schmertman, 1978; Puech and Foray, 2002) and possibly cone diameter (Sanglerat, 1972). Table 2 below compares the q_{cmax} and d_{crit} values measured with the mincone soundings with those reported by Puech and Foray for shallow penetration of standard cones in silica sands. As can be seen, the measured values of q_{cmax} are at the low end of the ranges reported by Puech and Foray but still within the limits, while the measured value of d_{crit} is lower for loose sand and the same for medium dense sand.

Table 3: Comparison of Measured Values with Published Data

Sand Consistency	Relative Density	Puech and Foray (2002)		Measured Values	
		q_{cmax}	d_{crit}	q_{cmax}	d_{crit}
	(%)	(MPa)	(m)	(MPa)	(m)
Loose	15-35	0.6-1.5	0.8	0.7	0.5
Med. Dense	35-65	1.5-7.0	0.8	2.6	0.8

Further testing and analysis is ongoing in test beds of different relative densities to add to the existing data set. Concurrent laboratory testing is being conducted to determine the friction angle of the sand at similar densities and stress conditions in the test beds. Once completed, various analytical methods will be compared to correlate measured cone resistance with relative density and friction angle.

4.2 *Comparison with Standard Cone*

Figure 5 compares the mincone tip resistance profile with the standard cone tip resistance profile for loose sand. The shapes of both curves are nearly identical and the d_{crit} is reached at about the same depth. However, the tip resistance values for the standard cone are larger than the minicone. The reason for this is unclear but it may be due to differences in cone design, scale effects, or more likely from boundary effects.

In calibration chamber testing of cone penetrometers, sidewall boundary effects are often evaluated through the diameter ratio (chamber diameter to cone diameter). The larger the diameter ratio the closer the measured resistances are to the free field conditions. Several investigators have suggested that for loose sands (in the range tested here) diameter ratios as low as 21 to 35 would not significantly affect the measured values (Ghionna and Jamilowski, 1992; Lunne et al, 1997, Parkin and Lunne, 1982; Parkin 1988). An equivalent diameter ratio (defined as the trench width to the cone diameter) value for the standard cone is 47, which suggests that the sidewall boundaries may have had little influence on the measured resistances.

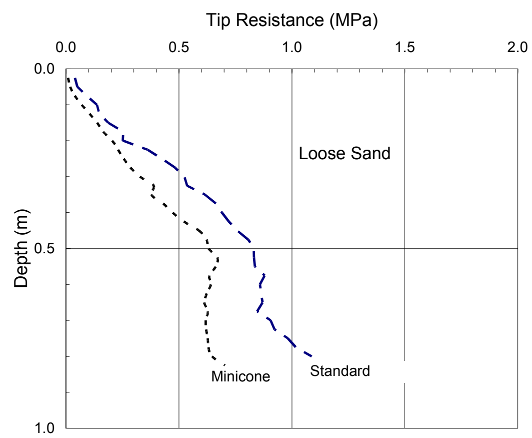

Figure 5. Comparison of tip resistance profile between mincone and standard cone

The affect of the rigid bottom boundary was to sharply increase the tip resistance values when the penetrometer reached very nearly the bottom of the trench. It has been suggested that the distance at which the cone can sense an approaching interface varies from about 5 to 20 cone diameters (Lunne et al, 1997; Schmertman, 1978). Using this as a guide the standard cone would sense the boundary beginning at a depth of 0.8 m to 1.4 m. This would not however explain the difference in values beginning at the soil surface. Nevertheless, the shape of the standard cone profile and critical depth seems to be unaffected. Further analysis is ongoing to fully evaluate the affects of the trench boundaries.

5 SUMMARY AND CONCLUSIONS

Preliminary experimental results of the penetration resistance of minicone soundings at shallow penetration in a sand test bed were presented. The test beds were created by a custom designed streamout feed system capable of layering sand into the test trench uniformly, repetitively, and at a range of relative densities up to about 70%.

The observed cone tip resistance behavior was similar to studies using standard cones in homogeneous sand provided in the literature. Specifically, the tip resistance initially increased rapidly below the ground surface until a critical depth was reached where the tip resistance essentially reached a maximum or constant value thereafter. Increasing the density of the sand increased the value of the maximum tip resistance and deeper penetrations were required to reach the critical depth. The measured maximum tip resistance and critical depth compared well with other published data on sands at shallow penetration. Side-by-side comparisons with a standard cone showed that the standard cone provided a greater tip resistance profile but a similar critical depth. Boundary effects may have been the cause. The study has added to the understanding of the minicone penetration response of sands at shallow depth.

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