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Characterisation of a Norwegian Quick Clay using a Piezoball Penetrometer

N.P. Boylan
Norwegian Geotechnical Institute (NGI), Perth, Australia (formerly of COFS, UWA)

A. Bihs
Department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

M. Long
School of Civil Engineering, University College Dublin (UCD), Dublin, Ireland

M.F. Randolph
Centre for Offshore Foundation Systems (COFS), University of Western Australia (UWA), Perth, Australia

S. Nordal
Department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

ABSTRACT: The piezoball, or ball penetrometer with pore pressure measurement, was developed for assessing the geotechnical properties of soft soils, particularly soft seabed sediments where the traditional cone penetrometer can have limitations. The measurement of pore pressure during this test can be beneficial for understanding the soil drainage conditions during penetration and thus assist the interpretation of the soil type and in-situ state. In addition, dissipation tests, where the pore pressure decay with time is monitored during a pause in penetration, can be used to assess the consolidation properties of the soil. In order to add to the experience base of piezoball testing in different soil types, testing was conducted at the Tiller quick clay site near Trondheim, mid-Norway. This paper presented the results of this testing with particular focus on the pore pressure response during penetration and the interpretation of consolidation properties from dissipation tests.

1 INTRODUCTION

The spherical ball penetrometer is increasingly being used for characterising soft seabed sediments, particularly the upper metres of the seabed, where the traditional cone penetrometer may prove inadequate. An enhancement of this device, referred to as a piezoball, incorporates a single or multiple pore pressure sensors on the surface of the ball to obtain parameters in addition to the penetration resistance, thus enabling estimation of the consolidation properties of soil. In recent years, research has focused on the interpretation of pore pressure measurements during ball penetration and the relationship with geotechnical parameters. Multiple experimentally based studies (e.g. Boylan et al. (2007, 2010), Colreavy et al (2016), DeJong et al (2008) and Low et al. (2007)) and numerical based studies (Mahmoodzadeh et al., 2015) have been carried out examining this topic. Experience to date has predominantly been in soft clays and silts of low to medium sensitivity. This paper describes research carried out using the UWA piezoball at the Tiller quick clay site, near Trondheim, Norway. The material at this site is characterised by its high shear strength sensitivity, and thus provides useful insight into the measured piezoball response in these soils and its relationship to geotechnical parameters. The paper examines the performance of the piezoball at this site and with particular focus on the pore pressure response during testing.

2 UWA PIEZOBALL PENETROMETER

For this research, a piezoball penetrometer was developed in-house at The University of Western Australia (UWA) (see Fig. 1). The ball has a diameter (D_b) of 60 mm and is connected to a reduced shaft section (d) of 20 mm diameter which results in shaft to penetrometer area ratio (A_s/A_p) of 0.11. The reduced shaft section is 185 mm long before tapering out to the standard rod diameter of 35.7 mm. This reduced shaft length is to minimise the migration of the excess pore pressures generated by the taper to the pore pressure field around the ball.

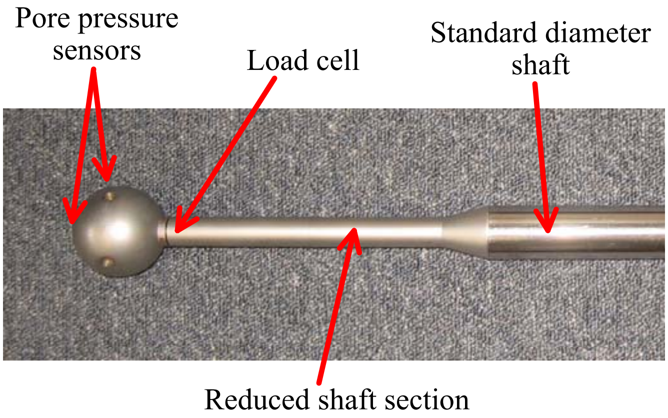


Figure 1. UWA piezoball penetrometer

On the ball, the pore pressure is measured simultaneously at both the tip (u_{tip}) and the mid-height (u_m), or equator of the ball. At the tip position there is a single pore pressure filter while at the mid-height there are four filter position located at 90° to each other. At each filter position, the pore pressure is measured by miniature total stress transducers (Kyowa PS-10KD) which are located in a recess close to the surface of the ball. The recess allows for a small fluid filled cavity covered by a porous high-density polyethylene (HDPE) filter which is flush with the surface of the ball. The locating of the sensor close to the surface of the ball is to minimize problems saturating the ball and ensures fast response times at the pore pressure filter locations.

The penetration and extraction resistance of the ball is measured by a load cell located directly behind the ball within the reduced shaft section. The load cell is a strain gauged section, fitted with a double full bridge of strain gauges and includes temperature compensation. The ambient temperature is also measured by a thermistor located alongside the load cell. The inclination of the ball during testing is monitored by an inclinometer within the standard diameter shaft section above the ball.

3 TILLER SITE

The Tiller site, which is locally referred to as Kvenild, is located to the south-east of Trondheim on the west coast of Norway. The site has been a research site of the Norwegian University of Science and Technology (NTNU) since the early 1980s due to the presence of a uniform deposit of highly sensitive clay and has been the subject of several soil characterization studies (see Table 1 of Gylland et al (2013) for a summary). Gylland et al. (2013) provide a detailed description of site and the geotechnical properties of the Tiller clay. Thus, only a brief description is provided in this paper.

Tiller clay is a marine clay having previously been below sea level during the last glaciation. The melting of the glaciers led to a post-glacial rebound of the land such that the site is now + 125 m above the present sea level. Since that time, the leaching of salt in the pore water of the clay has led to a situation whereby the clay has a high shear strength sensitivity and upon disturbance can transform to a fluid-like state.

Figure 2 shows the soil profile alongside data for the fall cone sensitivity (S_t) with depth. The fall cone sensitivity data has been obtained from a number of investigations since the early 1980's and the details are reported in Gylland et al (2013). Above 2 m, which is the lowest recorded level of the water table, the soil consists of a stiff clay crust layer. This is underlain by a predominantly lightly overconsolidated sensitive clay which transitions at a depth of approximately 8 m from a low to high sensitivity (i.e. $S_t > 30$) clay, into a quick clay. The definition of a quick clay is according to NGF (1982), which classifies it for conditions where the remoulded strength ($s_{u\text{-}rem}$) < 0.5 kPa. Within the quick clay deposit, sensitivity values of many hundreds are recorded, which indicate that the clay can transform dramatically into a near liquid state when disturbed. In all layers, the soil, which has an average clay content of 38%, is described as a low plasticity clay, having an average plasticity index (I_P) of 6.3%. Liquidity indices (I_L) are an average of 2 in the low-high sensitivity clay layer above 8 m, increasing to an average of 4 in the quick clay layer. The water content averages 38% and is relatively uniform with depth for the clay between 2 m and 20 m b.g.l.

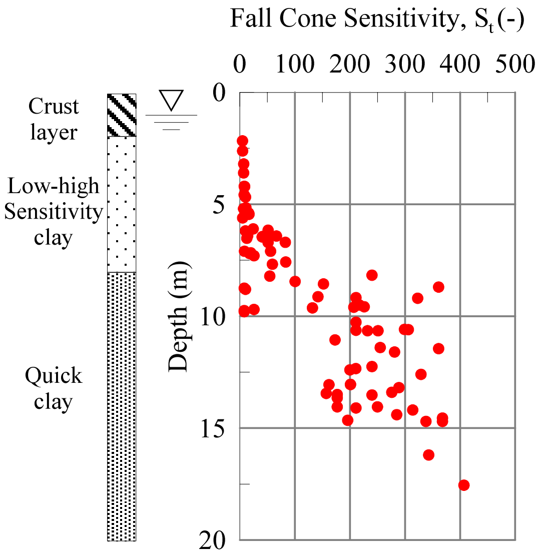


Figure 2. Soil profile and fall cone sensitivity

4 PENETROMETER TESTING

4.1 Equipment and Procedures

In-situ testing was carried out at the Tiller site using both a standard 10 cm^2 piezocone (CPTU) and the piezoball penetrometer described in Section 2. Prior to each test, the test locations were predrilled to between 1 m and 2 m b.g.l. through the surficial material. From examination of the predrilled holes, the water table was found to be within 1 m of the surface.

For the piezocone testing, the procedures and results have been reported by Bihs et al. (2012). For the piezoball tests, the ball was saturated by immersing the ball in a container of glycerine. A syringe was used to ensure no air bubbles remained in the fluid cavities on the surface of the ball and the filters were then inserted. A latex membrane was placed over the ball to maintain saturation prior to each test commencing. At the beginning of each test, the penetrometer was lowered into the borehole and allowed to equilibrate in the ground water. When the sensor readings reached equilibrium, zero readings were taken and the test commenced. Penetration and extraction were conducted at the standard rate of 20 mm/sec throughout. In a number of tests, dissipation tests were performed, whereby the penetration of the ball was halted at a particular depth, the rods clamped, and the decay of the pore pressures recorded. During each piezoball test, at least one cyclic penetrometer test was carried out to evaluate the symmetry of penetration and extraction resistance and allow the data to be re-zeroed if necessary. At the end of each test, zero readings of all sensors were taken for comparison to the readings taken at the beginning of the test.

4.2 Data Interpretation

For the piezocone tests, the net resistance (q_{net}) was calculated by correcting the measured cone resistance (q_c) for unequal pore pressure effects and overburden resistance using (Lunne et al, 1997):

$$q_{net} = q_t - \sigma_{v0} = q_c + (1-\alpha)u_2 - \sigma_{v0} \tag{1}$$

where q_t = corrected cone resistance, α = unequal area ratio of the cone (0.61 in this case) and u_2 = total pore pressure measured at the shoulder position behind the cone. The pore pressure parameter from piezocone tests (B_q) was calculated from:

$$B_q = \frac{u_2 - u_0}{q_{net}} = \frac{\Delta u}{q_{net}} \tag{2}$$

where u_0 = ambient pore pressure. For the piezoball tests, the net ball resistance (q_{ball}) was calculated by correcting the measured resistance (q_m) using the following expression (Chung & Randolph, 2004):

$$q_{ball} = q_m - [\sigma_{v0} - (1-\alpha)u_0]\frac{A_s}{A_p} \tag{3}$$

where α = unequal area ratio of the piezoball (0.85 in this case). The pore pressure parameter from piezoball tests (B_{ball}) was calculated for the pore pressure measured at the mid-height (u_m) and the pore pressure measured at the tip (u_{tip}) using the following expressions:

$$B_{ball-m} = \frac{u_m - u_0}{q_{ball}} = \frac{\Delta u_m}{q_{ball}} \tag{4}$$

$$B_{ball-tip} = \frac{u_{tip} - u_0}{q_{ball}} = \frac{\Delta u_{tip}}{q_{ball}} \tag{5}$$

For the mid-height pore pressure, u_m represents the average pore pressure measured by mid-height sensors.

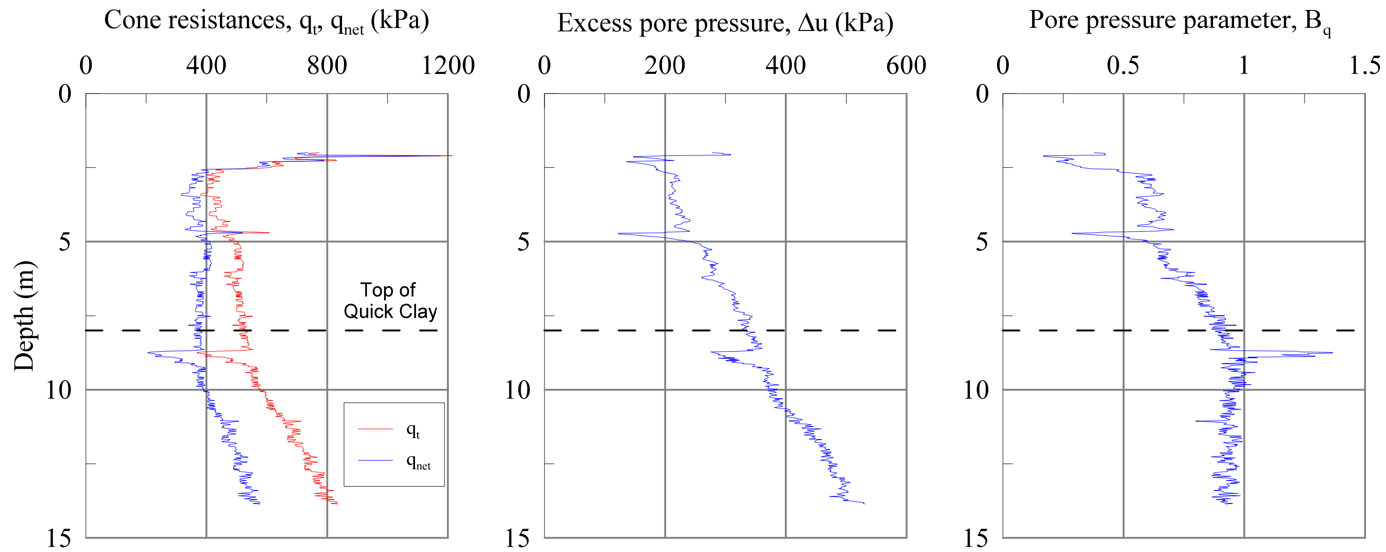
5 RESULTS AND DISCUSSION

5.1 Piezocone – Penetration Response

Figure 3 shows a typical piezocone test conducted at the Tiller site, in terms of both the corrected (q_t) and net cone resistance (q_{net}), excess pore pressure (Δu) and the pore pressure parameter (B_q). The net cone resistance initially reduces after penetration through the base of the crust. It then reaches a relatively uniform value of 400 kPa in the sensitive clay layer above 8 m, before increasing with depth at an average rate of ~ 40 kPa/m in the quick clay layer. Through penetration in the sensitive clay and quick clay layers, the excess pore pressure increases relatively linearly with depth from ~ 200 kPa at 2 m b.g.l. at a rate of ~ 25 kPa/m. B_q values increase from 0.5 to 0.9 in the sensitive clay layer and relatively uniform in the quick clay layer lying between 0.9 to 1. The trend of an increasing B_q with the soil sensitivity is consistent with the trends reported by Karlsrud et al (2005). A B_q ~ 1 is commonly used to identify quick clay layers in Norway.

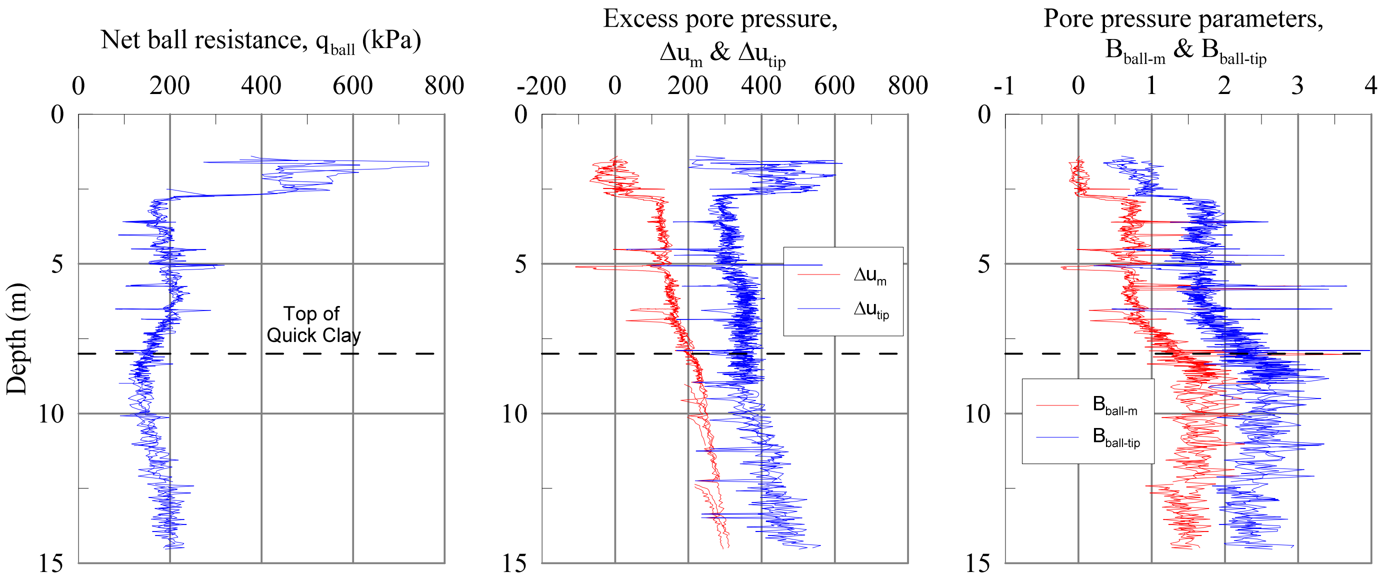
5.2 Piezoball – Penetration Response

Figure 4 shows the results of four piezoball tests conducted at the Tiller site. The results are shown in terms of the net ball resistance (q_{ball}), the excess pore pressures at the mid-height and tip (Δu_m & Δu_{tip}) and the pore pressure parameter at these positions (B_{ball-m} & $B_{ball-tip}$). Examining the results, the net ball resistance initially reduces from ~ 500 kPa in the crust layer to ~ 200 kPa in the upper portion of the sensitive clay layer and tends to reduce further towards the base of the layer where the soil sensitivity increases. The lowest ball resistance of ~ 140 kPa at the top of the quick layer before increasing at a rate of ~ 15 kPa/m. Overall, the ratio of ball to



(a) (b) (c)

Figure 3. Piezocone test result (a) Cone resistances (b) Excess pore pressure (c) Pore pressure parameter



(a) (b) (c)

Figure 4. Piezoball test results (a) Net ball resistance (b) Excess pore pressures (c) Pore pressure parameters

cone net resistance (q_{ball}/q_{net}) is between 0.3 to 0.5 in the sensitive clay and quick clay layers. The low q_{ball}/q_{net} ratio is perhaps surprising, but consistent with previous studies in high sensitivity clays. DeJong et al. (2012) report q_{ball}/q_{net} ratios of 0.5 to 0.7 in sensitive Canadian clays (S_t range of 33 to 85). The lowest ratios here are for the zone of quick clay, with S_t between 100 and 350, so showing a consistent trend. The main reason for such low ratios is the greater degree of remoulding, and hence lower average shear strength during initial penetration, for full-flow penetrometers compared with a cone penetrometer (Osman & Randolph, 2014). In addition, the insertion of the ball results in lower resistances being generated as the soil is able to flow around the penetrometer, while in the case of the cone this does not occur.

During penetration the excess pore pressure at the mid-height position (Δu_m) is close to zero and slightly negative in the crust layer while the tip position (Δu_{tip}) is strongly positive. As the ball penetrates into the sensitive clay layer, positive excess pore pressures are measured at both the mid-height and tip positions and increase linearly with penetration. In the sensitive clay layer, the ratio of mid-height to tip pore pressure ($\Delta u_m/\Delta u_{tip}$) is in the range 0.4 to 0.5 and increases to 0.6 to 0.7 in the quick clay layer. The difference between the response in the crust layer and the sensitive/quick clay layers at the two filter locations reflects the soil in-situ state, its sensitivity and the stress changes that occur at the relevant positions on the ball during penetration. At the tip position, the soil is in compression at all times and thus positive pore pressures are measured in all layers. At the mid-height position, the soil is subjected to shear stresses and the response depends on the state of the soil and the shear stress level. In the crust layer, the heavily overconsolidated nature of the soil causes the soil to dilate when sheared and thus low and negative excess pore pressures are induced. In contrast, in the sensitive and quick clay layers, the normally to lightly overconsolidated nature of the soil results in positive excess pore pressures during penetration in these layers.

The corresponding pore pressure parameters for the piezoball are shown on Figure 4c. Values of $B_{ball\text{-}m}$ are close to zero in the crust layer, lie between 0.5 and 1 in the sensitive clay layer and increase to between 1 and 2 in the quick clay layer. In contrast, $B_{ball\text{-}tip}$ values are between 0.5 and 1 in the crust layer, between 1.3 and 2 in the sensitive clay layer and between 2 to 3 in the quick clay layers. Thus compared to the cone, ratios of $B_{ball\text{-}m}/B_q$ are between 0.8 and 1.7 throughout the sensitive and quick clay layers. Ratios of $B_{ball\text{-}tip}/B_q$ are between 2 to 3 in the same layers.

5.3 Piezoball – Dissipation Tests

To assess the consolidation properties of the Tiller clay, a number of dissipation tests were performed at different depths in the soil profile. In total, four dissipation tests were performed in the sensitive clay layer at depths of 4.5 m and 6.5 m, and a single test in the quick clay layer at 9.5 m. The interpretation of the soil consolidation properties from piezoball tests requires the use of a theoretical/numerical dissipation curve to relate the recorded profile of pore pressure decay with time to the soil consolidation properties. To provide this relationship, Mahmoodzahed et al (2015) performed large deformation finite element analyses (LDFE) of the excess pore pressure dissipation process around shafted ball penetrometers with various shaft to ball diameter ratios (d/D_b) and considering a range of soil properties. These analyses showed that a unique dissipation response for different locations on the ball could be obtained by calculating the non-dimensional dissipation time (T_b) as follows:

$$T_b = \frac{c_h t}{D_b d I_r^{0.25}} \qquad (6)$$

where c_h is the operative coefficient of consolidation, t is the time from the commencement of the dissipation test and I_r is the soil rigidity index. Combining all the results of the LDFE assessments, Mahmoodzadeh et al. (2015) developed a unique dissipation profile for the piezoall, which is given by:

$$\frac{\Delta u}{\Delta u_i} \approx \frac{1}{1+T_b/T_{b50}} \quad for \quad \frac{\Delta u}{\Delta u_i} < 0.7 \qquad (7)$$

where $\Delta u/\Delta u_i$ is the normalised excess pore pressure and T_{b50} is the non-dimensional piezoball dissipation time for 50% dissipation. For the case of dissipation at the mid-height position on the ball, T_{b50} is 0.18.

Figure 5 compares the dissipation curves recorded in the five piezoball dissipation tests conducted at the Tiller site. In each case, c_h has been adjusted to match the backbone profile generated using Equation 7 and $T_b = 0.18$ in the region of $\Delta u/\Delta u_i \approx 0.5$. For $\Delta u/\Delta u_i < 0.6$, the gradient of the piezoball tests matches very well with the profile suggested by the backbone curve. For $\Delta u/\Delta u_i > 0.6$, the match between the piezoball tests and the backbone curve is less good but this can be attributed to the simplicity of the formulation of Equation 7, which is at the expense of obtaining close matches in that region.

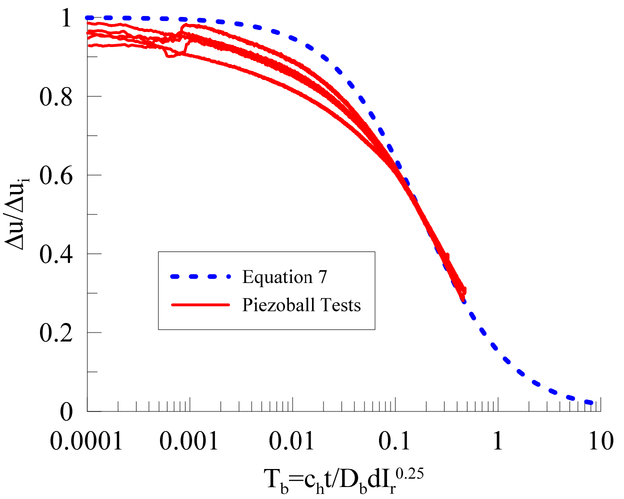


Figure 5. Piezoball mid-height position dissipation profiles at Tiller clay site

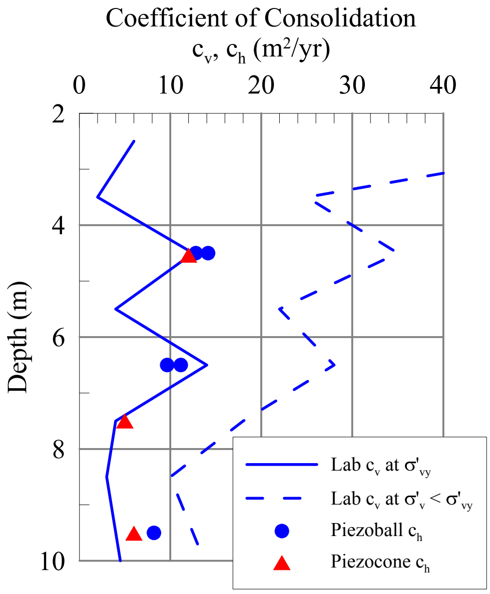


Figure 6. Comparison of consolidation properties of Tiller clay from both lab and field tests

Figure 6 compares the consolidation properties determined from the piezoball dissipation tests with values determined from piezocone dissipation tests reported by Bihs et al. (2012) and laboratory tests data reported by Sandven (1990). In the case of the piezocone dissipation tests, the consolidation properties are the values determined using the method proposed by Teh and Houlsby (1991). The laboratory test data was determined from continuous rate of strain (CRS) oedometer tests on the Tiller clay and coefficient of consolidation (c_v) profiles are shown for vertical effective stresses (σ'_v) equal to the yield stress (σ'_{vy}) and for stresses below this value. Based on comparison of the results, it can be see that there is reasonably good agreement between the c_h values determined from the piezoball and piezocone tests, with ratios between the two ($c_{h\text{-Ball}}/c_{h\text{-Cone}}$) ranging between 1.06 and 1.36. Compared to the laboratory test data, the measure c_h values for both penetrometers lie closest to the c_v values measured at the yield stress, thus corresponding to normally consolidated conditions.

6 CONCLUSIONS

This paper has examined the performance of a ball penetrometer with pore pressure measurements, termed piezoball, in sensitive and quick clay layers of the Tiller clay site near Trondheim, Norway. Particular focus has been on the pore pressure response during penetration and the dissipation of pore pressures during intended pauses in the penetration. Examination of the pore pressure response during penetration and comparison with the response obtained from the longer established piezocone tests, is useful for gaining reference test data and will ultimately assist in the development of soil classification charts for this test. Interpretation of piezoball dissipation tests using recently established methods has shown good agreement with the soil consolidation parameter determined from both in-situ piezocone tests and the results of laboratory tests on soil samples.

7 ACKNOWLEDGEMENTS

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