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Performance Of Vibrating Wire Piezometers In Very Low Permeable Clay

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SUMMARY: Pore-water pressure changes in stiff, very low permeable clay are best measured using diaphragm piezometers because of their inherent insignificant time-lag as opposed to traditional standpipe piezometers, which requires a relatively large amount of water inflow. Furthermore, diaphragm piezometers can be installed using the fully grouted method, which significantly simplifies installation procedures and allows for several piezometers per borehole. Based on field experience from several fully grouted, vibrating wire piezometer installations, it is evident that the fully grouted method is fully applicable for field measurements of pore-water pressure in low permeable clay strata. However, an often overlooked issue is the choice of piezometer filter. Apparently, the most frequently used filters have low air-entry values (LAE) even though some practitioners have been using filters with high air-entry values (HAE) – especially when attempting to measure negative pore-water pressures. This paper presents results from installations comprising both HAE and LAE filters in fully grouted boreholes and in intimate contact with the ground. It stands out distinctly that high air-entry filters have a high risk of malfunctioning if placed in fully grouted boreholes with no possibility of flushing the filters. Low air-entry filters should be the preferred choice of filter for non-flushable diaphragm piezometers in fully grouted boreholes.

KEYWORDS: Vibrating wire piezometers, HAE and LAE filters, fully grouted method, pore water pressure, field testing, high plasticity stiff overconsolidated clays.

1 INTRODUCTION

Research is currently undertaken by Geo (Danish Geotechnical Institute) and Aarhus University to investigate the effects of pile driving on pore-water pressures in stiff and highly overconsolidated, Eocene clays. The research opportunity has risen with the commencement of heavy construction work in areas of Denmark with surface near Eocene clay. (Simonsen & Sorensen, 2017b) presented preliminary results from pore-water pressure measurements at a construction site in relation to this research. Several challenges were faced during monitoring at active construction sites – especially in relation to measuring pore-water pressure – and in order to support and refine those measurements, a test field was initiated in 2016. The test field allows for piezometer installations and pore pressure measurements under controlled and well-known soil/groundwater conditions and the results presented in this paper are obtained in the test field.

In recent years vibrating wire (VW) piezometers have grown more and more popular and with that the installation in fully grouted boreholes. Several studies report successful installations from various sites around the world, e.g. (Contreras, Grosser, & Ver Strate, 2008; DiBiagio, 2003; Dunnicliff, 2008; Smith, van der Kamp, & Hendry, 2013). The VW piezometer contains a diaphragm sensor and therefore only require a very small amount of water flow to operate (Dunnicliff, 1988; A. Ridley, Brady, & Vaughan, 2003). The response time is fast and when installed in fully grouted boreholes, the installation method enables multi-level piezometer installations and thus allowing for pore-water pressure profiles with depth being obtained in a single borehole. This is a major advantage over other piezometer types. (Vaughan, 1969) and (Contreras et al., 2008) argue that the grout permeability should be less than 20 to 1000 times higher than that of the surrounding soil in order not to introduce errors to the pore-water pressure measurements. It is generally considered as good practice to choose a grout with permeability as close to that of the soil as possible.

The idea for the study presented in this paper originates from an ongoing research project about pore pressure development in stiff, overconsolidated clays in relation to pile driving. In the beginning of 2017 a test setup comprising piezometers in eight boreholes in different depths and distances from a planned driven concrete test pile were initiated. Nine of seventeen piezometers were equipped with fine pore sized ceramic (high air entry) filter tips and within weeks after starting-up, problems occurred. Piezometers equipped with high air entry filters yielded highly erroneous readings and after 8 months of measuring, only one out of nine piezometers gave credible readings. The main reason for the piezometers not to perform well were believed to be unsatisfactory filter saturation.

This paper presents and discuss the performance of vibrating wire piezometers under different installation methods, with different filter types and installed in grouts of different compositions. The aim is to outline guidelines for successful piezometer installations in very low permeable clays with use of vibrating wire piezometers.

2 TEST SITE

In most parts of Denmark, Eocene clays are found at great depths, but glacial activities during the Quaternary period have dislocated the clay or eroded younger soil strata and hence the clay can be found nearer the surface in certain areas. The grey bands in Figure 1 reaching north-westwards from the western part of Funen across Jutland, mark areas where Eocene clays are found right below the Quaternary deposits. Within these areas, the clay might be found within depths that can be of geotechnical interest. The test field (approx. 3000 m^2) is located within this band near a clay pit close to the town of Randers.

Before piezometer installations began a thorough ground investigation was performed in order to select the most suitable areas for piezometer installations. Hence, 11 borings with appertaining CPTu tests were carried out, from which the results are described in the following chapter.

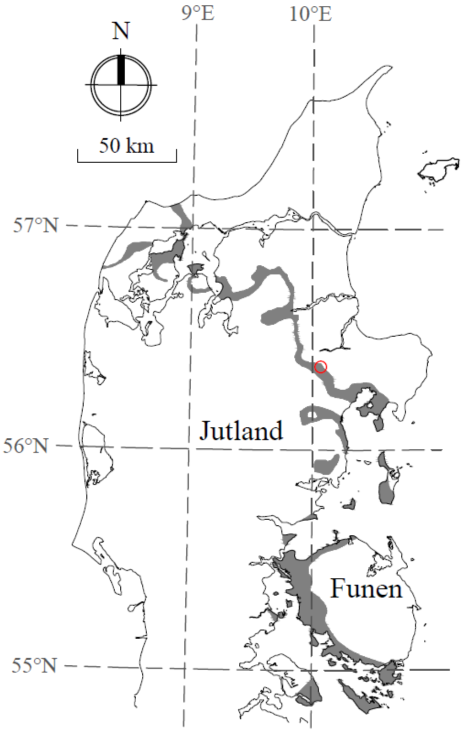


Figure 1. Map of Denmark (Jutland and Funen). Grey bands indicate areas within which Eocene clays make up the Pre-Quaternary surface. Test site is marked with a red circle near the town of Randers.

2.1 Geology and soil characteristics

The ground conditions in the test field are uniform and consist of approx. 4 meters of clay till with a sharp boundary to the underlying clay (Søvind Marl) which extends to at least 15 meters below terrain (no boreholes or CPTu tests have been taken deeper). The Søvind Marl Formation was deposited in a deep ocean during the middle and late Eocene from around 45 to 35 million years ago. It is a light grey to almost white, very fine-grained marl or calcareous clay. The carbonate content can vary from zero to around 70%. The Søvind Marl Formation includes thin beds of darker coloured, non- or slightly calcareous clay. Apart from these layers, bedding is indistinct due to heavy bioturbation. Although sand or silt lenses never will be found in Søvind Marl a few horizons within the formation are found to be rich in sand-sized glauconite (Heilmann-Clausen, Nielsen, & Gersner, 1984; Simonsen & Sorensen, 2017a).

Investigations from a nearby clay pit show that the clay fraction account for 65-70% of the soil mass and that there are practically no particles larger than 0.01mm (medium grained silt). Smectite minerals compose 60% of the clay fraction and the rest is evenly distributed between illite and chlorite.

Compared to other younger clay types Søvind Marl exhibit unusual geotechnical properties which is described by e.g. (Grønbech, Nielsen, Ibsen, & Stockmarr, 2015). This being primarily due to its high content of smectite and varying carbonate content. It shows extremely high plasticity and it is furthermore heavily overconsolidated due to the weight of eroded younger layers and numerous glaciers in the Quaternary period. The overconsolidation ratio has not been determined for the Søvind Marl in the test field, but expected to be in the order of 10 to 20. Triaxial tests, however, show that the clay behave more as a lightly overconsolidated clay. This is likely due to breakdown of the clay structure during swelling processes associated with unloading. Samples of Søvind Marl often appear fissured and with slickensides. Properties of Søvind Marl as determined on samples from the test field are listed in Table 1 and q_{net} profiles with geological interpretations are shown in Figure 2. In situ and laboratory determinations of the coefficient of permeability for Søvind Marl yielded values around $1 \cdot 10^{-11}$ to $3 \cdot 10^{-11}$ m/s (Simonsen & Sorensen, 2017a). Strength parameters have been determined from recently completed triaxial tests (unpublished).

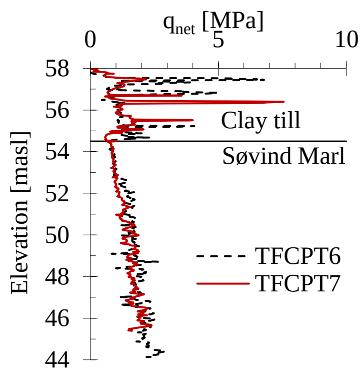


Figure 2. q_{net} profiles from CPTU soundings.

Table 1. Properties of Søvind Marl from the test site

Property	Value
Natural water content	44 – 62 %
Liquid limit	160 – 220 %
Plasticity index	110 – 177 %
Unit weight	17 – 19 kN/m^3
$CaCO_3$	8 – 30 %
c_u/c'	~ 70/25 kPa
ϕ'	~ 20°
k	~ $2 \cdot 10^{-11}$ m/s

The soil investigations show the ground profile to be very uniform across the site. Except from locally observed layers with high content of glauconite elsewhere in the test field (described in details by (Simonsen & Sorensen, 2017a)). The soil profile illustrated in Figure 2 can be taken as representative of the soil profile.

The water level in the top till layer has been measured regularly in stand pipes. It is highly dependent on precipitation, but is averagely measured around one meter below ground level.

3 METHODS

Based on the difficulties encountered with high air entry (HAE) filters as described in the introduction, a new series of piezometer installations were planned with special focus on different saturation methods. The purpose was to investigate the influence of saturation methods on the performance of fully grouted, vibrating wire piezometers equipped with HAE filters in very low permeable clay. Eighteen new piezometers were installed in boreholes TF4 – TF6 (see Figure 3 and Figure 4 for location). The piezometers, filters and data loggers were from two different manufacturers – in the remaining part of the paper denoted “manufacturer 1” and “manufacturer 2”. The tests and associated results are discussed in the following sections.

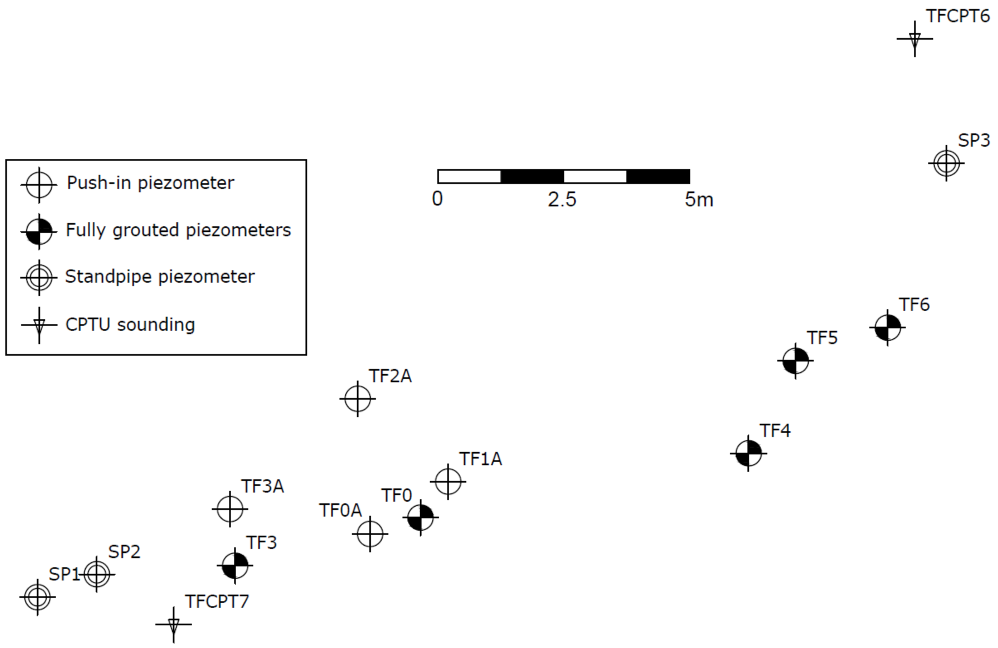


Figure 3. Site plan

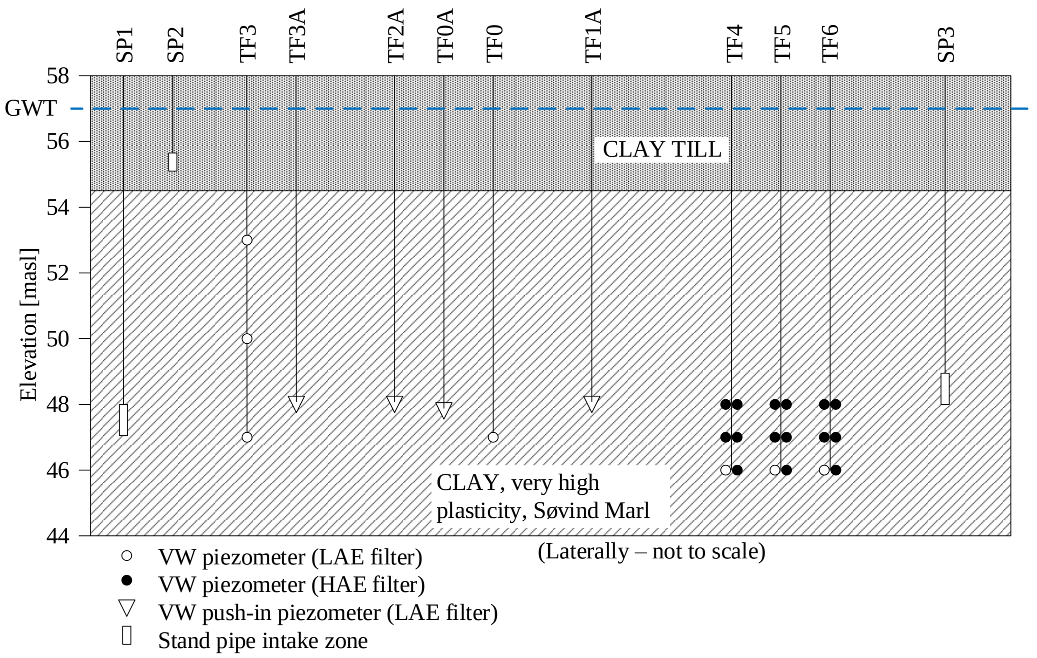


Figure 4. Cross section

3.1 Vibrating wire piezometers

Except from the stand pipes (SP1, SP2 and SP3) all piezometers used in this study were diaphragm piezometers of the vibrating wire (VW) type. The VW piezometer consists of a flexible, metallic diaphragm separating the pore-water from the measuring system behind a porous filter and a water-filled reservoir (Figure 5). A tensioned wire is attached to the diaphragm and when the diaphragm deflects (under a given pore-water pressure) the length and hence the tension of the wire changes. By inducing an electromagnetic field from the electrical coil, the wire vibrates and the voltage across the ends of the wire can be measured. As this voltage varies with the length of the wire, the measurement can be calibrated against the water pressure in the reservoir. The vibrating wire sensors used in this study were not vented to the atmosphere and hence read the gauge pressure as opposed to the absolute pressure read by vented instruments.

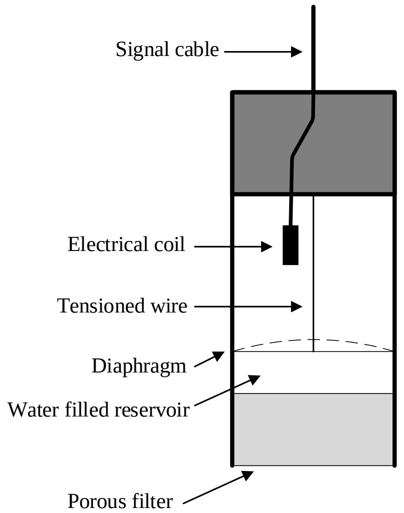


Figure 5. Vibrating wire piezometer principle sketch. Not to scale. Redrawn after (A. Ridley et al., 2003)

Modern vibrating wire piezometers have a hermetically sealed cavity around the tensioned wire and are generally considered very robust instruments. Several studies report of vibrating wire piezometers functioning for decades with minimal drift and no failure, e.g. (Sherard, 1981) and (DiBiagio, 2003). Furthermore, it come to equilibrium very rapidly in low permeability soils due to the small volume of water in the cavity allowing them to be installed directly in cement-bentonite grouts instead of conventional sand filters. This option allows for several piezometer installed in a single borehole and thereby reducing drilling costs. The saturated vibrating wire piezometer is practically a "no flow" piezometer in the sense that essentially no flow of water in or out of the tip is needed when the pore-water pressure changes (Sherard, 1981).

A major disadvantage of standard VW piezometers is that the closed reservoir makes it impossible to flush out air that might enter into the reservoir. If this occurs, the measurements will be incorrect and there are no means of re-saturating the filter and reservoir.

Vibrating wire piezometers can also be packaged with-in push-in housings enabling them to be pushed into place from the bottom of a borehole (or from ground level in soft soils) and thereby installed in direct contact with the surrounding soil. This method, however, only allows one piezometer per borehole.

The piezometers used in this study had standard ranges of 350 kPa and 690 kPa with resolutions of 0.025 % F.S. and ±0.1 % F.S. accuracy.

3.2 Piezometer filters and filter saturation

As described above, the vibrating wire is a very robust instrument, which are highly unlikely to fail under normal circumstances. Even under harsh conditions, the VW piezometers have been found to perform well (Bozozuk, Fellenius, & Samson, 1978; Hajduk & Paikowsky, 2000; Simonsen & Sorensen, 2017b). However, even the most robust and perfectly engineered VW piezometer will not give correct readings if the filter element is not properly functioning. The piezometer filter is the connection between the water in the piezometer cavity and the pore water, and if this pathway is interrupted with air, i.e. the filter and reservoir is no longer fully saturated, the piezometer readings will be incorrect. Although crucial for reliable pore-water pressure measurements, the filter is an often overlooked element. The majority of studies known to the authors, which involve standard vibrating wire piezometers with no means of flushing out intruding air from the filter element (i.e. non-flushable piezometers) do not present details of filter saturation methods nor filter type. Nonetheless, this information is regarded crucial by the authors and should be presented along with "standard" information about e.g. soil properties in order to fully assess the performance of a vibrating wire piezometer.

In this study, two types of filters have been used. That is Low Air Entry (LAE) and High Air Entry (HAE) filters. The filters differ in terms of their different air entry values (AEV). The AEV (also sometimes referred to as blow-through pressure or bubbling pressure) is defined as the maximum water/air pressure differential across a filter that can be sustained before air/gas penetrates (or blows through) the filter. This pressure differential is balanced by the surface tension forces at the air/water interface, which is governed by the radius of curvature of the menisci at the water surface of the filter. A fine-grained filter will have smaller menisci radii at its surface and hence a higher air/water pressure differential or AEV. The AEV of a LAE filter is typically in the order of 0.05 to 0.1 bar (5 to 10 kPa) whereas a HAE filter will have AEV's of or in excess of 1 bar (100 kPa). LAE filters are widely used for measuring positive pore pressures in a wide variety of soil types whereas the HAE filters originally went into environments where negative pore pressures were likely to occur such as in partly saturated soils in cores of embankment dams ((Dunnicliff, 1988) and (Sherard, 1981)).

In this study, VW piezometers from two different manufacturers were used and the HAE filters provided were porous ceramic filters. Filters from both manufacturers were nominally rated as 1 bar filters. During filter saturation, it became clear that the HAE filters were of different pore sizes and further enquiries revealed that filters from manufacturer 1 had an effective pore size of 3 μm whereas the filter from manufacturer 2 was 1.7 μm. According to (Sherard, 1981) the AEV (or bubbling pressure) in kPa is roughly connected to the filter pore size as *0.3/d* where *d* is the pore diameter in μm. Thus indicating that the AEV of the 3 μm filter is around 100 kPa (1 bar) and 176 kPa (1.76 bar) for the 1.7 μm filter. However, it is important to note that due to the structure of ceramic filters the AEV should not be reduced to a single value. There are two threshold pressures associated with measuring the air entry value (Sherard, 1981) and that is the air pressure at which the first isolated bubbles penetrates the ceramic (indicating air penetrating through the largest continous pore) and the higher air pressure at which air bubble emerge uniformly from the entire surface of the ceramic disc (indicating air flowing through the pore of average diameter). Furthermore, (A. M. Ridley & Burland, 1999) measured the air entry values of a 1 bar filter to around 170 kPa and >700 kPa for a 5 bar filter. The LAE filters used for both the fully grouted and push-in piezometers had an effective pore size of 50 μm. The different filter types used in this study are tabulated in Table 2.

As stated above the saturation of filters (especially HAE filters) are crucial for a good piezometer performance. However, there seem not to be any consensus or common preferred saturation method amongst manufacturers of today. Therefore, five different saturation methods obtained from different studies and manufacturers descriptions were chosen for saturation of HAE filters in this research project. These methods are regarded as some of the most common techniques used in the geotechnical community today. Each saturation method was imposed on three different filters for installation in three different boreholes (TF4, TF5 and TF6). Each of the manufacturers carried out their preferred saturation method on three filters and delivered them pre-saturated to the research project (saturation methods 4 and 5 in the following). The authors carried out the three remaining methods (methods 1 – 3).

3.2.1 Saturation method 1 (boiling)

The saturation method recommended by (Sherard, 1981) and recently used with success by (Wan & Standing, 2014) is the simple method of submerging the filter in boiling water. In this study, three HAE filters were boiled for two hours before transferring them into a jar together with the hot water making sure that the jar was absolutely filled with water. When left inside the jar with the lid on, the cooling will generate a vacuum, which help to ensure maintenance of the filters saturation. The filters were stored in the jar until field installation.

3.2.2 Saturation method 2 (hand-pump)

The “hand-pump method” is a manageable way of saturating the filter on site prior to installation. First, the loose filter was tightly fitted into a plastic tube connected to a hand vacuum-pump (Figure 6a) and then lowered into de-aired water. Next follows application of vacuum using the pump with vacuum kept for several minutes until water was observed coming through the filter. The pump used was a Mityvac vacuum pump capable of applying a vacuum of around 95 kPa (~ 40,000 microns). After releasing the vacuum, the process was repeated three times before carefully moving the filter into a bucket of de-aired water. While submerged, the filter was fitted onto the piezometer. Then the plastic tube filled with a small amount of de-aired water was fitted tightly onto the piezometer head (Figure 6b) and vacuum applied once again. Vacuum was applied three times and kept until air bubbles could no longer be seen rising from the filter. The saturated piezometer (with filter) was stored under de-aired water until installation. This method was not applied to any of the 1.7 μm filters as the vaccuum produced by the hand-pump was inadequate to draw any water through the filter.

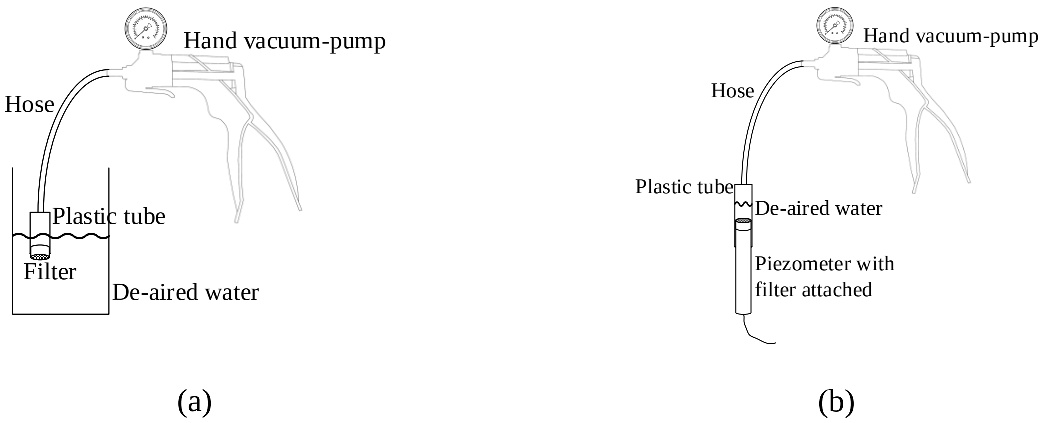


Figure 6. Schematic of saturation method 2. (a): Step one.(b): Step two. (Not to scale). Performed by the authors.

3.2.3 Saturation method 3 (vacuum chamber)

(Dunnicliff, 1988) describes the “vacuum chamber method” as a method of saturating HAE filters either in the laboratory or on site. In this study, the “vacuum chamber method” was carried out in the laboratory prior to field installation. Firstly, the dry filter was placed in a vacuum chamber on a perforated plate and then the chamber was evacuated by applying a vacuum. Then the bottom valve was slowly opened, whereby de-aired water flooded the filter driving out any air in the pores. The vacuum was kept for at least 12 hours where after it was slowly released and the filter carefully transferred into a container with de-aired water where it was stored until installation.

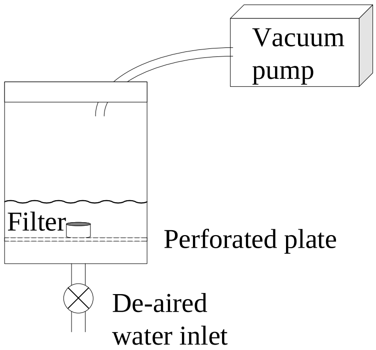


Figure 7. Schematic of saturation method 3 (Not to scale). Performed by the authors.

3.2.4 Saturation method 4 (Pre-saturation with saturation pump)

This method was carried out by manufacturer 1 and the description has been reproduced from their manual. Saturation of the filter is done with help of a saturation pump (Figure 8). First the cap of the pump was removed and the filter element mounted inside the cap. Then the piston screw was unwound, the pump chamber filled with de-aired water/glycol mix and the cap was refitted to the saturation pump. By slowly rotating the piston screw, the liquid was pushed through the filter. The generated pressure was observed and not allowed to exceed the filter rating (1 bar). When air bubbles were no longer seen in the liquid passing through the filter, the saturation was deemed complete. The filter was stored in de-aired water until installation.

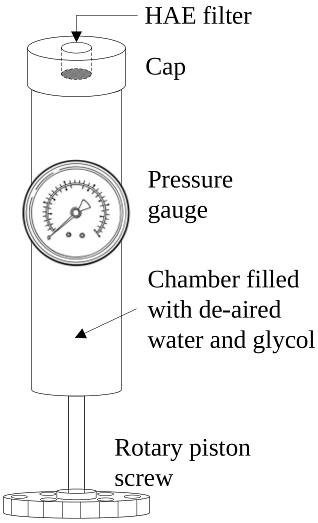


Figure 8. Schematic of saturation method 4 (Not to scale). Performed by manufacturer 1.

3.2.5 Saturation method 5 (Pre-saturation with special cap)

The last method aims at saturating the piezometer with the filter attached. This is done in order to avoid the problem of air entrapment in the piezometer cavity, which could occur when mounting the filter back onto the piezometer on site. This saturation was performed in the laboratory of manufacturer 2 and was performed by placing a special tightly fitted cap around the piezometer and filter (Figure 9). Then with the lower valve closed, the water chamber was filled about half way with de-aired water where after the upper cap was replaced. The hoses and valves were then connected to the water chamber and the vacuum pump and the piezometer were read by a read-out unit. The vacuum pump valve was then opened and the vacuum pump activated. The piezometer output and vacuum gauge were read simultaneously until the sensor reading reached a maximum without changing and the vacuum gauge reached the proper minimum value (~ 10 microns). Then the vacuum pump was closed and the water chamber were tipped upside down and its valve opened. This allowed water to flow through the filter and into the piezometer reservoir behind it. The piezometer output was read until it returned to zero pressure reading after which the hose to the special cap was removed. The hole from the hose was topped with de-aired water before installing a seal screw and thereby sealing the cap onto the fully saturated piezometer. The cap remained on the piezometer until installation where the screw was carefully loosened and the cap removed with the piezometer submerged.

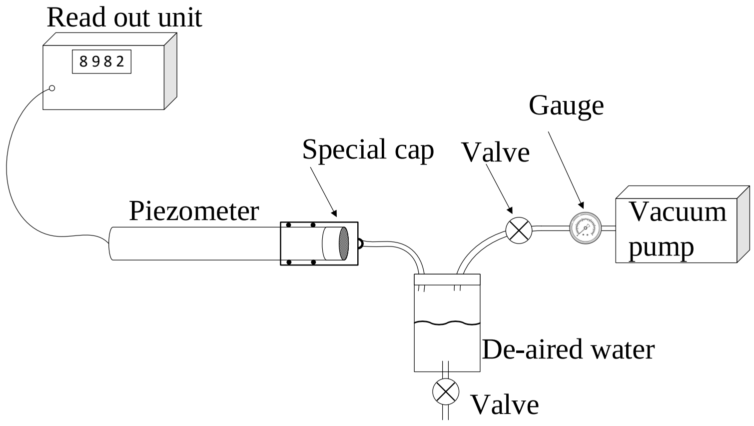


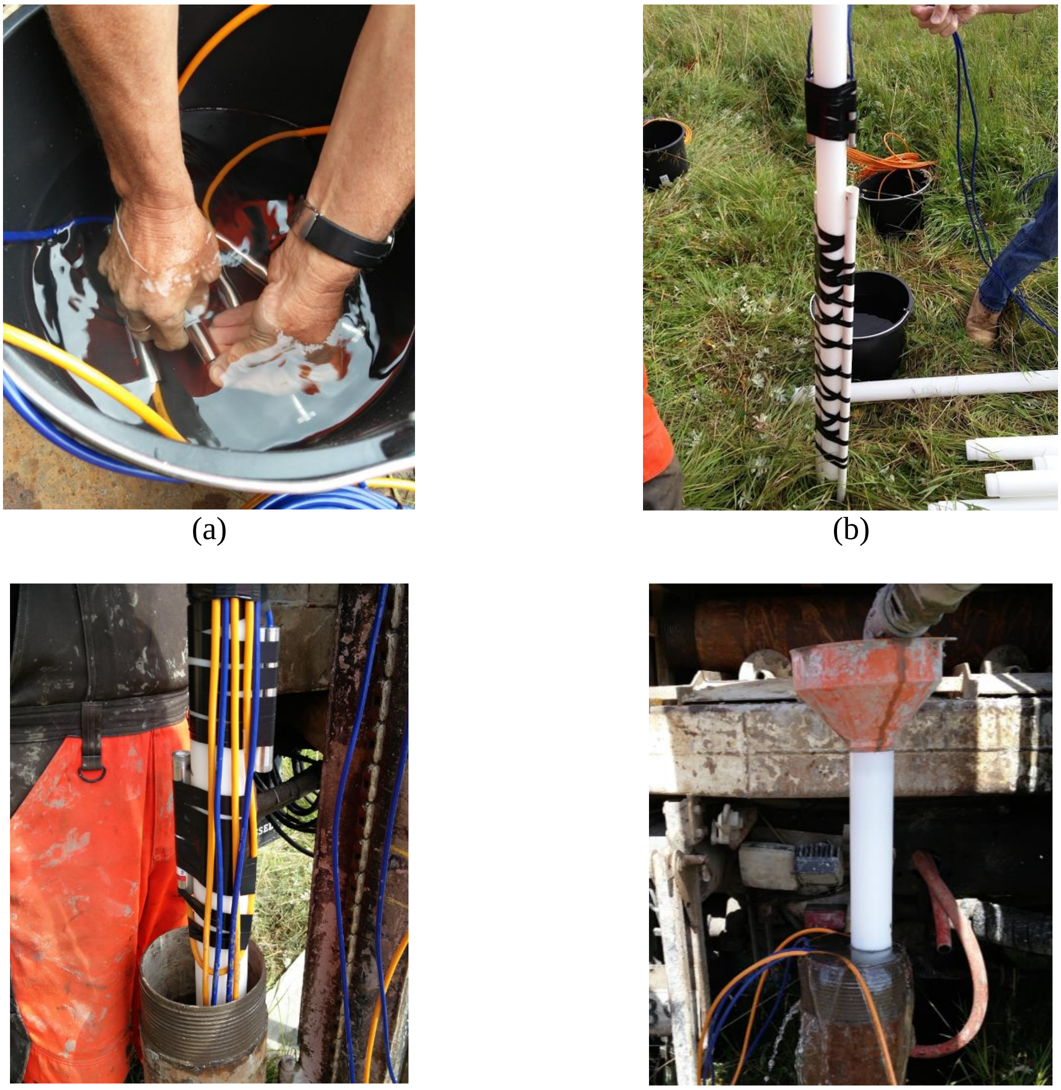
Figure 9. Schematic of saturation method 5 (Not to scale). Performed by manufacturer 2.

3.2.6 Saturation of LAE filters (immersion in water)

The saturation of LAE filters were simply carried out by immersing the filter into de-aired water prior to installation. However, as long as the piezometer is installed in a fully saturated soil strata, the saturation of a LAE filter is not a great matter of concern. (Bayrd, 2011) illustrated this in a series of laboratory tests set up to replicate different field installation techniques. His study clearly indicated that a VW piezometer with LAE filter, provided that there is sufficient water in the soil, will perform well even if not fully saturated at the time of installation.

3.3 Installation methods

The fully grouted piezometers in borehole TF4, TF5 and TF6 were installed in boreholes made with dry rotary drilling technique (6” dimension). All boreholes were drilled to approx. 1 meters below the depth of the lowermost pair of piezometers. During drilling, steel casings were used to support the borehole through the top till layer and a couple of meters into the Søvind Marl from where it was possible to drill further into the stiff clay without casing.



(a) (b)

(c) (d)

Figure 10. Photos from field installation: (a) mounting filter on piezometer under de-aired water, (b) fixing piezometers on grout pipe, (c) installation of piezometers in water-filled borehole, (d) backfilling borehole with grout.

After reaching target drilling depth the borehole was filled with water and a 63mm OD grout pipe mounted with two smaller 25mm OD pipes on each side providing headroom below the grout pipe for easier outflow of the grout in the borehole (see Figure 10b). Filling the borehole with water potentially enhances the swelling process in the clay initiated by stress relief from drilling. However, this was considered of no consequence to the outcome of the measurements. This procedure was chosen to minimize the exposure of the piezometers to air, which could potentially enhance de-saturation of the filters. Piezometers had their respective filters attached while submerged under de-aired water (Figure 10a) and base readings taken just prior to installation. Piezometers stayed under water until the grout pipe were ready for lowering into the borehole. Then the piezometers were attached to the grout pipe and immediately lowered into the water filled borehole. Piezometers from manufacturer 1 were installed with filters pointing up while piezometers from manufacturer 2 were pointing down.

Once the grout pipe was in place in the borehole, the grout was mixed and filled into the grout pipe (Figure 10c). Grout was poured in until all the water in the borehole had been displaced. Grout mix ratios was varied from borehole to borehole as listed in Table 2. This was to test the applicability of different grout compositions. The materials used were a basis Portland limestone cement (EN 197-

1:2011 – CEM II/A-LL 52,5R) and a Cebogel cement-stable (CSR) bentonite (supplied by Rotek A/S), which is a specially selected, activated sodium (Wyoming) bentonite whose expansive properties does not deteriorate when exposed to highly alkaline conditions.

Table 2. Overview of VW piezometer filter types and grout compositions used in boreholes TF4, TF5 and TF6

Borehole	Depth (m b.g.l.)	VW piezometer filter size and type	Saturation method	Grout composition, mix ratio (water/cement/bentonite)	Grout Marsh Funnel Viscosity (sec.)
TF4	10	1.7 µm (HAE)	5	2.0/1.0/0.5	50
	10	3 µm (HAE)	4	– ‖ –	– ‖ –
	11	3 µm (HAE)	3	– ‖ –	– ‖ –
	11	3 µm (HAE)	2	– ‖ –	– ‖ –
	12	1.7 µm (HAE)	1	– ‖ –	– ‖ –
	12	50 µm (LAE)		– ‖ –	– ‖ –
TF5	10	1.7 µm (HAE)	5	2.5/1.0/0.1	28
	10	3 µm (HAE)	4	– ‖ –	– ‖ –
	11	1.7 µm (HAE)	3	– ‖ –	– ‖ –
	11	3 µm (HAE)	2	– ‖ –	– ‖ –
	12	3 µm (HAE)	1	– ‖ –	– ‖ –
	12	50 µm (LAE)		– ‖ –	– ‖ –
TF6	10	1.7 µm (HAE)	5	2.5/1.0/0.3	34
	10	3 µm (HAE)	4	– ‖ –	– ‖ –
	11	1.7 µm (HAE)	3	– ‖ –	– ‖ –
	11	3 µm (HAE)	2	– ‖ –	– ‖ –
	12	3 µm (HAE)	1	– ‖ –	– ‖ –
	12	50 µm (LAE)		– ‖ –	– ‖ –

3.4 Laboratory testing

In none of the field tests described above could the influence of the grout itself on the HAE filter be analysed. It was therefore decided to carry out a simple indicative laboratory test to further investigate this relationship. The test simply consisted of a VW piezometer equipped with HAE filter being sealed in a block of cement-bentonite grout (w/c/b = 2.5/1.0/0.35) and lowered into a 3 m water column in a 425mm OD pipe (see Figure 11). The circular grout block was 150 mm in diameter (approx. corresponding to the diameter of a standard 6” borehole) and 250 mm in height and was left to cure for 4 days before installation in the “well”. The HAE filter had been saturated by boiling prior to installation (saturation method 1). The top of the pipe was sealed to minimize evaporation and to maintain the water table at a constant level.

By allowing the grout and piezometer abundant water it should become obvious if the chemical reaction in the grout while curing would have any effect on the performance of the piezometer. The results are discussed later.

Only one test has been carried out so far and further tests (also with LAE filters) are planned to validate the findings.

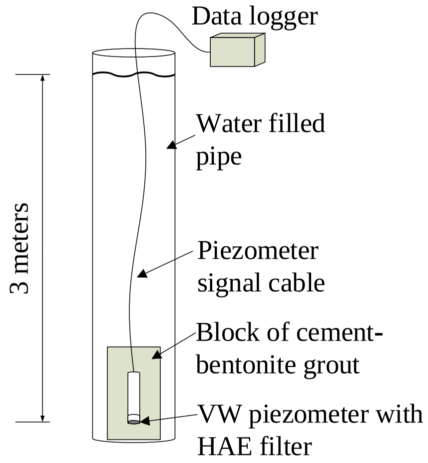


Figure 11. Laboratory setup. Not to scale

4 RESULTS

In the following section, the performance of the VW piezometers in borehole TF4, TF5 and TF6 will be presented and discussed. As previously described, the VW piezometers were installed both with HAE filters and LAE filters. The HAE piezometers were saturated in different ways and installed directly in cement-bentonite grout of different compositions, whereas the LAE piezometers were installed both in grout and in intimate contact with the clay (push-in piezometers).

4.1 Performance of VW piezometers with HAE filters

The measurements within the first 80 days of installation from the fifteen HAE piezometers installed in borehole TF4 – TF6 are presented in Figure 13. If functioning properly, the piezometers should all read a hydrostatic pore-water pressure corresponding to a water level approx. 1 m b.g.l. i.e. 110 kPa for the piezometers in 12 meters depth, 100 kPa for the piezometers at 11 meters depth and 90 kPa for the piezometers in 10 meters depth. Initially, the piezometers read a higher than hydrostatic water pressure due to the weight of the liquid grout. After the grout has set (within a couple of days) more or less all the piezometers start to read the expected hydrostatic pore-water pressure. However, after a period of time (days or weeks) pore pressure readings start to deviate from hydrostatic values in most of the piezometers (see Table 3).

An effective way of determining whether a non-vented VW piezometer is fully saturated and have low response time is by comparing it with barometric pressure fluctuations – ideally, the barometric pressure should be measured locally at the same time intervals as the piezometers. If this is not feasible, data from the nearest meteorological station may be used. In this study, a barometric logger was installed in the test field and set to record the barometric pressure in time intervals equivalent to the pore-pressure data loggers (30 minute intervals were found suitable). The barometric pressure acts on the surface as an atmospheric load, and as explained by (Skempton, 1954) any load applied to the surface will be shared by the pore-water and the porous matrix of the formation and hence generate a change in pore pressure. This also applies to atmospheric loading. Therefore, if the piezometer filter and reservoir are fully saturated, and full contact between the diaphragm and formation pore water exist, the piezometer should read the pore pressure changes from atmospheric loading without significant time lag. The ratio of the pore pressure response to the applied load is known as loading efficiency (Skempton, 1954; Smith et al., 2013) and is related to soil and water compressibility. Although barometric fluctuations are normally considered small in groundwater context, they are certainly measurable. The normal range of barometric pressures in Denmark are between 980 and 1040 hPa (i.e. 98 and 104 kPa) and the resolution of the piezometers are 0.025 % F.S. (i.e. 0.17 kPa for a 690 kPa piezometer).

The evaluation of piezometer performance by means of pore-water pressure response to fluctuations in atmospheric loading can simply be carried out visually by observing the piezometer response and compare it to the barometric pressure over time. Hence, from Figure 13 it can easily be judged which piezometers respond to barometric pressure changes and which who fail to do so. The piezometer performance can also be effectively evaluated by plotting the measured pore-water changes to the changes in barometric pressure change. Such plots are presented in Figure 12. Here showing two piezometers – a LAE and HAE from borehole TF4 – that respond very well to barometric pressure changes and one HAE piezometer from borehole TF6 that apparently has lost saturation and no longer respond to barometric pressure (see also Figure 13a). The data support that vibrating wire piezometers are very accurate sensors with very little time lag and hence very useful in very low permeable clay (when effectively saturated!).

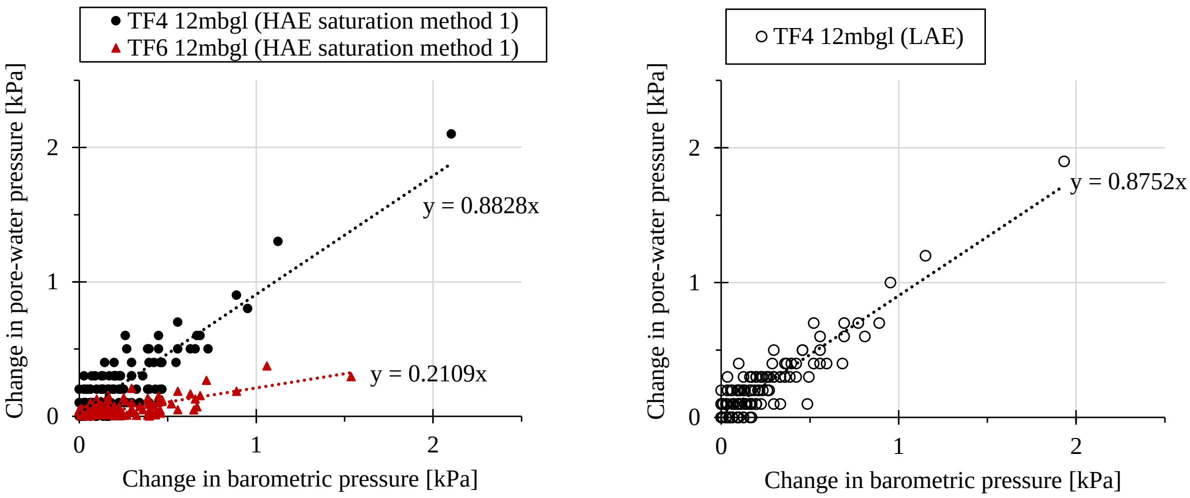
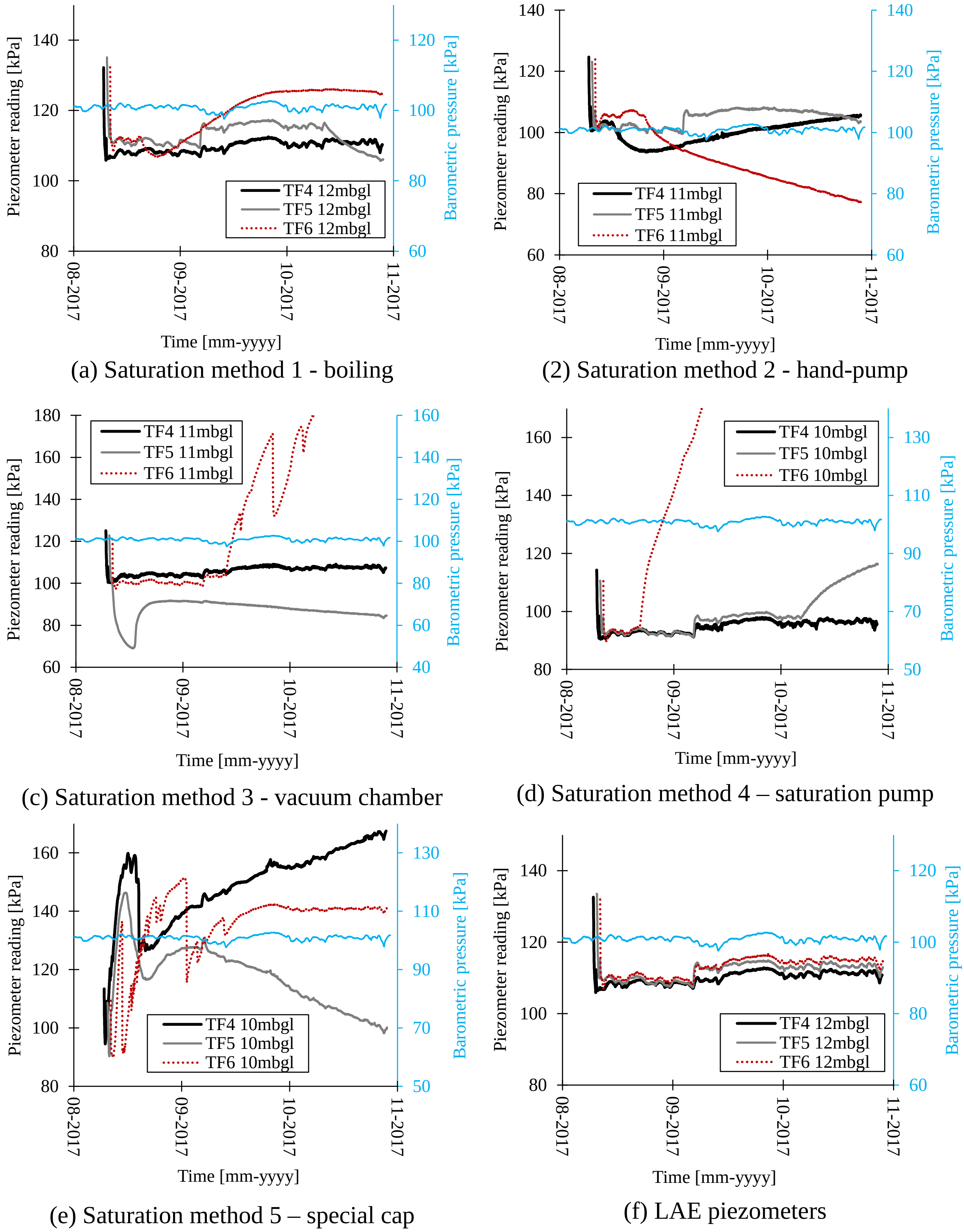


Figure 12. Pore-water pressure changes from barometric loading

When comparing the piezometers readings in Figure 13 with the barometric fluctuations, it can be further identified that only three out of fifteen piezometers have yielded credible readings throughout the three month period – that is TF4 (the black curve) in Figure 13 (a), (c) and (d). However, it is interesting to note that the piezometers observed in Figure 13 (e) that was pre-saturated by manufacturer 2 (saturation method 5 – “special cap”) apparently respond to barometric fluctuations, although the readings are obviously wrong.

The findings presented in Figure 13, clearly indicate problems with fully grouted VW piezometers equipped with HAE filters. The problems categorize into two trends. One showing erratic readings with abrupt leaps of up to almost 50 % of the hydrostatic pore-water pressure and one where the pore pressure curve “breaks” and flattens while going towards higher-than or lower-than-expected values. The magnitude of observed offset were for most of the piezometers in the range of 10 – 30 % of the hydrostatic water pressure (corresponding to water head change of approx. 1 – 3 meters). The possible reasons for the erroneous piezometer readings are discussed later.



(a) Saturation method 1 - boiling

(2) Saturation method 2 - hand-pump

(c) Saturation method 3 - vacuum chamber

(d) Saturation method 4 – saturation pump

(e) Saturation method 5 – special cap

(f) LAE piezometers

Figure 13. Performance of VW piezometers with HAE filters. Graphs (a) to (e) correspond to saturation method 1 to 5. Graph (6) show VW piezometers with LAE filters for comparison.

Measurements of variations in the free water table in the clay till layer (standpipe in borehole SP2) obtained with a Diver® water level logger clearly indicate that the hydrostatic pore-water pressure in the Søvind Marl is governed by the water table in the clay till layer. Changes in water table are seen to almost simultaneously affect the pore-water pressure in the Søvind Marl. For example, the general rise in pore-water pressure in early September (see e.g. Figure 13f) were caused by a precipitation event that was measured in the clay till as well. The water level measurements are not further presented in this paper.

Table 3. Overview of HAE piezometers performance in borehole TF4, TF5 and TF6.

Borehole	Saturation method	Depth (m b.g.l.)	No. of days before erroneous piezometer readings occur	Type of observed error response	Max deviation from hydrostatic pwp [%]
TF4	1	12	Still functioning	None	
	2	11	7	Decreasing but then increasing	±10
	3	11	Still functioning	None	
	4	10	Still functioning	None	
	5	10	1	With leaps but overall increasing	+80
TF5	1	12	62	Decreasing	−10
	2	11	27	Sluggish response to barometric pressure changes	
	3	11	2	Decreasing, increasing and decreasing	−45
	4	10	58	Increasing	+20
	5	10	1	With leaps but overall decreasing	+60
TF6	1	12	9	Decreasing but then increasing	+15
	2	11	15	Decreasing	−35
	3	11	33	Increasing with leaps	+110
	4	10	11	Increasing	+170
	5	10	1	With leaps but overall increasing	+65

4.2 Performance of VW piezometers with LAE filters

Eleven piezometers (both fully grouted and push-in piezometers) fitted with LAE filters were installed in the test field. Their performance are presented in Figure 14 and Figure 15 and they are obviously performing much better than the HAE filters. With a few exceptions they all read hydrostatic pore pressures as expected. The push-in piezometer TF2A 10mbgl reads a little less than expected which might be due to incorrect installation depth or a wrong zero reading. The fully grouted piezometer in TF0 11mbgl also gives values around 20 kPa lower than anticipated after a couple of months after installation. No explanation has been found for this behaviour.

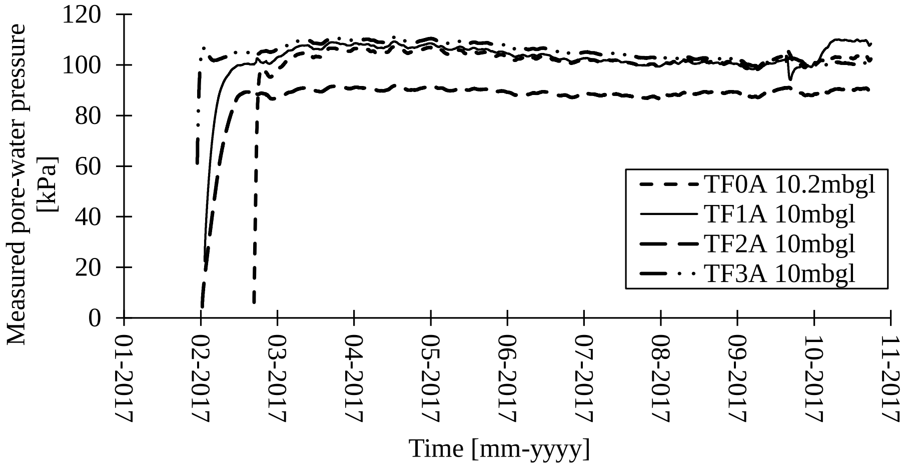


Figure 14. Performance of push-in vibrating wire piezometers with LAE filters

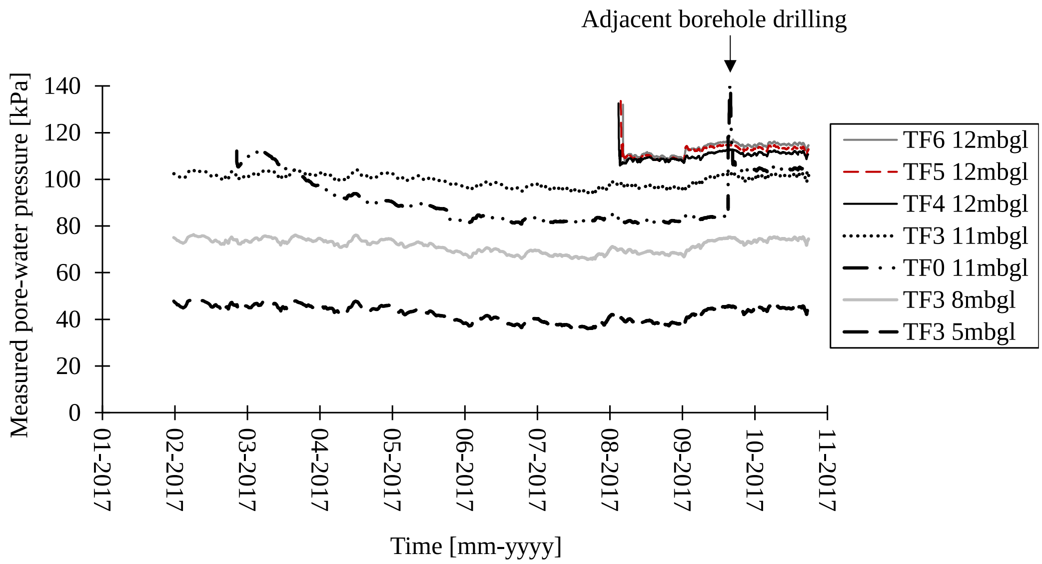


Figure 15. Performance of fully grouted vibrating wire piezometers with LAE filters

4.3 Laboratory test results

The results of the laboratory setup comprising a HAE piezometer installed in a grout block under hydrostatic water conditions (set-up shown in Figure 11) are shown in Figure 16. Piezometer readings were initially logged with one minute intervals until readings had stabilized. From then on, the interval was set to 30 minutes. The initial readings (Figure 16a) show that the pore-water pressure started to increase as soon as the grout block and piezometer were lowered into the pipe, which at that time had a water level 2 meters above the piezometer. During the subsequent filling of the pipe, the piezometer responded within minutes to the new water table. This indicated a well-functioning piezometer with a relatively short time-lag.

During the following approx. 28 days, the piezometer performed as expected. The start value was 30 kPa corresponding to 3 m head of water and the fluctuations observed in Figure 16b are perfectly matching the barometric pressure fluctuations as expected and described earlier. However, from day 28 and onwards the piezometer no longer responds to barometric pressure and apparently no longer records the correct pore-water pressure (the water level in the "well" had not changed, hence the piezometer should read 30 kPa ± the barometric variation). This finding was surprising and indicate that the cement-bentonite grout itself may lead to erroneous readings of piezometers with HAE filters.

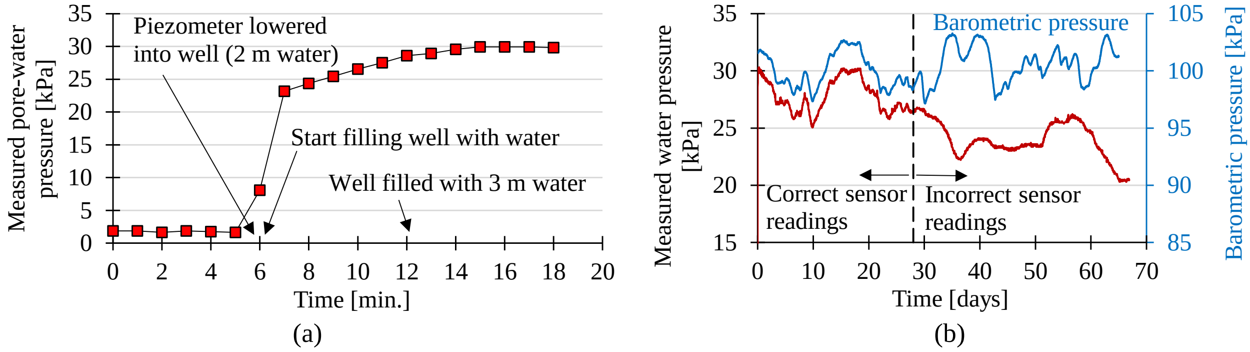


Figure 16. Results from laboratory "well" test. (a) initial readings and (b) long-term measurements.

5 CONCLUSIONS AND DISCUSSIONS

Through several field installations of vibrating wire piezometers with LAE and HAE filters in very low permeable clay, this study and ongoing parallel studies have documented serious problems with the functionality of VW piezometers with HAE filters in fully grouted boreholes whereas LAE filters perform well. Three different grout compositions, five different filter saturation methods and variations in filter direction (upwards or downwards) have been tested, of which none have proven unconditionally workable. Piezometers with HAE filters were displaying highly erroneous behaviour and their piezometer readings could generally be classified into two trends – 1) Erratic behaviour with sudden leaps and 2) Increasing or decreasing away from hydrostatic pressure. In addition to the field studies, a laboratory setup with a grouted-in HAE-filter piezometer left to measure a steady state pore-water pressure under 3 meters column of water, indicated that even when granted unlimited access to water, the fully grouted HAE piezometer may cease to read the correct pore-water pressure after a while.

The fact that a part of the atmospheric loading (e.g. barometric loading) will be transferred to the pore-water in a saturated soil has proven to be useful in verifying the piezometer performance of a non-vented, fully grouted VW piezometer. If the filter and water chamber are efficiently saturated, the piezometer will respond directly to barometric pressure changes with low response time. If a piezometer on the other hand does not measure the barometric pressure changes, it is most likely due to air ingress into the filter or cavity and the validity of the piezometer readings should be questioned. In this study, the piezometer response to barometric loading has been used for evaluating when a piezometer ceases to measure correct pore-water pressure. However, as also demonstrated, piezometers can be found to read obviously wrong pore-water pressures while responding well to the barometric pressure changes.

Before this research was undertaken, different hypothesises, trying to explain the piezometer performance, were put forward. E.g.: "zero drift" in the tensioned wire over time, diffusion of gas (formed at the Søvind Marl/grout interface) into the piezometer cavity, deficiency of water in the very low permeable clay causing the grout curing process to draw out water from the piezometer cavity and thereby de-saturating the filter. All of which can be rejected with the results presented in this study.

Moreover, ongoing measurements at another site with similar soil conditions have shown that VW piezometers with ceramic HAE filter tips can measure positive pore-water pressure correctly when placed in intimate contact with the clay (four piezometers have currently been measuring correctly for more than one and a half year). This, together with the presented results, undoubtedly points towards the cement-bentonite grout as the main problem. The fact that the observed piezometer behaviour varies a great deal further complicate the matter. How can it be explained that some piezometers read an increase in pore pressure, others a decrease and finally that some show highly erratic readings?

The reason for the highly erratic readings are hypothesised to be connected with the HAE filter not being completely fitted into place on the piezometer housing. This behaviour can be reproduced to some extent in the laboratory by mounting a HAE filter onto a VW piezometer while submerged making sure that the filter is not pushed entirely into place (the filter is thereby “floating” on the reservoir water). Then, when applying a pressure or tension on the edge of the filter element, the piezometer reading rapidly increases or decreases illustrating that the filter element imposes a pressure change to the diaphragm based on a total stress change rather than a change in pore-water pressure. This source of error can easily happen during field installation if the HAE filter is mounted too quickly and the excess reservoir water is not allowed to fully dissipate through the filter. Even small naturally occurring changes in total stresses in the soil are suspected to cause dramatic leaps in piezometer readings if the filter is not entirely fitted into place.

The mechanisms triggering uncontrolled increase or decrease in readings of some of the piezometers still have to be identified. The authors strongly suggest that more research be put into investigation of the physiochemical properties of the cement-bentonite grout and the interaction with ceramic porous filters such as HAE filters and potential osmotic effects (if HAE filters on non-flushable VW piezometers are not to be abandoned altogether).

Based on the findings presented herein, the use of HAE filters on diaphragm piezometers in fully grouted boreholes should be carefully considered. Serious concerns have been raised about the functionality of fully grouted VW piezometers with HAE filter tips and based on our present knowledge, it is highly recommended that low air-entry filters are chosen for non-flushable diaphragm piezometers in fully grouted boreholes.

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