The applicability of soil density measurements using a resistivity probe

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ABSTRACT: This paper presents the results of a series of laboratory tests used to validate a newly developed sensor to measure soil density around a penetrating probe. A probe incorporating three of these sensors is pushed into a saturated sand sample during a centrifuge test. The sensors correlate the change in electrical resistivity of the soil to the pore volume change. For loose to dense initial densities the density change near the probe is indicating an increase in pore volume. The measured porosity change varies between the three instrument locations as it depends on the penetration distance.

1 INTRODUCTION

The cone penetration test (CPT) is a well established in-situ measurement method, especially in soft soils. The test, which is originally designed to support pile bearing capacity design, still shows its merit in that discipline. The measured cone resistance is directly and indirectly converted to a pile bearing capacity, using, for instance, direct limit state methods developed by De Ruiter & Beringen (1979), Bustamante & Gianeselli (1982), Schmertmann (1978) and Eslami & Fellenius (1997).

However, the CPT potentially offer even more versatility by correlating the cone resistance and measured pore pressures to strength and stiffness properties as well as soil state (e.g. Teferra 1974, Been et al. 1986, Jamiolkowski et al. 1988). The calibration of these empirical relationships involves laboratory tests in which the CPT is penetrated in a sample of known initial conditions. For non-cohesive soils the initial conditions are the initial density and stress state. As Eiksund (1994) pointed out it can be questionable if the horizontal stress applied on the side of the sample really produces a similar horizontal stress in the middle of the sample where the test is performed. Also, the preparation of large homogenous samples still is very difficult.

Some authors equipped the cone with additional instrumentation for the in-situ measurement of soil density. For soil density characterization, or more precisely water content, nuclear probes or electrical resistivity probes have been used. Neutron scatter techniques, in which the source (radio-isotope) and detector (photomultiplier) are mounted on the same cone are most often used. The fast neutron (high energy levels) source radiates in the soil (and will be slowed in the pore water), whilst the slow neutron (also called thermal neutrons, low energy level neutrons) detector gives an indication for the received radiation level of slow neutrons. This neutron count, when calibrated in known soil conditions, is a measure of water content (or density for fully saturated soils). An overview of possible configurations used in the past is given in Ruygrok (1977). More recently the execution procedure and the detector quality have been improved by compensating for natural background radiation by Shibata et al. (1992). The background count is measured first by a cone that is only equipped with a detector, afterwards the source-detector cone is used. The method can be improved by adding an additional detector far from the source. This second detector, therefore, will only register the background count (Karthikeyan et al. 2007).

Electrical resistivity probes (Vlasblom 1977) measure the apparent resistivity of the pore water that can be correlated to the soil density. The probe has a current source that is applied on two conductors, whereas the resulting electrical field in the soil from this injected current is measured on two other conductors.

All correlations correlate the undisturbed initial properties to a cone resistance reading in disturbed conditions as the penetration of the CPT will influence the stress and density dependent soil properties adjacent to the cone. This is also the case for the in-situ density measurements. Ruygrok (1977) noted the possible influence of the CPT installation on the measured results.

The current paper will investigate the possible influence of the penetration process of the measurement probe on the measured in-situ density. For this a series of geotechnical centrifuge tests were performed in which an instrumented probe was pushed in a saturated sand sample with loose-dense initial densities. The density change was measured with an apparent resistance measurement technique. The test was originally designed to investigate jacked pile installation, but also contributes to a better understanding of CPT penetration.

2 MEASURING DENSITY NEAR A PROBE

Resistivity measurements have been used in geophysics for some time; e.g. Telford and Geldart (1990) for an introduction. Such measurements yield information on the stratigraphy of the deep subsoil. The method was first adopted for the use in combination with a CPT by GeoDelft (Vlasblom 1977). Four conducting rings were added to a CPT rod, with two rings providing a constant current and two rings measuring the resulting potential field. In this setup electrical resistance measurements were only made while the probe was stationary. In the analysis geometrical effects are not accounted for. Therefore, an apparent resistance is found instead of an absolute value for the electrical resistance.

Similar to the field probe used by Vlasblom (1977) in the current model tests the probe is equipped with four conductors for each instrument level. A potential field

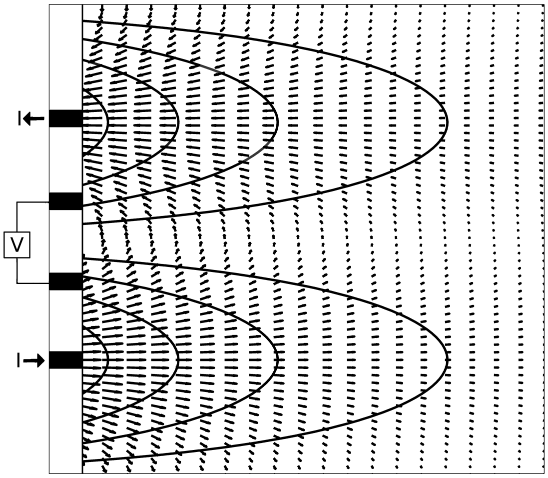


Figure. 1: Electrical field around the density probe.

with constant current I is applied to the outer set of conductors, vertically spaced at 10 mm. The inner set of conductors, spaced 3.3 mm apart, are used to measure the voltage drop V within this section of the potential field. All conductors are made of 1.5 mm thick stainless steel rings and are isolated from each other and the remainder of the probe. Combined, I and V yield the apparent resistance. The current I is derived from the measurement of a voltage V_c over a reference resistor R_{ref}, located in the power supply. The voltage drop in the soil V_s is measured over two inner conductors.

This yields:

$$R_{soil} = \frac{V_s R_{ref}}{V_c} \tag{1}$$

in which R_{soil} is the apparent resistance. A schematized representation of the electrical field around such a sensor is shown in Figure 1.The change in R_{soil} is converted to a porosity change by a calibrated linear relationship for each sensor. In order to allow this method to work properly saturated conditions are required, as well as a reasonable conductivity of the pore water. For this reason NaCl was added in all tests to the pore water to improve the measurements. Due to the averaging over a soil volume of about three times the probe diameter the method cannot distinguish porosity differences close the probe, or further than 15 mm into the far field. A full description of the measurement method is given in Dijkstra (2009).

3 MODEL TESTS

3.1 *Test Setup & Preparation*

During preparation, the probe, equipped with three instrument levels, is embedded into the saturated sand sample. A fourth reference sensor is placed on the bottom of the sample. Figure 2 shows the geometry of the strongbox and the locations of the probe and additional sensor.

Due to the rather high temperature sensitivity of the resistance measurement method the temperature as well as the pore pressures is monitored near the reference sensor. The maximum temperature deviation found was approximately 0.02 ^{o}C, which has a negligible influence on the measurements. The pore pressures did not measure an appreciable change other than the effects of the increase of gravitational acceleration. Therefore, the pore pressure results are not shown.

Next to the density measurements on the probe and in the sample, also the force on the (flat) base and on the top is registered during penetration.

The sand was prepared by pumping it in suspension into the model container in which the probe was already fixed in place, and allowing the sand to settle. In this way the probe was initially embedded in the sand sample. A loose sample was obtained, with a porosity *n* of approximately 0.455. The sample could subsequently be densified by a vertical shock wave propagating through the sample and allowing top and bottom drainage of the excess pore water at the same time. In this way porosities up to *n* = 0.382 were reached very consistently. During preparation care was taken to prevent excess vibration of both pile and model container. Still, density variations near the pile cannot be prevented by this method. This results in an uncertainty of the initial porosity near the pile at the start of the test. All tests have been performed in the beam centrifuge of Deltares (The Netherlands) at an acceleration level of 35g.

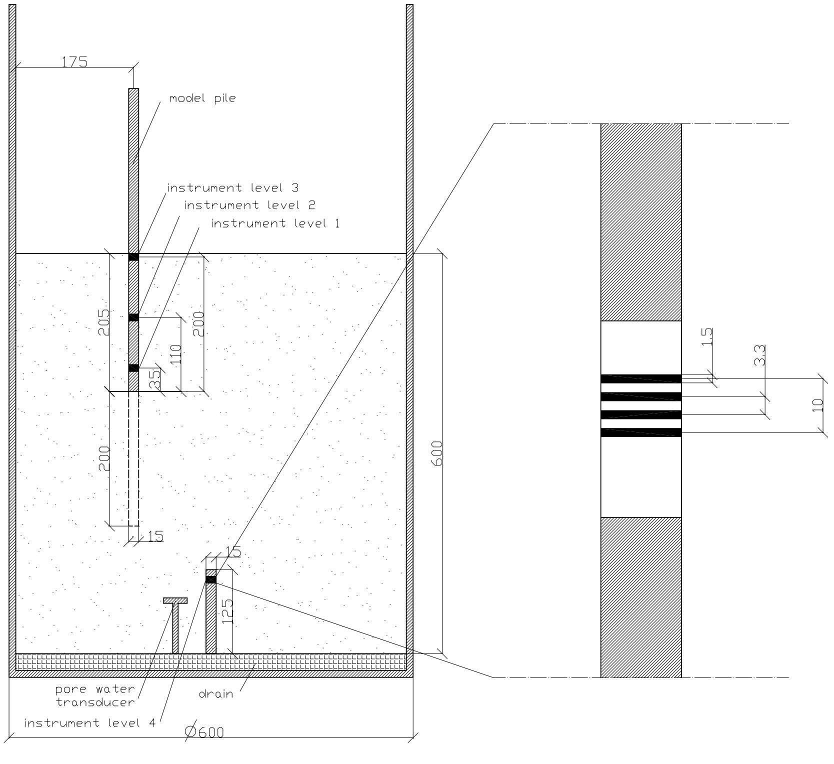


Figure. 2: Model setup for geotechnical centrifuge tests (insert shows the mechanical dimensions of one instrument level).

3.2 *Test Series*

Five tests have been performed where only initial porosity has been varied between loose and dense conditions (n_0 = 0.439 - 0.386), the dense and medium dense tests are repeated to test consistency. In the first test (n_0 = 0.386) an overshoot of the hydraulic plunger was observed. This was corrected by a progressive deceleration starting 2 mm before the desired installation depth was reached. The penetration rate was 1 mm/s at model scale.

4 RESULTS

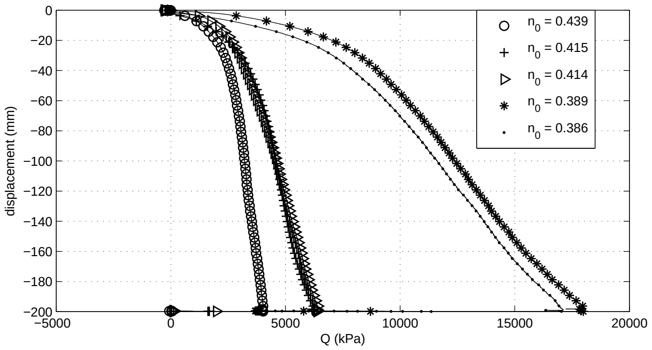
4.1 *Stress*

The measured base load is converted to a stress reading and the average shaft friction is derived from the difference of the head and base load divided by the embedded shaft surface area. The (submerged) weight of the probe is corrected for in the original force readings, before converting these to stress readings.

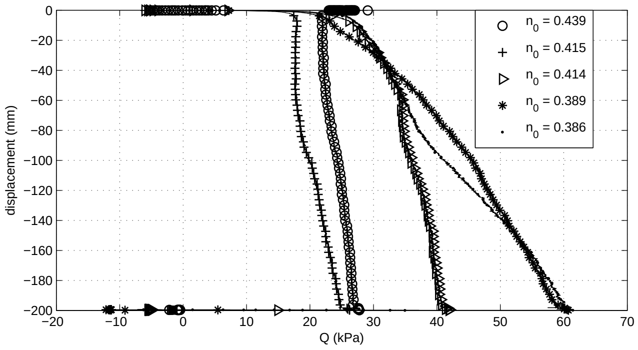
Figures 3a & 3b show the base and shaft response during penetration, whereas in Figures 4a & 4b these results are plotted for the subsequent unloading reloading stage. The displacements are plotted on the vertical axis the stress readings are plotted horizontally.

The duplex test show reproducible base resistances of 17-18 MPa for the dense conditions (n_0 = 0.386-0.389), and 6 MPa for the medium dense conditions (n_0 = 0.414-0.415). In the loose conditions (n_0 = 0.439) only one test was performed which yielded approximately 4 MPa.

When the average shaft friction is compared, a gradually decreasing rate of increase in shaft resistance with depth is found for penetration in loose and medium conditions. The dense tests still show a constant linear increase with depth of the shaft friction. A distinct difference in shaft response is found for the two medium dense tests. One test is yielding a 37% lower shaft resistance.



a) Base resistance



b) Average shaft friction during penetration

Figure. 3: Evolution of the measured base resistance and shaft friction during penetration at 1 mm/s.

4.2 *Density Measurements*

The measured porosity change Δn as measured during the penetration is plotted in Figures 4a-4c for one of the dense tests (n_0 = 0.389), one of the medium dense tests (n_0 = 0.414) and the loose test (n_0 = 0.439). Three data series are plotted in each Figure: one for each instrumentation level. The upper instrument level is not shifted and as a result of this starts at a displacement of 0 mm. The second instrument level is located 90 mm below the top instrument level and the plot for this instrument starts at -90 mm. Finally, the first instrument level near the pile base is shifted 165 mm below the top instrument.

The grey bands indicate the systematic error in the measured porosity change. For overlapping bands no significant differences have been measured.

All tests and all instrument levels show an increase of porosity with an increase of penetration. Most probably the initial porosity around the probe in the loose test is not as large as the average porosity in the complete sample, resulting in densification in the test.

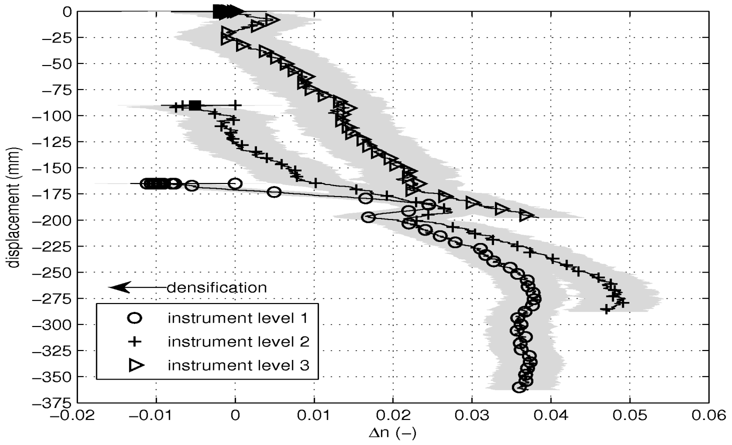
The densification notch around -200 mm is the moment when the instrument level is leaving the hole created by its installation in the suspended sand. This feature is found in all tests for all instrument levels.

These plots allow for the monitoring of the porosity change on a fixed depth below the surface. The arrival of a second instrument level at a certain depth shows a further increase in porosity

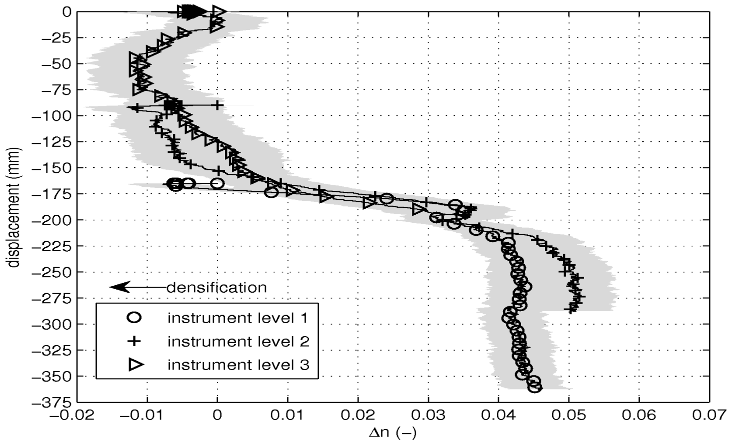
5 CONCLUSIONS

A new method to investigate the porosity change during penetration of a probe based on electrical resistance change is presented. Despite the uncertainty in the measurements and the inability to measure absolute densities consistent qualitative results are obtained in the current tests.

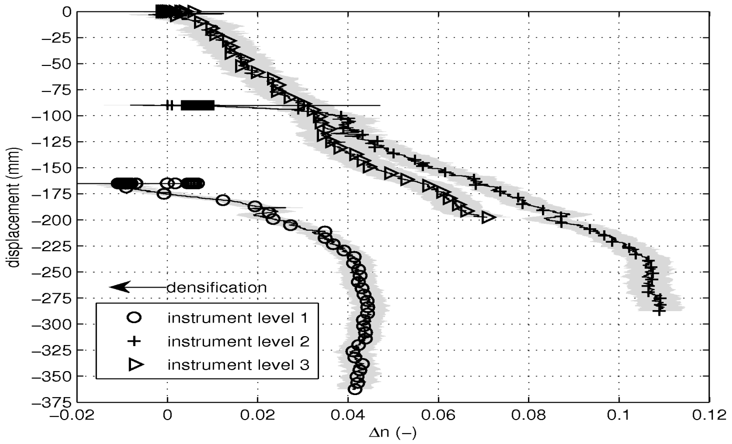
The installation of a probe in a non-cohesive material will quite significantly distort the soil located within one diameter around the probe. For in-situ density measurements one has to consider this polluting effect of the probe installation on the den-



a) Loose; $n_0 = 0.439$



b) medium dense; $n_0 = 0.414$



c) dense; $n_0 = 0.386$

Figure. 4: Evolution of the measured porosity change adjacent to the probe during penetration sity measurements. The measured porosity change depends on the instrument location and is a function of the penetration distance. This supports the sensitivity of the location of the friction sleeve as found in previous research, e.g. DeJong and Frost (2002). Regardless of the loose or dense initial conditions the soil near the probe loosened significantly during monotonic jacking.

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