The Norwegian GeoTest site infrastructure

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ABSTRACT: Benchmarking is a key to the reliability of solutions in geotechnical engineering. Throughout the world, a system of geotechnical experimentation sites with a wide range of geological ground conditions is available for testing and verifying innovative soil investigation methods and calibrating foundation solutions. These benchmark test sites provide easy access to well-characterized and documented field test sites for advancing the state of the art in areas such as in situ testing, instrumentation, prediction of soil behaviour, and foundation prototype testing. This lecture will give a short review of Norwegian experience with benckmark test sites and show examples of the practical use of geotest sites.

Keywords: Benchmark; soil characterization; in situ testing; calibration and verification of tools.

1. Introduction

Critical infrastructure—such as energy structures, roads, railways and buildings—is increasingly being built on difficult ground conditions such as soft clays, silt and loose sands. Problematic geo-materials are encountered in almost all modern development. Unfortunately, the tragic quick clay landslide at Gjerdrum in Norway on Dec. 30th, 2020 showed how important and complex the work of geoengineers is.

Geotechnical engineering is not an exact science. Design approaches, models, tools and analysis methods need to constantly be tested, verified and calibrated. Over the years a system of geotechnical bechmark test sites with a wide range of geological ground conditions has been developed throughout the world for testing and verifying innovative soil investigation methods and calibrating foundation solutions.

This paper gives a short overview of benchmark test site availble in Norway and internationally. Furthermore, some examples of large scale testing and comaprison of in situ testing methods at the Norwegian Geotest site facility (NGTS) are presented.

2. What is a geotechnical benchmark test site?

The term benchmark test site or reference site, as used in this paper refers to a site that is well characterized and that can be used to compare measurements or observations made by different techniques or methods. This means that a test site must be well defined in terms of geological history, soil classification parameters and strength, deformation and flow parameters. Other requirements or specification for a test site usually include, but are not necessarily limited to i) representative soil conditions for an area or project type, ii) ease of access, iii) availability, iv) size—e.g. large enough for model testing, and v) relevant infrastructure is in place; e.g. access road, water supply and electricity.

Figure 1 presents the approximate location of well-known benchmark test sites in the world. Tests sites are available for a range of soil conditions in many different countries. Example of well-known test sites are the

- Test sites in Canada; e.g. Gloucester clay site near Ottawa; [1, 2]
- National Geotechnical Experimentation Sites (NGES) in the USA; [3]
- Perinö clay site in Finland; [4]
- Sarapuí I and II sites near Rio de Janeiro, Brasil; [5]
- Treporti site on silty sediments near Venice, Italy; [6]
- Uitdam peat site, Netherlands; [7]
- Soft clay sites at Ballina and Burswood, Australia; [8-10]
- Several sites in Ireland on silt and peat; [11]
- Bothkennar National test site on soft clay, U.K.; [12]
- Cuxhaven test site on dense sand, Germany; [13]
- Ariake soft clay test site, Japan; [14]

Figure 1. Location and overview of well-known benchmark test site in the world, after [15].

3. Benchmark test sites in Norway

The NGTS research infrastructure is a national research facility for geotechnical research. The five benchmark test sites are located in Norway and on Svalbard and have been developed as field laboratories for the testing and verification of innovative soil

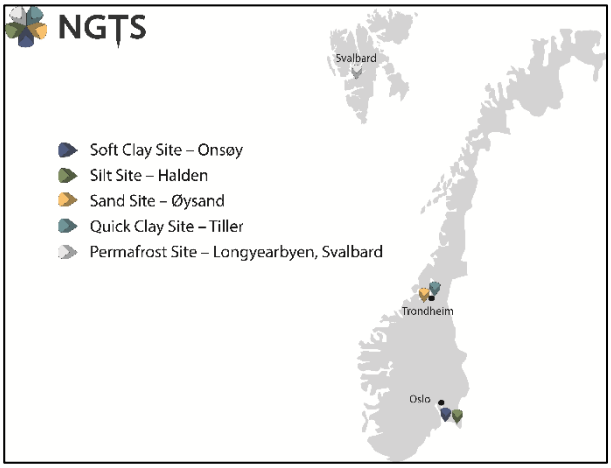

Figure 2. Location of the NGTS geotechnical research sites in Norway.

investigation and testing methods (Fig. 2). The sites include soft clay, quick clay, silt and sand. One of the sites is in permafrost on Svalbard where detection, sampling, in situ testing and laboratory testing of frozen ground present significant challenges.

The test sites serve as reference sites for the industry, public authorities, research organizations and academia. The benchmarked data can be used to develop soil material models, new investigation methods, new foundation solutions and advance the state-of-the-art.

Permanent installation and instrumentation at all NGTS test sites include:

- Access road, water and electricity
- Work shelter which can be used as local office and lab
- Weather station
- Thermistor strings for continuous monitoring of ground temperature
- Piezometer for continuous monitoring of porewater pressure

3.1. Soft clay site at Onsøy

The engineering properties of the Onsøy clay site have previously been documented extensively [16]. Because of the thickness of the clay deposit and its very uniform nature, the Onsøy site has been used for research purposes for many years. The site is located in southeastern Norway, about 100 km south of Oslo (Fig. 2). The new area of investigation at Onsøy is about of 3,500 m^2 (i.e. 50 x 70 m).

The natural water content varies between 45 and 65%. The average plasticity index varies from about 50 in the upper 9m to about 30 below 9m. The sensitivity (S_t) measured by fall cone tests is constant at about 6. The over-consolidation ratio (OCR) decreases from about 4 near the surface to 1.2 at 30 m depth.

The soils at the Onsøy site are marine clays. Such clays were deposited during deglaciation and the early postglacial period (Holocene) at times of higher relative sea level. Marine clays are found extensively in Norway, Sweden and Finland. The Onsøy clay has many similarities to marine clays in, e.g. Canada, Japan and

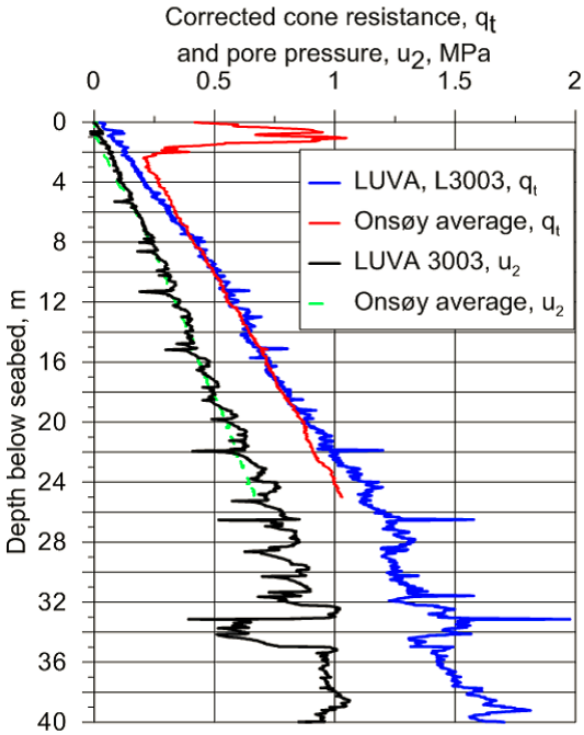

Figure 3. Comparison of corrected tip resistance and pore pressure at Onsøy and at the Luva gas field offshore Norway, from [17].

southeast Asia. The Onsøy clay is also remarkably similar to clays found offshore at the Troll, Gjøa, Luva later renamed Aasta Hansteen oil and gas fields. The apparent preconsolidation at all these sites is caused by ageing.

Figure 3 presents a comparison of CPTU results from Onsøy and the Luva gas field. The similarities in characteristic and behaviour with many clays around the world illustrate the significance of the Onsøy deposit as a benchmark site.

3.2. Silt site at Halden

Intermediate soils such as silts are challenging materials in geotechnical design. The Halden test site, located approximately 120 km south of Oslo (Fig. 1), provides a great opportunity to test tools and methods in such deposit. The site consists of a uniform marine silt up to 10 m thick (Fig. 4). The natural water content in the silt decreases only slightly between depths of 4.5 to 11m, with values at about 30%. From 11 to 15m, the water content decreases more rapidly to about 21%. Soil classification charts suggest the Halden silt to be in the zones at the interface between "transitional soil" and "silt and low rigidity index ' Ir ' clays. Classification tests in the laboratory indicate a low plasticity silt with bulky grains. The clay content in the silt varies slightly from 9 to 15%. A full overview of the Halden silt site facility is presented in Blaker et al. [18].

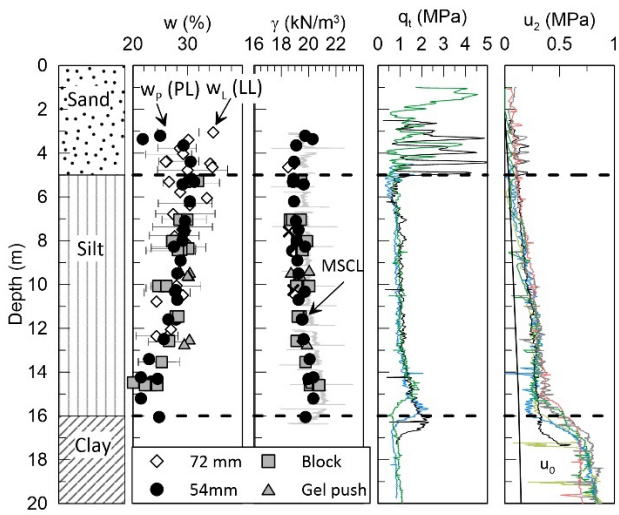

Figure 4. Soil profile at Halden from different sampling techniques and cone penetration tests, after [18].

3.3. Quick clay site at Tiller-Flotten

Deposits of sensitive marine clay can be found over large areas of Scandinavia and north America. Such deposits are extremely challenging to work with for geotechnical engineers. In addition, landslides occur frequently due to both natural and man-induced triggers. The site at Tiller-Flotten is composed of homogenous marine clay, defined as quick (remoulded strength less than 0.5 kPa) from 7 m below terrain and until a depth of 25 m. The sensitivity (S_t) of the clay is about 150. A typical soil profile from Tiller-Flotten is presented in Fig. 5. For more information about the site see L'Heureux et al. [19].

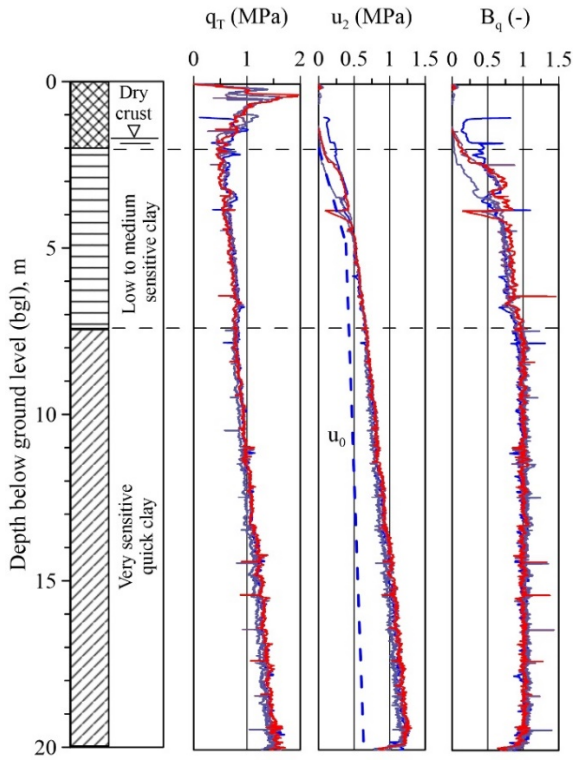

Figure 5. Typical soil profile at Tiller-Flotten with results from cone penetration tests (after [19]).

3.4. Sand site at Øysand

The NGTS facility includes a site with loose to medium dense sand near Trondheim at Øysand. The glaciofluvial and deltaic deposit at this site is approximately 20-25 m thick, relatively homogenous, and consists mostly of fine to medium uniform sand with predominance of quartz minerals, some plagioclase and micas. A full overview of the sand site facility is presented [20].

Soil sample quality at Øysand is presently being evaluated using several techniques including: (i) Geonor 54 mm fixed piston composite sampler, (ii) 72 mm thin walled fixed piston sampler, (iii) Gel-Push sampler (without success so far, only two samples obtained) and (iv) soil freezing. Results from the ground freezing investigation are in progress. Reconstituted specimens are also being tested, and the results of "intact" and reconstituted advanced tests will be compared later.

3.5. Permafrost site in Longyearbyen

There are two permafrost sites available for testing in Longyearbyen on Svalbard [21]. These sites are included within the NGTS infrastructure to investigate topics including foundation methodology, site investigation techniques, embankment behavior, and artificial cooling systems in saline marine clays and intermediate permafrost soils. These sites were selected as they are representative of the soil conditions in Svalbard and other Arctic locations. Access to both sites is easy as they are located close to the University research centre (UNIS) on Svalbard. An example of testing conditions at the permafrost site outside Longyearbyen is shown in Fig. 6.

Figure 6. Typical soil profile at Tiller-Flotten with results from cone penetration tests (from [21]).

4. Data and instrumentation at the NGTS sites

A comprehensive and high-quality soil database is available for all NGTS test sites. The database includes information from in situ geotechnical tests, geophysical tests and laboratory test as shown in Table 1 and 2. Some of the test are material specific and have not been performed on all sites. Additional tests can be performed upon request. For more information, and for a full overview of the data and equipment available at the NGTS facility, the reader is referred to [16, 18-21].

Table 1. Example of in situ tests, sampling techniques and geophysical investigations carried out at the NGTS facility.

	Testing methods
In situ tests	Cone penetrometer also with resistivity and seismic modules (CPTU, SCPTU, RCPTU)
	Dilatometer (DMT) and Seismic dilatometer (SDMT)
	Push-in-pressure cells
	Piezometers
	Field vane test
	Rotary pressure soundings
	Hydraulic fracture test
	Screw plate load test
	Self-boring pressuremeter test
Sampling techniques	Geonor (ϕ 72 mm) fixed piston
	Geonor (ϕ 54 mm) fixed piston
	Sherbrooke block (ϕ 250 mm)
	Mini-block (ϕ 160 mm)
	Gel-push sampler (ϕ 83.5 mm)
Geophysics	Multiple analysis of surface waves (MASW)
	Electrical resistivity tomography (ERT)
	Ground penetrating radar (GPR)

Table 2. Example of laboratory data available at the NGTS facility.

Water content analysis (WC)	Multi sensor core logging (MSCL) including gamma density and magnetic susceptibility (MS)
Unit weight (density)	Split core imaging
Unit weight of solid particles	Oedometer tests at constant rate of strain (CRS)
Atterberg limits	Hydraulic conductivity
Grain size distribution (GSD)	Triaxial - Anisotropically consolidated undrained compression tests (CAUC)
Fall cone test (FC)	Triaxial - Anisotropically consolidated undrained extension tests (CAUE)
Salinity	Direct simple shear (DSS)
X-ray diffraction (XRD)	Bender element test
X-ray inspection (XRI)	Scanning Electron Microscopy (SEM)
Unconfined compression tests (UC)	

All work carried out at the NGTS facility is available through the Datamap application at http://www.geocalcs.com/datamap.

Information from these sites includes results from field and laboratory tests, published articles and reports. Access to the dataset can be accomplished in two steps. First, users register with the system at http://www.geocalcs.com/datamap by creating a user name and password. Once logged in, the user navigates to the "Join Project" tab by first clicking the "My Projects" link in the upper right-hand corner of the map viewing screen. They then, must enter the details in Table 3 and click on the "Join Project" button. Users can then navigate back to the Map view by clicking a link in the upper right corner.

Table 3. Access codes and project names to access data from geotechnical research sites in the Datamap application.

Site	**Soil**	**Project name**	**Code**
Onsøy	Soft marine clay	NGTS-Clay	NGTS2016
Halden	Silt / clayey silt	NGTS-silt	NGTS2016
Øysand	Gravelly sand to silty sand	NGTS-Sand	NGTS2016
Tiller-Flotten	Very sensitive marine clay	NGTS-Quick_clay	NGTS2016
Long-yearbyen	Permafrost	NGTS-Permaforst	NGTS2016

5. Use of test sites for large scale testing and verification of geotechnical tools

The availability of the NGTS sites, the high-quality database and the established facility has already led to its use for e.g. large-scale testing and for verification/calibration of investigation techniques. Example of tests and problems earlier performed at the NGTS facility includes:

- Benchmarking of soil investigation methods for on- and off-shore applications (e.g. CPTU, T-ball, SDMT, sampling tools, etc.)
- Testing of new instrumentation and monitoring technology (e.g. passive seismics, sensor technologies)
- Field testing of various foundation propotype (e.g. pile capacity tests, testing of suction anchors, etc.)
- Investigation of soil-structure interaction and comparison of field/lab measurement and numerical models (e.g. piles, sheetpiles, retaining wall, anchors, excavation, slopes, embankment, etc.)
- Testing of new and innovative soil stabilisation methods (lime-cement, bioash, biocementation, salt, etc.)
- Permafrost related problems in a changing climate (e.g. foundation methodology in frozen soils, artificial cooling systems, solifluction and creep related problems, etc.)

Below are some example of projects performed at the NGTS facility in quick clay at Tiller-Flotten.

5.1. Testing and verification of installation methods for quick clay stabilization with salt

Lime-cement stabilization is often used as a basic reinforcement in construction projects in areas with quick clay, especially in connection with road projects. But this method leads to large CO_2 emissions from cement production. Also there is a large risk of pore pressure increase in the soil during the installation phase.

Wells filled with potassium chloride (KCl) can be used as an alternative to conventional stabilizing methods in sensitive clays, see [22]. However, there is currently no standard installation method for such salt wells. In the period 2018-2019 a collaborative project between the municipality of Stjørdal, the Norwegian Public Road Administration (NPRA), BaneNor, NGI and Multiconsult used the NGTS site at Tiller-Flotten to test the impact of various salt installation procedures on excess pore pressure generation in the sensitive clay deposits. Results example are shown in Fig. 7. The salt installation methods tested included:

- Ischebeck-stag with cross drill bit + KCl slurry
- Total sounding with cross drill bit + KCl slurry
- Total sounding with + KCl poles (or sticks)
- Sonic drill + KCl slurry

The benefit-cost factors related to these procedures were found to be small compared to conventional landslide mitigation measures. Base on the results, guidelines for safe and cost-efficient installation procedures were proposed by using potassium-chloride as a sustainable landslide mitigation-measure in slopes with highly sensitive quick-clay deposits. A full overview of the study and results is presented in [23].

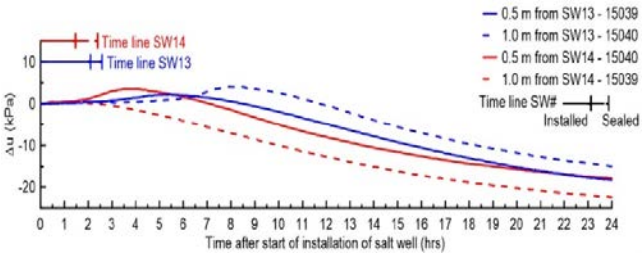

Figure 7. Example of pore-pressure response (Δu) the first 24 hours after installing the KCl poles at Tiller-Flotten, after [23].

5.2. Impact of cone penetrometer type on measured CPTU parameters

It has been recognized for a long time that CPTU probes of different design can give different results, even if they all fulfill the requirements given by international standards. This can be problematic when soil investigation contractors using different cones in the same area, and especially on the same project.

In 2017-2018, five different cone manufacturers were invited to test their equipment at the NGTS sites. A total of eight different penetrometers were tested and compared. Two to four tests were carried out with each cone type and the results have been systematically compared and documented [24-26]. An example of CPTU results comparison at the NGTS Tiller-Flotten site is shown in Fig. 8. In general, the main findings of this comparitive study are:

1. For all of the cones, penetration pore pressure u_2 gave the most repeatable results. When comparing tests with different cone types, seven of the cones give very similar u_2 values at all sites. One cone type using a slot filter and lower penetration rate gave lower u_2 values. At the quick clay site, all of the cone types give similar u_2 readings, but the scatter increased with depth.
2. Corrected cone resistance, q_t, generally varies somewhat more than u_2, regarding test with the same cone, and more when comparing one cone type with another.
3. Some of the cone types give good repeatability for sleeve friction, f_s, readings, while some show relatively large variation. When comparing f_s from different cone types the variation is quite large, which is in line with previous experience. An attempt has been made to understand the reasons for the large f_s variations, but there are still unanswered questions [24].
4. Due to the large uncertainties with the f_s readings one should be careful with using this parameter, and also the friction ratio, when interpreting soil parameters for design.
5. The measured u_2 values appear to frequently be the most reliable parameter and should be used in addition to q_t for deriving soil parameters.

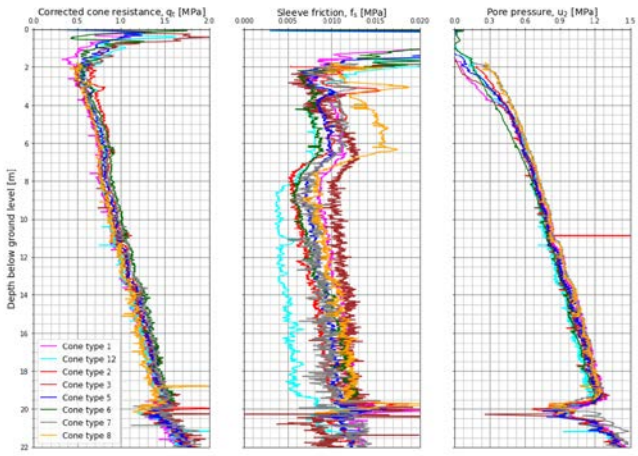

Figure 8. Comparison of CPTU results at the NGTS quick clay site at Tiller-Flotten, after [25].

5.3. Comparison of methods for in situ assessment of shear-wave velocity (V_s)

Characterizing of the stress–strain behavior of soils is an integral part of many geotechnical design applications including site characterization, settlement analyses, seismic hazard analyses, site response analysis, and soil-structure interaction. Several field techniques exists for the measurement of V_s and these are generally divided into two categories: invasive and non-invasive methods. Common invasive methods include seismic dilatometer (SDMT), seismic cone penetrometer (SCPTU) and crosshole logging. Non-invasive geophysical methods include e.g. spectral analysis of surface waves (SASW),

multichannel analysis of surface waves (MASW), seismic refraction and reflection.

There are many advantages in using non-invasive methods in practice as such methods allow relatively large volumes of soil to be investigated and are cost-effective. However, methods like the MASW often suffer loss in resolution with depth. Also, larger volumes will encompass factors such as layering and anisotropy, which are not evident in smaller-scale testing.

Shear-wave velocity data were obtained in situ by means of seismic dilatometer (SDMT), seismic cone penetration tests (SCPTU) and multichannel analysis of surface wave (MASW) at the NGTS Tiller-Flotten site. In the laboratory, V_s data were acquired using bender elements on high quality block samples prior to testing in the triaxial cell (i.e. unconfined state) and inside the triaxial cell at in situ stresses (p'_0). A comparison of all acquired V_s data and estimated G_{max} data is presented in Fig. 9. As seen on this figure, the results obtained using the different in situ field techniques are for all practical purposes very similar. The measured values show V_s to increase from approximately 120 m/s below the dry crust to 225 m/s at 20 m below ground level. These are characteristic values for Norwegian soft marine clays and are very similar to measured values for other sites in the Trondheim area [27].

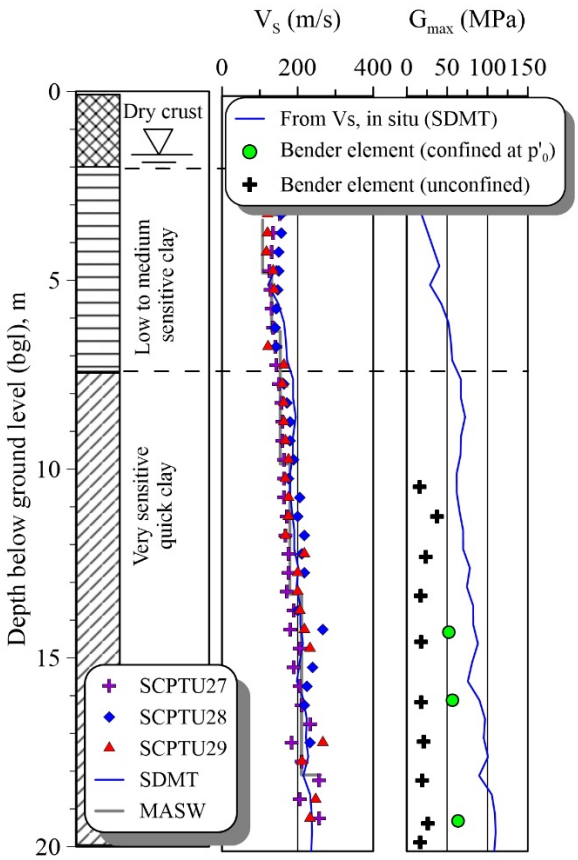

Figure 9. Comparison of V_s and G_{max} measurement at Tiller-Flotten, after [19].

The shear stiffness of soils is primarily function of density, void ratio, and effective stress, with secondary influences including soil type, age, depositional environment, cementation, and stress history c.f., Hardin and Drnevich [28]. Results from Tiller-Flotten show that V_s values obtained in the laboratory on high quality block samples are consistently lower than those obtained in situ (Fig. 9). This is attributed to both stress relief in the samples following sampling and to sample disturbance effects. Reconsolidation to in situ stresses gave shear wave velocity values 20% less than in situ values. In terms of G_{max}, and according to the elastic theory, this results in a percent change of 44%. Such differences can have important consequences in practice.

5.4. Comparison of methods for assessment of K_0

The coefficient of earth pressure at rest, K_0, is defined as the ratio of the effective horizontal stress σ'_H to the effective vertical stress σ'_V. The K_0-parameter is used in the design of e.g. foundations, retaining walls and tunnels. It is also used to generate initial stresses when using advanced numerical methods of complex geo-engineering problems. The results of laboratory tests also strongly depend on the estimate of K_0 (e.g. small strain shear modulus, G_{max}, from resonant column tests, strength and moduli from static and cyclic triaxial tests). Although K_0 can have a significant impact on inputs and calculation results, the reliability in the estimates of K_0 is still uncertain today. Results from dilatometer tests were evaluated using both the original Marchetti [29] equation and the equation proposed by Lacasse and Lunne [30] for estimation of K_0. The Marchetti equation was used with $\beta k = 2$ as proposed by Hamouche et al. [31] for intact sensitive soils, while the Lacasse and Lunne equation was used with m = 0.64 for low plastic clays. Results show K_0 values decreasing from values close to 2.0 in the dry crust to values in the range 0.65–0.70 from 15 m below ground level and deeper.

Using laboratory and field data L'Heureux et al. [32] performed regression analyses and showed that for Norwegian clays the K_0 could be evaluated using the following equation:

$$K_0 = 0.53 \cdot OCR^{0.47} \quad (1)$$

where OCR is the overconsolidation ration of the soil. Eq. (1) was used to estimate K_0 from OCR through laboratory data (i.e. oedometer tests) and field data (i.e. CPTU) at Tiller-Flotten (Fig. 10). Results are fairly consistent with that estimated from dilatometer data. Push-in pressure cells were installed in the Tiller-Flotten clay to assess the horizontal stresses in the ground and evaluate K_0. At first, five different cells were installed at a depth of 5 m to assess the repeatability of the equipment. As seen on Fig. 10, large scatter in K_0 was obtained. The reason for the unreliability of this tool may be attributed to the degree of disturbance during the installation, but also to the fragility of the tool that easily bend during the installation and thus measured stresses induced by bending moments [19, 33]. In general the push-in pressure cells gave lower K_0 values than that estimated by other techniques at the site.

The litterature suggest good experience with hydraulic fracturing testing for in situ assessment of K_0 in normally consolidated clay deposits. However, there is no experience available with such technique in Norwegian high sensitive clays. Galdon [34] performed several hydraulic fracturing tests at the NGTS Tiller-Flotten site.

The obtained data is presented in Fig. 10 while a comprehensive instrument presentation is given in Galdon [34].

In general, K_0 obtained by hydraulic fracturing were between 20 and 40% higher than those obtained from dilatometer, CPTU or by Eq. (1). Those higher values may indicate that, perhaps, the horizontal stress was not correctly measured, i.e. no vertical cracks open when injecting the fluid in the ground. It is likely that the hydraulic fracturing tests lead to a cavity expansion in the very sensitive clay, hence explaining the high K_0 values.

Finally, in situ horizontal stresses were also assessed using the self-boring pressuremeter tests (SBPT) at the NGTS sites at Halden and Onsøy. Results from these tests are presented in Blaker et al. [18] and Gundersen et al. [16]. Despite uncertainties associated with the K_0 interpretation, results from SBPT and DMT data at these sites show a fairly good agreement with K_0 values generally in the range between 0.45 and 0.60.

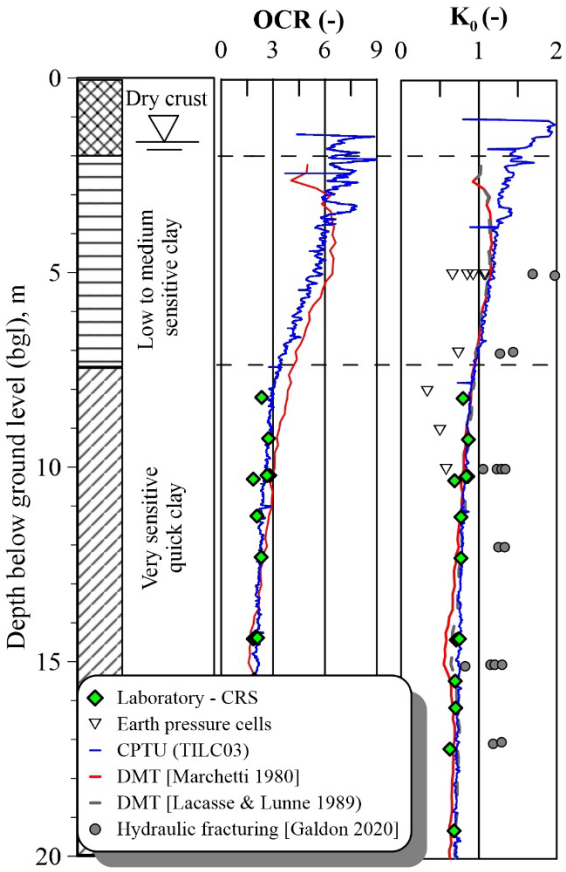

Figure 10. (Left) Overconsolidation ratio (OCR) and (right) comparison of coefficient of earth pressure at rest (K0) with depth obtained with several methods at the NGTS quick clay site at Tiller-Flotten, after [19].

6. Conclusions

The NGTS testing facility is a system of multi-user test sites that is available for the entire geotechnical profession for the purpose of basic and applied research, and education. The immediate availability of high quality data and facilities is already leading to a general use of the NGTS in Norway thus significantly enhancing the possibilities for development and implementation of new and cost effective solutions thereby leveraging research investments in geosciences. It is hoped that the next years will see an increase use of these benchmark sites as a research tool, as training and teaching facilities and as ground for development of soil models, testing of new investigation methods and further advance the state-of-the-art.

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