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Evaluation of parameters inducing desaturation of a piezocone: Saturation liquid viscosity and exposure to dry sand

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ABSTRACT: Several CPTU tests were performed in both ideal and adverse conditions at a test site in Zwijnaarde. The influence of exposure to unsaturated soils was examined by holding well-saturated piezocones in dry sand for several minutes without a protective rubber membrane. After the exposure to dry sand, penetration was performed from the ground level through the unsaturated and saturated subsoil. These tests show suboptimal pore pressure measurements, compared to the tests under ideal circumstances, regardless of the duration of the exposure to dry sand. Results reveal that, in adverse conditions, the densely packed sandy top layer, rather than the exposure to dry sand, has contributed to the desaturation of the piezocones. The impact of the viscosity of the saturation liquid on pore pressure quality was studied by performing tests with a 50 and 100 cSt silicone oil. Under ideal circumstances, the viscosity does not play a role in terms of quality of the pore pressure measurements. However, in adverse conditions, results showed a better performance for a silicone oil with 100 cSt viscosity.

1 INTRODUCTION

The repeatability of CPTU parameters has been evaluated in many research studies. Generally a reasonably good repeatability is found for pore water pressure measurements, provided good saturation is achieved and maintained, even when performed with equipment from different manufacturers, as described by e.g. Paniagua et al. (2021), Lunne et al. (2018), Powell et al. (2005). Although dynamic pore water pressure measurements might be a reliable parameter, it is known that many aspects can influence these measurements, such as the element location, design and volume of ports, the type and degree of saturation of the fluids, cavitation of the element fluid system, resaturation lag time, depth and saturation of soil during testing (ASTM 2012). The importance of properly saturating a piezocone sensor has been elaborately documented in literature (e.g. Lunne et al. 1997, ISO 22476-1:2012, ASTM 2012). The need for de-airing the saturation liquid in a vacuum chamber has often been emphasized.

In our daily practice, we experience that even well-saturated piezocones may produce poor pore water pressure measurements, if penetration is started above the groundwater level. This is generally avoided by executing a pre-drilling. However, the problem still occurs in cases where the groundwater level is not exactly known or where the groundwater is to be found at considerable depth. In these situations in presence of unsaturated soils we noticed that the penetrometers seem to be quite prone to desaturation.

In this paper, the influence of the viscosity of the silicone oil on the quality of the pore water pressure measurements is evaluated. Also the influence of exposure to unsaturated soils is evaluated by holding the penetrometer several minutes in dry sand.

2 TEST SITE IN ZWIJNAARDE

The test site in Zwijnaarde is located in the south of Ghent, Belgium. The subsoil consists of Quaternary sand layers, with small sublayers of sandy silt to silt, as can be seen in Figure 1. The Quaternary layers have a thickness of approximately 17 m. With a depth of 15 m, all CPTUs in this testing campaign were performed in the Quaternary layers.

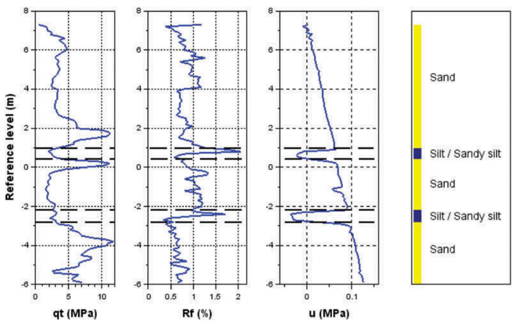

Figure 1. CPTU-data and soil classification.

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In the sandy layers, the measured pore water pressures equal the hydrostatic pressure, since the sand is permeable. When passing through the silty layers a drop in the pore water pressure can be noticed in Figure 1. This reduction in pore water pressure is noticed for all pore pressure measurements and is caused by dilative behavior of the dense silt layers, when being sheared during penetration. Although the tests are performed in a small area, there are some spatial variations, both in terms of level and magnitude of the peak cone resistance in the sand layers as well as in the occurrence of the small silt layers, causing pressure drops in the pore pressure measurements.

3 TEST CAMPAIGN AND CONE PENETROMETER DATA

The test campaign took place from March to April 2020. All tests were carried out within an area of 10 by 25 m with a distance of approx. 1 m between two neighboring test points. Four identical piezocones from the same manufacturer were used. The piezocones are of the compression type.

The pore pressure is measured at the u_2 location, which is just above the conical part. A silicone oil, with varying viscosity, was used as saturation fluid.

An overview of the piezometer characteristics is given in Table 1.

Table 1. Cone penetrometer data.

Cone type		Compression
Ac		10 cm²
Filter type		HDPE - 10 micron
Capacity*	q_c	75 MPa
	f_s	1 MPa
	u_2	2 MPa
Saturation fluid		Silicone oil

* Nominal values – penetrometers calibrated according to EN ISO 22476-1 2012 class 2

The same saturation procedure has been used for all tests, according to EN ISO 22476-1 (2012). The silicone oil was de-aired in a vacuum chamber together with the filters for a duration of at least 24 hours. In a next step, the cone tip was filled with de-aired silicone oil using a syringe. Thereafter, the cone was assembled with a pre-saturated filter and placed back in the vacuum chamber for at least 2 hours at vacuum followed by 20 minutes at atmospheric pressure before removing and covering it with a protective rubber membrane.

4 TEST PROGRAM

4.1 *Exposure to dry sand*

To examine the impact on desaturation, well-saturated piezocones were kept in a bucket with dry sand for a certain time interval before executing a CPTU test. The piezocones were protected with a rubber membrane which was removed right before entering a bucket of dry sand. The dry sand is known as ‘Mol Sand’, characterized by a median particle diameter D_{50} of 0.2 mm and a uniformity coefficient UC = D_{60}/D_{10} of 1.6. Four different time intervals were considered: 5 min, 15 min, 30 min and 60 min.

Immediately after exposure to dry sand, CPTU tests were performed over a depth of 15 m. The results of these pore pressure measurements in adverse conditions are evaluated and compared with CPTU tests performed in the same test field, however, this time starting from the saturated subsoil (ideal conditions). To achieve this, these CPTUs were initiated from a pre-drilled borehole of a depth of 1.5 m. PVC tubes along the shaft prevented collapse of the borehole. The piezocone filters were covered with a rubber membrane directly after saturation. Water was added to the drilling hole, while descending the piezocone in the borehole. The additional water dissipated entirely in the sandy top layers before penetration through the saturated subsoil started. The CPTUs performed according to best practices are referred to as tests under ideal circumstances. Adverse conditions in the present research refers to exposure to dry sand, absence of the protective rubber membrane and no pre-drilling.

4.2 *Viscosity*

The standard saturation liquid, as recommended by the piezocone manufacturer, is a silicone oil with a viscosity of 50 cSt, combined with a filter with a 10 μm pore diameter. In order to decrease desaturation, a more viscous silicone oil of 100 cSt was also used to saturate the piezocone. Similar CPTU tests were carried out as with the 50 cSt liquid.

Table 2 gives an overview of the parameters that were varied in relation to the number of tests performed.

Table 2. Test program.

Parameter	Tested values	Number of tests
Viscosity	50 cSt	12
	100 cSt	12
Duration in dry sand	0 min*	9
	5 min**	4
	15 min	4
	30 min	3
	60 min	4

* Zero minutes in dry sand corresponds to ‘ideal circumstances’.
** For one test the duration was 7 min instead of 5 min.

4.3 *Evaluation criteria*

All pore pressure measurements were evaluated and divided into 4 quality categories: good, fair, mediocre and poor. Evaluation criteria were: similarity to the hydrostatic pressure line and speed of response of the sensor.

Based on a borehole measurement, the water table is at about 7.3 m above sea level, which corresponds to 1.5 to 1.7 m depth. At a depth of 15 m a short dissipation test was conducted for all soundings, resulting in a slightly lower water table. Pore pressure measurements show this slight shift in hydrostatic line too at approximately 0 to 1 m reference level, where a small silty layer occurs. For this reason, an upper and lower hydrostatic line is drawn in all pore water pressure figures, indicated by $u_{0\text{-}u}$ and $u_{0\text{-}l}$ respectively.

Figure 2 shows an example of pore pressure measurements for each category. The blue dashed line represents a good measurement as it coincides well with the hydrostatic pressure lines and shows a quick response after a pressure drop, as can be seen at e.g. a level of 6.5 m. Some small peaks above the hydrostatic pressure can be noticed between level -3 and -5 m. Unfortunately, there are no cohesive soils at the test site that would generate large and sustained positive pore pressures which would facilitate the evaluation of the sensor response. The pore pressure drops in Figure 2 are not the result of a drop in penetration speed. A constant speed of 2 cm/s was achieved, using a continuous sounding technique. However, the drops agree well with the occurrence of small silty layers in the corresponding CPT-profile.

The green dotted line represents a 'fair' pore pressure measurement. Slightly slow response is noticed after a pressure drop, for instance at around 5 m and -0.5 m. However, it still rejoins the good measurement line. The red dotted line shows the 'mediocre' results, for which the sensor shows even slower response and a larger deviation from the hydrostatic line.

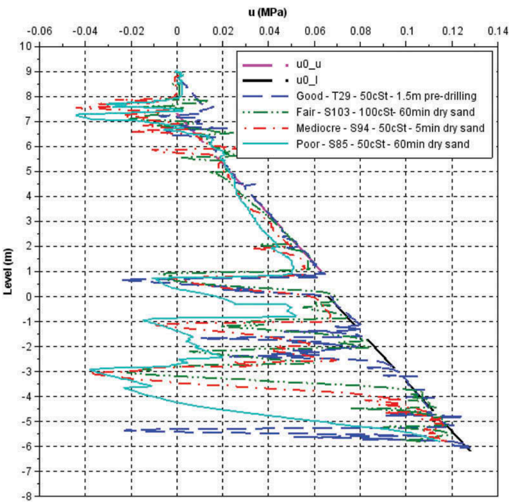

Figure 2. Examples of 4 quality categories of pore pressure measurements versus reference level.

For the 'poor' measurements, in Figure 2 indicated with a light blue solid line, a clear sluggish res-ponse is noticed and it is impossible to determine the hydrostatic line from the pore pressure measurements.

5 TEST RESULTS

5.1 *Comparison of measured data*

Figure 3 shows the measured cone resistance q_c, sleeve friction f_s and pore water pressure u_2 for all tests, grouped according to their pore pressure quality category. The reference level is based on the depth measurements corrected for inclination and elevation.

As expected, all tests performed under ideal circumstances show good pore pressure measurements. Remarkably in this group, one outlier has been 60 minutes in dry sand and still shows no clear signs of desaturation. This is not the case for the other tests that have been a certain time in dry sand without the protection of a rubber membrane.

Although not the purpose of this study, it is worthwhile to have a look at the q_c and f_s measurements as well. For the top layers the repeatability of q_c is generally quite good. The values of f_s show more scattering. Larger variations for f_s compared to q_c are also found in literature (Paniagua et al. 2021, Lunne et al. 2018). Some anomalies also drew our attention: S112 (cone 2) and T59 (cone 3) show lower q_c and f_s values, whereas T31 and S94 (both cone 4) give higher f_s values. It is unclear what might have caused these anomalies. Since the pore water pressure measurements don't seem to be affected, they were not excluded from the analysis.

Note that the less reliable pore pressure measurements cannot be attributed to a single underperforming piezocone, since all 4 piezocones showed very similar pore pressure measurements in ideal circumstances and because no correlation was observed between any pore pressure quality category and a particular piezocone.

5.2 *Viscosity*

Since all tests with zero exposure to dry sand produced good pore pressure measurements, regardless of the viscosity of the silicone oil, it can be stated that the viscosity has no influence on the results, if they are performed under ideal circumstances.

However, when the piezocone is exposed to dry sand and subjected to relatively high suction pressures during shearing, it seems that the viscosity does play a role. Based on the results depicted in Figure 4, it is likely that a 100 cSt viscosity might withstand better to desaturation than a 50 cSt viscosity. However, the results should be interpreted with caution given the relatively small number of tests. Further research is to

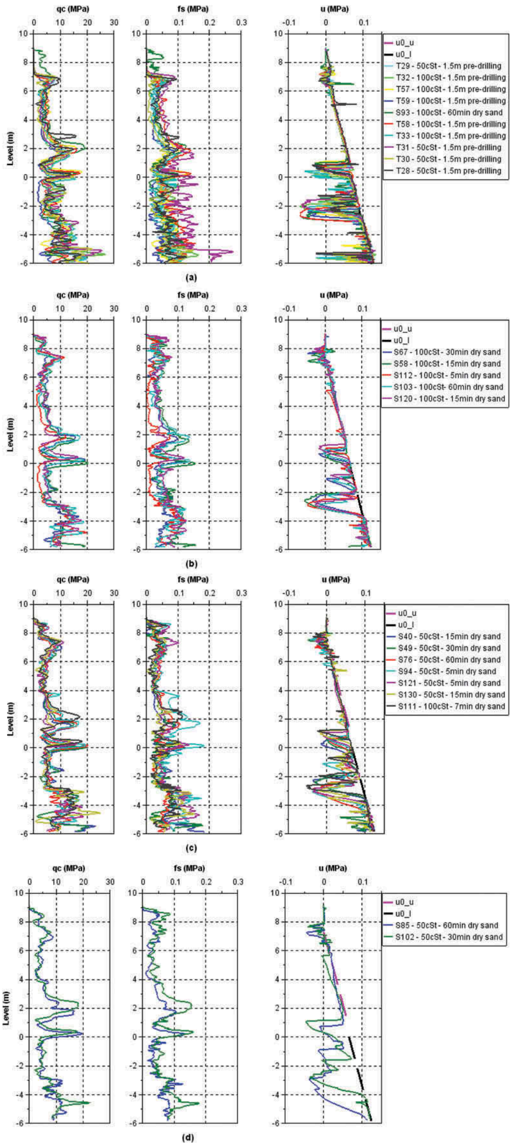

Figure 3. Measured qc, fs and u grouped by quality category based on the pore pressure measurements (a) good, (b) fair, (c) mediocre and (d) poor.

be carried out to better understand the advantages and possible drawbacks of using a more viscous silicone oil.

5.3 *Exposure to dry sand*

The impact on the quality of the pore pressure measurements as a function of the time of contact with dry sand is presented in the bubble plots of

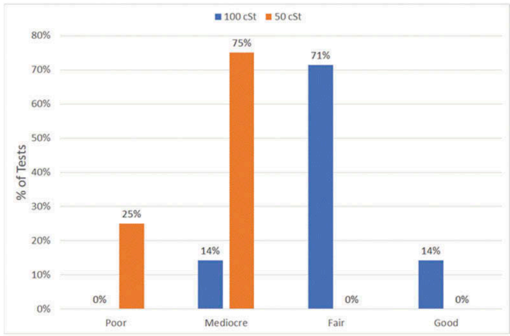

Figure 4. Percentage of tests under adverse conditions as a function of pore pressure quality categories for 100 cSt and 50 cSt viscosity of silicone oil.

Figure 5 for both silicone oil viscosities, 50 cSt and 100 cSt.

Each bubble shows the number of tests for a certain combination of pore pressure quality category and number of minutes in dry sand. One would expect a descending trendline showing decreasing quality in the pore pressure measurements for increasing minutes in dry sand. However, this is not the case, especially not for the plot with 100cSt. There is no clear relation between pore pressure quality and contact duration in dry sand. Only zero minutes in dry sand results in an obvious link with good quality measurements.

During pore water pressure observation tests in dry sand, no or very small suction pressures - smaller than the measurement accuracy- were measured. On the other hand, significant negative pore water pressures were observed going from -30 to -50 kPa during penetration for the tests in adverse conditions. For this reason, it seems likely that the negative pressures, occurring shortly after penetration, have been more detrimental to the saturation of the piezocone than the static contact with dry sand. At small depth fairly high q_c values are registered (up to approx. 10 MPa), indicating a high relative density of the sand layer. This sand dilates during penetration and it mobilizes negative pore pressures. This might explain why the contact time in dry sand seems not to be decisive on the quality of the pore pressure measurement and moreover, it might explain why the outlier (CPTU S93), which remained 60 minutes in contact with dry sand, still produced good pore pressure measurements. During penetration this test experienced rather small q_c values (max. 6.5 MPa) just above the water table and consequently small suction pressures were measured (up to -15 kPa), which is in the same order of magnitude as for the other tests producing good results.

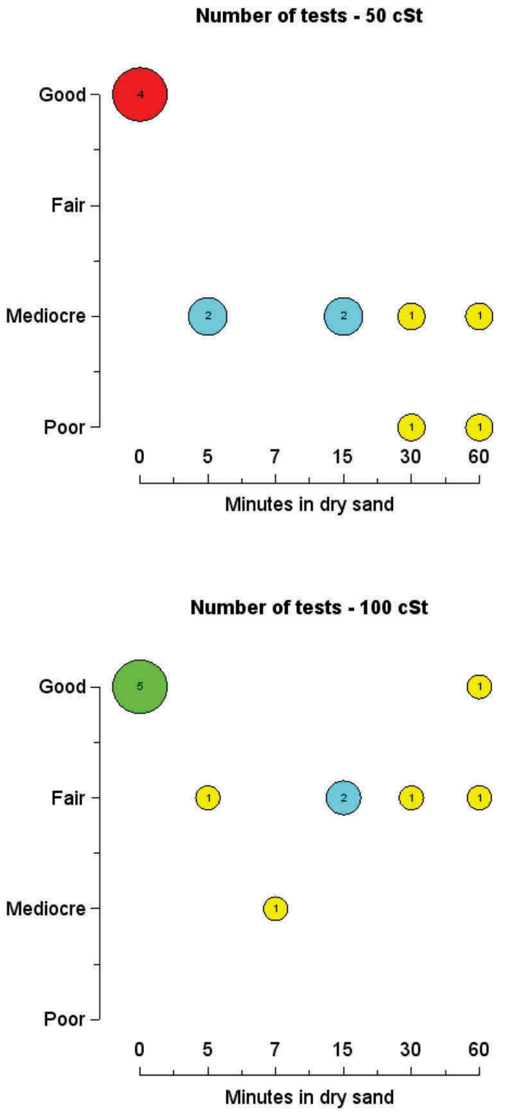

Figure 5. Pore pressure quality category in relation to the exposure to dry sand for 50 cSt and 100 cSt silicone oil.

6 CONCLUSIONS

Twenty-four CPTUs were performed at the test site in Zwijnaarde in both 'ideal' and 'adverse' circumstances in order to compare pore pressure measurements.

The tests have been performed for two different values of viscosity of the saturation liquid, i.e. 50 and 100 cSt. The results showed that, under optimal conditions, good pore pressure measurements are observed, regardless of the viscosity. However, in adverse conditions, the results suggest that cone penetrometers saturated with 100 cSt silicone oil might withstand better to desaturation compared to those saturated with 50 cSt silicone oil. Further research is to be carried out to evaluate the impact of the viscosity of the silicone oil on desaturation.

The influence of exposure to unsaturated soils was simulated by holding initially well-saturated piezocones in contact with dry sand for several minutes. During their exposure to dry sand the piezocones were not protected by a rubber membrane. All but one piezocones showed clear signs of desaturation during penetration, even when exposed briefly to dry sand. Since no or very small suction pressures were generated during the pore pressure observation tests in dry sand, it is likely that mainly the negative pressures, associated with dilation during penetration of the sandy top layer, have adversely impacted the saturation rather than the exposure to dry sand. In a subsequent study it would be interesting to separate the effect of exposure to dry sand and initial penetration through the unsaturated dense sandy layer, by also performing a pre-drilling for the penetrometers exposed to dry sand.

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