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Flow cone – new CPTU add-on module trialled in Halden silt

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ABSTRACT: Hydraulic conductivity is an important soil parameter for design of shallow foundation concepts for offshore wind, and there is a need for a new tool that can measure this parameter in a reliable way. A new module has been developed that can be mounted behind a standard piezocone test (CPTU) probe. Water can be injected in a controlled manner into the CPTU equipment and flow out into the surrounding soil through a filter an offset behind the friction sleeve, while water pressure (u_f) is measured by a transducer mounted in the filter itself. During penetration of the CPTU probe, water flows out at a constant rate, while u_f is measured in addition to CPTU parameters q_c, f_s and u_2. At desired depth intervals penetration can be stopped and either a dissipation test or constant flow rate test can be carried out to determine hydraulic conductivity.

Hydraulic fracture tests can be performed in low permeability soils, where water flow is used to induce a vertical crack in the soil. The vertical crack is then allowed to close while pore pressure is monitored, from which the closing pressure can be determined and subsequently used to determine the in-situ K_0-condition.

This paper describes a series of hydraulic conductivity tests and a hydraulic fracture test carried out at one of Norway's recently established geotechnical test sites, a silt dominated site in Halden. Several tests were successfully carried out and the results were benchmarked against hydraulic conductivity as measured by falling head tests in standpipes and laboratory tests. In general, the results compared well to credible benchmarking tests, showing a promising potential for this tool.

1 INTRODUCTION

Hydraulic conductivity (k) and coefficient of earth pressure at rest (K_0) are required parameters for a wide range of geotechnical engineering problems, including design of shallow foundation solutions for offshore wind. However, these parameters are challenging to measure accurately, both in-situ and in the laboratory. The purpose of the flow cone add-on module is to measure hydraulic conductivity in sands but trial testing at the Halden silt site suggests a wider range of application for the tool. This paper presents results from cone penetration testing, dissipation testing and hydraulic fracture testing in Halden silt, including current interpretation methodology for flow cone dissipation data in low permeability soils.

2 HALDEN SITE

The site is located close to the city Halden in a recreational park, Rødsparken. A silty, clayey sand constitutes the topsoil and extends down to about 4.5-5.0 m below ground level (Unit I), being generally loose to medium dense, with some organic material. The normally consolidated clayey silt layers below (Units II and III) extend down to about 15-16 m below ground level (bgl) in the southwest corner of the site. The silt is uniform and structureless to mottled, with primary bedding and laminations almost absent due to bioturbation. Units II and III contain similar amounts of quartz (40%), plagioclase (30%), feldspar (12%), clay minerals and mafic minerals (amphibole). Classification and in-situ tests suggest that the silt becomes sandier closer to the deeper soil unit, which consists of a low to medium strength clay (Unit IV). The clay unit has a slightly laminated structure, with occasional shell fragments and drop stones (Blaker et al., 2019).

3 OVERVIEW OF TESTS

This paper presents a range of laboratory and in-situ tests as part of the assessment of flow cone results. To facilitate easy reading, Table 1 is included providing a general overview of benchmark tests and flow cone tests, number of tests carried out, nomenclature and depth ranges.

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Table 1. Overview of benchmark tests and flow cone tests.

Equipment	Test type	Number of tests	Test abbreviation	Location IDs	Test IDs	Depth range	Comments
Oedometer	Constant head*	22	Oedometer	-	-	4.5-18.7 m bgl	Benchmark tests
Triaxial	Constant head	13	Triaxial	-	-	5.3-14.6 m bgl	Benchmark tests
Standpipe	Falling head	10	HA-SLT	1 to 5	1 to 2	6-15 m bgl	Benchmark tests
CPTU	Cone penetration	1	HA-CPTU	-	-	2-18 m bgl	Benchmark test
Flow cone	Cone penetration	4	HA-FCPTU	1 to 4	-	2-18 m bgl	
Flow cone	Dissipation	13	HA-FCPTU	1 to 4	1 to 4	6-15 m bgl	
Flow cone	Hydraulic fracture	1	HA-FCPTU	4	5	16.41 m bgl	

* Hydraulic conductivities at zero axial strain (back-extrapolated along the linear e-log(k) line)

4 BENCHMARK TESTS

4.1 *Oedometer and triaxial tests*

Constant-head hydraulic conductivity tests were conducted at different stress levels during a selected number of oedometer tests and during the consolidation stage of several triaxial tests (Sandbækken et al., 1986, Berre, 1982). Hydraulic conductivity was determined by flowing de-aired water through the specimens. Values from oedometer tests represent hydraulic conductivity at zero axial strain (i.e., at a void ratio comparable to in-situ conditions). Values from triaxial test specimens represent the hydraulic conductivity at the in-situ effective stress state (i.e., after consolidation and some subsequent change in void ratio).

4.2 *In-situ falling head tests*

Ten in-situ falling head tests (slug tests) were conducted in parallel with flow cone testing at five corresponding depths. The excess pore pressure from standpipe installation could dissipate for 24 hours before falling head tests were initiated by pouring clean tap water into the standpipes. Figure 1 illustrates pressure heads with velocity and best fit linear regression lines, showing good repeatability for all tests except the tests 15 m bgl, which may be explained by a small gap between the standpipe and surrounding soil for test HA-SLT-5-1.

For interpretation of hydraulic conductivity, the velocity method was preferred over time lag method due to its simplicity and independence of piezometric level (Chapuis, 2012). From the slope, m_v, of the linear regression lines in Figure 1, the hydraulic conductivity, k, was determined using Equation (1), refer to Daniel (1989) for further details, where A is the internal cross-sectional area of the standpipe and L and D are the length and diameter of the well screen, respectively.

$$k = \frac{A*\ln\left(\frac{L}{D}+\sqrt{1+\left(\frac{L}{D}\right)^2}\right)}{m_v\left(2\pi L - 2.8D*\ln\left(\frac{L}{D}+\sqrt{1+\left(\frac{L}{D}\right)^2}\right)\right)} \qquad (1)$$

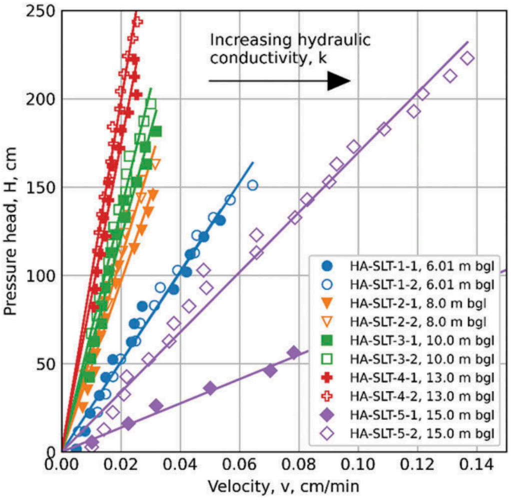

Figure 1. Pressure head with velocity from in-situ falling head tests. Measured results and best fit linear regression lines.

5 EQUIPMENT AND PROCEDURES

The flow cone is a standard cone penetrometer paired with a custom-built hydraulic module, see Figure 2 (Gundersen et al., 2019). The hydraulic module consists of a bronze filter offset behind the cone sleeve and a control system at ground surface. The control system handles data acquisition and provides flow rate control by means of a linear step motor driving a piston. Parameters such as ambient pressure, system pressure, water pressure inside filter (u_f) and flow rates are recorded. During cone

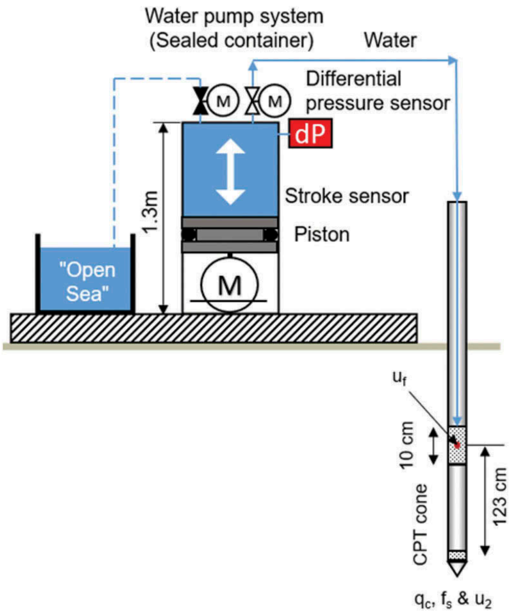

Figure 2. Equipment and setup of the flow cone (Gundersen et al., 2019). The offset between u_2 and u_f measurements is 123 cm.

penetration, water flows into the surrounding soil through the filter at a constant rate while u_f is measured in addition to cone resistance (q_c), sleeve friction (f_s) and pore pressure (u_2). The purpose of water flow during cone penetration in low permeability soils is to maintain filter saturation and prevent filter clogging. At desired depths penetration can be stopped and either a dissipation test, constant flow rate test or hydraulic fracture test can be conducted.

A hydraulic fracture test is performed by inducing a crack in the soil by water flow for subsequent monitoring of pore pressure decay. The test is intended for low permeability soils with $K_0 < 1$, meaning that the in-situ horizontal stress is lower than the vertical, and thus a vertical crack is expected to initiate first. To split the soil, a sufficiently high flow rate must be applied. At Halden, 30 ml/min was selected based on previous experience from testing in soft clays. The vertical crack closes when the pore pressure equals the soil pressure normal to the crack, and the basis for K_0 derivation is that this soil pressure is equal to the in-situ total horizontal stress, σ_{h0} (Bjerrum and Andersen, 1972).

All tests at Halden were carried out using a standard 10 cm^2 Geotech Nova cone with acoustic data transmission from probe to user interface, with standard penetration rate of 20 mm/s ± 5 mm/s. In total, 13 dissipation tests were carried out to a target 75 % dissipation of initial excess pore pressure where all CPTU parameters were logged including u_f.

6 MEASURED AND DERIVED PARAMETERS

6.1 *Cone penetration tests*

Figure 3 illustrates the corrected cone resistance (q_t), sleeve friction (f_s) and pore pressures (u_2 & u_f) with depth below ground level corrected for inclination. The figure includes results from a standard CPTU (HA-CPTU), suggesting that a constant flow rate of 5 ml/min during cone penetration, which was selected based on previous experience, has negligible effect on the standard cone penetration measurements (i.e., q_c, f_s, and u_2).

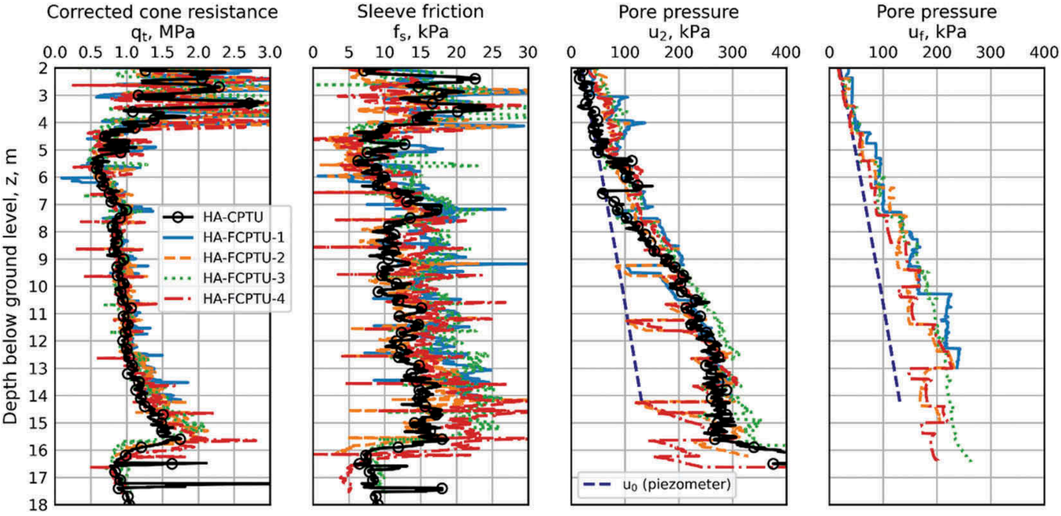

Figure 3. Corrected cone resistance, q_t, sleeve friction, f_s, pore pressure behind cone shoulder, u_2, and pore pressure, u_f, with depth.

6.2 *Pore pressure dissipation tests*

Figures 4 and 5 illustrate the measured pore pressures u_2 and u_f with square root of time. Most of the tests in Figure 4 exhibit dilative behavior (non-monotonic), which is consistent with previous dissipation tests conducted at the Halden site (Carroll and Paniagua, 2018). The pore pressure, u_f, generally exhibits a monotonic decrease with time but a small delay in pore pressure decay is evident in Figure 5.

The square root method proposed by Sully et al. (1999) was used to determine hydraulic conductivity from u_2-dissipation data, back-calculating the initial pore pressure, assuming an initial linear relationship between pore pressure and square root of time.

Rigidity index ($I_r = G/s_u$) and constrained modulus (M) are required for estimating hydraulic conductivity from flow cone dissipation tests. Teh and Houlsby (1991) showed that I_r influences the plastic failure zone around the cone tip during penetration and hence the associated stresses and pore pressures. Carroll and Paniagua (2018) interpreted u_2-dissipation results from Halden using I_r based on advanced laboratory testing and conservative undrained shear strength. In addition, two methods proposed by Krage et al. (2014) were examined, Method-A and Method-B. The latter compared the best with advanced laboratory data and has thus been applied. Method-B rigidity index is calculated using Equation (2), where G_{max} is the small strain shear modulus and σ_{v0} and σ'_{v0} are the in-situ total and effective vertical stress, respectively.

$$I_r = 0.26\left(\frac{G_{max}}{\sigma'_{v0}}\right)\left(\frac{1}{0.33\left[0.33\left(\frac{q_t-\sigma_{v0}}{\sigma'_{v0}}\right)\right]^{0.75}}\right) \qquad (2)$$

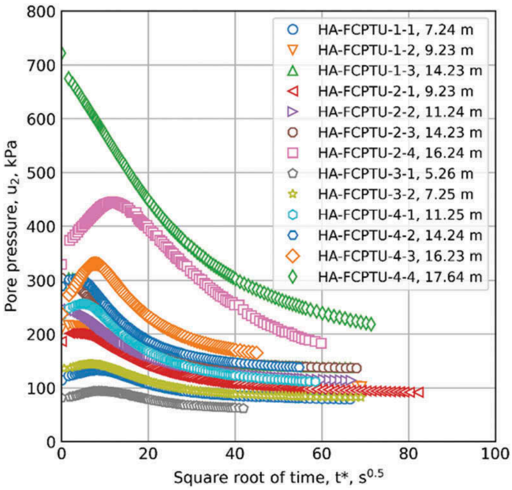

Figure 4. Measured pore pressure u_2 with square root of time.

Best estimate values of G_{max}, σ_{v0}, σ'_{v0} and M found in Blaker et al. (2019) were used as basis for interpretation of hydraulic conductivity. Input of corrected cone resistance in Equation 2 was derived from linear interpolation of the results presented in Figure 4.

As part of proposing an interpretation methodology for u_f-dissipation, triple element CPTU results from Halden were reviewed. This review suggested that the initial excess pore pressure, $u_{f,i}$, is primarily caused by the cone penetration itself, not the input water flow of 5 ml/min. On this basis, it was concluded that the Teh and Houlsby (1991) framework for location 10 radii behind the cone shoulder could be used to estimate the hydraulic conductivity. Figures 6 and 7 show the head ratio with dimensionless time factor for u_2-dissipation and u_f-dissipation using the framework by Teh and Houlsby (1991). The figures show a good fit to the shape of the theoretical solutions, which is discussed further in Section 7.

6.3 *Hydraulic fracture test*

One hydraulic fracture test was conducted 16.41 m below ground level, the result of which is illustrated in Figure 8. The figure shows measured pore pressure with velocity (i.e., how quickly the pore pressure decays). The pressure at which the crack closes was estimated to 2240 cm. Based on piezometric level from standpipe falling head tests and an average soil unit weight of 19.2 kN/m^3, this yields a K_0 value of 0.44, which falls within the expected K_0-range (0.4 to 0.65) for the Halden site.

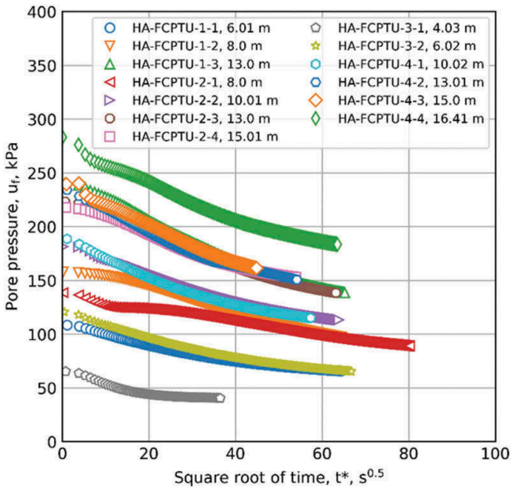

Figure 5. Measured pore pressure u_f with square root of time.

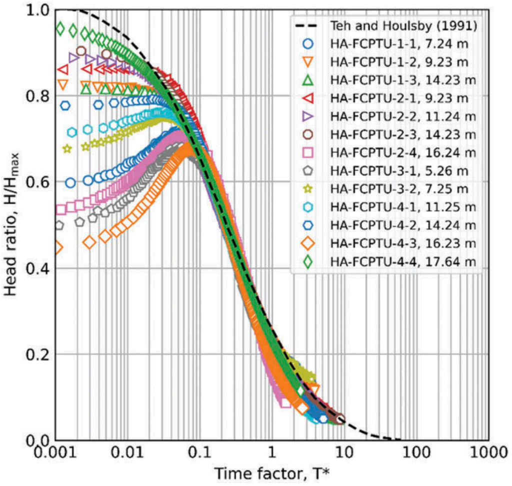

Figure 6. Pore pressure, u_2, head ratio with dimensionless time factor proposed by Teh and Houlsby (1991).

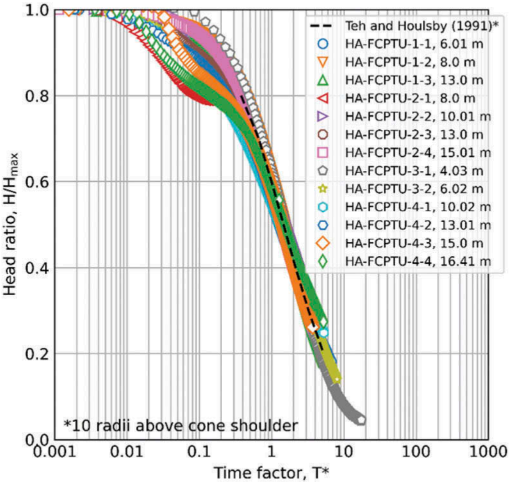

Figure 7. Pore pressure, u_f, head ratio with dimensionless time factor proposed by Teh and Houlsby (1991).

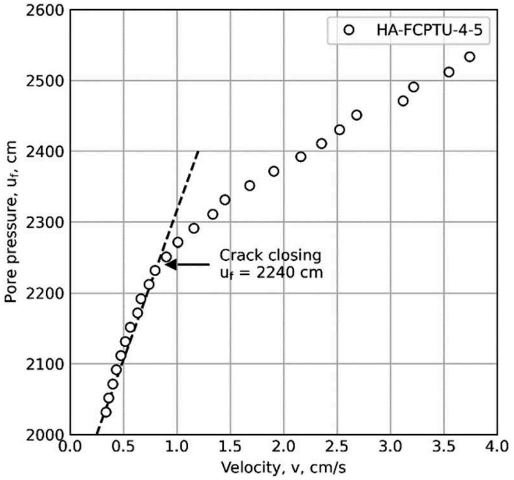

Figure 8. Pore pressure, u_f, with rate of change in pore pressure, velocity, including discontinuous interpretation line.

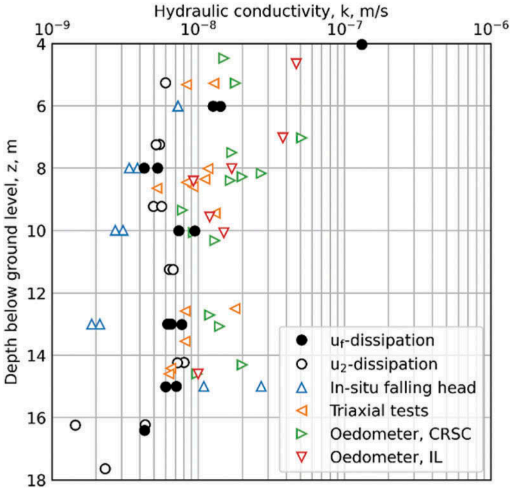

Figure 9. Hydraulic conductivity from benchmark tests and flow cone tests with depth.

7 DISCUSSION AND COMPARISON

Figure 9 illustrates the hydraulic conductivities from benchmark tests (oedometer, triaxial and in-situ falling head tests) and flow cone u_2-dissipation and u_f-dissipation tests with depth. Oedometer and in-situ falling head tests generally present the highest and lowest hydraulic conductivities, respectively. The difference may be explained by the oedometer values being picked at zero axial strain with presumably higher void ratio than in-situ conditions. For the in-situ falling head tests, a concern is filter clogging during installation, causing reduced water injection area and lower calculated hydraulic conductivities. Other aspects of the in-situ falling head tests involve soil disturbance, stress changes, transient consolidation, variations in piezometric level, shape factor, etc.

Hydraulic conductivities from u_2-dissipation and u_f-dissipation show good agreement with triaxial test results, especially from 10 m to 15 m bgl. It is evident from Figure 9 that u_2-dissipation and u_f-dissipation tests can identify the main soil layering i.e., the clay below 16 m bgl and the sand 4 m bgl presenting significantly lower and higher hydraulic conductivities, respectively, as expected.

Except for falling head and u_2-dissipation results below 14.5 m bgl, in-situ tests show good repeatability. In contrast, oedometer results show some scatter which may be due to disturbance during sampling and sample handling having significant influence on the results due to small sample size.

Distribution of excess pore pressures around the cone tip and shoulder are generally more complex than alongside friction sleeve and CPTU rods. Based on Teh and Houlsby (1991) it is expected that flow patterns for u_f are predominantly radial and more repeatable compared to u_2. With pure radial flow, the influence of filter size is expected to be negligible, however this should be investigated for confirmation.

The laboratory and in-situ tests differ in that for laboratory tests, de-aired water was used for hydraulic conductivity testing, while clean tap water was used for in-situ tests. For future in-situ testing water with properties as in the field should be used. In addition, the laboratory tests gave vertical hydraulic conductivity while horizontal consolidation properties dominate in-situ dissipation, suggesting hydraulic conductivity anisotropy ratio close to one at Halden.

The proposed interpretation methodology for flow cone hydraulic conductivity requires input of rigidity index and constrained modulus, which may be unknown or difficult to determine. The impact of these parameters on the estimated hydraulic conductivity should be further investigated.

From the testing at Halden it is evident that the effect of water flow during cone penetration is pore pressure build-up. However, the influence of 5 ml/min of water flow on the excess pore pressure was negligible compared to that from cone penetration itself. It is suggested that flow rate be determined based on experience and equations from Gundersen et al. (2019) to produce project specific hydraulic heads. It is considered most important to avoid flow rates yielding excessive hydraulic heads and thereby zero effective stresses in the soil surrounding the u_f-filter also leading to significant soil disturbance and/or erosion.

The determined K_0-value from hydraulic fracture test compares well with the general trend presented in Blaker et al. (2019). However, more tests should be carried out before conclusions can be drawn on the appropriateness of K_0-determination using flow cone module.

8 SUMMARY AND CONCLUSIONS

The flow cone is a standard cone penetrometer paired with a custom-built hydraulic module including a pressure transducer inside a porous cylindrical filter located an offset behind the friction sleeve and was trialled at the Halden silt site. Pore pressure development with time was measured at two locations, behind cone shoulder, u_2, and 1.23 m behind cone shoulder, u_f. The majority of u_2 dissipation plots suggest dilative behavior and a square root of time method was used to correct the initial pore pressure.

Hydraulic conductivity from flow cone dissipation (u_2, u_f), in-situ falling head and constant head oedometer and triaxial tests were compared. u_f dissipation presents best repeatability, whereas in-situ falling head tests and constant head oedometer tests yielded the lowest and highest values of hydraulic conductivity respectively. Due to the larger volume of soil and greater height of the triaxial test specimen, the hydraulic conductivity measurements made on these specimens are generally expected to be more reliable. Results from flow cone dissipation and constant head triaxial tests compare well. These observations present a confident potential of the proposed methodology for u_f dissipation, which is based on classical uncoupled solution for undrained cone penetration and subsequent pore pressure dissipation. However, further studies should be carried out to fully verify the proposed interpretation methodology, also considering the influence of rigidity index, compressibility, filter size, soil disturbance and general soil behavior.

One hydraulic fracture test was conducted in the clay unit at Halden resulting in a coefficient of earth pressure at rest that compares well with the general trend from literature.

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