REPORT

Characterization of Norwegian peat

WORK FOR 2019

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NGI.NO

Project

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Client:	Norges forskningsråd & Norsk Geoteknisk Forening
Client contact person:	Anne Kibsgaard & Carsten Hauser
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for NGI

Project manager:	Priscilla Paniagua
Prepared by:	Priscilla Paniagua
Reviewed by:	Jean-Sébastien L'Heureux

Summary

The present report summarizes the results of the GBV 20190149 and 2019 NGF scholarship on Characterization of Norwegian peat. Data from 19 sites have been collected, in addition to data from 4 large scale tests. A database of peat properties, including index data, strength and deformation characteristics and geophysical data has been established. Furthermore, 7 sites were chosen to collect additional field and laboratory data. This work was carried out during summer 2019. Correlations based on water content and shear wave velocity for strength estimation have been tested and compared to DSS tests results on block samples collected. Additionally, deformation tests (i.e. CRS and peat odometer tests) have been carried out.

Most of the peat samples in the database have water contents around 600-800%. The peat thickness at the sites generally ranges from 3-4 m with exceptional sites having peat thicknesses up to 12 m. The most common von Post number is 3 which means very slight degree of humification/decomposition. The shear wave velocity values are mostly around 16-24 m/s.

From the 7 sites that were surveyed, the peat deposits have a degree of humification varying from H2-H3 (insignificant-very slight) at shallow depths (< 0,5 m) to H2-H5 (slight-moderate) up to 3,5 m depth. After that the deepest peat deposit shows a classification of H3 (slight) down to 7,5 m depth. The highest decomposition value found was H7 (strong). With rrespect to the amount of fine fibres and coarse fibres, both characteristics vary between low to moderate.

One-dimension consolidation tests results with constant rate of strain (CRS) and peat odometer apparatus indicate a yield or preconsolidation stress around 10-12 kPa. The modulus number varies between 7-10. A good match is observed between the DSS undrained shear strength values and the values obtained from correlations found in the literature. In general, undrained shear strength from DSS varies between 2 kPa and 8 kPa.

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Review and reference page

1 Introduction

Peat is frequently found in the high latitudes of the Northern Hemisphere. Canada and Russia have the most extensive areas of peatlands although extensive areas are found in northern Europe, especially Fennoscandia. This type of soil has high compressibility and low strength when subjected to external loads from civil engineering structures. To geotechnical engineers, peat is an example of extreme type of soft soil (or problematic type of soils) often leading to problems like differential settlements or slides that have an impact on society. Therefore, a common solution is to remove the peat layer in many civil engineering works.

Due to population increase and demand for social improvements, there is a strong need to find better ways to cope with peat soils while keeping project cost as low as possible. Understanding peat behaviour is necessary to help overcome some of today's challenges, like for example resilience of infrastructure, CO2 emission and climate change adaptation.

According to NIBIO, there is 28 300 km² of peat in Norway which represents 9% of its country area. Trøndelag is the largest peat region in Norway where peat covers 18% of its surface area. Norwegian peat areas contain carbon equivalent to Norway's total climate emissions for 66 years (SABIMA, 2015).

1.1 Scope of the project

The project's main objective is to characterize the Norwegian peat. This has been carried out by the activities presented in the chart below:

Database work	Field & Laboratory work	Analysis work
•Collecting peat data from different road projects and field tests performed in Norway during the last 60 years. •Establishing a database with the collected peat data	•Field work on selected sites to general characterization and shear wave velocity measurements •Laboratory work for measurements of water content, organic content, deformation properties (CRS & peat odometers), strength properties (DSS) (DSS)	•Evaluation of correlations for strength estimation in peat based on DSS undrained shear strength, Vs and water content •Performing a back calculation (i.e. numerical analysis) of a peat slide that occurred in Klæbu, Trøndelag in 2017 to evaluate the in-situ undrained shear strength

The present report presents the results of the activities mentioned above in four main chapters:

- Chapter 2 - Tests sites and data: database
- Chapter 3 – Field and laboratory work: procedures
- Chapter 4 – Field and laboratory work: results
- Chapter 5 – Correlations for peat strength determination

1.2 Summary of the activities carried out

The activities presented initially in the project proposal ("planned" in Table 1) were slightly modified during the year as specified in Table 1 (See "activity executed" in Table 1). The chapters in the present report that refer to each activity are also specified.

Table 1 Summary of activities as part of the present research project

Activity	Activity planned	Activity executed	Chapter
A	Collecting peat data from different road projects and field tests performed in Norway during the last 60 years. Basic and advanced peat data like water content, von Post classification, density, organic content, shear wave velocity and/or undrained shear strength will be gathered.	Data from 19 sites were collected, in addition to data from 4 large scale tests data.	2.1 & 4
B	Establishing a Norwegian database on peat that will mainly include full-scale peat behaviour in embankments or dykes or any foundations where full-scale monitoring data is available. This database will also be available to the Norwegian geotechnical engineers.	The data was collected, and it is summarized in this report. It will be published as an article in NGM 2020.	2.2 & 4
C	Establishing correlations between the data gathered, as a first order approach, towards estimating deformation and strength properties for Norwegian peat, following the example presented before by UCD.	The existing data (previous the work executed in this project) was very limited. Therefore, the scope of this activity changed towards the use of the new gathered data from activity D and E to analyse correlations for strength estimation. The basic data to establish correlations for deformation properties has been collected in the project and it is planned to be used in 2020.	4 & 5.1
D	Field visiting some of the projects in Trøndelag where field tests and roads have been built on peat to see the status of them and the possibility of performing additional field tests.	Some sites from activity A and B where chosen to perform field and laboratory work. The results will be published in peer-review journal in 2020.	3.1 & 4
E	Establish a soil investigations program at the peat sites visited in item d.	The field investigations program was established, and laboratory work executed.	3.2 and 3.3
F	Performing a back calculation (i.e. numerical analysis) of a peat slide that occurred in Klæbu, Trøndelag in 2017. This will be done in collaboration with SVV and NTNU as a master project.	The work has been carried out by the NTNU master student Omar Berbar. It will be submitted in December 2019.	5.2 and Appendix G

2 Test sites and data: database

2.1 Data collection

Data from 19 sites around Norway has been collected. The database is saved on: P:\2019\01\20190149\Calculations\Database_Norwegian_peat_latest_version.xlsx. The sites included in the database are presented in Table 2. Selection of the sites was based on two main criteria: a) available information regarding peat thickness and b) sample availability. The type of data collected is described in Table 3, while the site location are shown on Figure 1.

Table 2 Overview of sites included in the database

Site	Project number	Full scale tests	Sampling	Soundings	ERT	AEM/EM
Brumunddal-Lillehammer	20150441		x			x
Dyrstad (Fv17)	20170931		x	x		
Betna-Klettelva (Betnamyra)	Extern		x	x		
Haukvanet	Extern			x		
Havstein	Extern		x	x		
Heimdalsmyra (Kattem)	Extern	x	x			
Leirbrumyra-Granåsen	Extern	x	x	x		
Leistad (Ranheim-Værnes)	20160099			x		x
Lund	Extern		x	x		
Moss	20170752		x	x		
Nybakk-Slomarka	20120491		x			
Paulertjønn + Solum	20091752		x	x		
Ramdalsmyra	Extern		?	x		
Ringeriksbanen E16	20180516-20160173		x	x	x	x
Rv710 Selva-Agdenes	Extern	x	x			
Steinanmyra/Dragvoll	Extern		x		x	
Tanemsmyra-Klæbu	20140332		x	x		
Tiller-Flotten	20160154			x	x	
Ugla	Extern			x		

Table 3 Type of data included in the database.

Basic info									Index							Compressibility						Time related				Strength		Vs		Resisti	
ID	Project	Name	Location	Sample name	Sampler type	Sample depth	Peat thickness (m)	Test type	In situ effective stress po' (kPa)	Water content (%)	Bulk density (kN/m³)	Specific gravity Gs (-)	Initial void ratio eo (-)	Organic content (%)	von Post	pc' (kPa)	OCR (-)	Constrained modulus Mo (MPa)	Compression index Cc (-)	Swelling index Cs (-)	Modulus number m (-)	Coef consolidation cvo (kPa)	Coef consolidation cv* (kPa)	Creep - strain Csec (-)	Creep - void ratio C α (-)	Shear strenght (kPa)	Method	MASW	Vs-probe	ERT	Airborne geoscanning

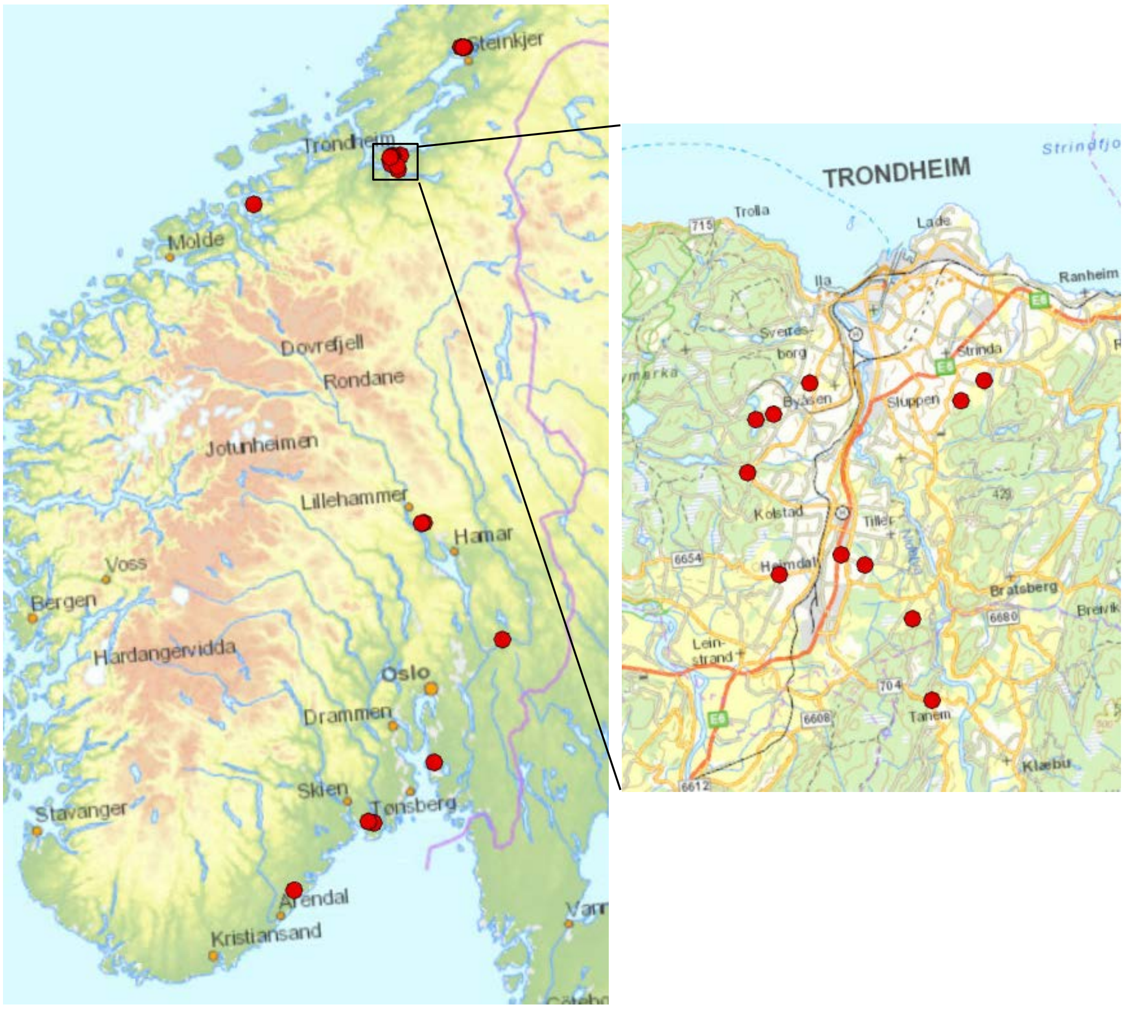


Figure 1 Location of sites included in the database

Figure 2 shows the range of water content, peat thickness, von Post number and shear wave velocity available in the database. For example, natural water content (w) range from 100% to 3000%, with most of the data in the range 600-800%. These values agree well with Kjærnsli (1989) who specified water contents varying between 300-3000%. The most common peat thickness is 3-4 m with some samples coming from peat areas with thicknesses between 11-12 m. The most common von Post number is 3 which means very slight degree of humification. The shear wave velocity values are mostly around 16-24 m/s.

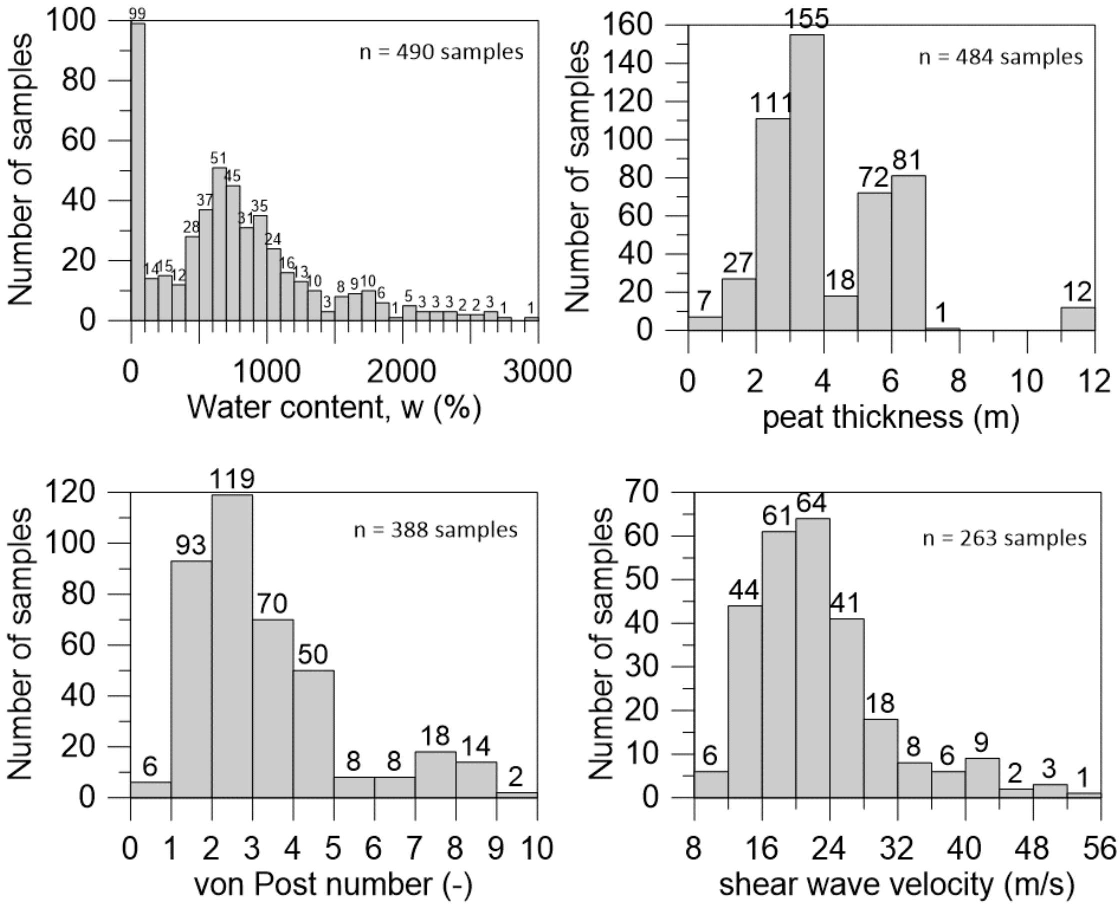


Figure 2 Typical values of the data in NGIs peat database.

2.2 Large scale field tests

Reports from large scale field testing on peat areas in Norway are available in the literature. An example is the work of Gautschi (1967) with test fields near Kongsvinger and Oslo where dams were built on peat areas and settlements at different depths were registered during a period of 100 days.

Hove (1972) presented the results of full-scale loading trials at Heimdalmyra, Norway. Full-scale loading trials were undertaken to assess the feasibility of constructing noise protection bunds of locally excavated peat. Several loading trials were undertaken; for example, a 2,5 m high noise protection bund at Station 5 (c. 25 kPa load) and the 0,5 m gravel platform at Station 3 (c. 10 kPa load). Long & Boylan (2013) have further analysed this data and discussed that at Station 3 the consolidation was rapid, and that primary compression was completed about 2 days after initial loading. It was assumed that the applied stresses did not exceed the yield stress (especially for Station 3) and hence the rapid rate of consolidation.

Trondheim municipality (2015) presented some measurements of the peat layer thickness at Granåsen (Leirbrumyra). The area had been used as a parking place since 1980 and filling with gravel has periodically been done during 1980s-2010s. Settlements have been observed during this period. In 2015, soundings indicated that the gravel layer was varying between 0,7-1,4 m thickness with some points up to 3,7 m. Measurements from 2015 estimate that the peat layer has experienced around 30-50% vertical deformation during a period of around 30 years.

SVV (1978) summarized the settlement measurements performed at Rv.710 Selva-Agdenes where a road was built on a peat layer with thickness up to 2,3 m. The road embankment was built higher than needed to compensate for settlements after 1,5 years. Settlements were registered for 5 months.

These four cases are assembled together in a publication as specified in Chapter 6, to compare peat consolidation parameters from field tests and from the laboratory tests collected in this project.

3 Field and laboratory work at specific sites

3.1 Sites in Trøndelag

Seven sites from the database were selected to conduct field work during summer 2019. The sites are in Trøndelag, near Trondheim. Six of the sites are located under the marine limit (Figure 3). The sediment map from the Geological Survey of Norway (NGU) categorize the deposits at these sites as peat.

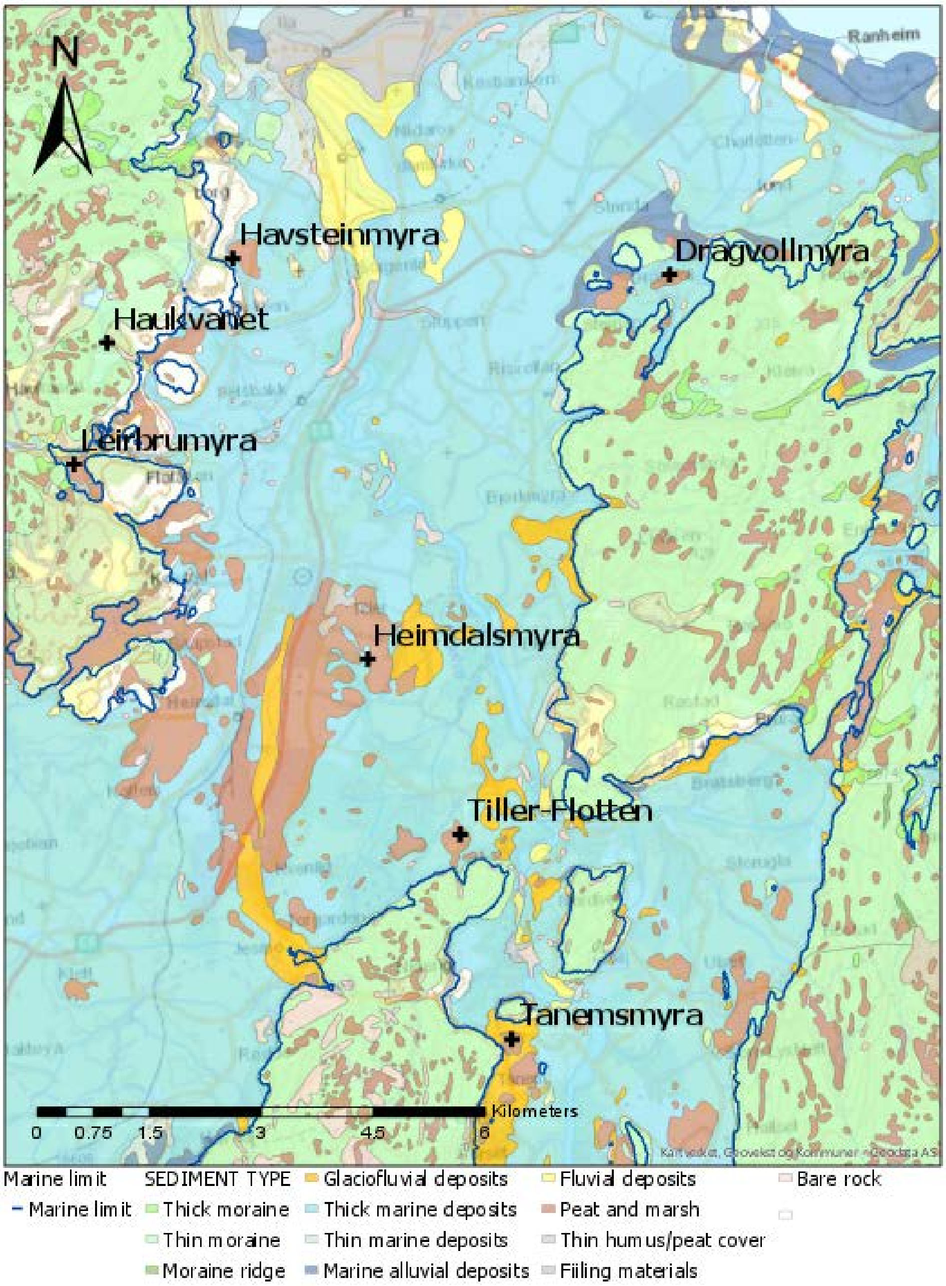


Figure 3 Location of sites included in the 2019 fieldwork.

The existing data for each site is presented in Appendix A. Table 4 presents a summary of the main characteristics of each site.

Table 4 General description of the sites in the municipality of Trondheim where field work was conducted in 2019.

Site	Description of the sites before 2019 field work
Dragvollmyra	The site is in Dragvoll. It has a relatively flat topography. The area is dominated by peat of 5 m thickness over quick clay. Bedrock is found under the quick clay.
Haukvanet	The site is situated at Ugla. It has a relatively flat ground and lies over the marine limit. Peat thickness is varying between 2 m and 6 m depth. Under the peat layer, soundings show a stiff cohesive masses with layer of coarse material. Bedrock is estimated to be shallow.
Havstein	The site is located at Byåsen and it has a relatively variable topography mainly due to mass movements made due to construction projects in recent years. The peat thickness varies between 2 and 4 m.
Heimdalmyra	Heimdalsmyra at Tiller has an elevation varying between 140-145 m.a.s.l. The peat thickness ranges from 2-4 m and lies on top a middle stiff to stiff clay. Large and intense drainage of the area were carried out during the 70's that caused settlements in the peat layer.
Leirbrumyra	Leirbrumyra is located in Granåsen. The site has a relatively flat topography. The peat layer has a variable thickness in the area and can be up to 11 m thick over moraine and weathered material, with some soundings indicating either sand and gravel or silt/clay.
Tanemsmyra	Tanemsmyra is located in Klæbu. It has a relatively flat topography. Field investigations show significant depths of peat from 2.5 - 7 m within the area. There was a peat slide in 2017 because of some excavation works (ref).
Tiller-Flotten (Nonsmyra)	The Nonsmyra bog is situated at the NGTS Tiller-Flotten site (L'Heureux et al. 2019). The research site is relatively flat. The area is dominated by peat over quick clay. The peat thickness is around 5-6 m near the sampling point. The landowner dug some trenches to drain the bog in the area in the 1970's.

3.2 Field work

Field work was carried out during the summer of 2019. It included sampling with a peat sampler and shear wave velocity measurements. Block samples were also taken for advanced testing.

3.2.1 Sampling

Sampling was done at the seven sites presented in Table 4 with a manual peat sampler from Eijkelkamp Soil & Water. Appendix B has more information about the sampler. The bottom part of the peat sampler has an auger body consisting of a half cylindrical sample containing section or “gouge” (see Figure 4, number (1)) with a massive cone (Figure 4, number (2)) at its bottom end. The gouge has one cutting edge and is sealed off by a hooked blade or “fin” (Figure 4, number (3)) inging on the auger body. The blade’s top and bottom end’s width are identical to the auger’s width, but it is wider in the middle. The protruding, rounded side has a cutting edge. The massive cone serves to push aside the soil when the sampler is inserted. At that stage, the blade seals off the gouge. When the auger is given a half turn (180°) to fill the gouge, resistance will cause the blade to remain in position. When the auger is hoisted, the other side of the blade seals off the gouge. The peat sampler’s operational depth is 50 cm. The gouge’s diameter is 60 mm, contents ca. 0.5 litre (sample diameter 52 mm).

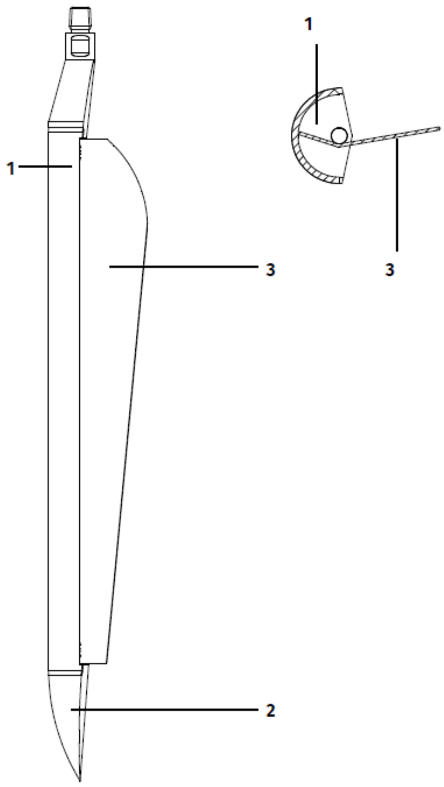


Figure 4 Peat sampler

The peat sampler was pushed within the entire depth of the peat layer until the underlying clay layer or a different deposit was reached. Samples were taken every 10 cm to measure water content. The peat deposit was also logged every 10 cm using the von Post classification system. Figure 5 present some examples of peat samples taken with the peat sampler at Tanemsmyra.

(a)  (b) 

Figure 5 Examples of peat samples taken at Tanemsmyra at depths between (a) 4-4,5 m and (b) 7-7,5 m where the clay boundary was encountered.

Block samples were taken at 0,5 m and 0,6 m at six of the seven sites (it was not possible to take block samples at Havsteinmyra) to perform advanced testing (see chapters 4.3.3, 4.3.4, 4.3.5 and 4.3.6). The samples were taken by hand and wrapped with plastic foil to avoid changes in the water content. Figure 6 shows some examples of the block samples taken.

(a)  *(b)* 

Figure 6 Examples of peat samples taken at (a) Tanemsmyra and (b) at Nonsmyra at Tiller-Flotten.

3.2.2 von Post classification

The peat was classified in the field according to the extended version (Hobbs 1986) of the original classification described by von Post and Granlund (1926). The best known classification system for peats is that of von Post (von Post and Granlund, 1926). It is based on categorisation of botanical composition, degree of humification (H), water content (B), content of fine (F) and coarse fibres (R) and content of woody (W) remnants. It was originally devised to aid the development of an inventory of peat resources in southern Sweden. According to the von Post scale peat is classified as being between H1 (completely unhumified fibrous peat) and H10 (completely amorphous non fibrous peat). Hobbs (1986) extended the system with categories for organic content, tensile strength, odour, plasticity and acidity.

The von Post classification was used at intervals through the full peat column to determine the vertical variations in humification and water content. Special attention was taken where visible interfaces were observed in the retrieved samples. Table 5 and Table 6 below provide details on the classification used in the field assessments.

Table 5 von Post classification system (von Post and Garland 1926), taken from Trafford (2017).

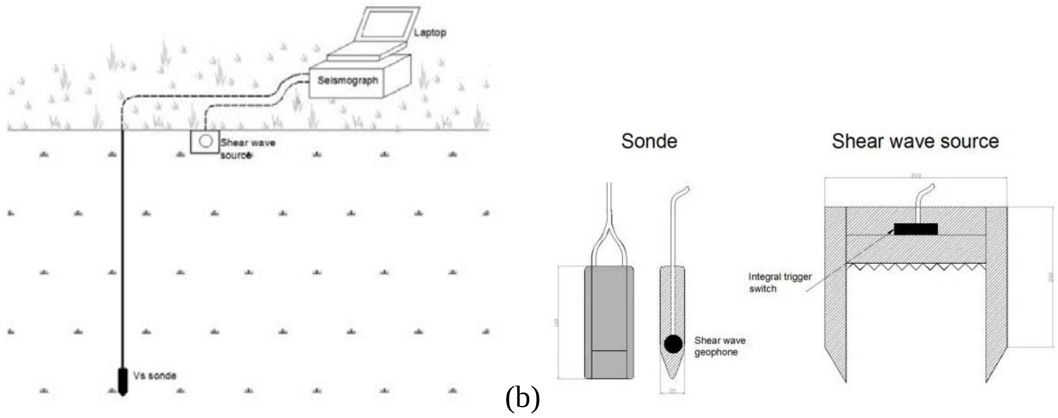
Degree of Humification	Decomposition	Plant Structure	Amorphous Material Content	Extruded Material on squeezing	Nature of Residual
H1	None	Easily ID	None	Clear, colourless water	Not Pasty
H2	Insignificant	Easily ID	None	Yellow water	Not Pasty
H3	Very Slight	Still ID	Slight	Brown muddy water NO Peat	Not Pasty
H4	Slight	Not Easily ID	Some	Dark brown muddy water NO Peat	Some what Pasty
H5	Moderate	Recognisable but Vague	Considerable	Muddy water and some Peat	Strongly Pasty
H6	Moderately Strong	Indistinct (more distinct after squeezing)	Considerable	About 1/3 peat squeezed out. Any water dark brown	
H7	Strong	Faintly Recognisable	High	About ½ Peat squeezed out. Any water very dark brown.	
H8	Very Strong	Very Indistinct	High	About 2/3 Peat squeezed out, also some pasty water.	
H9	Near Complete	Almost Unrecognisable	All	Nearly all Peat squeezed out as uniform paste.	
H10	Complete	Not Discernable	All	All Peat squeezed out, no free water.	

Table 6 Eleven stage field classification system, taken from Trafford (2017).

Stage	Description					
1	**Plant Types**					
2	**Designation (Plants)**					
3	**Humification**	**H1** →				**H10**
4	**Water Content** (test required)	**B1** DRY →	**B2** <500%	**B3** >500%	**B4** >1000%	**B5** >2000% WET
5	**Fine Fibres (<1mm)**	**F0** Nil	**F1** Low	**F2** Mod	**F3** High	
6	**Coarse Fibres (>1mm)** Fibres, stems, rootlets	**R0** Nil	**R1** Low	**R2** Mod	**R3** High	
7	**Wood & shrub (W)** Remnants	**W0** Nil	**W1** Low	**W2** Mod	**W3** High	
8	**Organic Content (N)** (test required)	**N1** 20-40%	**N2** 40-60%	**N3** 60-80%	**N4** 80-95%	**N5** >95%
9	**Tensile Strength**	***T0*** Nil 0	***T1*** Low <2	***T2*** Mod 2-10	***T3*** High >10kN/m^2	
10	**Smell**	**A0** None	**A1** Slight	**A2** Mod	**A3** Strong	
11	**Plasticity**	**P1** Possible		**P2** Not Possible		

3.2.3 Shear wave velocity (V_s) measurements

A portable downhole probe developed by Trafford (2017) was used to take V_s readings through the vertical peat column. The weather during the days of field work was sunny, with temperatures between 25-30°C and no clouds or wind. The probe was connected to a seismograph and recorded as single channel data at different depths within the peat. A shear wave was produced at the surface by striking a hammer against a block within the surface of the peat layer. An integral trigger within the source was used to start the recording of the traces. A reference geophone was also used to check the consistency of the time break. The integral trigger switch was found to be both reliable and repeatable. The down-hole field set-up is shown on Figure 7a. The down-hole probe and shear wave source are shown in diagrammatic form on Figure 7b. More details can be found in Trafford (2017) and Trafford & Long (2016).



(a) (b)

Figure 7 (a) Downhole field setup and (b) downhole probe and shear wave source (from Trafford & Long (2016).

3.3 Laboratory work

3.3.1 Water content

Water content measurements (oven dried at 80 °C for 24-48 h) were taken at 10 cm intervals throughout the full peat column. These were tested in accordance with BS1377-02 (1990). Figure 8 shows some examples of the dried samples used to determine water contents.

Figure 8 Samples after oven dried to measure water content.

3.3.2 Loss of ignition (LOI)

Selected number of LOI tests were carried out on the collected samples. LOI testing was obtained by determination of the loss on ignition at 440 °C for 5 h (Arman 1971).

3.3.3 Constant rate of strain (CRS) tests

Constant rate of strain (CRS) tests were carried out to investigate strain-rate effects and deformation properties of the peat samples. These tests were undertaken on 20 mm high samples at the Norwegian University for Science and Technology (NTNU) using the procedures outlined by Sandbakken et al. (1986). The rate of strain used was varied between 3%/hr, 5%/ hr and 10%/hr in samples from Heimdalmyra to calibrate the rate of strain to be used in the following tests, see chapter 4.3.3 for details on these results. This was done following the standard guidelines for CRS test in Norway that state that the rate must give pore pressures between 3-10% of the total vertical stress (Vegdirektoratet 2014). The samples were loaded to a maximum of 200 kPa in total vertical stress. To obtain pore pressures in the range 6-20 kPa the chosen rate of strain was fixed at 3%/hr.

3.3.4 Janbu torvodometer tests

Tests were carried out on thicker samples using the Janbu torvodometer (Janbu 1970). Samples in the torvodometer had a diameter of 54 mm and a height of 50 mm. Five load steps (i.e. 5 kPa, 10 kPa, 20 kPa, 40 kPa and 80 kPa) were carried out with time intervals of at least 3 hours between them.

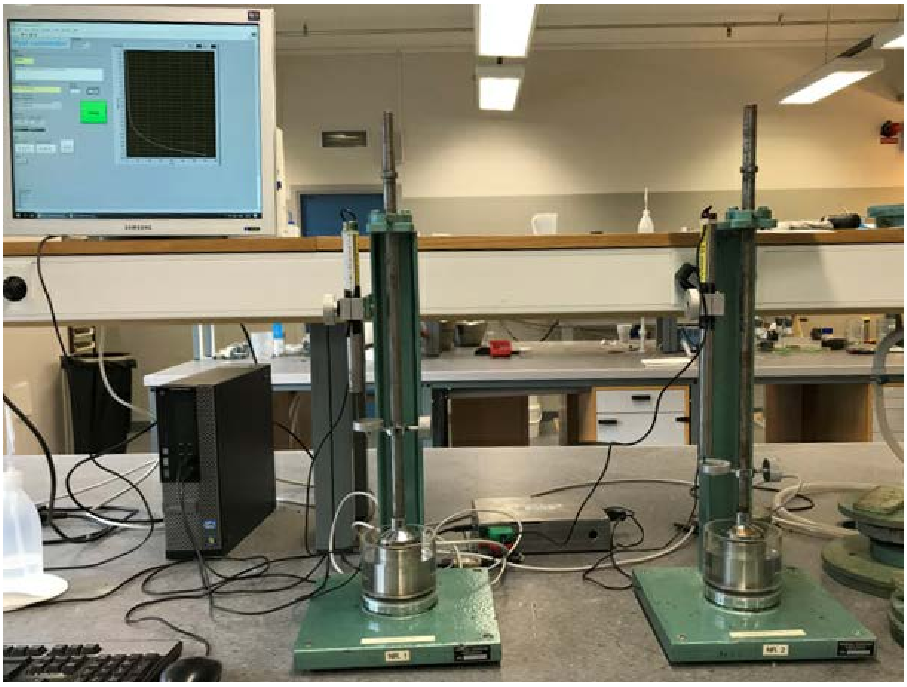


Figure 9 Set-up for the Janbu torvodometer apparatus.

3.3.5 Direct shear stress (DSS) tests

Direct Simple Shear (DSS) testing was carried out at University College of Dublin (UCD) using a Geonor H12 Direct Simple Shear apparatus with load cells and displacement transducers connected to a remote computer to allow continuous automatic data logging (Figure 10). Bjerrum and Landva (1966) provide a full description of the apparatus. Vertical and horizontal load cells are installed on the apparatus to measure the stresses applied to the peat sample during the consolidation (vertical) and shear (vertical and horizontal) phases of testing.

The shearing phase of the testing involves recording the vertical and horizontal displacement as well as the vertical and horizontal load. The shearing is controlled by a motor driven piston that shears the sample at c. 4% horizontal strain per hour or c. 0,8 mm/hour. The undrained shear strength (c_{uDSS}) is taken to be equal to the peak horizontal shear stress ($\tau_{h\text{-}max}$) attained during shearing or the shear stress at 15% shear strain, whichever occurs first.

Figure 10 DSS apparatus at UCD and sample set up to the right.

3.3.6 Shear wave bender element testing

Bender element testing was carried out at UCD to measure the V_S of peat in the laboratory using the procedure described in Trafford (2017), see Figure 11. The purpose was to check for relationships that may exist between water content, consolidation stress and undrained shear strength, as well as to correlate with results from the in situ measurement of V_S using equipment described in chapter 4.2.3.

Figure 11 Shear wave bender element apparatus at UCD.

4 Results and discussion

The results for the field work are presented in Appendix C for all 7 sites. The shear wave profiling along with routinely used methods (water content and Von Post classification) carried out at the sites allowed to establish the layering, thickness, distribution and strength profile of the peat at each study area. Figure 12 shows an example of the output from the vertical shear wave profiling showing correlation between physical log and undrained shear strength profile.

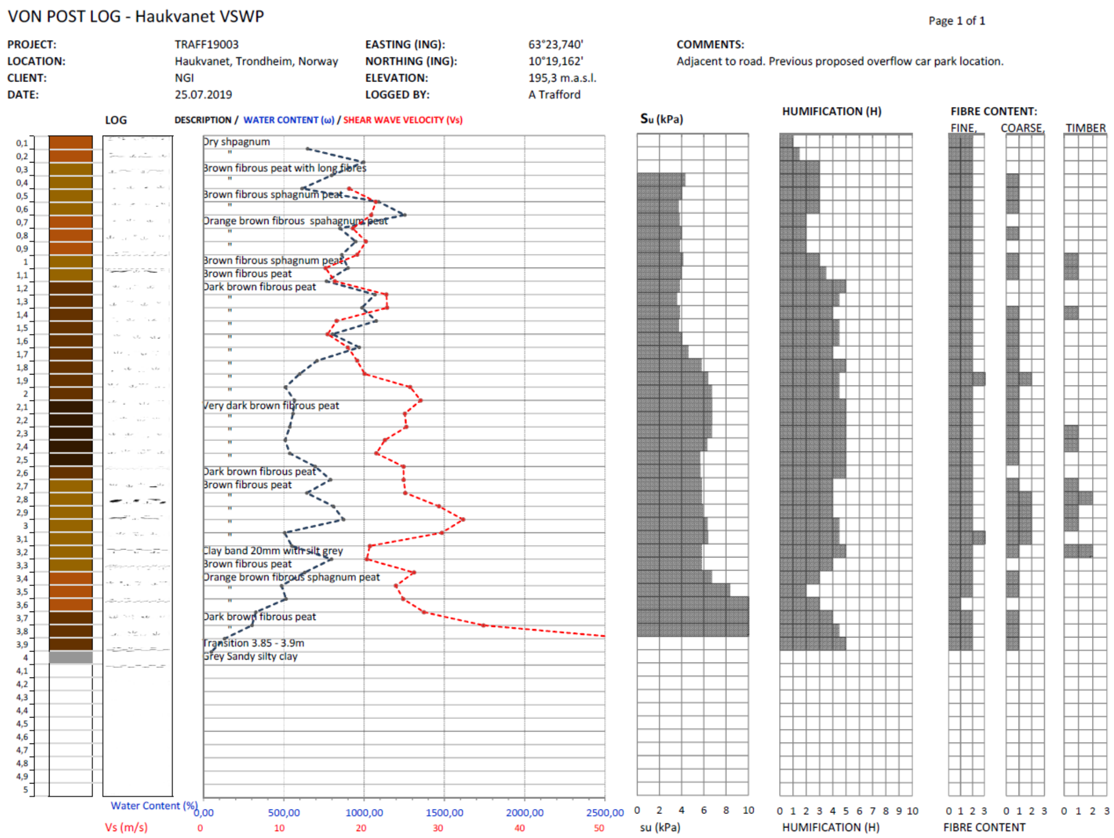


Figure 12 Example output from vertical shear wave profiling showing correlation between physical log and undrained shear strength profile for Haukvanet.

4.1 von Post classification

Figure 13 shows a summary of von Post logging for all the 7 sites in the municipality of Trondheim. Tanemsmyra (which is the deepest peat deposit), Heimdalmyra and Tiller-Flotten sites have the lowest H (i.e. show less decomposition). Leirbrumyra, Havstein and Haukvanet have the highest H (i.e. higher decomposition). This could be related to the geographical location of the sites and their common geological background. Haukvanet is the only site above the marine limit (ca. 176 m.a.s.l.). However, Leirbrumyra and Tanemsmyra are quite close to the marine limit, followed by Dragvollmyra, Heimdalmyra, Havstein and Tiller-Flotten. It is important to remark that these last four sites have been intensively drained in the past and this could have influence the rate of natural decomposition.

Figure 13 shows that Leirbrumyra and Haukvatnet have high F (i.e. content of fine fibers) while Heimdalmyra and Dragvollmyra have high R (i.e. content of coarse fibers). These again could be related to the geographical location and maybe the amount of sun (heat) the deposits receive during the year. Leirbrumya, Haukvanet and Havstein are located on the west part of Trondheim, areas that during the winter receive a limited amount of sun respect to the areas located on the east parts. This need further study as mentioned in Chapter 7.

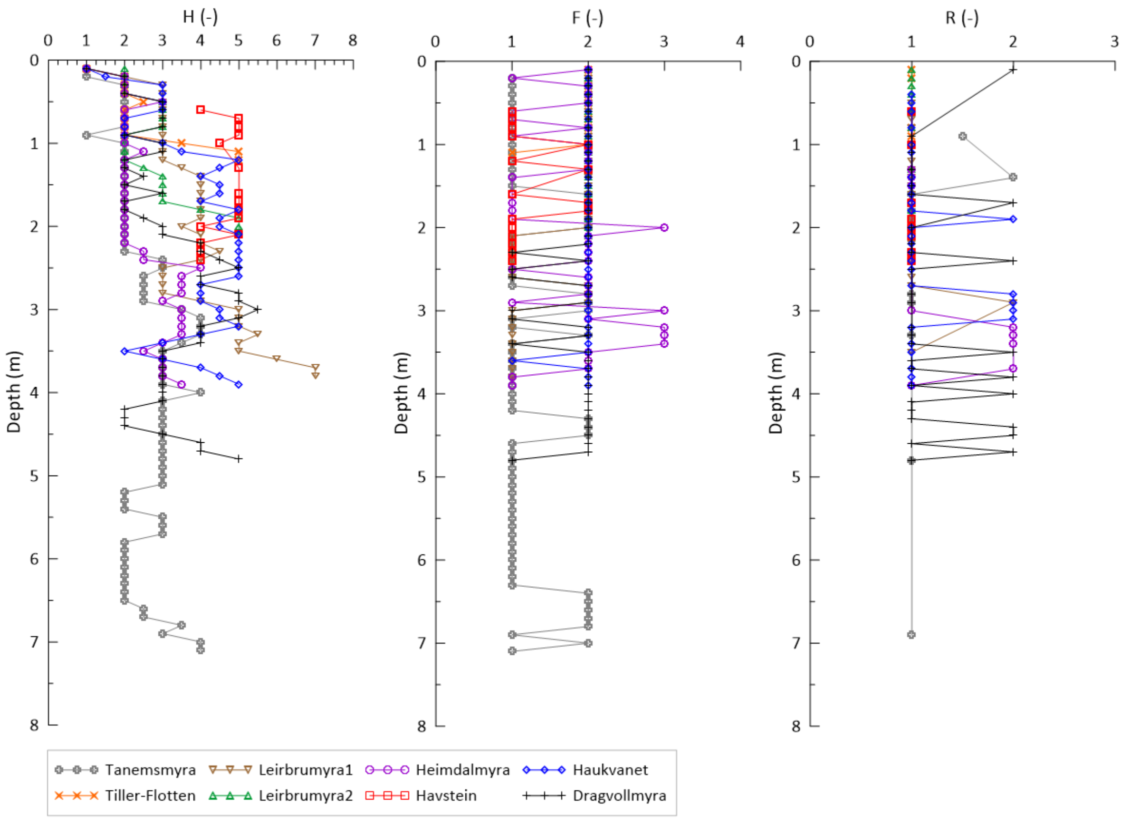


Figure 13 Summary of von Post logging for all the 7 sites.

In general, from the 7 sites that were surveyed, one can conclude that the peat deposits have a degree of humification varying from H2-H3 (insignificant-very slight) at shallow depths (< 0,5 m). At depths down to 3,5m the degree of humification ranges from H2-H5 (slight-moderate). For the thicker peat deposit a degree of humification of H3 (slight) down to 7,5 m depth is found. The highest decomposition value found was H7 (strong). With respect to the amount of fine fibres and coarse fibres, both characteristics vary between low to moderate. Plots of the variation of these values with elevation are found in Appendix C.

4.2 Shear wave velocity, water content and LOI values

Figure 14 shows the shear wave velocity, water content and LOI measurements for all 7 sites. In general, the V_s seems to increase with depth for all sites, from values ranging between 10-30 m/s near the surface to values up to 55 m/s at a depth of 3,5 m and deeper. On the inverse, the plots of water content show a reduction/decrease with depth. Tanemsmyra is a "stand-out" site with the highest water content values, the lowest shear wave velocities and organic content close to the 100%. As it was mentioned before, it is also the deepest peat deposit surveyed in this study and it is close to, but under the marine limit.

From Figure 14 the next "group" with low V_s is composed by Heimdalsmyra and Leirbrumyra1, and the next "group" with a higher V_s is formed by Leirbrumyra2, Dragvollmyra and Haukvanet. Havstein shows the highest V_s for all the sites. In general, the shear wave velocities registered varied between 10-30 m/s. A couple of sites like Havstein and Heimdalmyra (in particular for depth under 2,5-3,0 m) show values up to 40-50 m/s which are the some of the sites that have been under drainage measurements or peat replacement in adjacent areas over several years. Leirbrumyra1 has low V_s but not high %w. This might be due to the low organic content where the deposit was on the classification limit between organic clay or peat.

Regarding the water content, there is a tendency of reduction in water content with depth. The lowest water content values are observed for Havstein. In general, the water content values are between 500-1000% down to 2 meters depth. Heimdalmyra shows a bit larger values up to 1500% from 1 meter to 2,2 meters depth. After that, almost all the sites have water contents around 500-700% down to 3,5 meters depth. Dragvollmyra shows an increase in water content that corresponds also with a change in H from being more humified to less humified with depth. The clay boundary is clearly found also when the water content drops to be lower than 100% and the LOI also decreases.

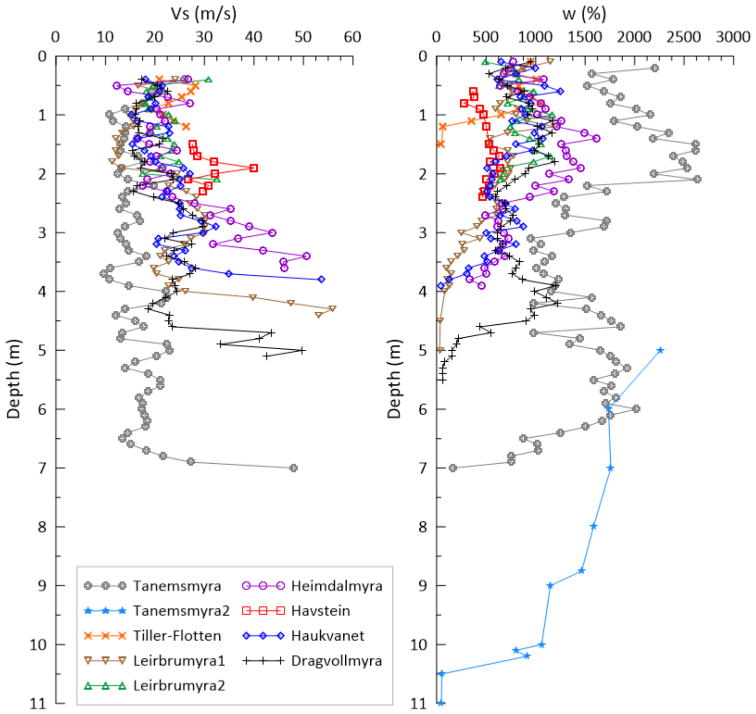


Figure 14 Summary of shear wave velocities, water content and LOI values for all the 7 sites.

As a summary, the V_s for the peat sites investigated varied between 10-30 m/s, with water contents between 500-1200% mostly and organic content are higher than 95% with some exceptions of 85% for Havstein (highly affected by drainage) and Haukvanet (over the marine limit).

4.3 Constant rate of strain (CRS) tests

The first part of the CRS tests consisted in selecting the strain rate to be used. For this, samples from Heimdalmyra were tested at three different rates based on the assumption already stated in Section 4.3.3. The strain rate of 3%/hr was tested on the sample being turned (i.e. to look at the compressibility on the horizontal direction) and being in the sampling direction (i.e. the compressibility in the vertical direction). The strain rate of 3%/hr was chosen according to the pore pressure development, even though no differences on the stress-strain behaviour were observed when changing the strain rate (Figure 15). This agrees with Long & Boyland (2013) who stated that there is only marginal difference between the test results at different test rates. Other deformation parameters (like the oedometer modulus M) are not influenced by the strain rate. The same authors state that there does appear to be a relationship between the yield stress or preconsolidation stress and strain rate. The values for Heimdalmyra show that the yield stress did not vary significantly (i.e. 1-2 kPa) with the strain rate.

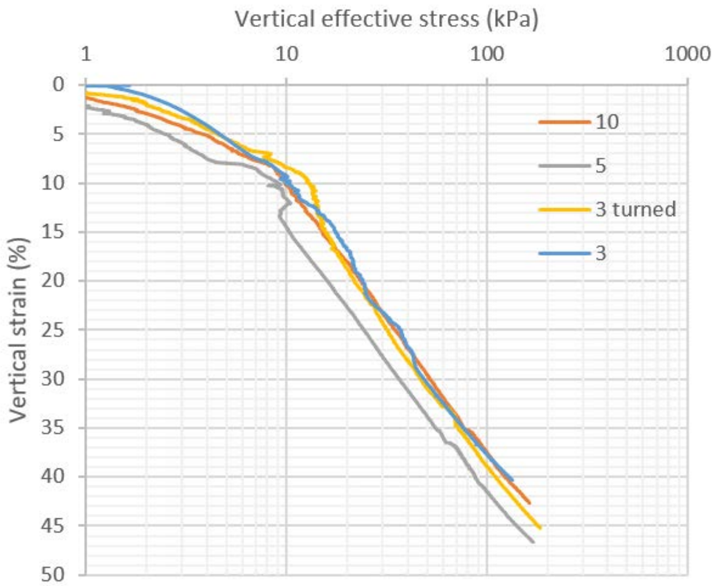


Figure 15 CRS test results with 3 different rates (given in strain % per hour) for Heimdalmyra.

Figure 16 shows the stress-strain curves and the oedometer modulus (M)-stress curves for the CRS tests performed using block samples for six peat sites of this study. Heimdalmyra shows the highest resistance to 1D deformation (i.e. greater stiffness) as a result of the intensive drainage campaign carried out in the area during the 70's. Tanemsmyra shows the highest vertical strains (i.e. lowest stiffness), which might be related to its low values of V_s and high water contents (i.e. more "virgin" peat). Based on these plots, it is possible to interpret a yield or preconsolidation stress around 10-12 kPa with a lower bound of 8 kPa for Tanemsmyra and the highest yield stress for Heimdalmyra. The modulus number for these curves vary between 7-10 with some m values close to 14 for Tanemsmyra and Tiller-Flotten. Janbu (1970) presented modulus number for Steinanmyra, Trondheim in the range of 5-7.

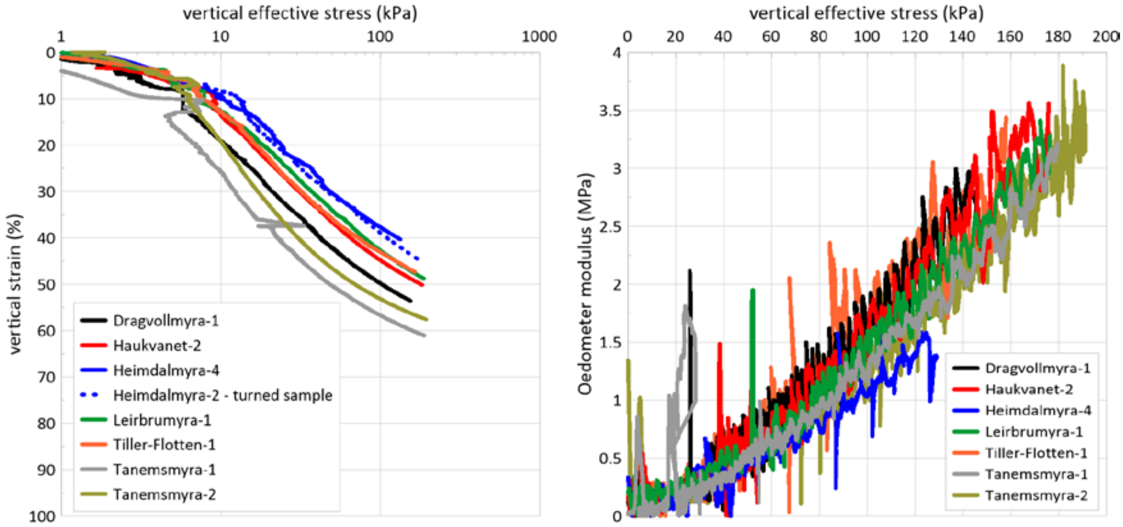


Figure 16 CRS test results (3%/hr) for the peat sites where block samples were taken

When comparing these results with previously proposed curves for Norwegian peat (Figure 17), the stress-strain curves agree, as expected, with the trend that higher water content implies higher susceptibility to deformations. The curves are close to the "soft" peat as suggested by Janbu and are close to the curve for w = 1000% as proposed by Flaate (1967).

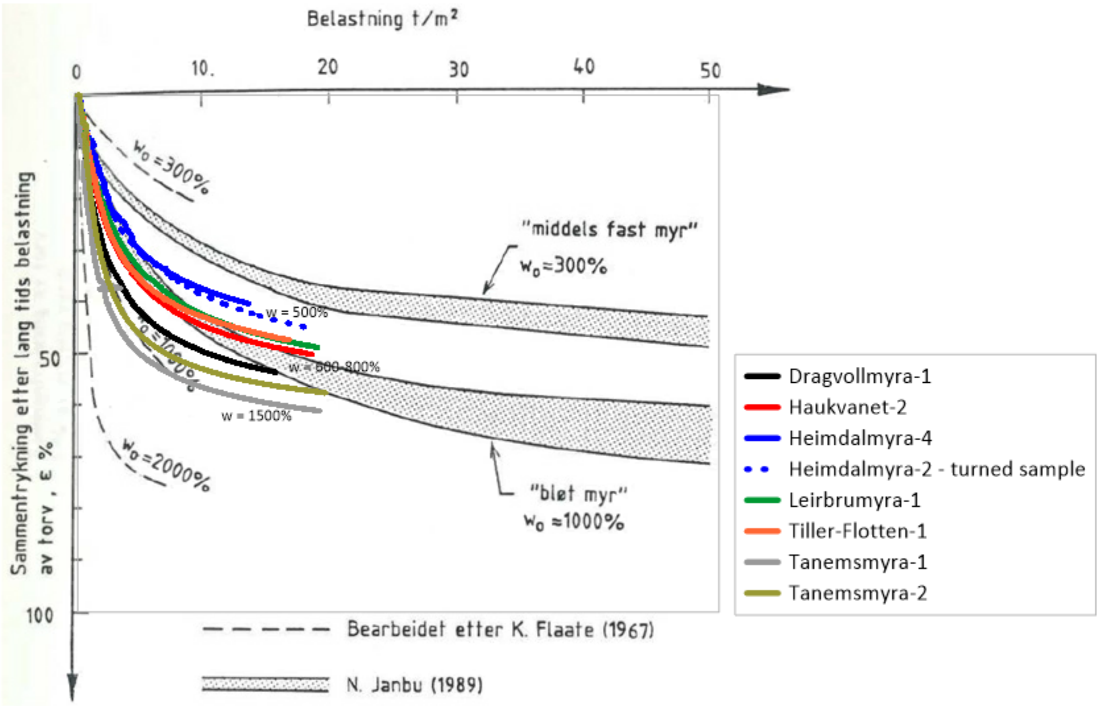


Figure 17 CRS test results compared to data from Flaate (1967) and Janbu (1989).

The interpretation of permeability and coefficient of consolidation at 20 kPa of vertical effective stress gives that the permeability varies between 0,2-1,1 m/year being the lowest values for the sites with higher water content. The coefficient of consolidation varies between 2,5 m^2/year and 28 m^2/year being the highest value for Tanemsmyra. It is observed that the pore pressure developed during the tests varies a lot between the different test and sites. Therefore, the importance of understanding the geological background of these sites. This will be further investigated in 2020.

4.4 Peat odometer tests

Figure 18 shows the stress-strain curves with two types of scale in the x-axis for the peat odometer (torvodometer) tests performed using block samples for six peat sites of this study. Two tests were performed for each site. As seen for the CRS tests results, Tanemsmyra shows also the highest vertical strains (i.e. more "virgin" peat). The other sites tend to be in the same range of deformation with for example a difference of 10% in vertical strains at 40 kPa. Based on these plots, it is possible to interpret a yield or preconsolidation stress around 10-13 kPa with a lower bound of 8-9 kPa for Tanemsmyra. Future work will include the comparison of these results with the CRS results, and their use as parameter estimation for settlements calculations.

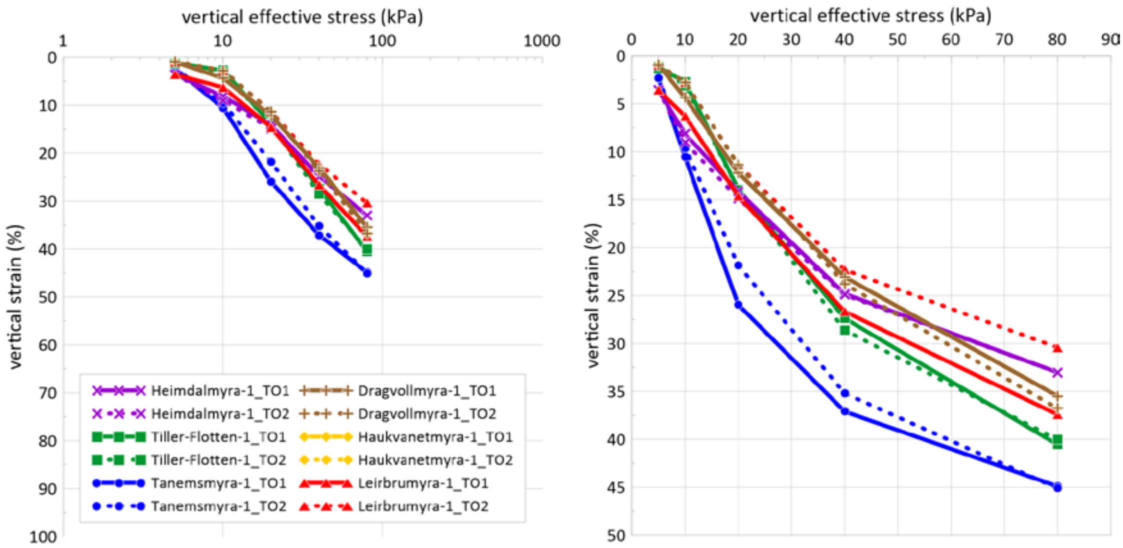


Figure 18 Peat odometer tests results for the peat sites where block samples were taken

4.5 Direct shear stress (DSS) tests

Figure 19 shows the values for the DSS undrained shear strength profile obtained with the correlation proposed (eq. [1]) by Trafford & Long (2020) and the values of the DSS performed at different samples taken from the sites. A good match is observed between the laboratory data and the values obtained with the correlation. The difference between laboratory and correlated values are between 0,2-1 kPa which is the resolution of the

DSS apparatus .This validates the use of this equation for estimating the undrained shear strength in DSS for Norwegian peat.

$$s_{uDSS} = 55{,}80\left(\frac{V_s}{w}\right)^{0{,}683} \qquad r^2 = 0{,}9566 \qquad [1]$$

In general, the DSS undrained shear strength varies between 2 kPa and 8 kPa, being the lowest profile the one for Tanemsmyra and the highest profile the one for Havstein and Heimdalmyra (but just after 2,5 m depth). The increase in strength at certain depths relates to a different deposit from the peat like an organic clay or sensitive clay, where the equation might not be valid. Table 7 presents the input data obtained from the DSS tests performed for this study in block samples.

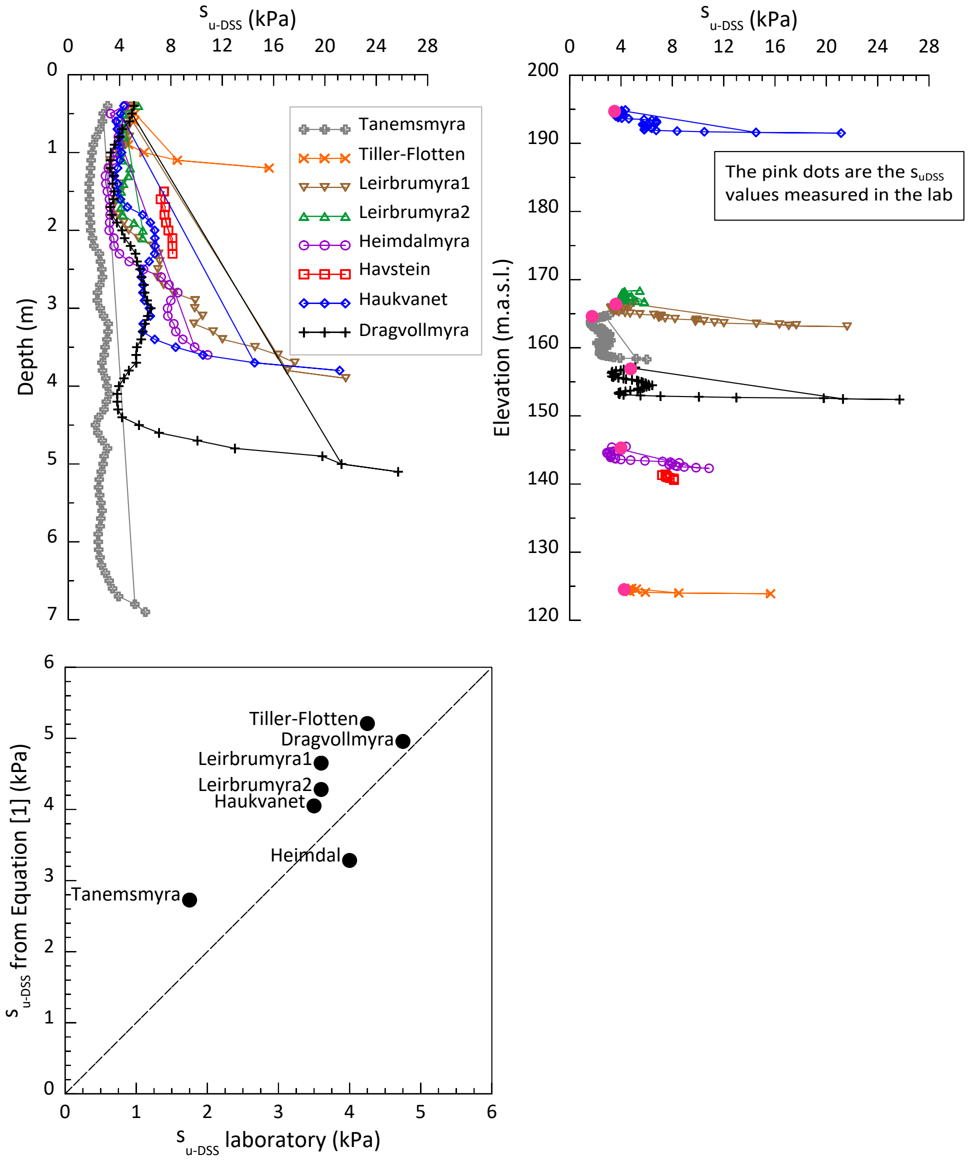


Figure 19 Variation of s_{uDSS} with depth and elevation for the sites. Comparison between laboratory and correlated values of s_{uDSS}.

Table 7 Input data obtained from the DSS tests performed for this study in block samples.

Site	1) In Situ ω (%)	2) In Situ V_s	3) ω/V_s	4) DSS s_u	5) DSS ω	6) DSS $σ_{vc}$ (KPa)	DSS Density (Mg/m^3)	7) Bender Element ω	8) Bender Element V_s (m/s)	9) Bender Element $σ_{vc}$ (KPa)
Tanemsmyra	1855	19	0,010	1,75	1576	3,22	0,901	1696	25	2,5
Tiller-Flotten 1	846	27	0,032	4	878	5,51	0,987	873	28	4
Tiller-Flotten 1a	846	27	0,032	4,25	829	4,33	0,987	-	-	-
Tiller-Flotten 2	846	27	0,032	4,5	887	4,55	0,975	-	-	-
Heimdalmyra	818	20	0,024	4	943	4,00	0,919	886	28	4
Leirbrumyra	760	20	0,026	3,6	664	4,23	1,050	-	-	-
Dragvollmyra	886	23	0,026	4,75	772	4,02	1,003	-	-	-
Havstein	530	28	0,053		-			-	-	-
Haukvanet	1250	20	0,016	3,5	1183	3,27	0,936	-	-	-

1 - Taken from lab analysis of field samples
2 - Measured in the field using VSWP method
3 - Relationship used to estimate in situ undrained shear strength value
4 - Undrained shear strength measured in lab using DSS apparatus (taken as peak stress or stress at 15% vertical strain)
5 - Water content taken from sheared peat disc sample (post consolidation)
6 - Vertical consolidation applied to peat sample during shearing phase
7 - Water content of sample testes in lab for shear wave velocity
8 - Shear wave velocity derived from bender element testing.
9 - Vertical consolidation applied to peat sample during shear wave testing

5 Correlations for determining peat strength

5.1 DSS data from Norway vs European sites

The data obtained in the present study is compared to previous lab and field data collected by Trafford & Long (2020) for sites in Scotland, the Netherlands, Ireland and Sweden. Figure 20 present the Norwegian data of the present study compared to the correlation between water content and s_{uDSS} from Trafford & Long (2020). The data for this study is slightly below previous trend. Leirbrumyra and Tanemsmyra seem to be even lower. Tanemsmyra has very high water content values. Hovewer, Leirbrumyra seem to be off the expected trend even though its water content is similar to that in the previous studies. There is no clear relationship between V_s and s_{uDSS}, which may indicate that the water content must be included to establish a relationship.

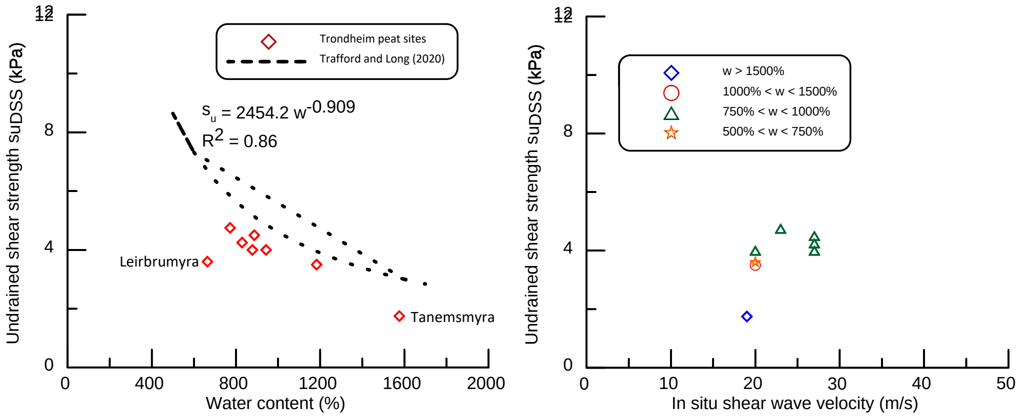


Figure 20 Variation of s_{uDSS} with water content and in situ V_s

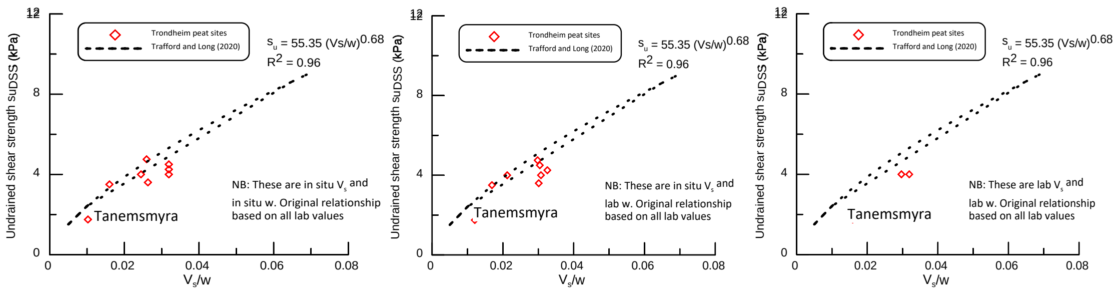


Figure 21 Variation of s_{uDSS} with V_s/w using different V_s and w inputs

Figure 21 presents the variation of s_{uDSS} with V_s/w using different V_s and w inputs i.e. in situ V_s and in situ w, in situ V_s and laboratory w under DSS tests, and lab V_s ad laboratory w under DSS tests. The equation presented is based on all laboratory values. In general, it seems that the data tend to be slightly below the proposed correlation with the data from Tanemsmyra being the lowest value on the plot.

It should be commented about the influence of consolidation stress on the DSS results. In Trafford (2017), the peat samples came from a greater range of depths (up to 1,6 meters) and therefore were consolidated for DSS tests at higher stresses (average was 6,5 kPa). Comparing to Trondheim peat tests, all the samples are from a shallow depth and an average consolidation stress of 4,1 kPa was used. This must be one reason for the difference in the two sets of results. The difference is very small (around 1 kPa) which is close to the resolution of the equipment. However, there is a consistent difference between the two sets of results and it may be that the consolidation stress plays a big role.

Figure 22 shows the variation of V_s with consolidation stress for samples from Tiller-Flotten and Heimdal. When plotting the data in a logarithmic scale, it is possible to identify a somehow yield or preconsolidation stress. For Tiller-Flotten appears to be near 7-10 kPa and for Heimdal near 10-15 kPa. These ranges agree well with the values obtained from CRS tests on samples at the same depth as mentioned in section 5.3.

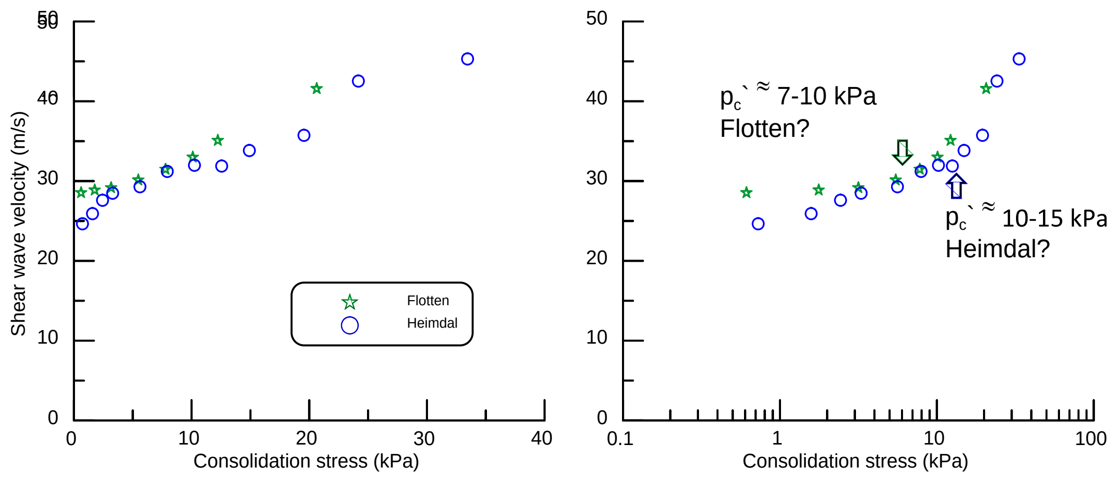


Figure 22 Variation of V_s with consolidation stress for samples from Tiller-Flotten and Heimdal

5.2 Back-calculation for a peat slide at Tanemsmyra

During an excavation in Tanemsmyra, Klæbu in 2017, a peat slide occurred. During the Fall of 2019, a master student has been working on back-calculating the slide to define the in-situ shear strength to be compared to the measurements and correlations established for Tanemsmyra. At the time of writing the present report, the student calculated an undrained shear strength (active) of 8,1 kPa for the short-term stability. These results suggest that DSS tests will underestimate the "operational" strength of peat due to partial drainage and/or fibres effects in the field.

Consolidation analysis are being also performed by the student since it was reported that the excavation was open for at least 12 hours prior failure. Additionally, different geometries for the excavation are being tested to find some recommendations about excavation in peat. The project report will be included in Appendix G after it is delivered at NTNU early January 2020.

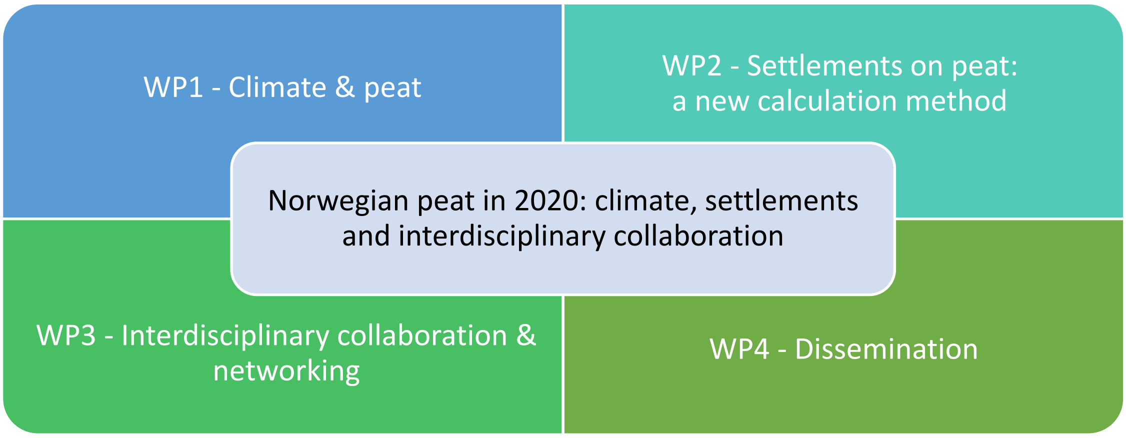
6 Publications

Several publications are under preparation for this work. The following list presents a summary of them:

Conference/Journal	**Title**
NGM2020	Characterization of Norwegian peat: database To be submitted on 03.02.2020
ISC'6	The work of the ELGIP peat group To be submitted on 02.03.2020
ASCE Journal of Geotechnical and Geoenvironmental Engineering	Strength, deformation and geophysical properties for Norwegian peat To be submitted on 01.04.2020
"Når telen går" NGF general assembly	Results of the NGF scholarship: Characterization of Norwegian peat "*Torv – må den graves bort eller kan vi utvikle vår forståelse og fremme mer bærekraftige geotekniske løsninger?*" To be presented in March 2020.

7 Future work

The work for 2019 was successful and accomplished the objectives proposed at the beginning of the project. For 2020, a new GBV project is planned to cover the following activities grouped in four work packages (WP) as presented in the chart below:



The proposed topics for 2020 are suggested based on the following research questions:

Work package	Research questions: what to solve?	Hypothesis
WP1: Climate & peat	Which climate conditions in geological time have allowed the formation of thick peat deposits in Norway up to 10 meters in Klæbu for example? How climate change will affect these areas? How much peat is OK to remove without significant consequences for CO_2 budget in an infrastructure or building project? How does this CO_2 emission calculation compare to other CO_2 emissions caused by traditional methods of stabilizing peat?	Boreal peat accumulation rates are typically 1 mm/year or less (Gorham, 1991). Higher accumulation rates are typical for warmer climates. The conditions for thick formations of peat in some parts of Norway might be related to local climate conditions and local water table. By relating the climate conditions and the geological time for peat deposition one could be able to predict the future of peat areas because of climate change, and then plan its future managing when dealing with infrastructure or building projects.
WP2 - Settlements on peat: a new calculation method	How can the water content, organic content, in situ shear velocity and deformation parameters from CRS and peat odometer tests be related to estimate settlements on peat areas? Short term and long term? Which laboratory tests are the	The data collected during the 2019 GBV will be used to establish correlations for settlements estimation (short term and long term) as it has been done for strength estimation. In addition, a standard laboratory procedure for peat deformation parameters and a

Work package	Research questions: what to solve?	Hypothesis
	most suitable or needed for estimation of deformation parameters on peat? How can the peat classification system be more quantitative?	new quantitative method for peat classification will add input to the correlations.
WP3 - Interdisciplinary collaboration & networking	In which EU projects is Norway involved related to peat restoration where a geotechnical approach should be also included? How can NGI contribute to ELGIP Core Group specific research activities?	Restoration of peat areas must be seen from an interdisciplinary approach. Exchange of results and research activities in the ELGIP Core Group adds also to this networking activities.
WP4 - Dissemination	Which publication plan is suggested for conferences papers/presentations/journal papers to show the results?	Results of the work that has already been carried out in 2019 needs to be disseminate as a research quality control and contribution to the standard practice in the Norwegian geotechnical community.

WP1 - Climate & peat

- Geological dating by C14 of the peat sites tested during 2019 and its correlation to the type of climate at specific geological times. These will define the accumulation rates of these peat areas and help to predict what will it happen when warmer or colder conditions might occur because of climate change.
- Calculation of the climate effect, in terms of CO2 emissions, that the removal of a certain peat volume will have respect to the CO2 budget in an infrastructure or building project. How this climate effect compares to traditional methods for peat stabilization? As case studies, some of the sites already characterized in 2019 will be used.
- Suggest incorporating the CO2 emissions calculations for the different peat improvement methods in the Handbook V221 Grunnforsterkning, fyllinger og skråninger so the results contribute in the decision-making during planning and execution of infrastructure projects.

WP2 - Settlements on peat: a new calculation method

- New method for calculations of settlements on peat. Study of the relationships between shear wave velocities, index parameters (like water content and organic content) and deformation parameters of peat for settlements calculations (short term and long term - creep): the data collected during 2019 will be supplemented with new data if needed and evaluated towards establishing correlations for an improved method to calculate settlements on peat. This is a work that will be carried out in collaboration with Statens Vegvesen (Samson Degago and Øystein Holstad) in order to provide an improved method in the revised Handbook V220. The results will be applied in a case-study (to be defined) to evaluate the long-term performance of a road constructed on peat.

- Improve the classification system for peat. The extended version (Hobbs 1986) of the original classification described by von Post and Granlund (1926) is very qualitative. This work will be done in collaboration with Swedish Geotechnical Institute (SGI, contact Bo Vesterberg). Some activities might include a short research visit at SGI, exchange of samples for diverse laboratory testing like shear wave velocity measurements, measurement of the turbidity of the free water, the organic content and the content of fibres. All these measurements need to be done quantitative to avoid qualitative interpretations in the classification system.
- Optional activity: Validation of a numerical model for peat. The work is based on Prof. Gustav Grimstad (NTNU) work where thermodynamics are applied to predict the mechanical behaviour of peat. Other models used internationally such as Plaxis Soft Soil Creep Model could also be examined along with field data. The data collected during 2019 will be used.
- Optional activity: Maintenance of the Norwegian peat database including new data available.

WP3 - Interdisciplinary collaboration & networking

- Mapping of the EU projects about peat area restoration where Norwegian institutions participate. It is known that several efforts are already ongoing in this topic, without including the area of geotechnical engineering. The idea is to approach these already established groups to encourage joint efforts in understanding the geotechnics of peat drainage and its mechanical behaviour, to evaluate the impact of restoration and create an interdisciplinary group for future joint projects.
- Organization of the ELGIP Core Group Workshop that will be held in Trondheim in September 2020. It will be open to the industry, geotechnical and the peat community in Norway. The idea is to have an interdisciplinary workshop with exchange of ideas for future common research and development. Part of the budget will be covered by ELGIP.

WP4: Dissemination

- Preparation of publications described in Chapter 6.

8 Background about ELGIP core group on peat

NGI has in 2018 become a member of the ELGIP working group on peat (ELGIP stands for European Large Geotechnical Institutes Platform) together with Deltares (The Netherlands), University College Dublin (UCD, Ireland), Swedish Geotechnical Institute (SGI, Sweden), Building Research Institute (ITB, Poland) and University of Cambridge (UK). The main purpose of the group is to collaborate in solving engineering peat related problems and improving tools for practical engineering. The group is working towards a common understanding of the peat mechanics, geology, geophysics and chemistry, by experimental laboratory and field tests and numerical simulations.

During the 2018 workshop of the working group in Linköping, NGI presented some examples about road projects and the standard practice when dealing with peat in geotechnical projects which generally includes peat removal and replacement. At the same time, the other institutions presented the advancements on peat research and finally, a working agenda for the core group was established for 2019. In October 2019 a new workshop was held in Dublin where NGI presented the work carried out as part of the present project. The actions for 2019 were revised and re-established for the coming year of 2020.

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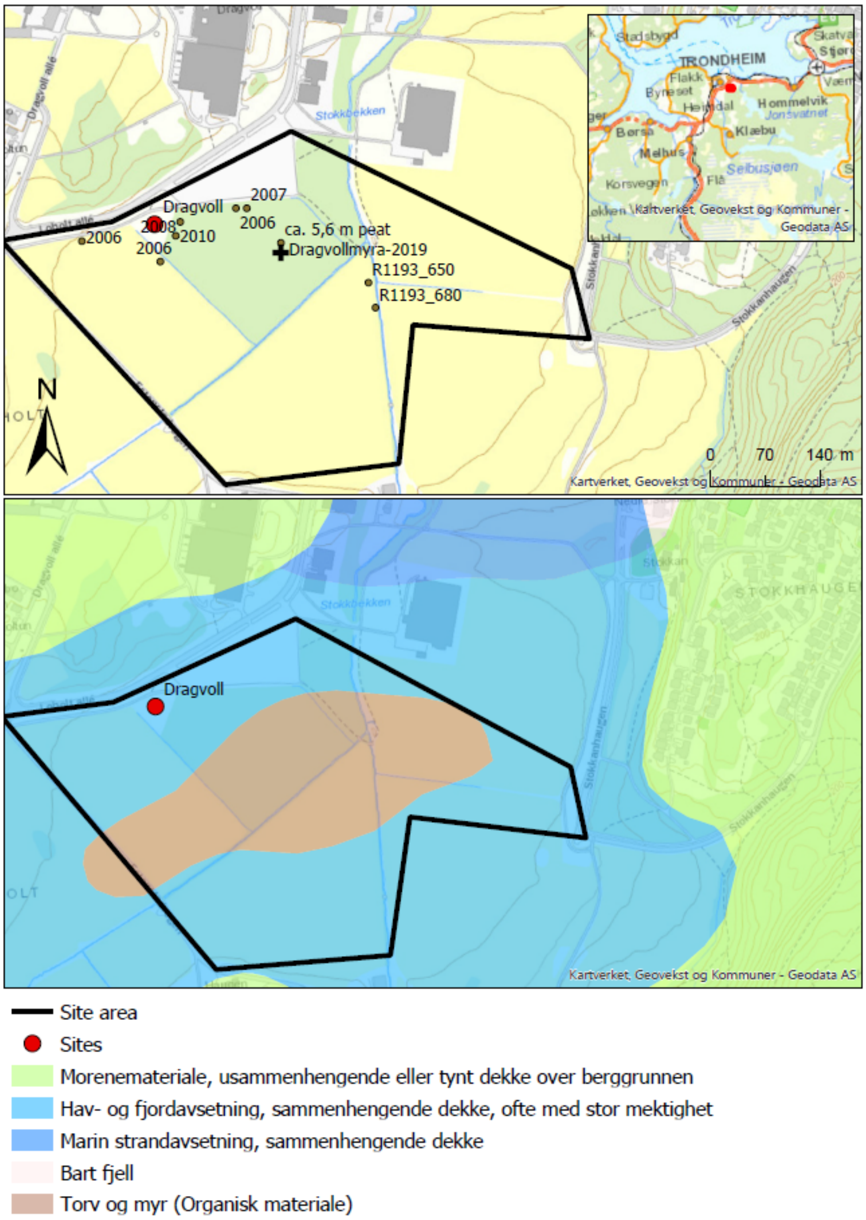
Vedlegg A

EXISTING DATA FOR 2019 FIELDWORK SITES

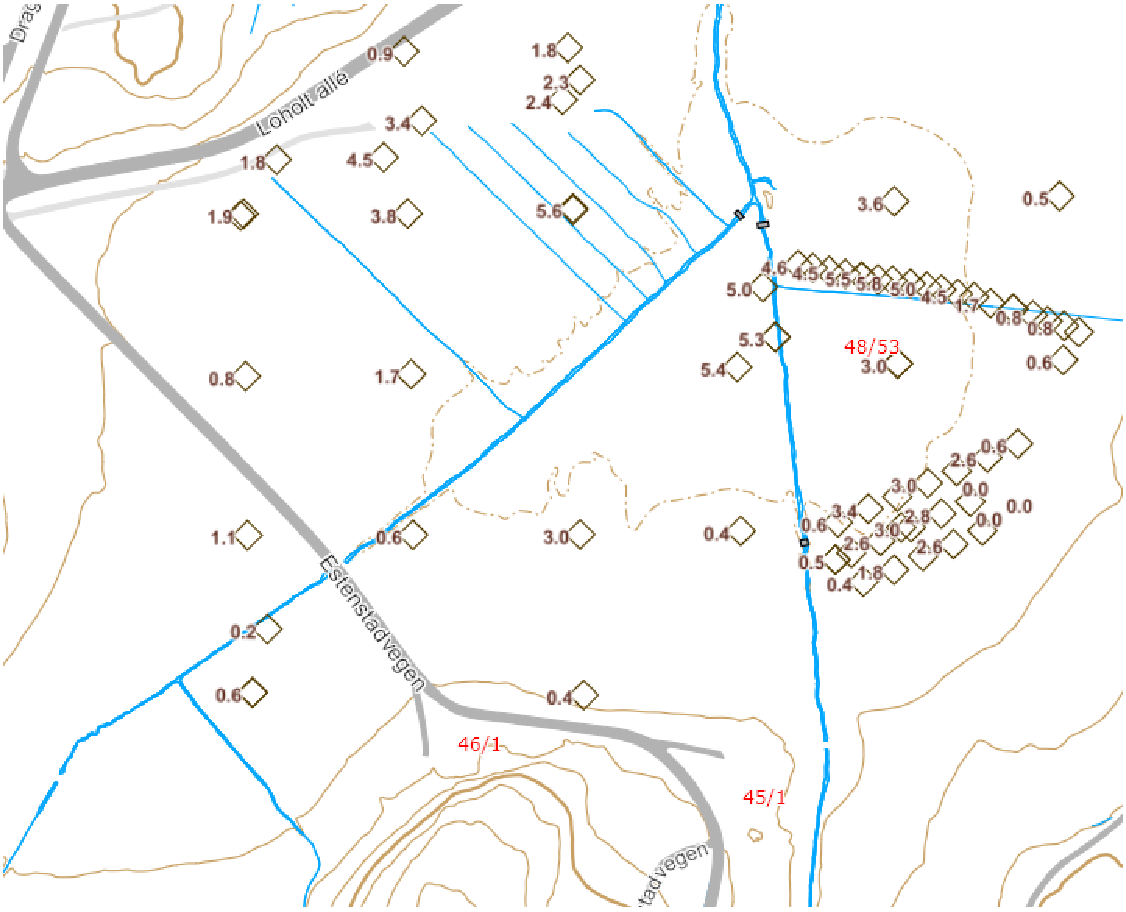
Site location

Dragvollmyra is located in Dragvoll, on the east part of Trondheim, Norway. The site has elevations varying between 159 m.a.s.l. on the northwest towards 153 m.a.s.l. towards the southwest. The area is limited by Stokkbekken in the south and east, a parking area and Loholt alle in the north and Estentadvegen on the west. The site slopes slightly to the south and surface water is drained into the small creek running southwest to northeast. The elevation of the test area is some 157 m.a.s.l. It is currently used as farmland and mostly for grass production.

Location of the site, with field investigations and sediments type:



Peat depths from Trondheim municipality (not completely updated):



As the Dragvoll / Stokkanmyra area is elevated about +157 meter above sea level, this implies that the sediments has been subjected to rather shallow waters (15 m and less) after sedimentation, i.e. the area emerged from the salt water environment fairly rapidly. Hafsten & Mack (1990) show that the area 11500 year BP was part of the fjord landscape whereas 1000 years later the isostatic land heave caused by the ongoing deglaciation had elevated the area so that it became a bay of brackish water limited by the outcropping rock and moraine to the north.

Further land heave changed the bay into a lake, slowly developing into a swamp, thereafter to a bog area that there are still remains of today. The area is now cultivated into farmland with still some very wet spots. These are now drained into the creek Stokkanbekken running to the northeast through the area.

In the central parts of Stokkanmyra sediment depths up to 50 m thick can be found (Hafsten and Mack, 1990).

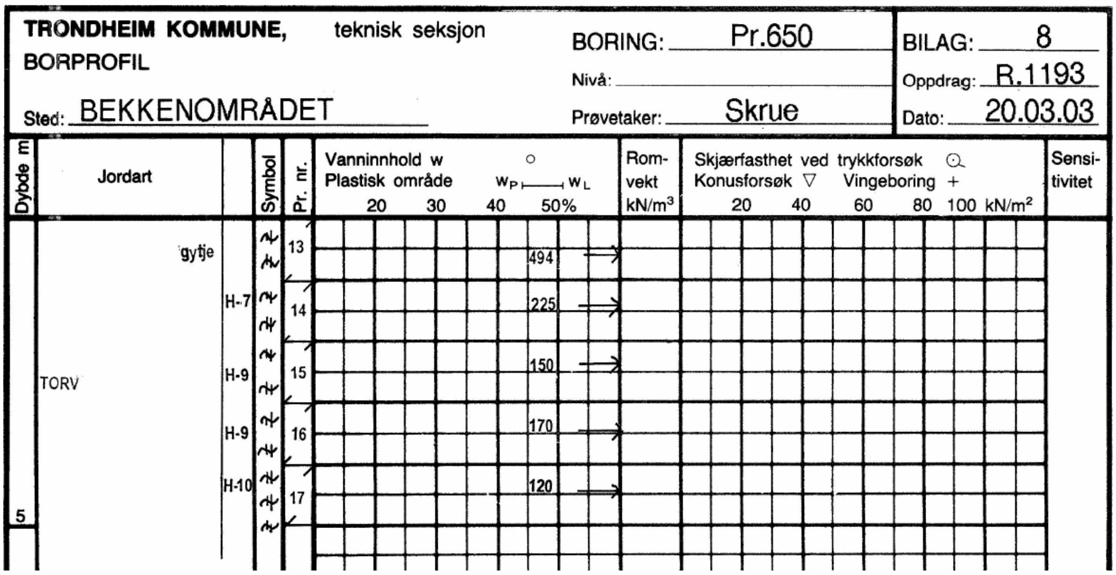
Soil conditions

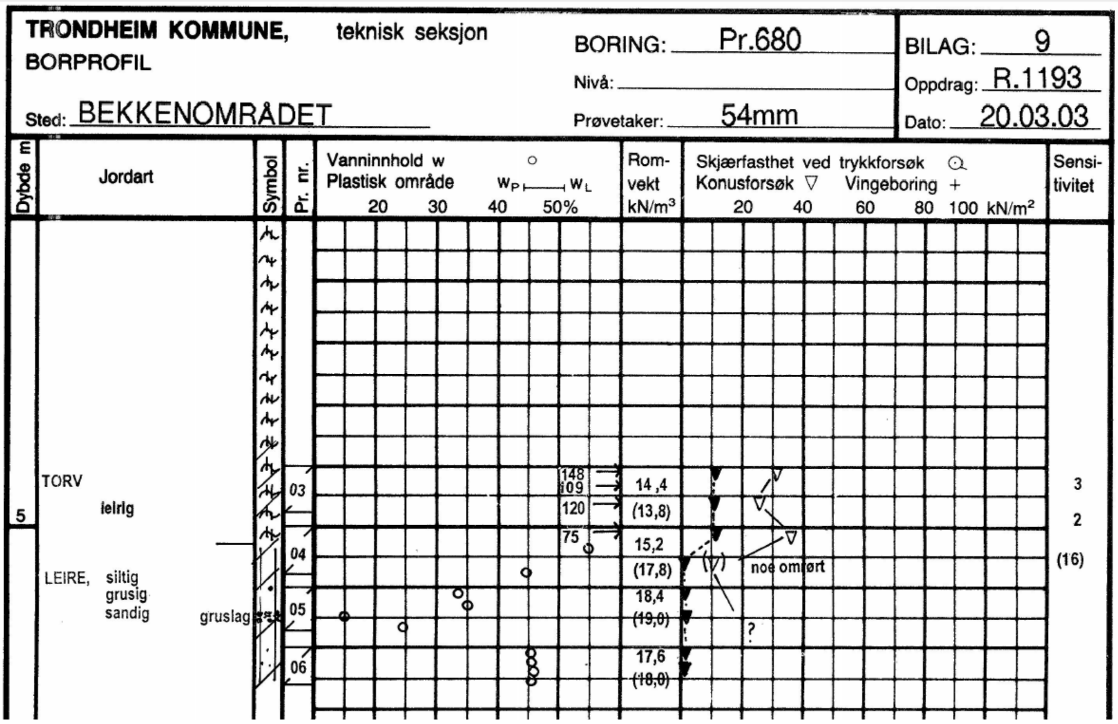
The area is dominated by peat over quick clay. The bedrock is found under the quick clay. The peat thickness is around 5 m. Bedrock outcrops are visible towards the east of the site and the south.

Existing field work relevant for peat characterization

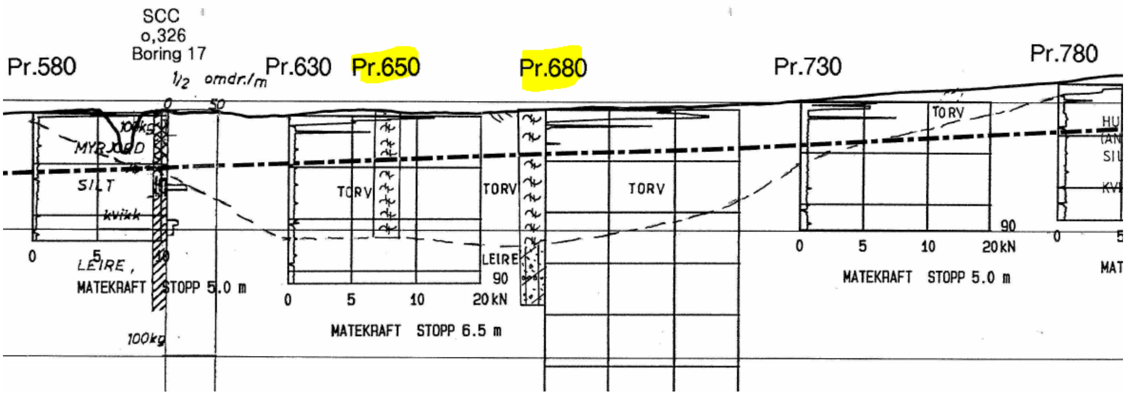
There are pore pressure measurements in the area (point R1193_650). The GWT is about 0.6 m depth at this point.

These are the results from sampling at the site:



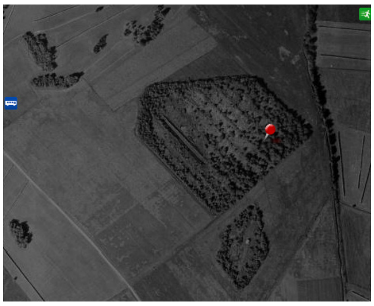


Some examples of the soundings are presented below:



Aerial photos from 1937-2017

1937



1964

2017

References

Trondheim kommune (2003)
R.1193 Bekkenområdet, 22.04.2013

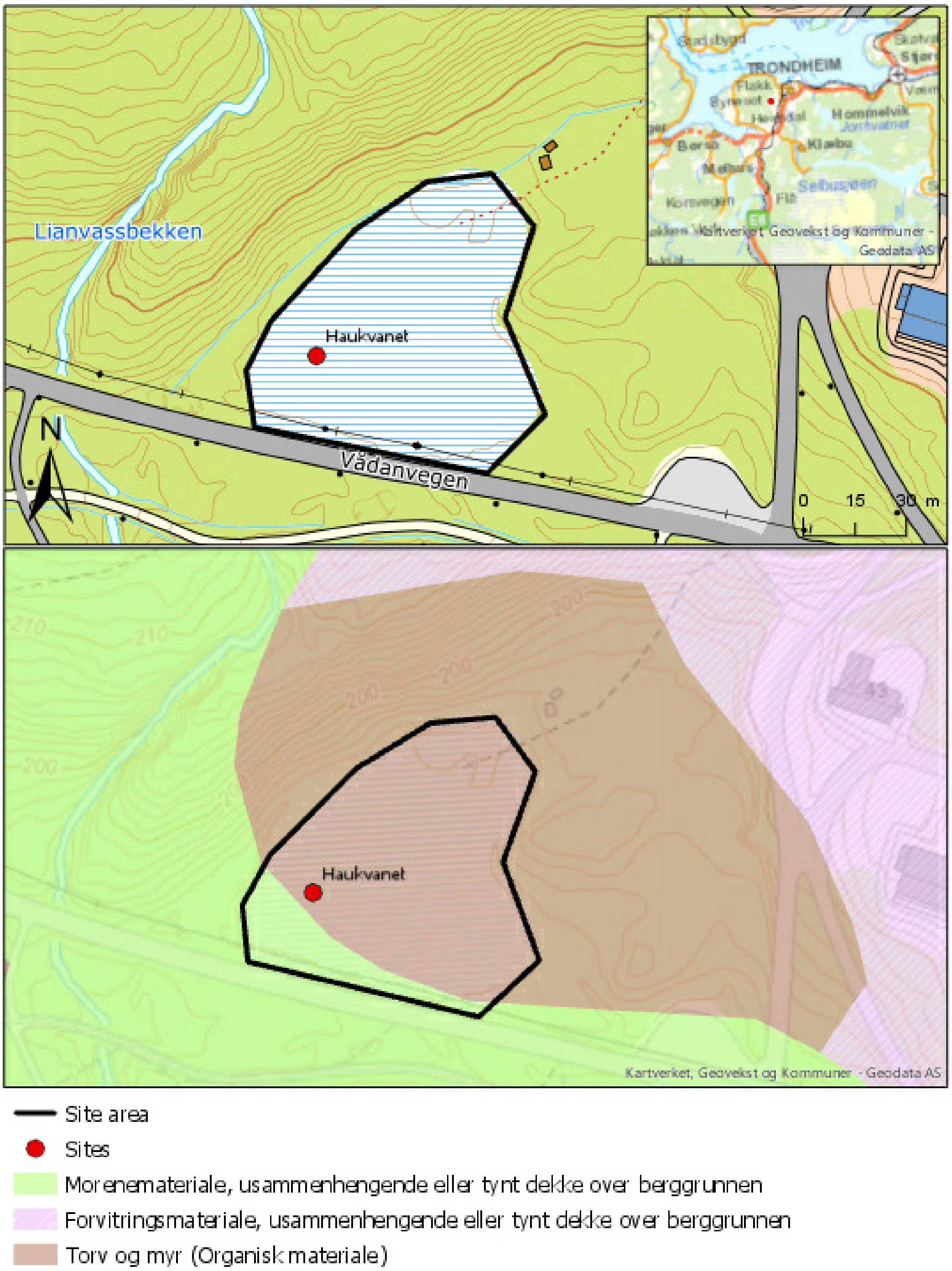
Long, M. & Boylan, N. (2013)
Predictions of settlement in peat soils. *Quarterly Journal of Engineering Geology and Hydrogeology* 2013, v.46; p 303-322

Emdal A, Long M, Bihs A, et al. (2012)
Characterisation of Quick Clay at Dragvoll, Trondheim, Norway. *Geotech Eng J SEAGS AGSSEA* 43: 11‑23.

Site location

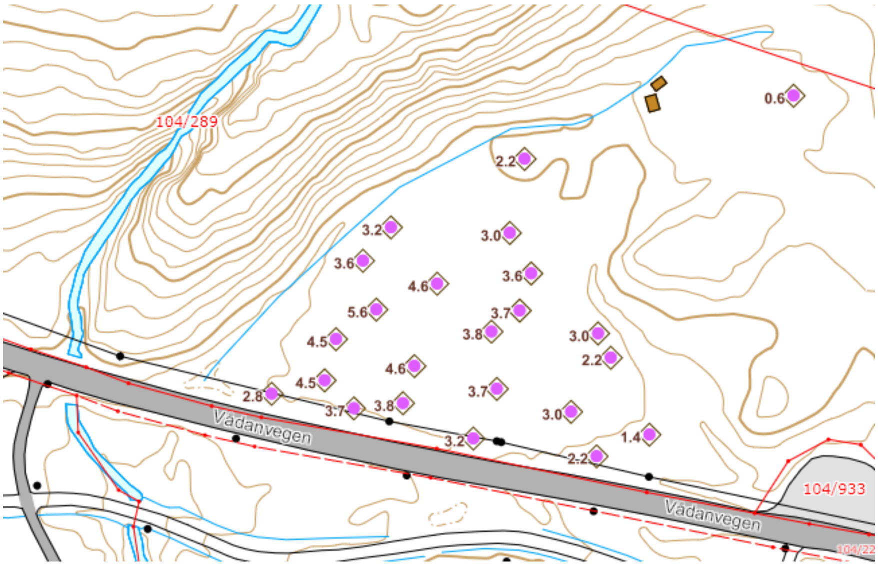
Haukvanetmyra is located in Ugla, on the west part of Trondheim, Norway. The site has elevations between 194-195 m.a.s.l. The area is limited by Vådanvegen in the south, Lianvassbekken in the west, a steep slope on the north towards Haukåsen and Haukåsen sykehus to the east. The site is over the marin limit.

Location of the site, with field investigations and sediments type:



Haukvanetmyra-Trondheim

Peat depths from Trondheim municipality:



Soil conditions

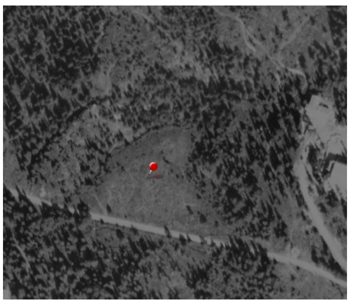
Peat is varying between 2 m and 6 m depth. Under the peat layer, it is reported hart cohesive masses with layer of coarse material. Bedrock is estimated to be shallow.

Existing field work relevant for peat characterization

No field work registered on site.

Aerial photos from 1947-2019

1947



2010

2019

References

Trondheim kommune (1988)
R.0746 Haukåsen, parkeringsplass, 10.11.1988

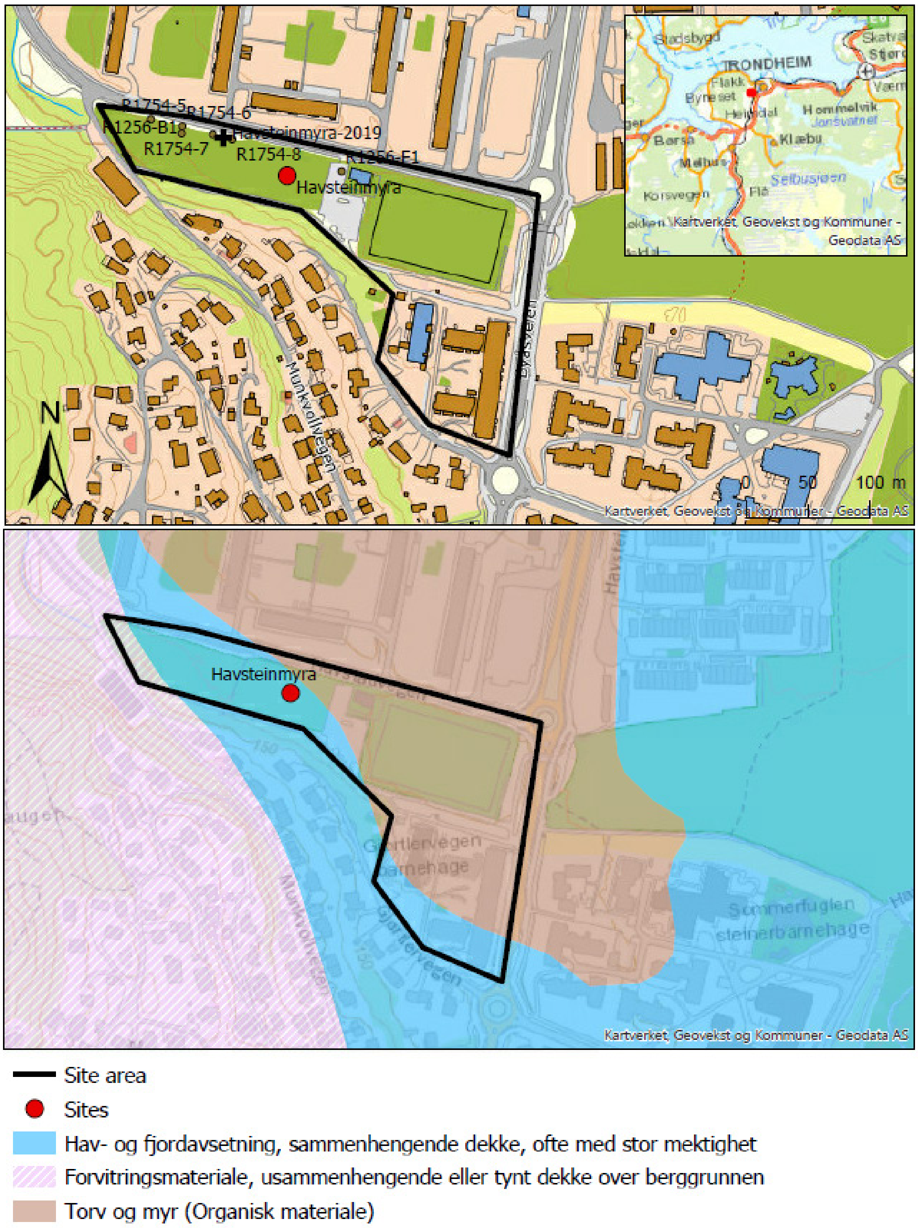
Trondheim kommune (1970)
R.0203 Haukåsen skoletomt spesialskole/ungdomsskole

Havsteinmyra-Trondheim

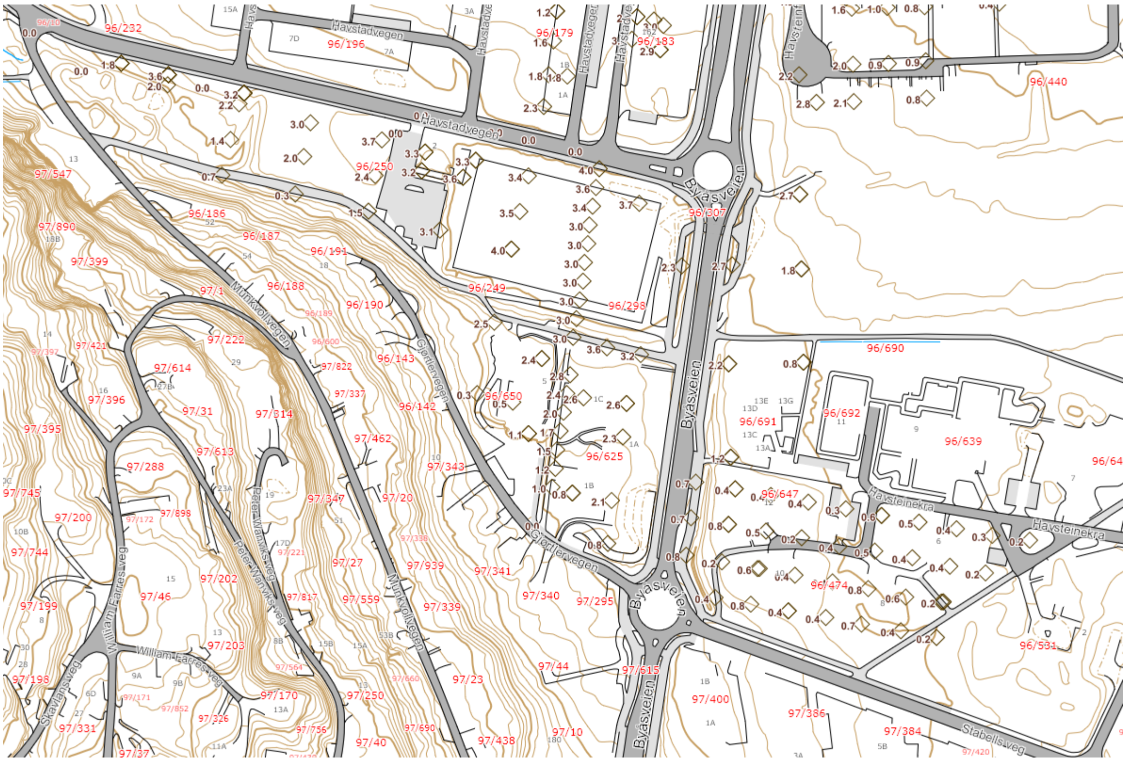
Site location

Havsteinmyra is located in Byåsen, on the west part of Trondheim, Norway. The site has elevations varying between 140 m.a.s.l. on the northeast to 150 m.a.s.l. towards the southwest. The area is limited by Gjortlervegen in the south, Storhaugen in the southwest with 233 m.a.s.l., Munkvollvegen in the west, Havstadvegen in the north and Byåsveien in the east. The topography of the site has been changed during the last 20 years because of building up two soccer fields in the area. Recently, some field work has been carried out due to development of the pedestrian path along Havstadvegen.

Location of the site, with field investigations and sediments type:



Peat depths from Trondheim municipality (not complete updated):

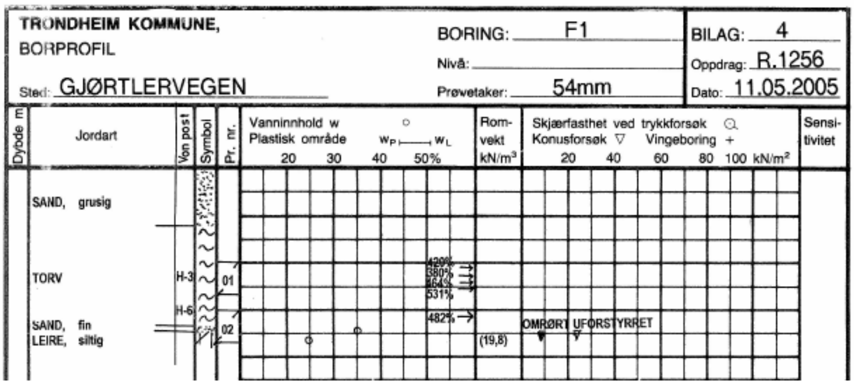


Soil conditions

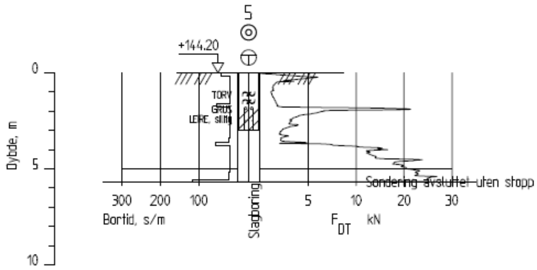
Bedrock is found near the surface towards the west. A peat layer of 2-4 m is found between points 5 and 8. There are many cables undreground after point 8 and to the east which make difficult to perform a sounding. From Havstad idrettspark to the east, recent soundings did not find peat, since it was recommended before to remove the peat layer before the installation of the soccer field.

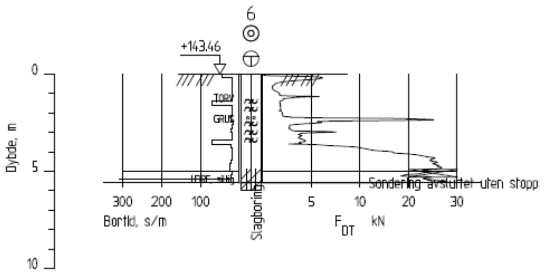
Existing field work relevant for peat characterization

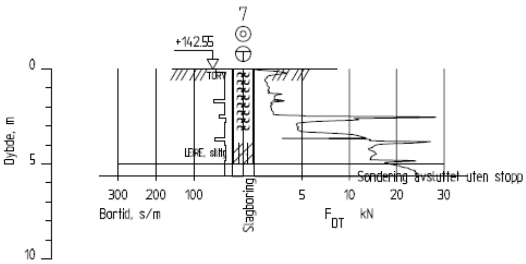
There are not pore pressure measurements in the area. These are the results from sampling at the site:

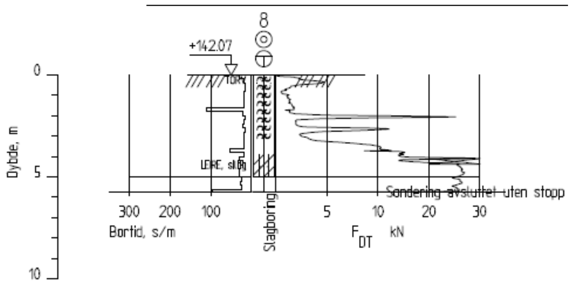


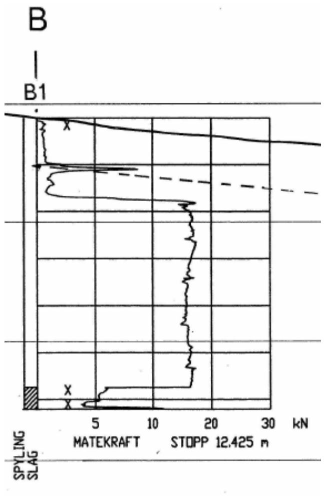
Some examples of the soundings are presented below:





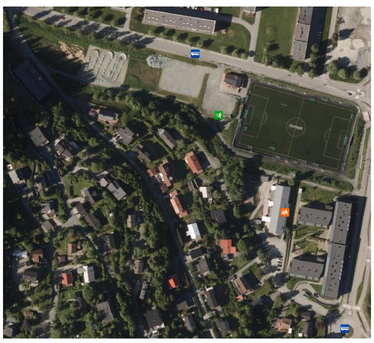






Aerial photos from 2006-2017

2017 2015 2006



References

Trondheim kommune (2019)
R.1754 Havstadvegen, 17.01.2019

Trondheim kommune (2005)
R.1256 Gjørtlervegen

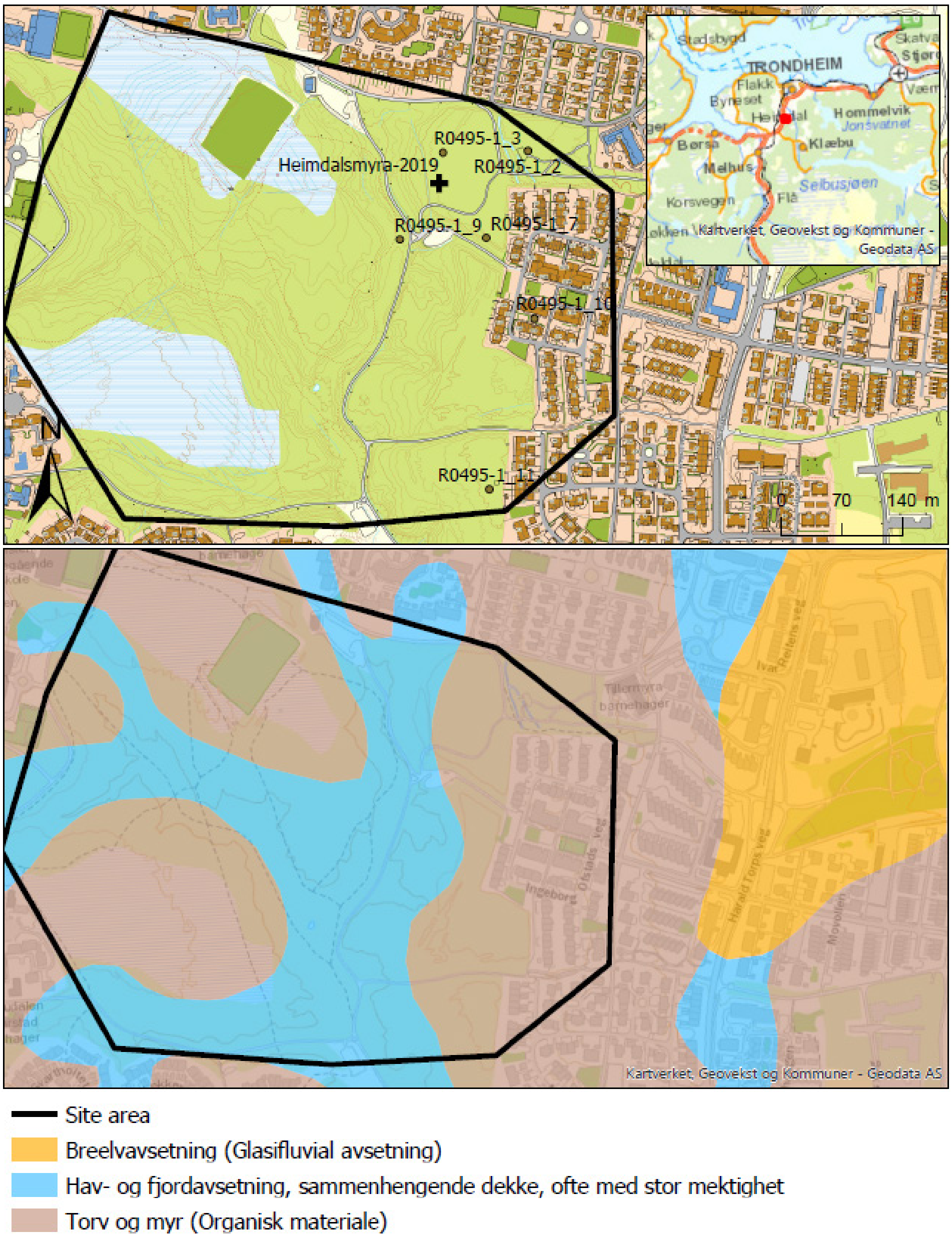
Trondheim kommune (2004)
R.1234 Bukkvollan

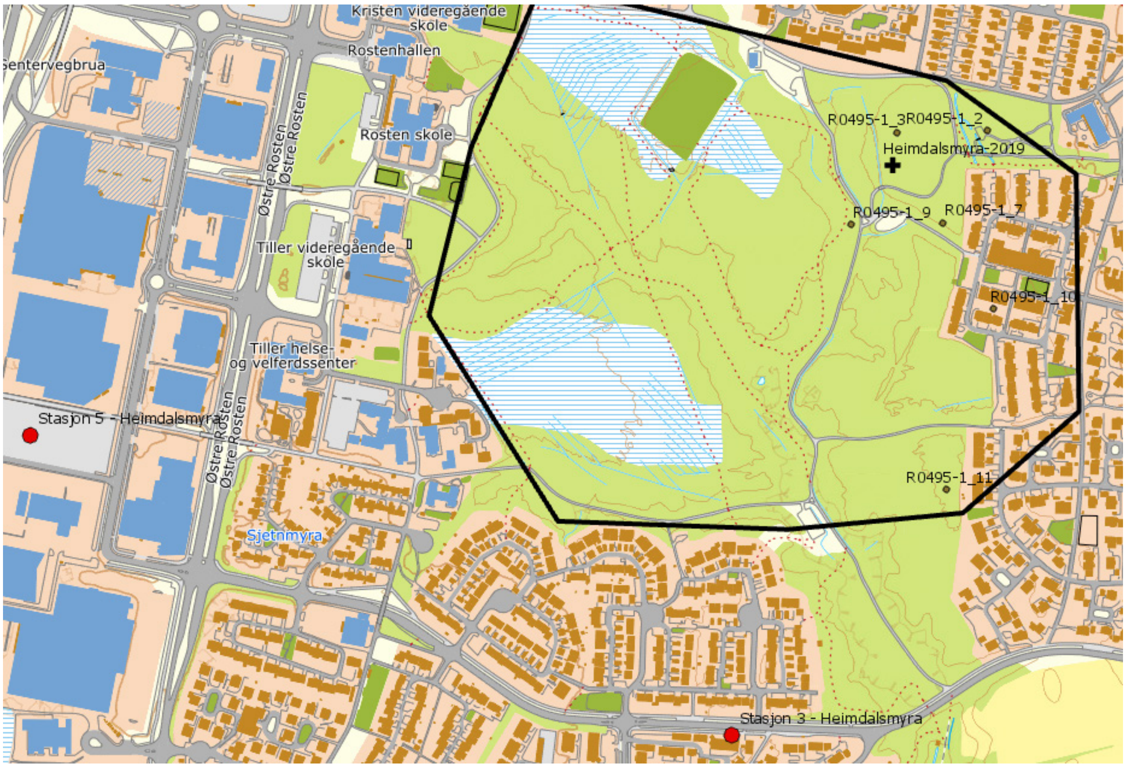
Trondheim kommune (1970)
R.152 Gjørtlervegen

Site location

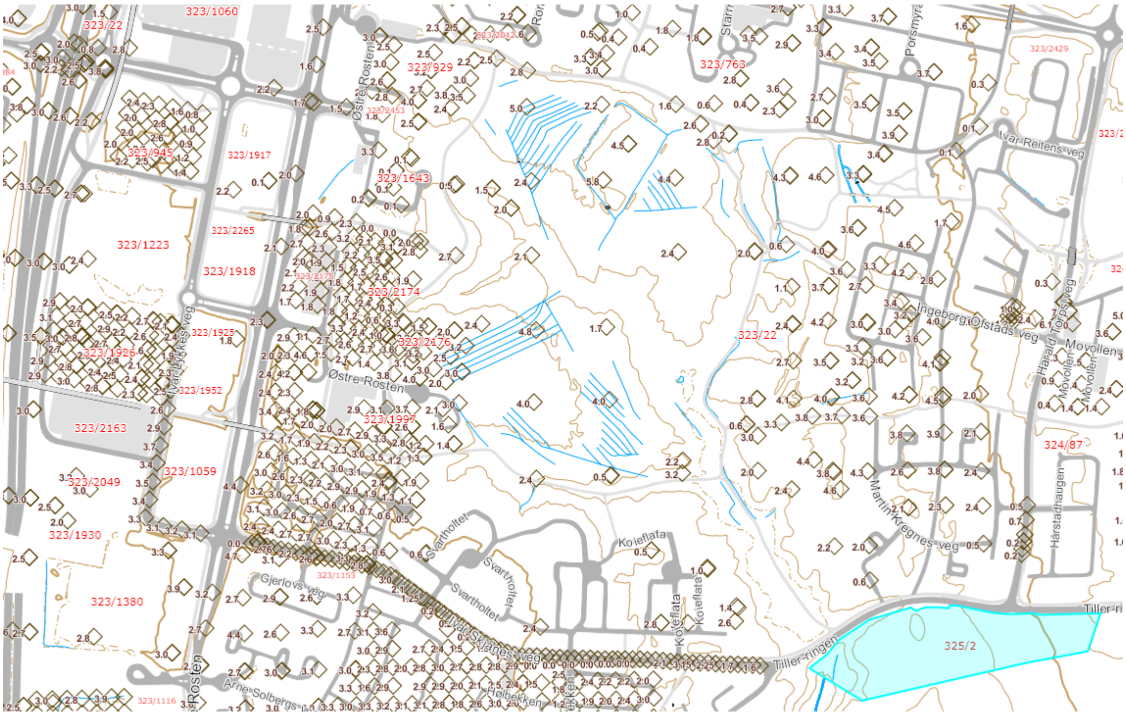
Heimdalsmyra is located in Tiller, about 11 km south from Trondheim city, Norway. The site has elevations varying between 140-145 m.a.s.l. The area is am open-air park limited by residential areas: Ingeborg Ofstads veg on the east, Romemyra and Starmyra on the north, Østre Rosten on the west and Svartholtet-Koieflata on the south. The topography of the site is dominated by a small valley in the middle connecting Starmyra with Ivar Skjænes veg. The site is close to the full-scale tests by Hove (1972) (i.e. Stations 3 and Stations 5).

Location of the site, with field investigations and sediments type:





Peat depths from Trondheim municipality (not completely updated):



Soil conditions

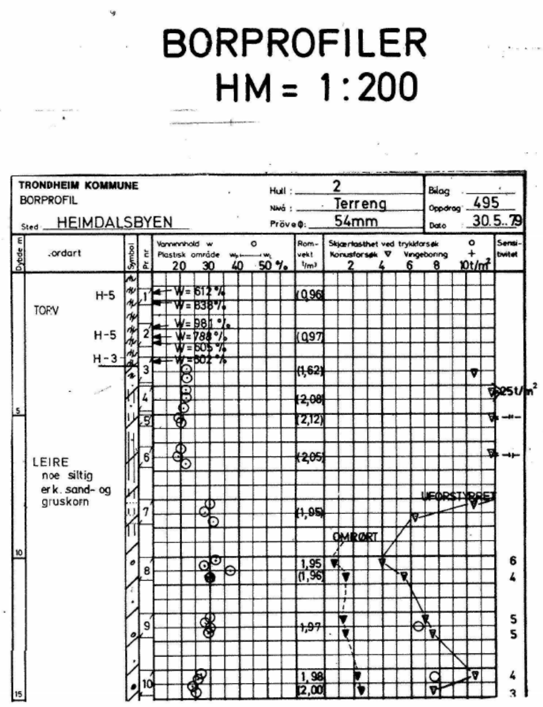
The main layering in the area consists of 2-4 m of peat over either a middle hard to hard clay of 0-5 m thickness towards the northeast or a soft clay that can be quick with 4-30 m thickness towards the southwest.

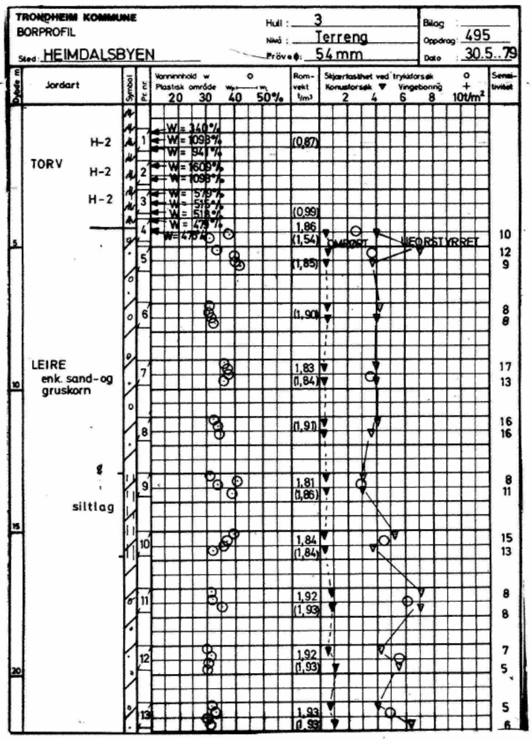
In 1979, Trondheim municipality (Trondheim kommune, 1979) carried out measurements of the peat thickness in the area. The thickness measured reached 3-4 m, with some single areas of 4.6 m. This thickness was compared to the one measured in 1968 (Kummeneje, 1968) that reached 4-5 m. The reduction in thickness of the peat layer may be due to settlements in the peat layer as a result of the 10 years of drainage work done in 1968 (i.e. by 1979 had 10 years).

Existing field work relevant for peat characterization

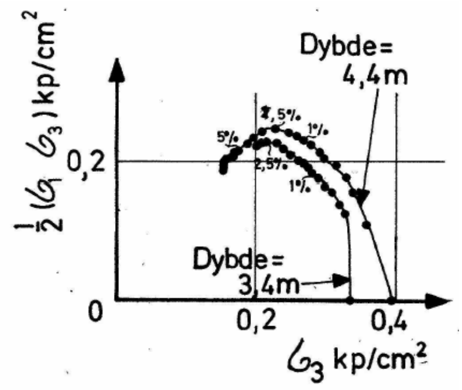
There are not pore pressure measurements in the area.

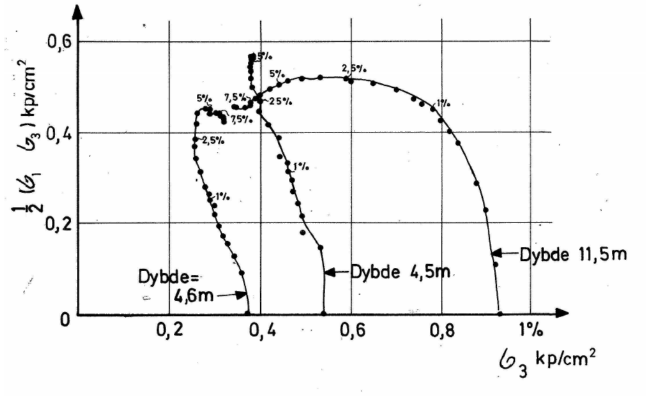
These are the results from sampling at the site:

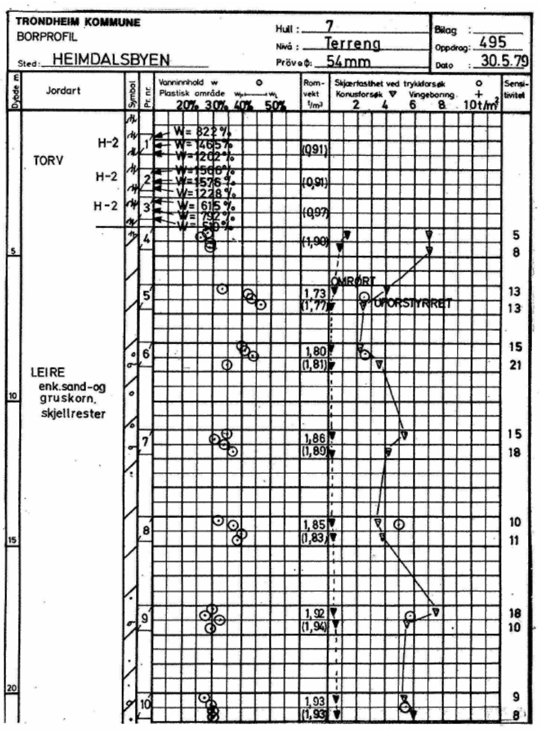


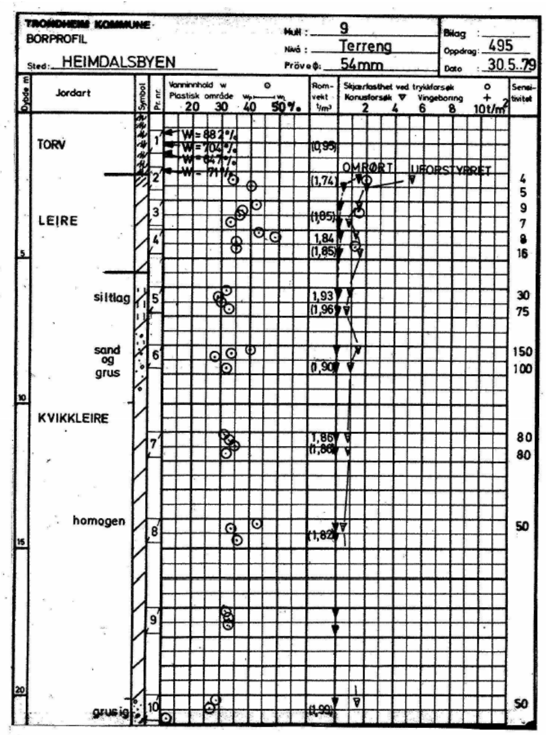


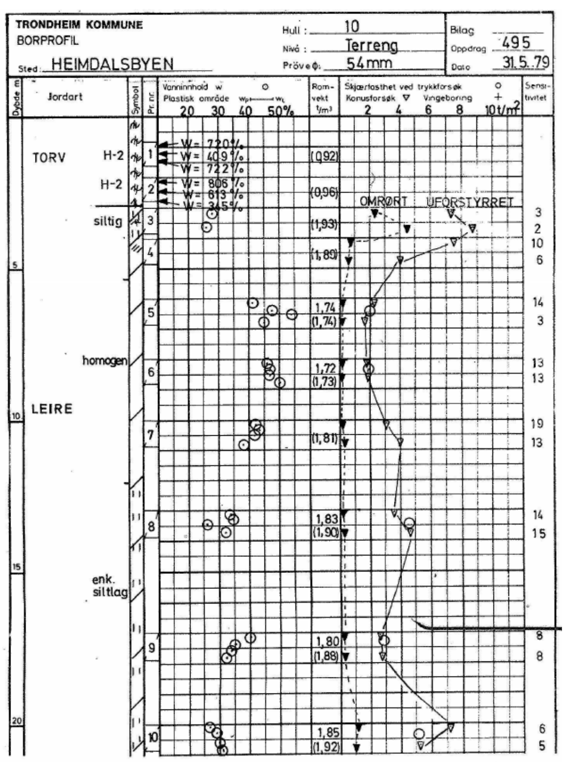
Point R0495-1_3:

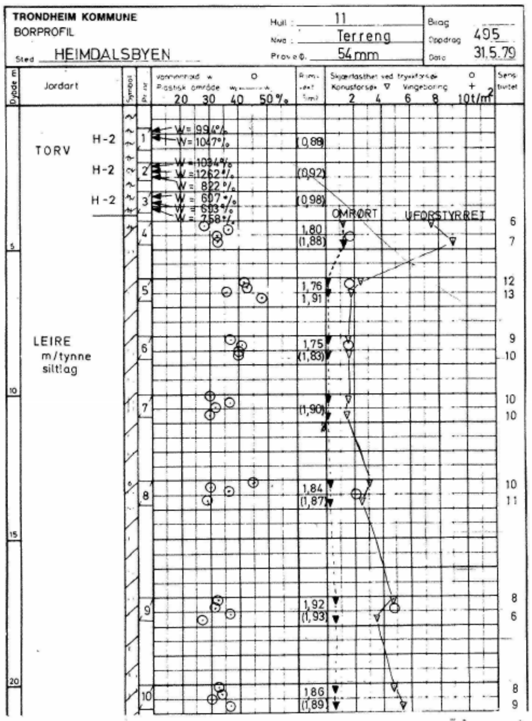








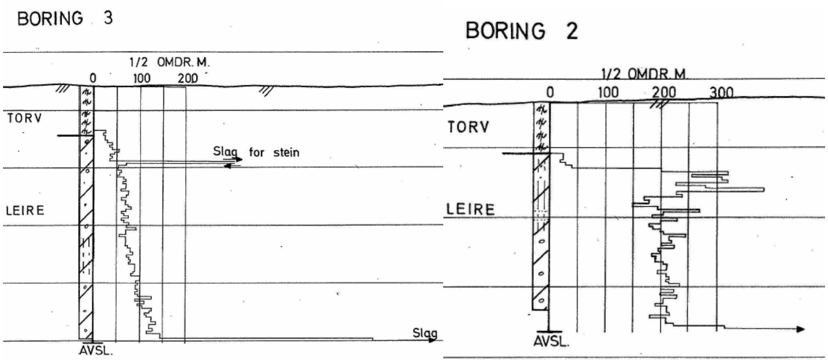


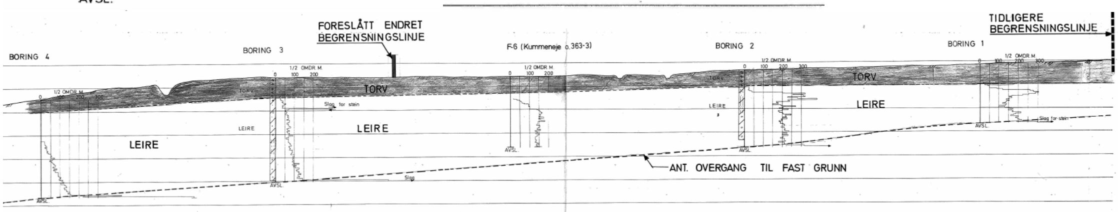


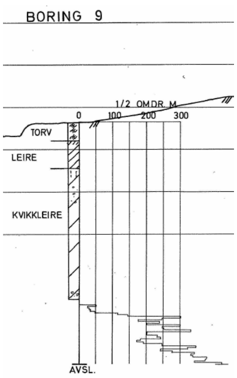
BORPROFIL BORING 11

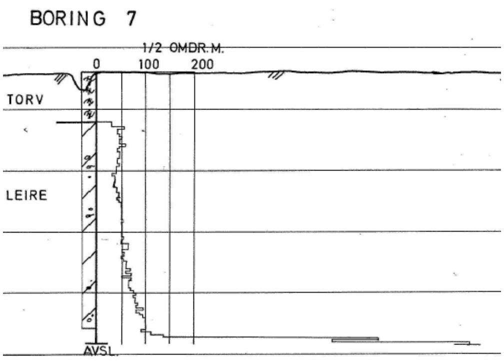
Some examples of the soundings are presented below:

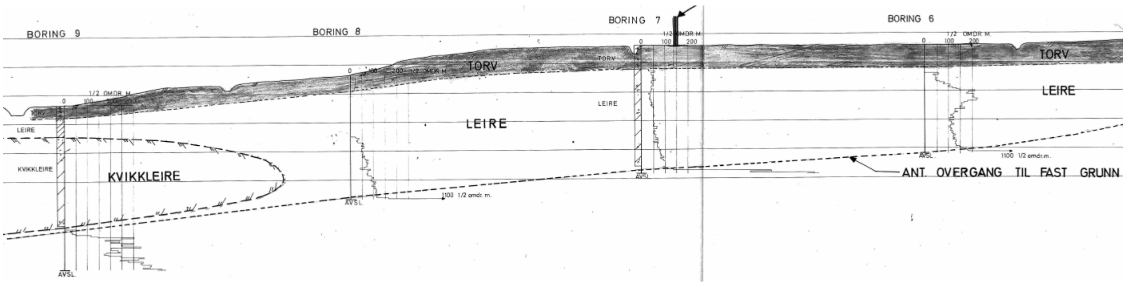
R0495-1 (Trondheim kommune, 1979):

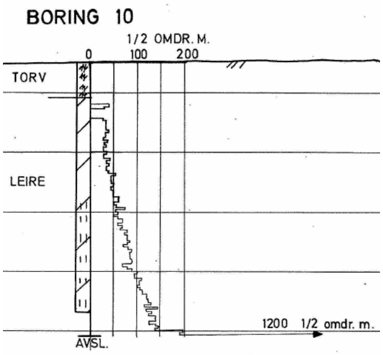


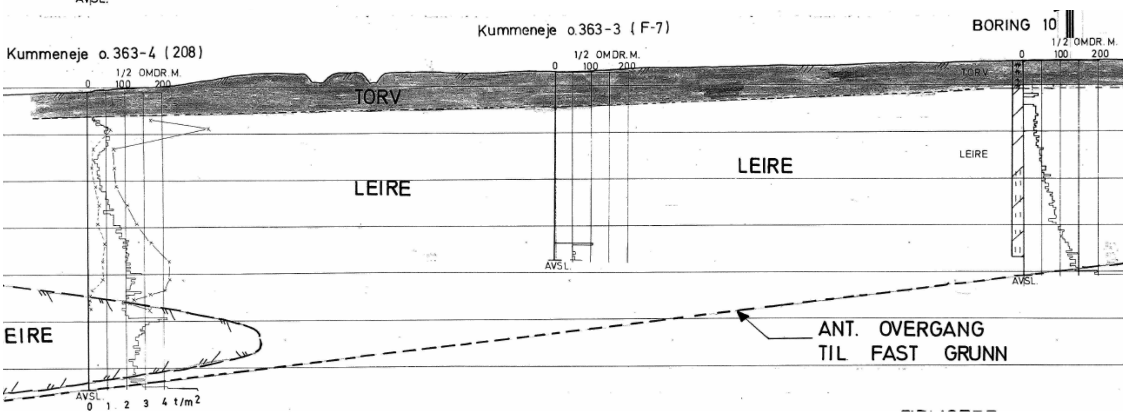




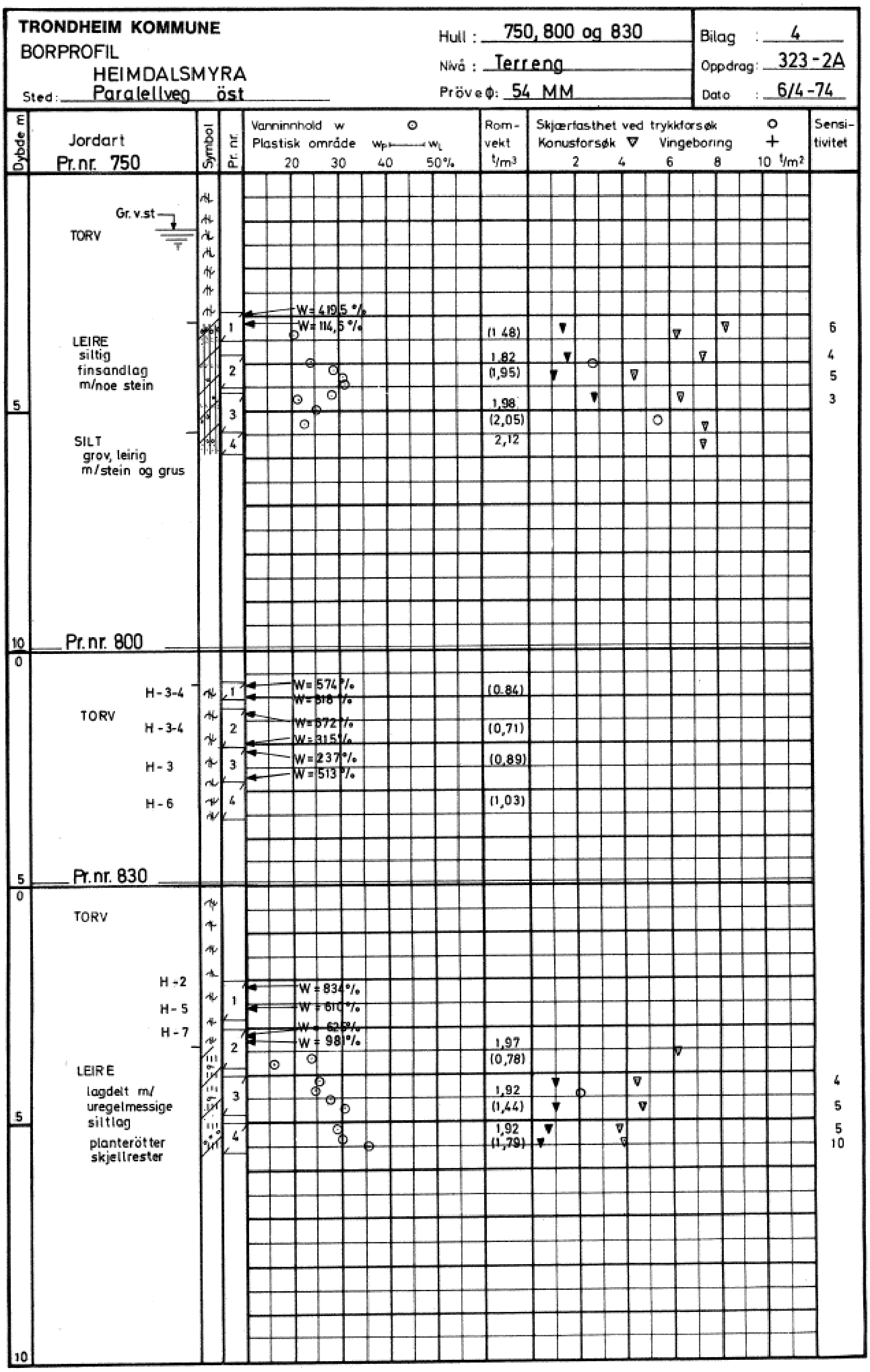


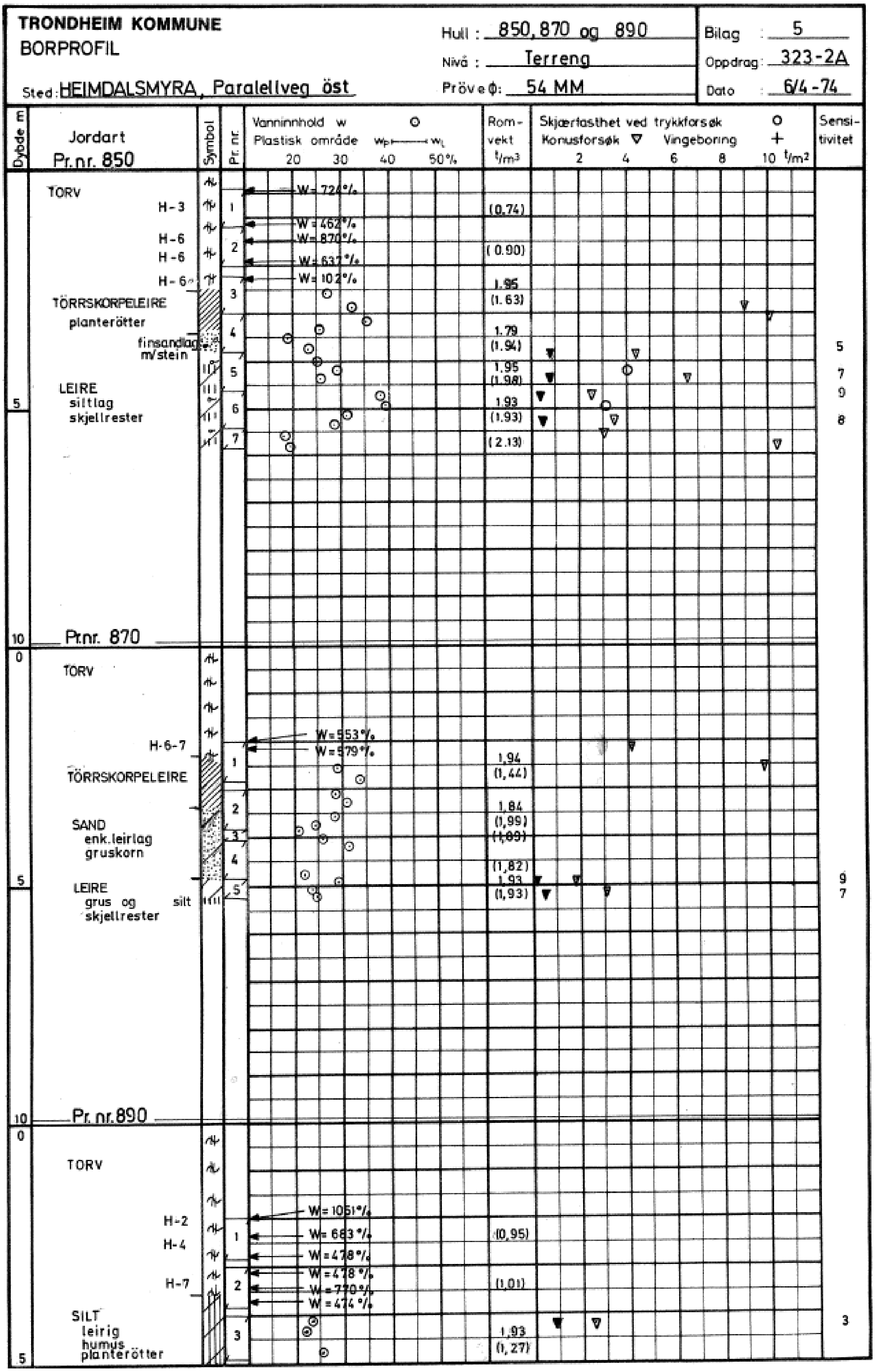


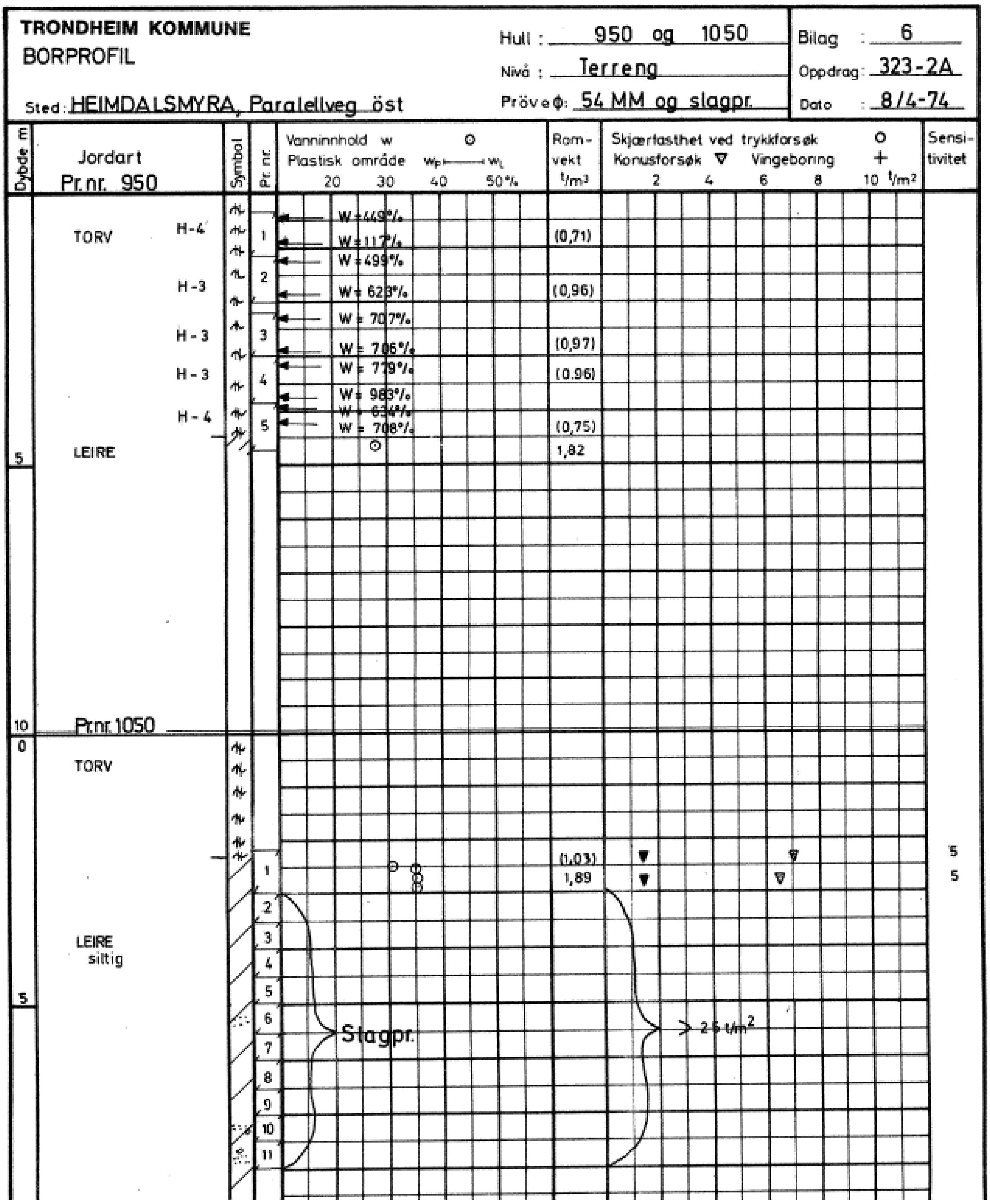


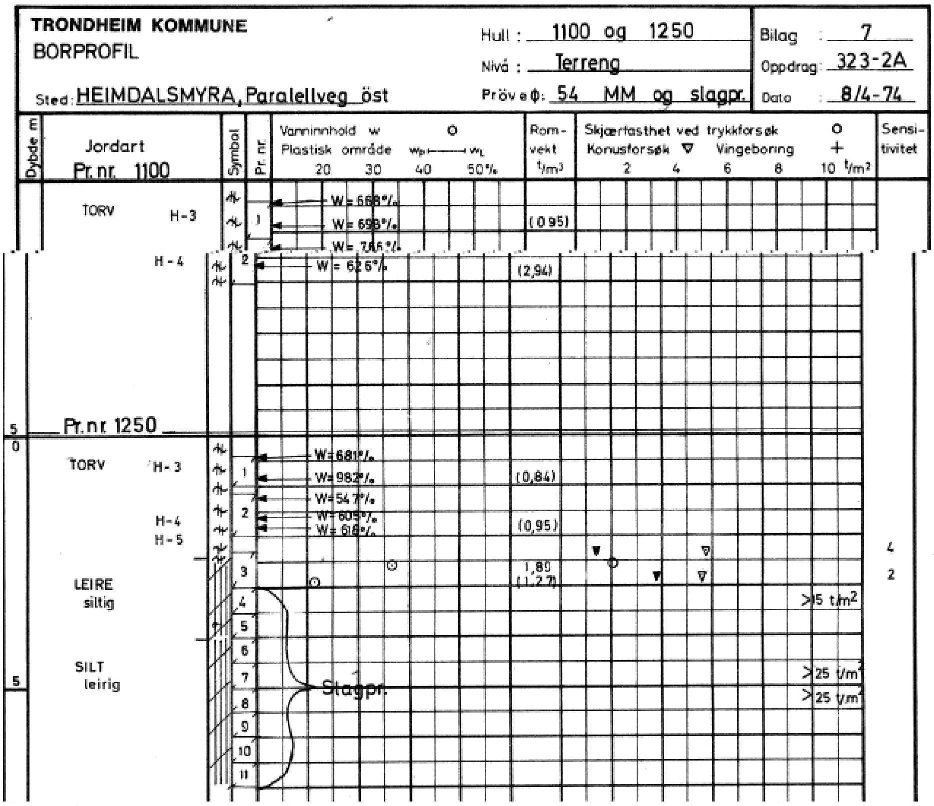


R.0323-2A, profiles 800-910 and 950 for odometer tests (Trondheim kommune, 1974):


TRONDHEIM KOMMUNE
BORPROFIL
HEIMDALSMYRA
Sted: Paralellveg öst
Hull: 750, 800 og 830
Nivå: Terreng
Pröve φ: 54 MM
Bilag: 4
Oppdrag: 323-2A
Dato: 6/4-74
Dybde m
Jordart
Pr.nr. 750
Symbol
Pr. nr.
Vanninnhold w
Plastisk område
20 30 40 50%
Rom-vekt t/m³
Skjærfasthet ved trykkforsøk
Konusforsøk
Vingeboring
2 4 6 8 10 t/m²
Sensi-tivitet
Gr. v.st
TORV
W = 419,5 %
W = 114,5 %
LEIRE
siltig
finsandlag
m/noe stein
SILT
grov, leirig
m/stein og grus
(1,48)
1,82
(1,95)
1,98
(2,05)
2,12
6
4
5
3
Pr.nr. 800
H-3-4
H-3-4
H-3
H-6
W = 574 %
W = 318 %
W = 572 %
W = 315 %
W = 237 %
W = 513 %
(0,84)
(0,71)
(0,89)
(1,03)
Pr.nr. 830
H-2
H-5
H-7
W = 834 %
W = 610 %
W = 625 %
W = 981 %
LEIRE
lagdelt m/
uregelmessige
siltlag
planterötter
skjellrester
1,97
(0,78)
1,92
(1,44)
1,92
(1,79)
4
5
5
10


TRONDHEIM KOMMUNE
BORPROFIL
Sted: HEIMDALSMYRA, Paralellveg öst
Hull : 850, 870 og 890
Nivå : Terreng
Pröve ϕ: 54 MM
Bilag : 5
Oppdrag: 323-2A
Dato : 6/4-74
Dybde m
Jordart
Symbol
Pr. nr.
Vanninnhold w
Plastisk område w_P — w_L
20 30 40 50%
Rom-vekt t/m3
Skjærfasthet ved trykkforsøk
Konusforsøk
Vingeboring
2 4 6 8 10 t/m2
Sensi-tivitet
Pr.nr. 850
TORV
H-3
H-6
H-6
H-6
TÖRRSKORPELEIRE
planterötter
finsandlag m/stein
LEIRE
siltlag
skjellrester
W= 724%
W= 462%
W= 870%
W= 637%
W= 102%
(0,74)
(0.90)
1.95
(1.63)
1.79
(1.94)
1.95
(1.98)
1.93
(1.93)
(2.13)
5
7
9
8
Pr.nr. 870
TORV
H-6-7
TÖRRSKORPELEIRE
SAND
enk. leirlag
gruskorn
LEIRE
grus og silt
skjellrester
W= 553%
W= 579%
1,94
(1,44)
1,84
(1,99)
(1,82)
1,93
(1,93)
9
7
Pr. nr. 890
TORV
H-2
H-4
H-7
SILT
leirig
humus
planterötter
W= 1051%
W= 663%
W= 478%
W= 478%
W= 770%
W= 474%
(0,95)
(1,01)
1,93
(1,27)
3

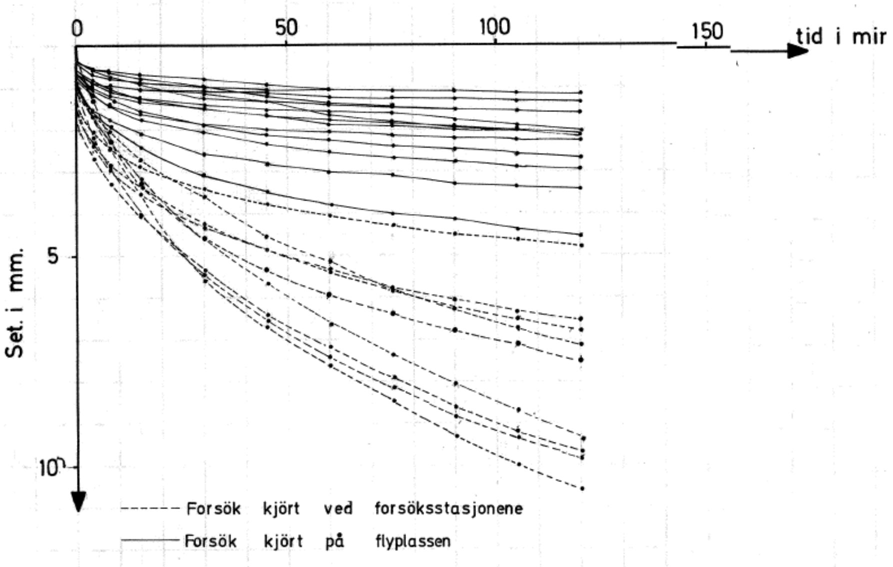

TRONDHEIM KOMMUNE
BORPROFIL
Sted: HEIMDALSMYRA, Paralellveg öst
Hull : 950 og 1050
Nivå : Terreng
Pröve ϕ: 54 MM og slagpr.
Bilag : 6
Oppdrag: 323-2A
Dato : 8/4-74
Dybde m
Jordart
Pr.nr. 950
Symbol
Pr. nr.
Vanninnhold w
Plastisk område
20 30 40 50%
Rom-vekt t/m³
Skjærfasthet ved trykkforsøk
Konusforsøk
Vingeboring
2 4 6 8 10 t/m²
Sensi-tivitet
TORV
H-4
H-3
H-3
H-3
H-4
LEIRE
W = 449%
W = 117%
W = 499%
W = 623%
W = 707%
W = 706%
W = 779%
W = 983%
W = 634%
W = 708%
(0,71)
(0,96)
(0,97)
(0.96)
(0,75)
1,82
Pr.nr. 1050
TORV
LEIRE
siltig
(1,03)
1,89
Slagpr.
> 25 t/m²
5
5



SAMMENLIGNING AV KOMPRESSOMETERRESULTATER

Alle kurver tilsvarer et lastrinn på 1 t/m²

Lastrinnene er fra 0-3 t/m²



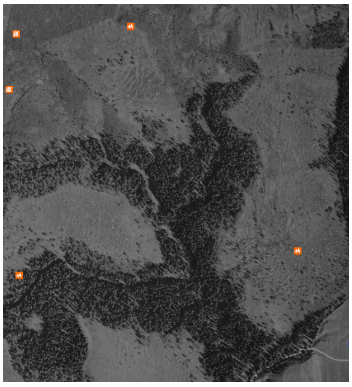
$$\frac{\text{Gjennomsnittelig setning på flyplassen}}{\text{Gjennomsnittelig setning på forsökstasjon}} = \frac{2{,}09}{8{,}04} = 0{,}26$$

Aerial photos from 1947-2017

2017

1986

1947



References

Hove, S. (1972)
Setnings- og stabilitetsundersøkelser på Heimdalsmyra. Master thesis, NTH.

Trondheim kommune (1984)
R611-4 Heimdalsbyen, Søndre boligkvadrant, 05.09.1984

Trondheim kommune (1979)
R.495-1 Heimdalsbyen. Byggelinje mot vest i Østre boligkvadrant, 28.08.1979

Trondheim kommune (1979)
R.495-2 Heimdalsbyen. Myrdybder østre boligkvadrant, 11.09.1979

Trondheim kommune (1974)
R.323-2A Heimdalsbyen. Paralellveg øst, 13.07.1974

Kummeneje (1968)
Report O.363-2A

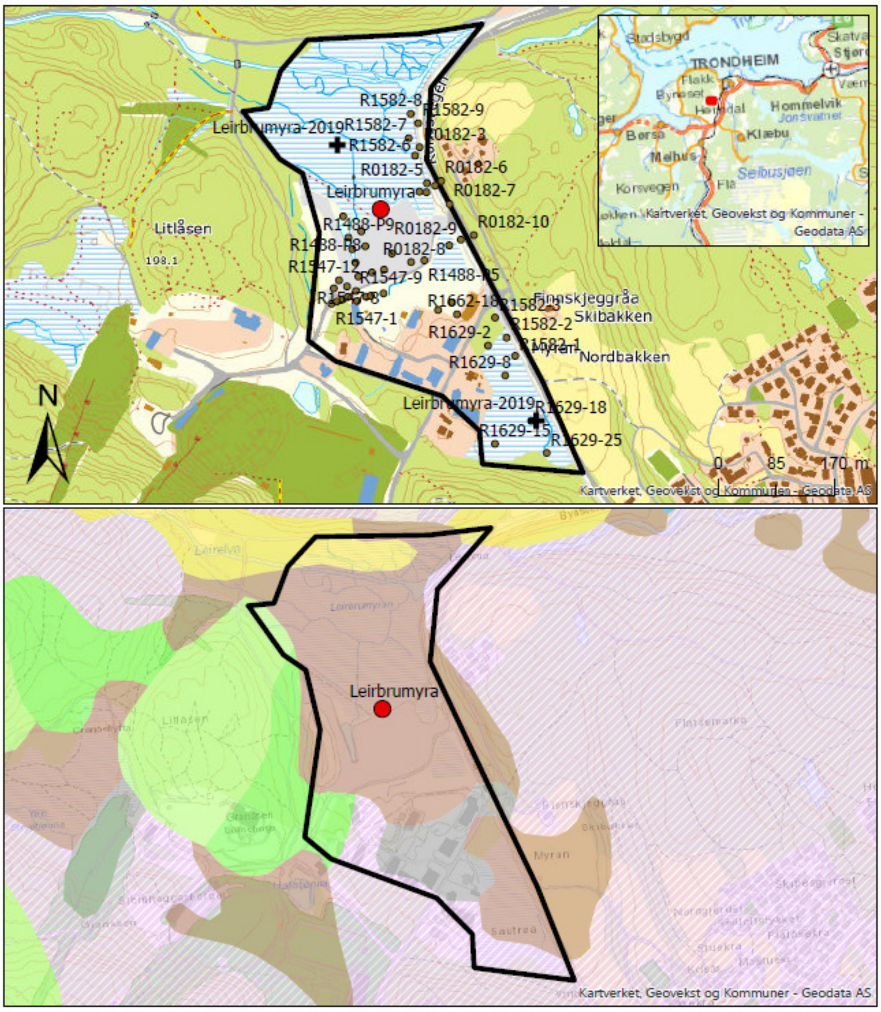
Statens vegvesen (1973)
Motorveg E6 sør – parsell Tonstad – Heimdal sør. Profile 5800-9300, 01.06.1973

Leirbrumyra-Granåsen

Site location

Leirbrumyra - Granåsen is located about 10 km south from Trondheim, Norway. The site has a relatively flat topography with elevations varying between 170 and 172 m.a.s.l. The site is located at the ski arena Granåsen limited by Flatåsmarka in the east, Granåasen ski arena in the south, Litlåsen in the west and Leirelva in the north. The area has been under study during several years due to the establishment and recently the enlargement of the of the ski arena.

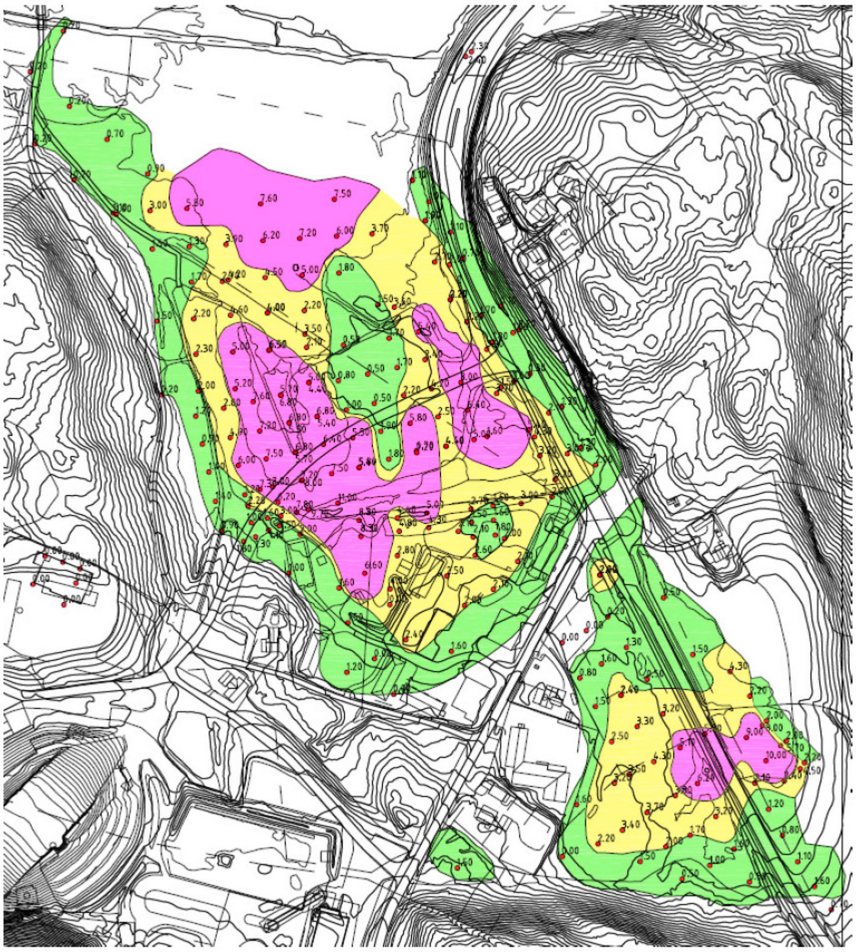
Location of the site, with field investigations and sediments type:



- Site area
- Sites
- Morenemateriale, usammenhengende eller tynt dekke over berggrunnen
- Morenemateriale, sammenhengende dekke, stedvis med stor mektighet
- Elve- og bekkeavsetning (Fluvial avsetning)
- Hav- og fjordavsetning, sammenhengende dekke, ofte med stor mektighet
- Forvitringsmateriale, usammenhengende eller tynt dekke over berggrunnen
- Bart fjell
- Torv og myr (Organisk materiale)
- Fyllmasse (antropogent materiale)

Soil conditions

The ground conditions vary around the area. Previous soils investigations show moraine and weathered material, with some soundings indicating either sand and gravel or silt/clay under the peat layer. Soft and compressible layers, some of them quick, are also found under the peat layer in some parts. The peat layer has a variable thickness in the area and can be up to 11 m thick as presented in the figure below (Trondheim kommune, 2016) where green for peat with less than 2 m thickness, yellow for peat between 2-5 m thickness and purple is for peat with more than 5 m thickness.



The terrain in the area has been changed over time, mainly before the improvement of the ski arena for the World Cup in 1997. The peat area was then filled with gravel. A summary of the most relevant reports is presented below:

<u>R.806-2 Leirbrumyra</u>

In 1994, field investigations were carried out for the parking facilities for the ski World Cup in 1997. Peat depths between 0.5 and 11.0 meters were recorded. It was pointed out that filling with one meter of rock masses in the area with the largest peat thickness could provide as much as 1 m settlements. Bedrock were assumed to be 1 - 5 m below the peat. The clay under the peat was characterized as soft clay.

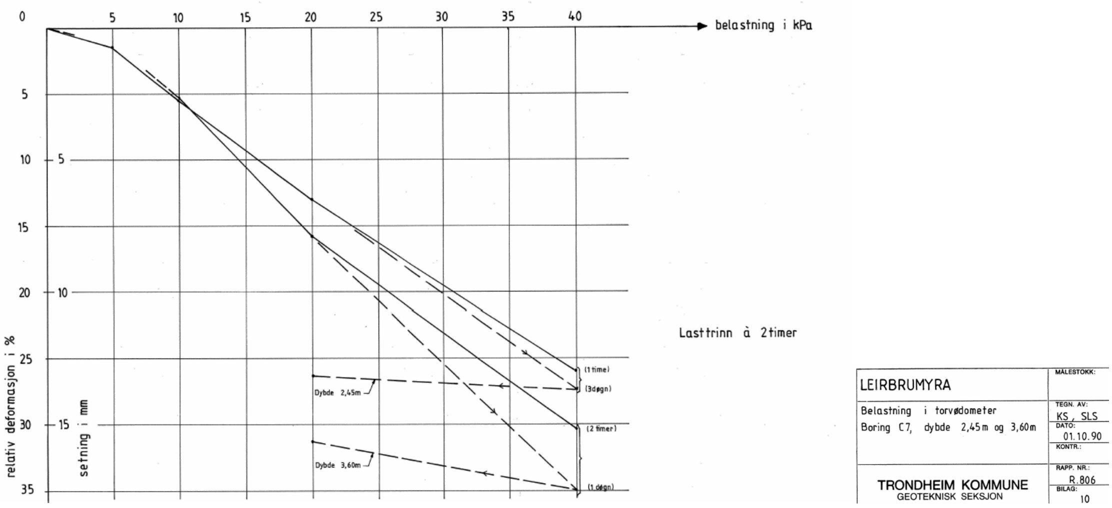
<u>10318-2 Civil Defence School</u>
Kummenje conducted basic soundings for an exercise platform in the Civil Defence Camp. Peat depths varied between 8.3 meters in the west and 1.6 meters in the east. Rotary pressures and peat depth were also made in the south-east quadrant of the hall area. The ground consisted of 0.5-2 meter fillings over peat to 5-6.6 meters below ground. During this, there were "soft masses" down to between 9 and 11 meters below ground. Under the soft layer, there were hard masses believed to be moraine. Kummeneje proposed to fundament on piles the exercise platform.

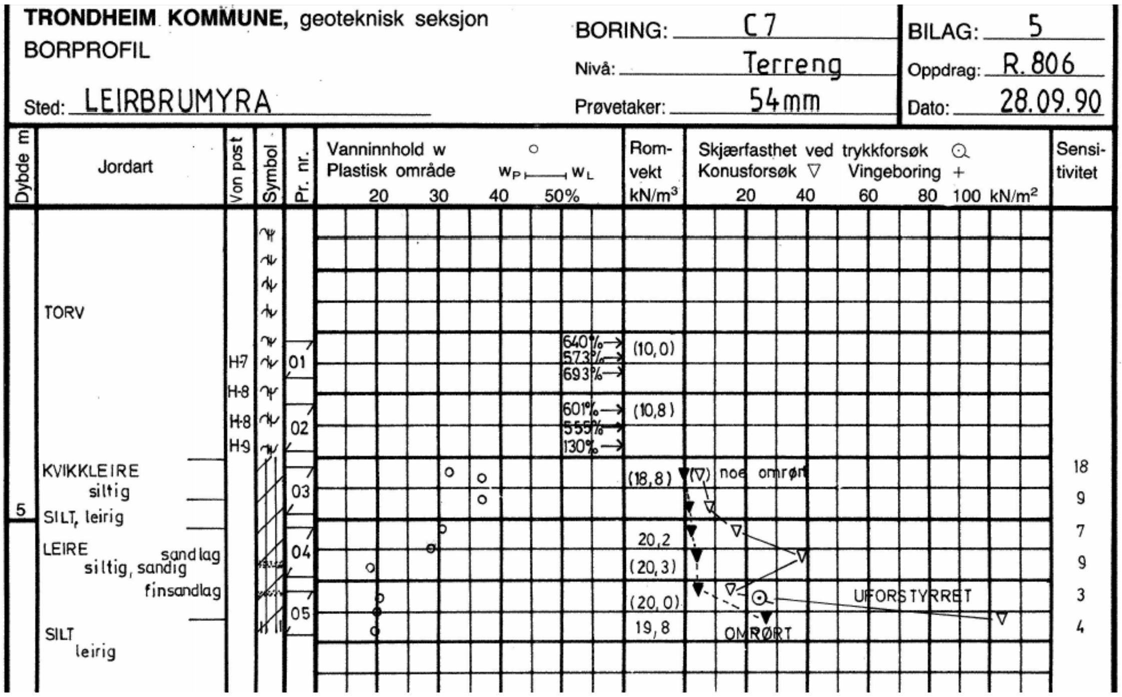
<u>R.1448 Parking lot Leirbruvegen</u>
In 2010, Trondheim municipality made soundings in the parking lot at Granåsen. The purpose of the soundings was to see how much the peat layer had been compressed as a result of the parking lot being built. When establishing the parking lot, the ground consisted of a peat layer with a thickness of 0.5-11.0 m with one top layer of gravel. The recordings in 2010 showed that there was 0.7-1.4 m of fill material in the area, with the exception of one point where 3.7 meters of gravel were found over the peat. Under the peat there was a soft clay over bedrock. The clay had relatively low strength. Comparison of today's peat depths with measurements from the 90s suggests that peat is very compressible. The peat had settled considerably, from 0.8 to 2.5 m even though the area was only filled up with an average of 1 m of gravel. At the point of 3.7 m of gravel, the peat had settled 4.3 meters.

Existing field work relevant for peat characterization

There are not pore pressure measurements in the area. However, it can be assumed that the GWT is close to the surface in peat areas.

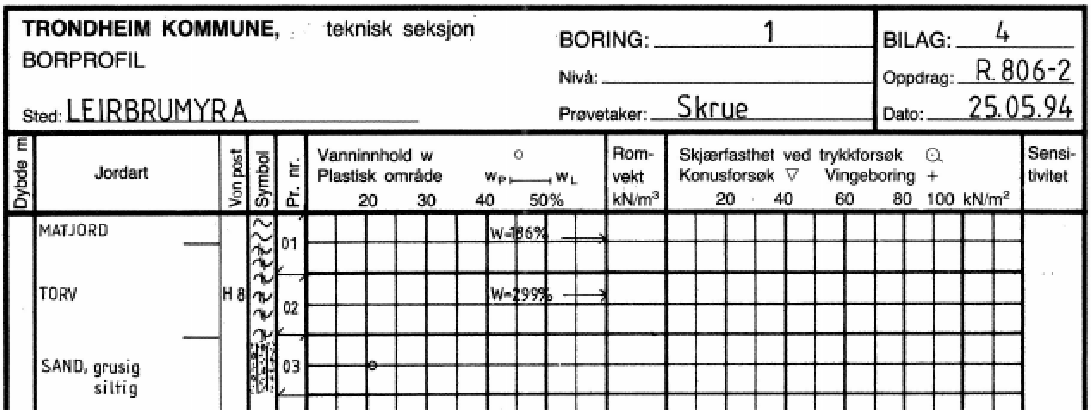
These are the results from sampling at the site:



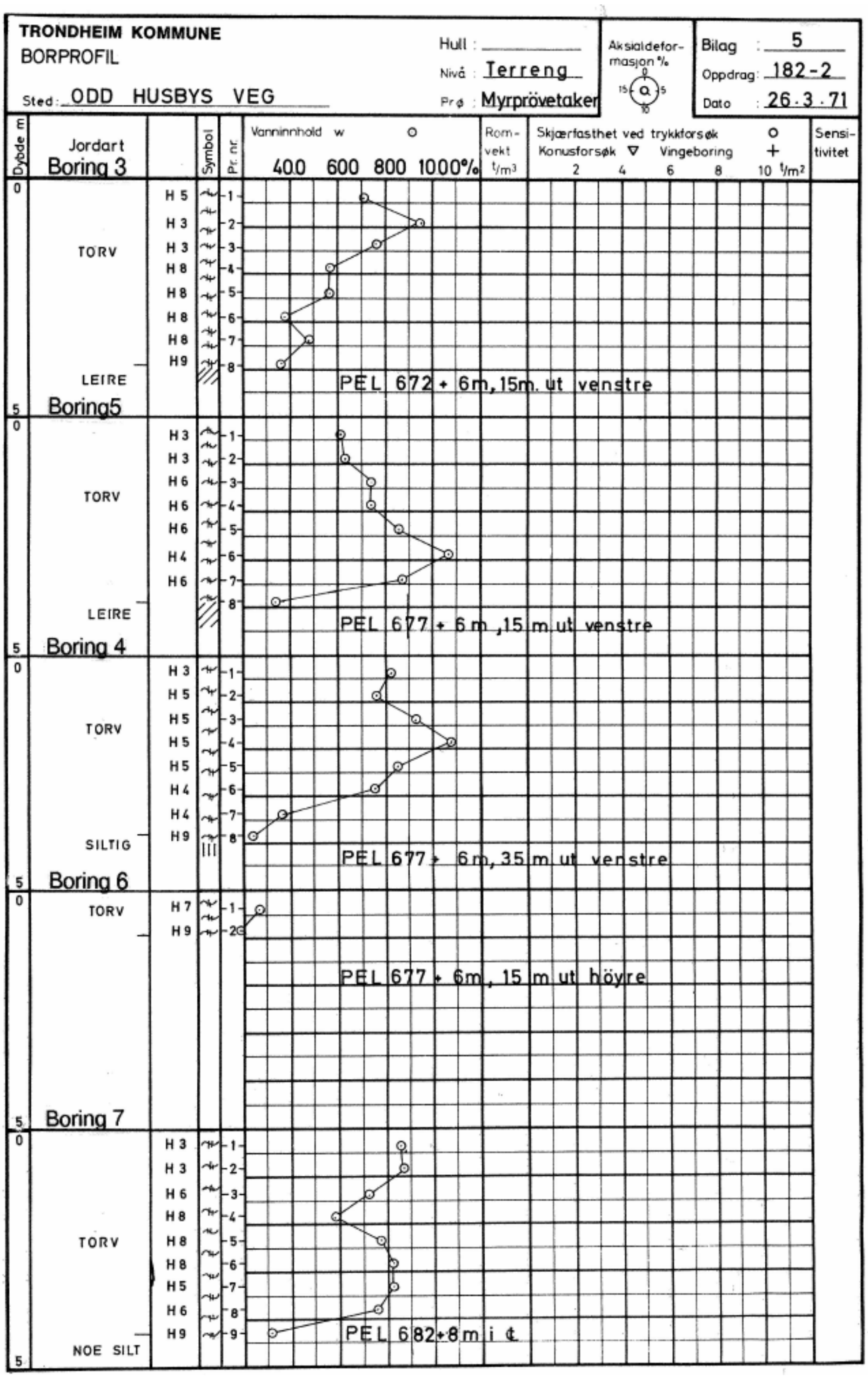


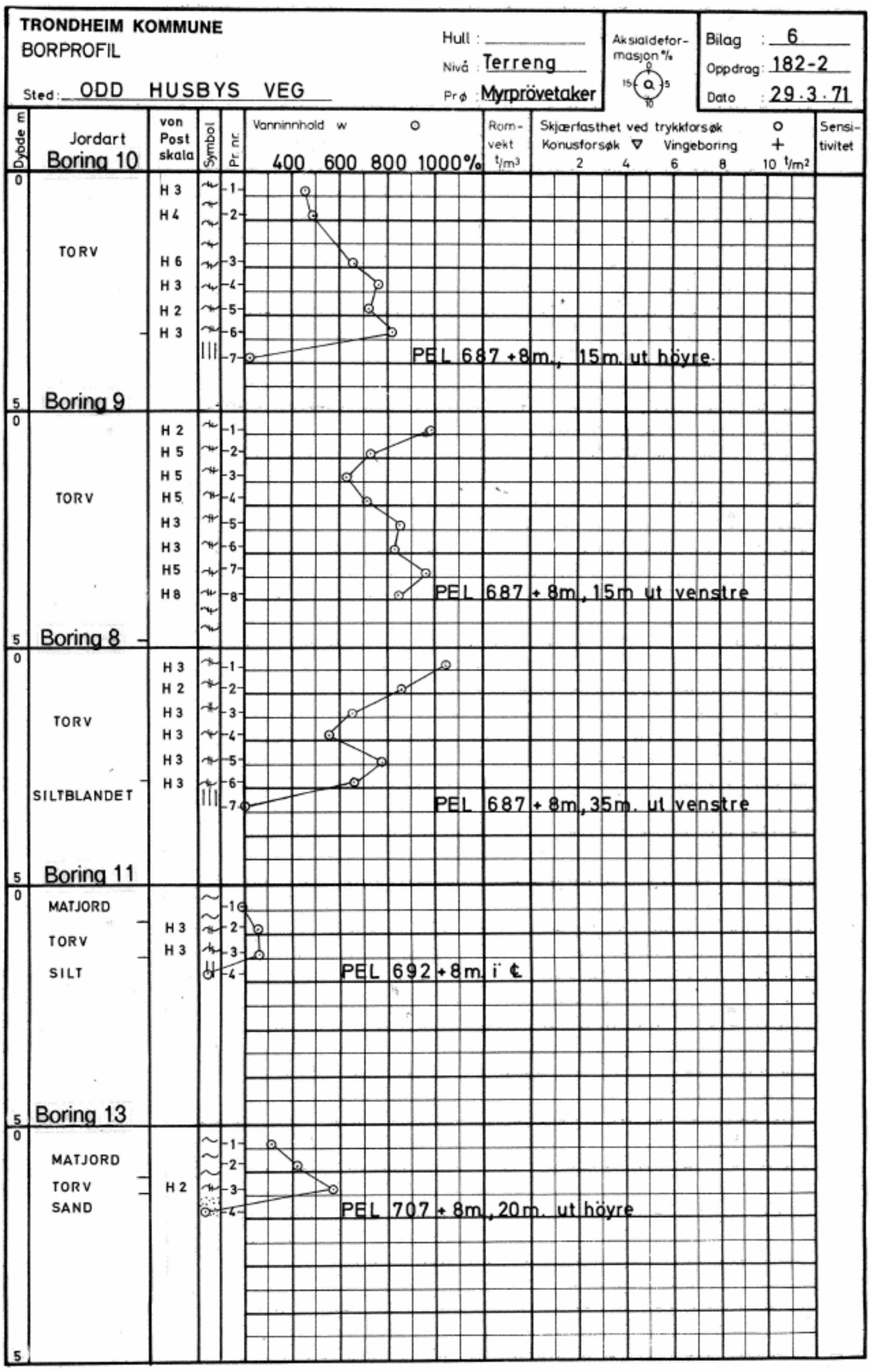
TRONDHEIM KOMMUNE, geoteknisk seksjon
BORPROFIL
Sted: LEIRBRUMYRA
BORING: C7
Nivå: Terreng
Prøvetaker: 54mm
BILAG: 5
Oppdrag: R.806
Dato: 28.09.90
Dybde m
Jordart
Von post
Symbol
Pr. nr.
Vanninnhold w
Plastisk område
20 30 40 50%
Rom-vekt kN/m³
Skjærfasthet ved trykkforsøk
Konusforsøk
Vingeboring
20 40 60 80 100 kN/m²
Sensi-tivitet
TORV
H-7
H-8
H-8
H-9
01
02
03
04
05
640%
573%
693%
601%
555%
130%
(10,0)
(10,8)
KVIKKLEIRE
siltig
5
SILT, leirig
LEIRE
sandlag
siltig, sandig
finsandlag
SILT
leirig
(18,8)
20,2
(20,3)
(20,0)
19,8
noe omrørt
UFORSTYRRET
OMRØRT
18
9
7
9
3
4

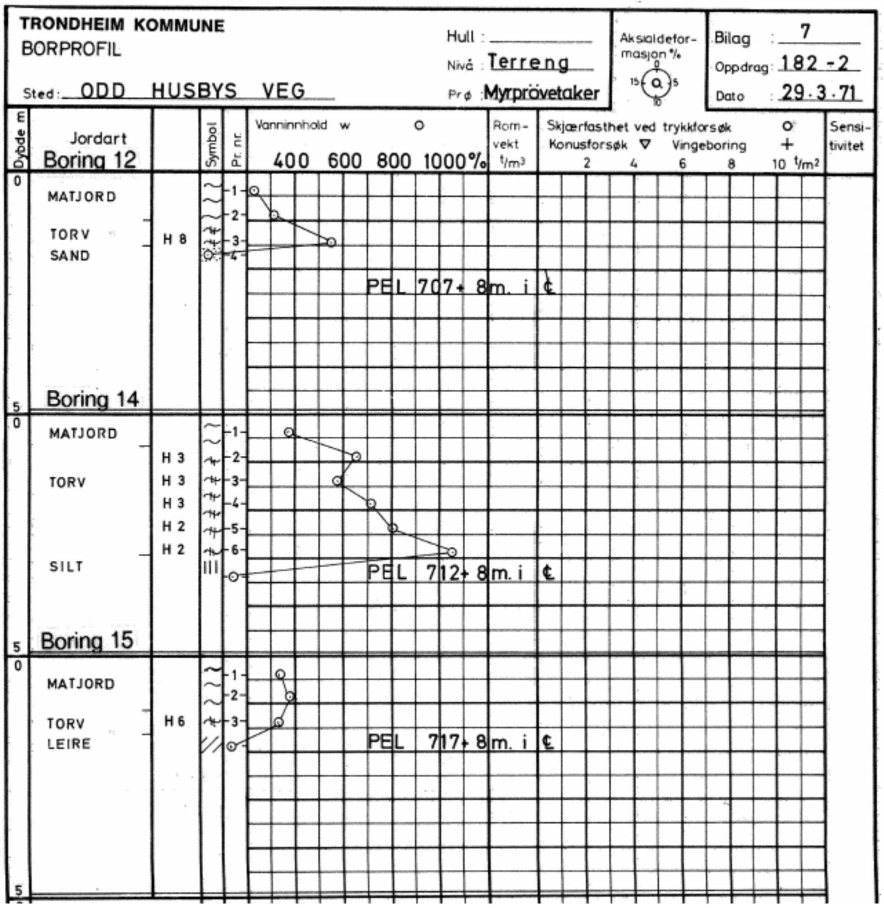
From R182-2:



TRONDHEIM KOMMUNE, teknisk seksjon
BORPROFIL
Sted: LEIRBRUMYRA
BORING: 1
Nivå:
Prøvetaker: Skrue
BILAG: 4
Oppdrag: R.806-2
Dato: 25.05.94
Dybde m
Jordart
Von post
Symbol
Pr. nr.
Vanninnhold w
Plastisk område
20 30 40 50%
Rom-vekt kN/m³
Skjærfasthet ved trykkforsøk
Konusforsøk
Vingeboring
20 40 60 80 100 kN/m²
Sensi-tivitet
MATJORD
TORV
H 8
SAND, grusig
siltig
01
02
03
W=186%
W=299%


TRONDHEIM KOMMUNE
BORPROFIL
Sted: ODD HUSBYS VEG
Hull:
Nivå: Terreng
Prø: Myrprövetaker
Aksialdeformasjon %
Bilag: 5
Oppdrag: 182-2
Dato: 26.3.71
Dybde m
Jordart
Symbol
Pr. nr.
Vanninnhold w
400 600 800 1000%
Romvekt t/m³
Skjærfasthet ved trykkforsøk
Konusforsøk
Vingeboring
2 4 6 8 10 t/m²
Sensitivitet
Boring 3
TORV
LEIRE
PEL 672 + 6m, 15m. ut venstre
Boring5
TORV
LEIRE
PEL 677 + 6 m, 15 m ut venstre
Boring 4
TORV
SILTIG
PEL 677 + 6m, 35 m ut venstre
Boring 6
TORV
PEL 677 + 6m, 15 m ut höyre
Boring 7
TORV
NOE SILT
PEL 682+8m i ¢

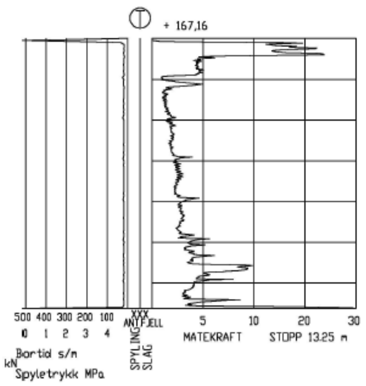

TRONDHEIM KOMMUNE
BORPROFIL
Sted: ODD HUSBYS VEG
Hull :
Nivå : Terreng
Prø : Myrprövetaker
Aksialdeformasjon %
Bilag : 6
Oppdrag : 182-2
Dato : 29.3.71
Dybde m
Jordart
von Post skala
Symbol
Pr. nr.
Vanninnhold w
400 600 800 1000%
Romvekt t/m³
Skjærfasthet ved trykkforsøk
Konusforsøk
Vingeboring
2 4 6 8 10 t/m²
Sensitivitet
Boring 10
TORV
H 3
H 4
H 6
H 3
H 2
H 3
PEL 687 + 8m, 15m ut höyre
Boring 9
TORV
H 2
H 5
H 5
H 5
H 3
H 3
H 5
H 8
PEL 687 + 8m, 15m ut venstre
Boring 8
TORV
SILTBLANDET
H 3
H 2
H 3
H 3
H 3
H 3
PEL 687 + 8m, 35m ut venstre
Boring 11
MATJORD
TORV
SILT
H 3
H 3
PEL 692 + 8m i ¢
Boring 13
MATJORD
TORV
SAND
H 2
PEL 707 + 8m, 20m ut höyre



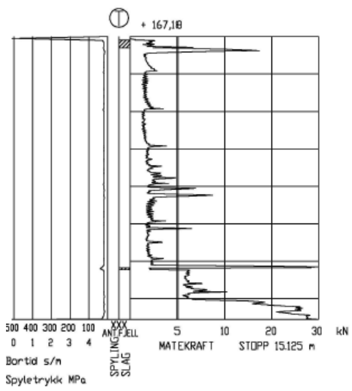
Some examples of the soundings are presented below:

From R1488:

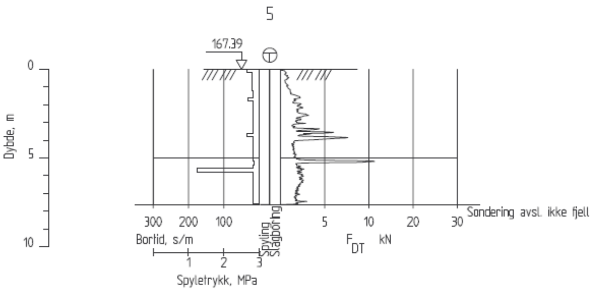
P.2

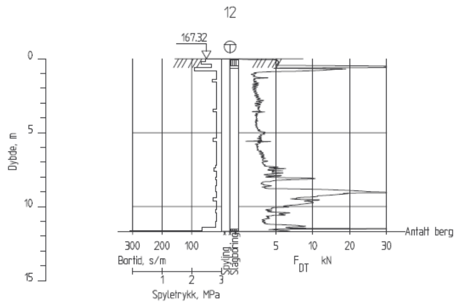


P.11

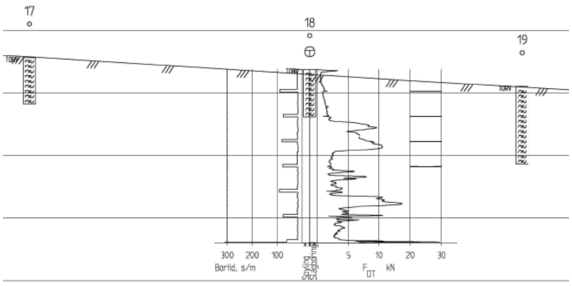


From R1547:

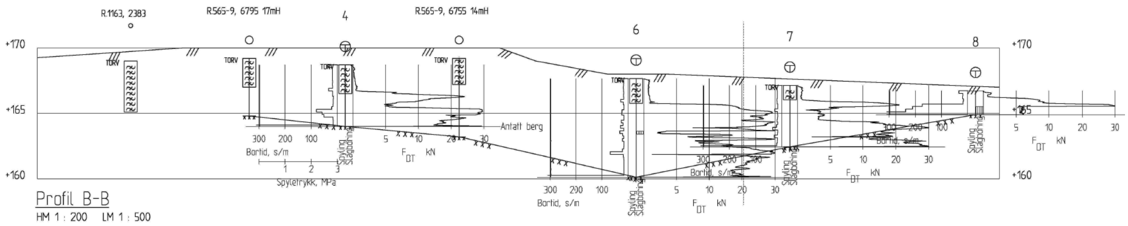




From R1629:



From R1582:



Aerial photos from 1947-2017


1947


1957

1999

2003

2008

2014

2014

2017

References

Multiconsult (2017)
Granåsen områdeplan: geoteknisk vurdering detaljregulering, 16.11.2017

Multiconsult (2015)
Områdeplan Granåsen skisenter, 31.08.2015

Trondheim kommune (2012)
R.1547 Granåsen, Torvdybder supplerende, 19.09.2012

Trondheim kommune (1971)
R182-2 Odd Husbys ved Leirbrua, 26.03.1971

Trondheim kommune (1990)
R806 Parkeringsplass Leirbrumyra, 08.10.1990

Trondheim kommune (1994)
R806-2 Leirbrumyra, 27.05.1994

Trondheim kommune (2002)
R1163 Kolstad-Høgåsen, 14.01.2002

Trondheim kommune (2015)
R1488-rev. 01 Parkeringsplass Leirbrumyra, 08.03.2015

Trondheim kommune (2014)
R1551 Granåsen II, 15.08.2014

Trondheim kommune (2014)
R1582 Granåsen - Leirbura, 02.01.2014

Trondheim kommune (2015)
R1629 rev.01 Granåsen områdeplan - torvdybder, 17.02.2015

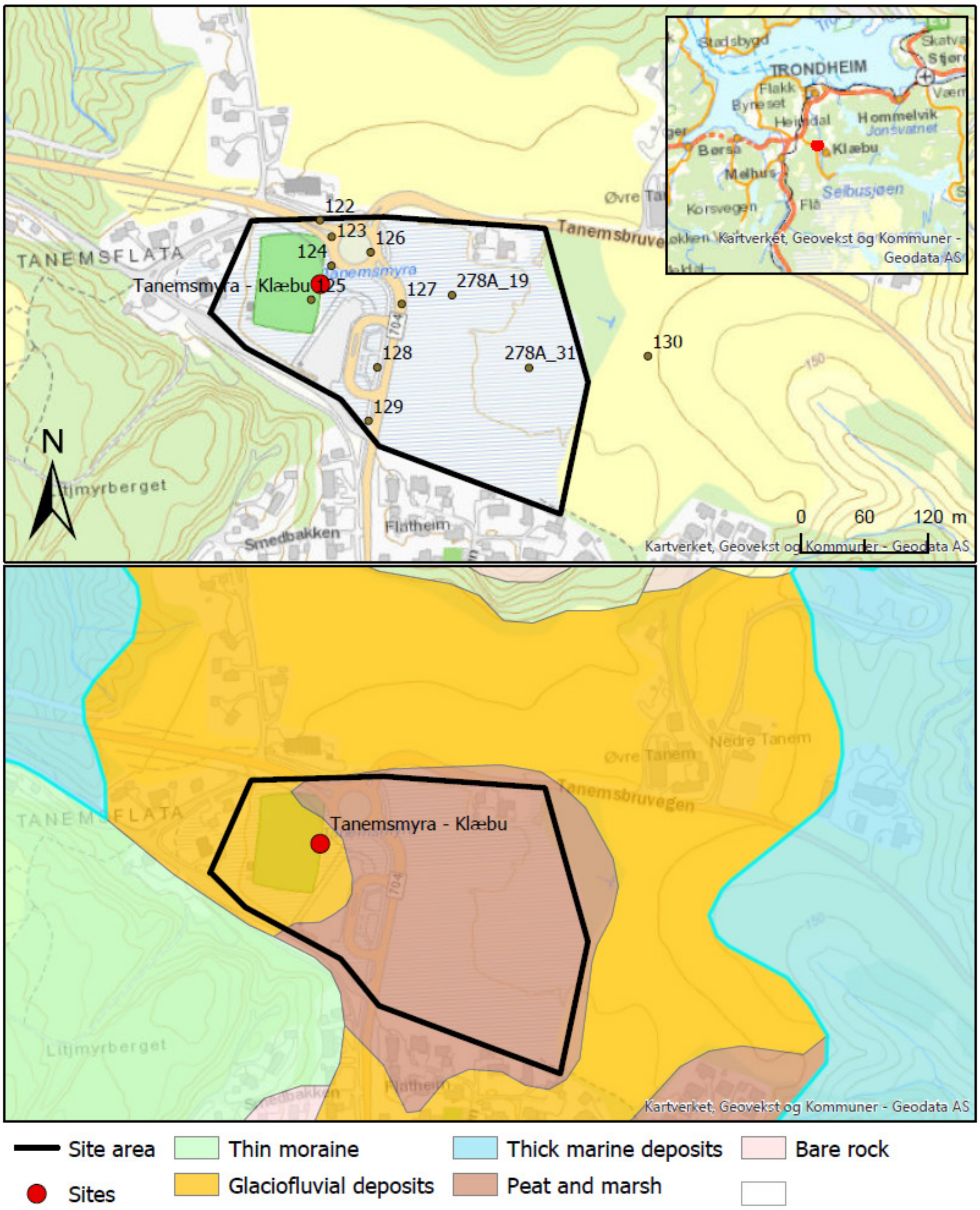
Trondheim kommune (2015)
R1629-2 Granåsen – mulig hallområde, 11.05.2015

Trondheim kommune (2016)
R1662 Granåsen sivilforsvarsleir, 16.02.2016

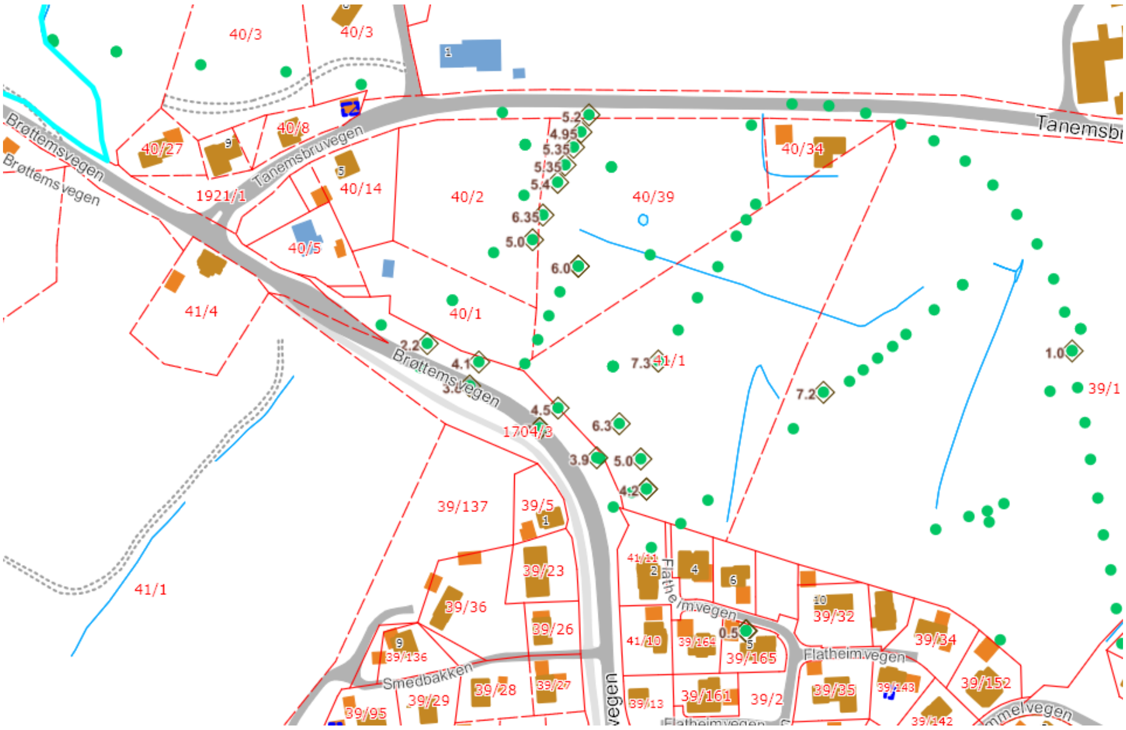
Site location

Tanemsmyra - Klæbu is located about 16 km south from Trondheim, Norway. The site has a relatively flat topography with elevations varying between 171 and 173 m.a.s.l. The site is limited by Tanem town in the south, Brøttemsvegen in the west, Tanemsbruvegen in the nord and east. The area has recently been under study due to a road construction for Fv. 704 Sandmoen – Tulluan where a roundabout, parking areas and bus stop will be/has been established.

Location of the site, with field investigations and sediments type:



Peat depths from Trondheim municipality (not completely updated):



Soil conditions

Field investigations show, to some extent, significant depths of peat from 2.5 - 7 m within the area. The roundabout and along Brøttemsvegen towards Tanem have peat depths of 4 - 5 m.

Total soundings and sampling under the peat layer at the roundabout and along Brøttemsvegen towards Tanem shows 4-13 m clay. Under the clay, the soil investigations are finished against hard layers. Field tests towards towards Tanem show that the clay is much deeper, to 21.5 and 24 m, without reaching bedrock.

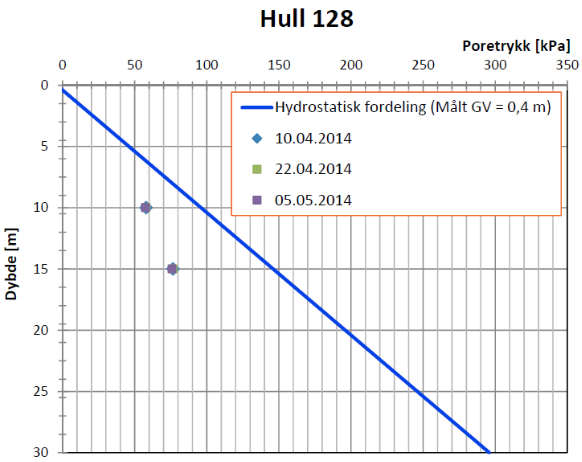
Undisturbed sampling is performed at point 122 west of the roundabout and 128 along the exit towards Tanem in the west. Point 122 consists of clay and silty clay with water content between 22-45%, s_u = 32-75 kPa from falling cone tests. The samples are not sensitive except for one falling cone test showing remoulded shear strength of 1.9 kPa.

Point 128 consists of clay, somewhat silty and sandy with water content between 28-48% and s_u = 32-88 kPa from falling cone tests. The samples show that the clay is partially sensitive down to 7.5 - 10.5 m depth with remoulded shear strength between 1.2 - 1.7 kPa, and a point of 6.6 kPa.

There are 3 soundings (points 130-132) and a sampling towards the valley located east for Tanemsmyra. The soundings show signs of thick layers of quick clay down in the valley, however not up against the peat. The depth to hard masses is approx. 15 m at points 130 and 131 at the top of the valley and about 30 m in the bottom of the valley. In point 130, disturbed samples have been recorded at 7 m depth, showing fill masses of soft sandy, clayey silt to 4 m depth. Underneath there is a layer of sensitive silty clay.

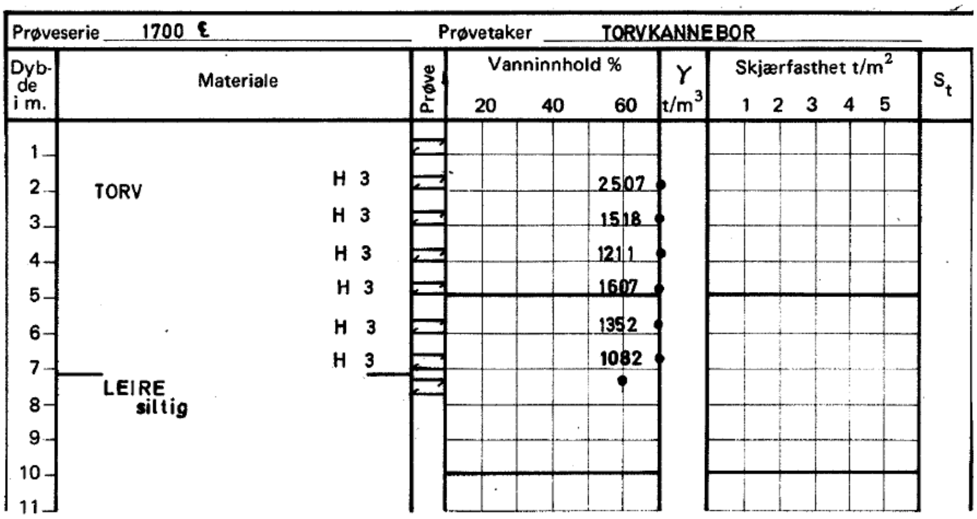
Existing field work relevant for peat characterization

There are pore pressure measurements at point 128 that show a gradient of about 5.5 kPa/m from 0.4 m depth.



These are the results from sampling at the site:

278A-19

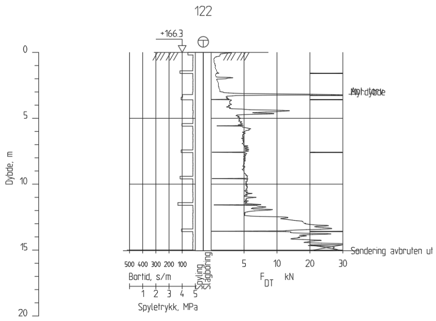


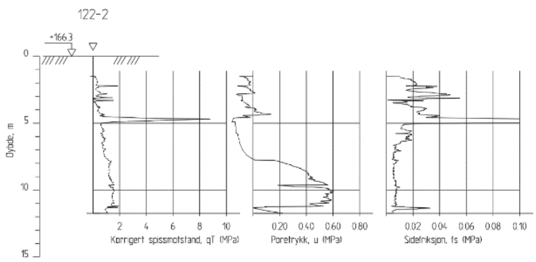
278A-31

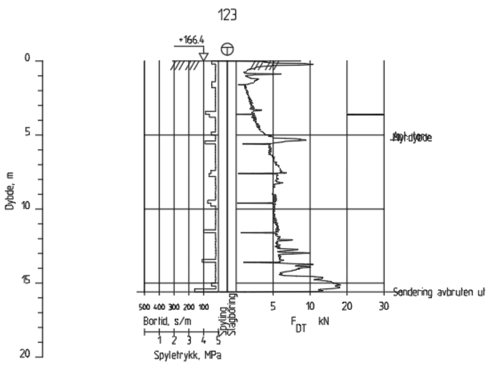
Prøveserie 1800 Ç   Prøvetaker TORVKANNEBOR

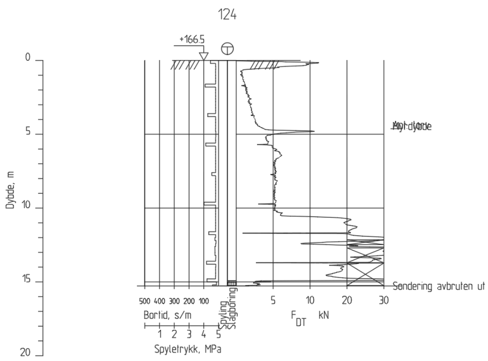
Dybde i m.	Materiale		Prøve	Vanninnhold % (20 40 60)	γ t/m³	Skjærfasthet t/m² (1 2 3 4 5)	S_t
1		H 2		2257			
2	TORV	H 2		2490			
3		H 2		2375			
4		H 2-3		2242			
5		H 3		2954			
6		H 3-4		1623			
7		H 4		2066			
8		H 4		2078			
9		H 4		2727			
10		H 4		1696			
11		H 4		830			
12	SILT			278			

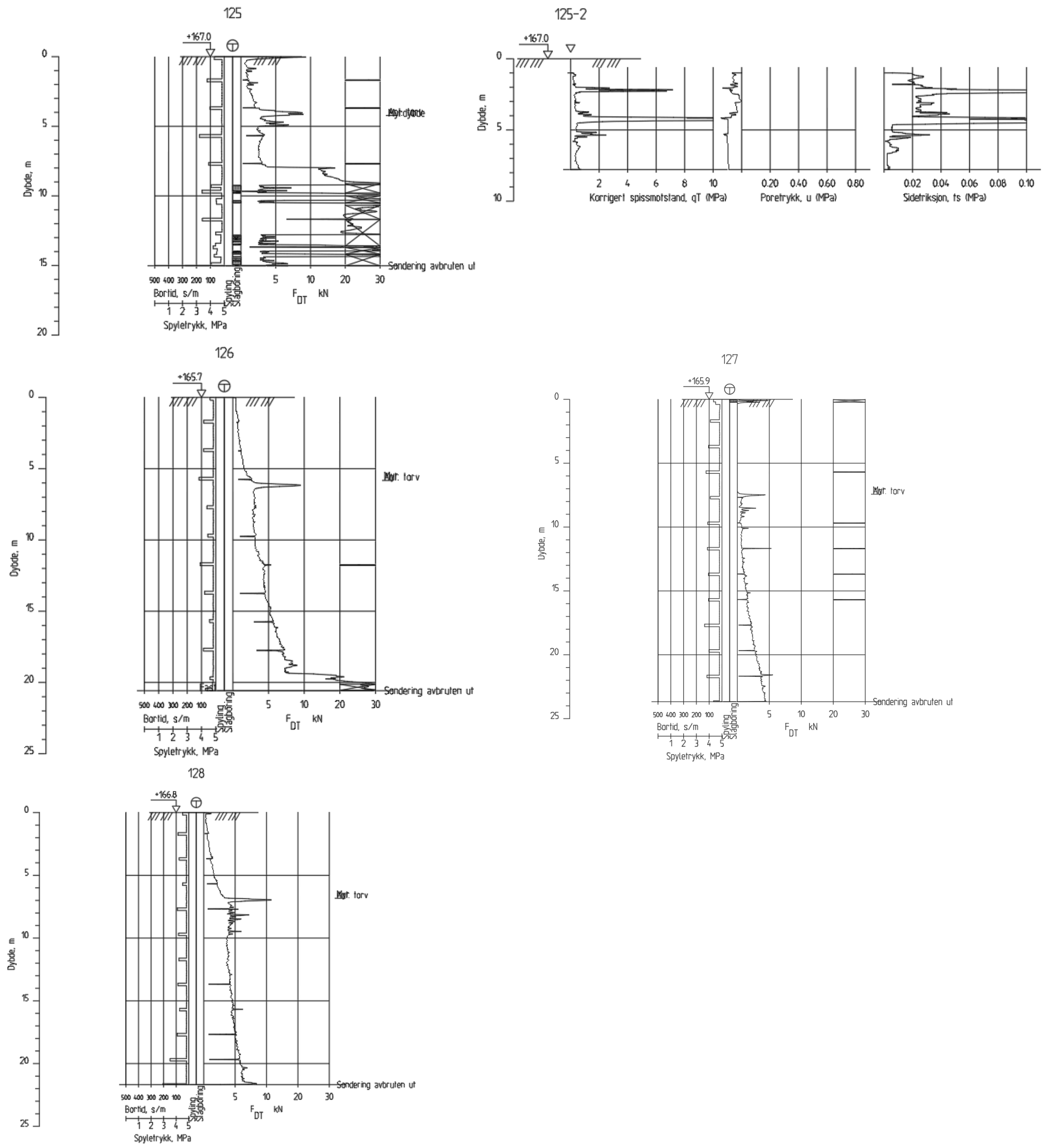
Some examples of the soundings are presented below:











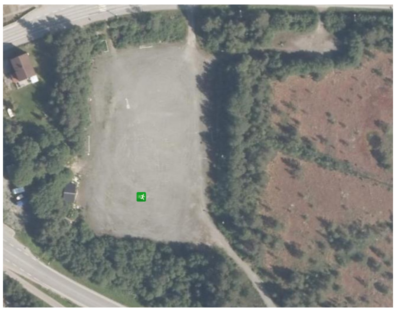
A trial pit at the football field was excavated in September 2016 (SVV, 2016). The peat depth was 6 m at the test site. A cut with 1:2 slope was excavated first, then it became 1: 1.5, it was even slightly steeper locally in the slope. The width of the excavation was 10-12 m which is 2 times the peat depth.

The peat type was of a homogeneous fiber peat type. It was assumed that the groundwater level was just below the surface. At a depth of 5.5 m, water flowed into the bottom of the excavation for a short time (2-3 times). It seemed like there was a pocket on a higher level that drained against the pit. There were little roots. After the clay layer was reached, it took 15 min before the excavation collapsed. The slope went down 1 m and the width at the top of the slide was 2 m. The inclination of the slope 1:1.5. The digging started on Monday 5/9 where 3-4 m were excavated. The work continued the morning after. The slide took place at about 12 o'clock of the 6/9. So the pit had been open for a few hours with about 5 m excavation depth.

Before

After

Aerial view from 2014



Aerial view from 2017

References

SVV (1978)
Ud278Ar01 Orienterende grunnundersøkelser Rv. 704 Tanemsflata, 01.12.1978

SVV (1989)
Ud543Ar01 Grunnundersøkelser Rv. 704 Gang- og sykkelveg ved Tanem, 30.01.1989

SVV (1989)
Ud278Ar02 Grunnundersøkelser Rv. 704 Tanemsflata, 03.10.1989

SVV (2014)
Ud543Br01 Datarapport Fv. 704 Sandmoen – Tulluan, 31.03.2014

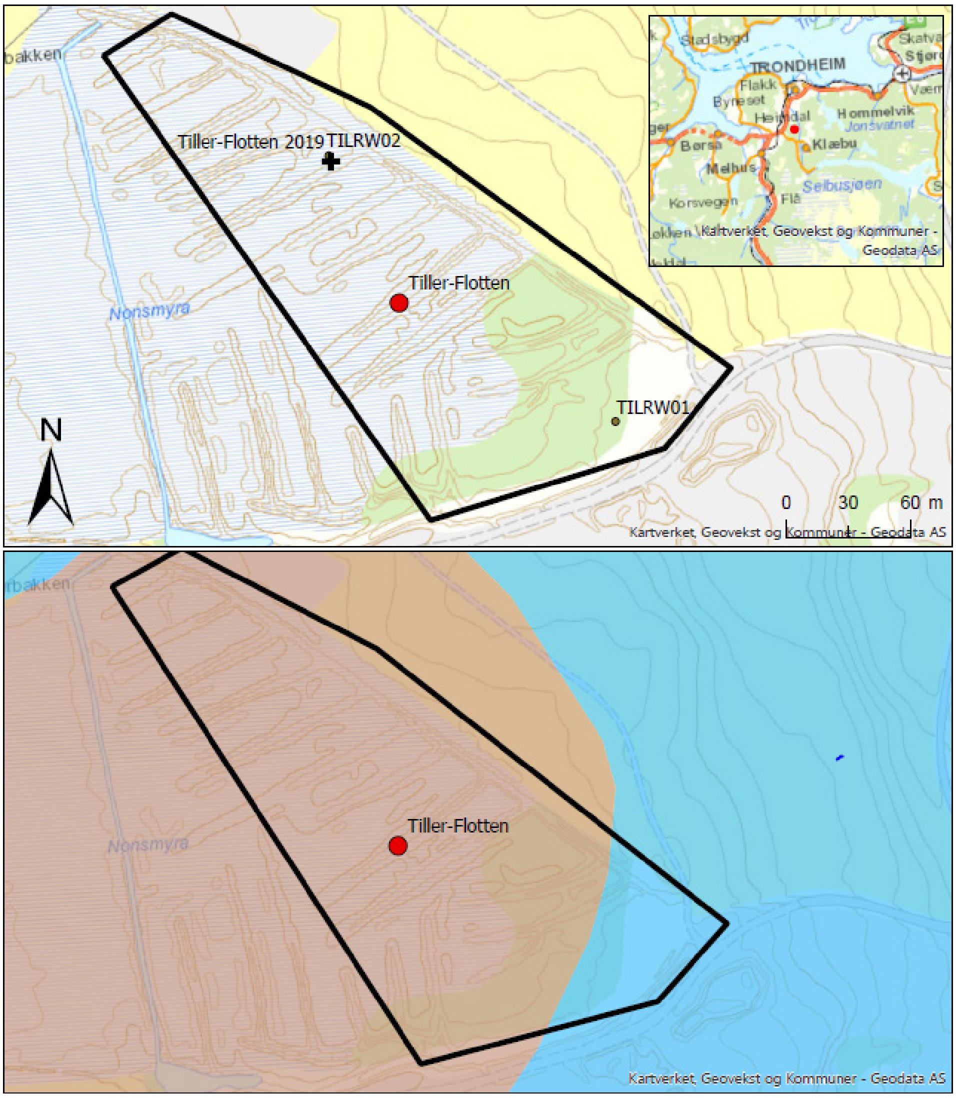
SVV (2015)
Ud543Br02 Geoteknisk vurderingsrapport Fv. 704 Sandmoen – Tulluan, 05.01.2015

SVV (2016)
Ud543Br-N02 Prøvegraving i torv ved Tanem Fv. 704 Klæbu, 07.09.2016

Site location

The Tiller-Flotten research site is situated approximately 20 km south of Trondheim in mid Norway. The site is primarily used for agricultural purposes and the area available for geotechnical studies is about 150 m by 300 m. Deposits at the site consist of marine and glaciomarine sediments that emerged from the sea following a fall in relative sea-level around the Trondheimsfjord region during the Holocene. The research site is at an elevation of 125 m.a.s.l. and drains towards the Nidelva river located at an elevation of 72 m.a.s.l. approximately 700 m to the southeast.

Location of the site, with field investigations and sediments type:



Site area

Sites

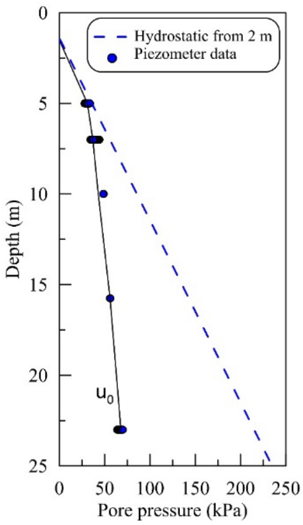
Hav- og fjordavsetning, sammenhengende dekke, ofte med stor mektighet

Torv og myr (Organisk materiale)

Soil conditions

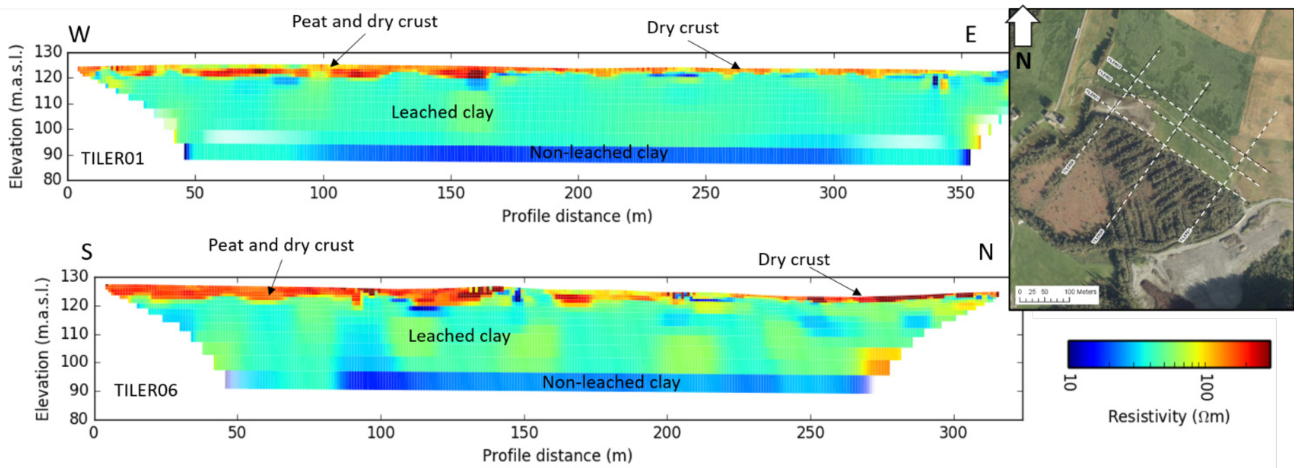
The area is dominated by peat over quick clay. The peat thickness is around 5-6 m near the sampling point.

Existing field work relevant for peat characterization



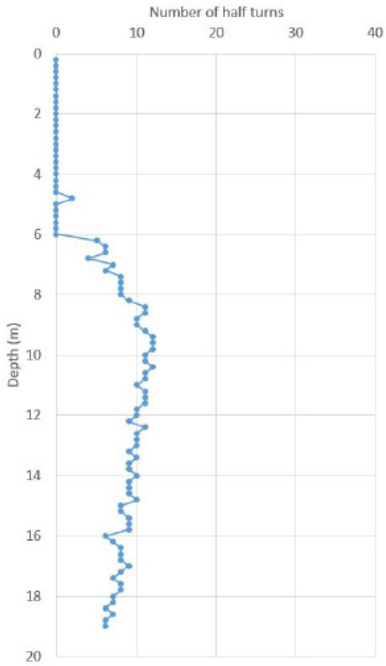
Groundwater level at the site is presently located 1 m to 2 m below ground level. The groundwater pressure is below hydrostatic conditions and show a nearly linear increase with depth between 5 m to 23 m below ground level. It is thought that the downward gradient observed is caused by drainage to the east due to the regional groundwater flow in the area and the large differences in ground elevation.

A total of six Electrical Resistivity Tomography (ERT) profiles were performed in November 2017 at the Tiller-Flotten site. On all ERT profiles, the top 1-5 meters is marked by a resistive ($\rho > 100$ Ωm) layer. This top layer corresponds to the dry crust in the North and to a combination of the dry crust and overlying peat in the South where the resistive interval is thickest. Below the dry crust the ERT results are fairly constant with values ranging from 30 to 40 Ωm down to a 35 m below ground level (i.e. elevation 90 m.a.s.l.). The ERT data at greater depth shows the presence of a more conductive layer with resistivity less than 10 Ωm. This could indicate that the clay at greater depth has not yet been leached.

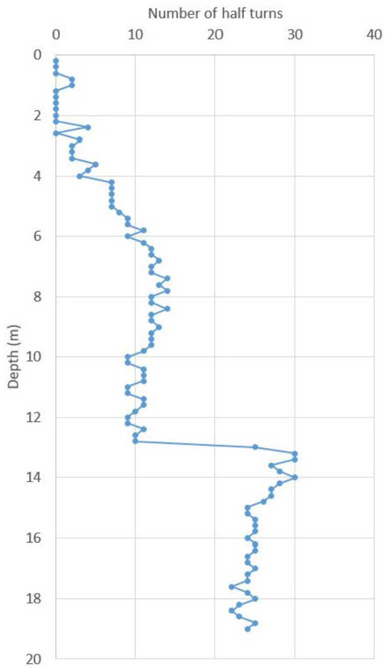


Some examples of the soundings are presented below:

TILRW02

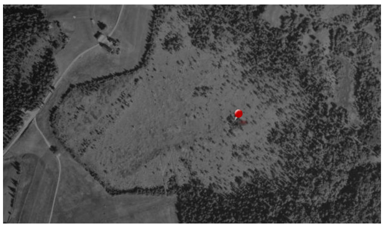


TILRW01



Aerial photos from 1937-2017

1947



1999

2017

References

L'Heureux, J.-S., Lindgård, A. & Emdal, A. (2019)
The Tiller-Flotten research site: Geotechnical characterization of a very sensitive clay deposit. AIMS Geosciences 5 (4): 831-867. doi: 10.3934/geosci.2019.4.831.

Appendix B

FIELD WORK 2019

Contents

B1 Dragvollmyra

Fieldwork:



Borehole logs:

 0-0,5 m	 0,5-1,0 m	 1,0-1,5 m
 1,5-2,0 m	 2,0-2,5 m	 2,5-3,0 m
 3,0-3,5 m	 3,5-4,0 m	 4,0-4,5 m

	
4,5-5,0 m	5,0-5,5 m

B2 Haukvanet

Fieldwork:

Borehole logs:
No pictures available.

B3 Havstein

Fieldwork:

Borehole logs:
No pictures available.

B4 Heimdalmyra

Fieldwork:

Borehole logs:
No pictures available.

B5 Leirbrumyra

Fieldwork:
Borehole 1

Borehole 2

Borehole logs bh1:

 0-0,5 m	 0,5-1,0 m	 1,0-1,5 m
 1,5-2,0 m	 2,0-2,5 m	 2, 5-3,0 m


3,0-3,5 m


3,5-4,0 m


4,0-4,5 m


4,5-5,0 m

Borehole logs bh2:


0-0,5 m


0,5-1,0 m


1,0-1,5 m


1,5-2,0 m


2,0-2,4 m


2, 5 m


2,6 m

B6 Tanemsmyra

Fieldwork:
Borehole 1

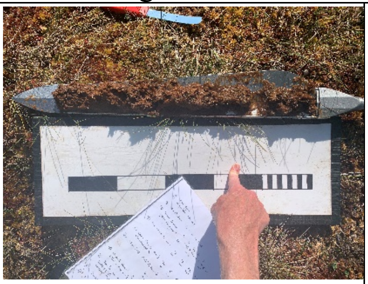
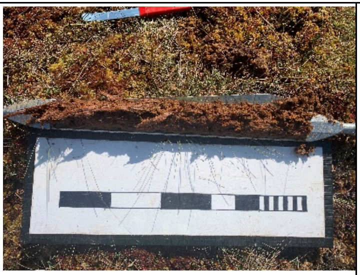
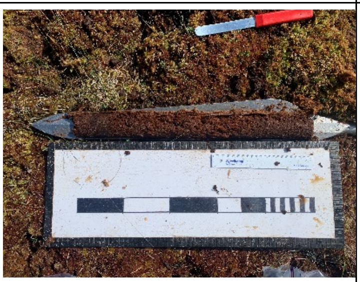




Borehole 2

Borehole logs:

 0-0,5 m	 0,5-1,0 m	 1,0-1,5 m
 1,5-2,0 m	 2,0-2,5 m	 2,5-3,0 m
 3,0-3,5 m	 3,5-4,0 m	 4,0-4, 5 m
 4,5-5,0 m	 5,0-5,5 m	 5,5-6,0 m


6,0-6,5 m


6,5-7,0 m


7,0-7,5 m


Close up at 7,5 m

B7 Tiller-Flotten

Fieldwork:

Borehole logs:


0-0,5 m


0, 5-1,0 m


1,0-1,5 m

B8 Peat sampler operating instructions

Eijkelkamp
Soil & Water

Peat sampler

Operating instructions

Meet the difference

Eijkelkamp Soil & Water
Nijverheidsstraat 30, 6987 EM
Giesbeek, the Netherlands

T +31 313 880 200
E info@eijkelkamp.com
I www.eijkelkamp.com

M-0409E

Contents

On these operating instructions

If the text follows a mark (as shown on the left), this means that an important instruction follows.

If the text follows a mark (as shown on the left), this means that an important warning follows relating to danger to the user or damage to the apparatus.The user is always responsible for its own personal protection.

Italic indicated text indicates that the text concerned appears in writing on the display(or must be typed).

1. Description

The standard peat sampler set consists, among other things, of the peat sampler and Edelman auger bottom parts, an upper part with detachable grip, extension rods, push/pull handle, a utility probe and various accessories. To connect these parts a conical screw thread connection is used. The complete set is contained in an aluminium transport case.

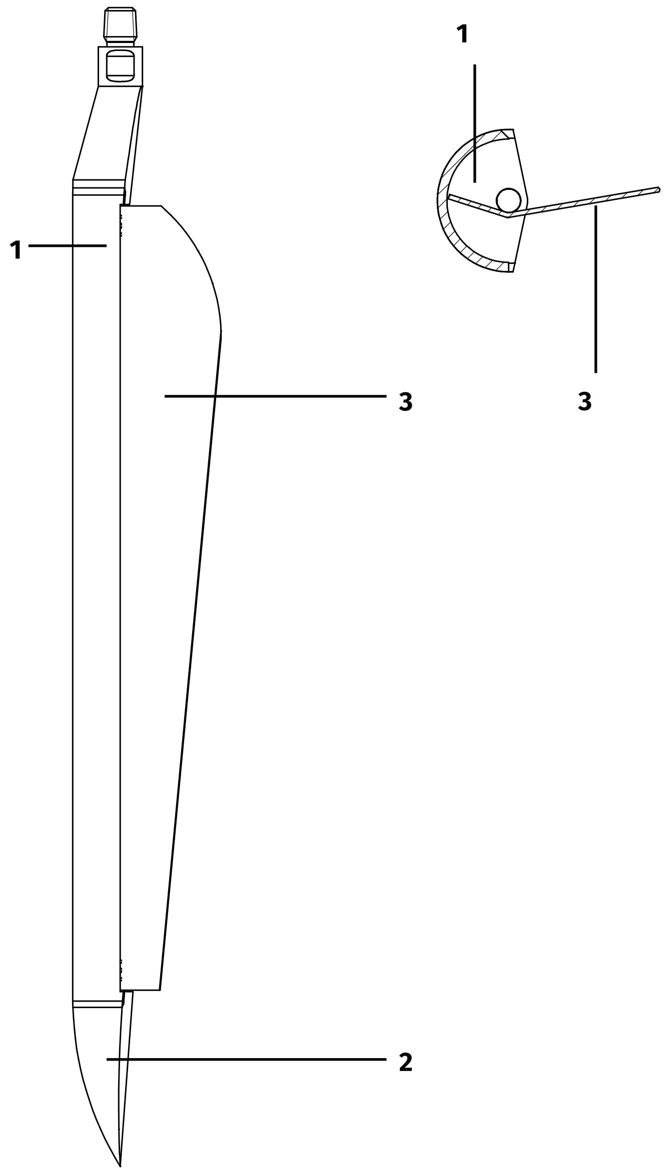
1.1 Peat sampler

The stainless steel bottom part of the peat sampler has an auger body consisting of a half-cylindrical sample containing section or “gouge” (1) with a massive cone (2) at its bottom end. The gouge has one cutting edge and is sealed off by a hooked blade or “fin” (3) hinging on the auger body. The blade’s top and bottom end’s width is identical to the auger’s width, but is wider in the middle. The protruding, rounded side has a cutting edge.

The massive cone serves to push aside the soil when the sampler is inserted. At that stage, the blade seals off the gouge. When the auger is given a half turn (180°) to fill the, resistance will cause the blade to remain in position. When the auger is hoisted, the other side of the blade seals off the gouge.

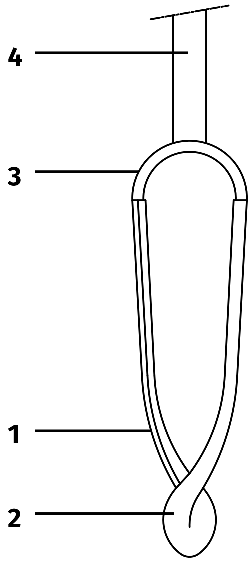
The peat sampler’s operational depth is 50 cm. The gouge’s diameter is 60 mm, contents ca. 0.5 litre (Sample diameter 52 mm).

The upper part measures 60 cm and has a detachable, synthetic handle. The extension rods measure 1 m.



Peat sampler, side view (left) and cross section (right).

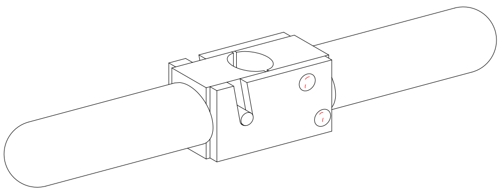
1.2 Edelman auger, combination type



The Edelman auger body (see figure) is conical in shape and consists of two blades (1) joined in a cone (2). The top of the blades is welded to a bracket (3), which is connected to the auger rod (4). The blades are vaulted and when entering the soil the sample is dug up and evenly guided into the inside of the auger body. The vaulting of the blades not only promotes digging up but also ensures a firm grip of the sample while permitting easy emptying of the auger body.

The Edelman combination type auger's diameter (measured diagonally between the blades at the broadest part of the auger body) measures 10 cm, the blades measure 50 mm in width. This permits a good hold of moderately cohesive soils, while cohesive soils can easily be removed.

1.3 Attachments



Push/pull handle.
The push/pull handle has two parts that can be fitted around a rod.
Once pressure is exercised on the two bars of the handle its construction ensures a firm hold of the rod.

Utility probe.
The fibre glass utility probe measures 105 cm and has a 19-mm cone diameter. The probe is well insulated; this ensures safely checking the substratum for cables, tubes and pipes in all types of soils.

2. Safety instructions

Prior to augering check for cables, tubes and pipes (inquire at your municipality or other relevant organisations). Use the utility probe to safely check the spot for augering. If necessary, select another spot.

While augering, hold the auger by its synthetic handle. It is fully insulated should you hit an electricity cable.

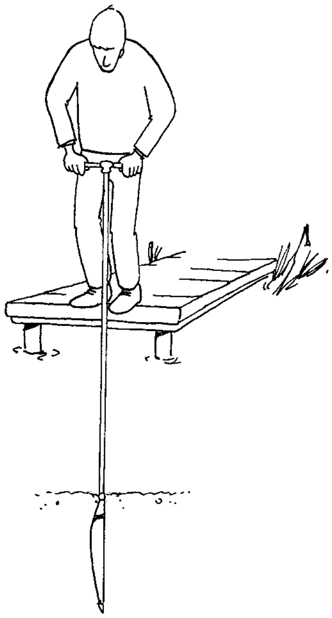
Do not force, or pound on, the peat sampler. The use of a hammer may cause serious damage. Force may cause torsion of the blade, which may bend or snap.

Augers over 4 m should be handled in parts. This will prevent damage to the rods and reduce the risk of being hit by augers tipping over. This applies to inserting and hoisting the auger.

Be cautious during a thunderstorm. Lightning strokes often occur in the open field, in particular when one holds a metal auger.

3. Use of peat sampler and Edelman auger

3.1 Peat sampler



Prior to augering check for cables, tubes and pipes (inquire at your municipality or other relevant organisations). Use the utility probe to safely check the spot for augering. If necessary, select another spot.

1. Screw the synthetic handle onto the upper part.

2. Attach the bottom part with auger body to the upper part. If necessary, use one or more extension rods. Use spanner 20x22 to tighten the connections.

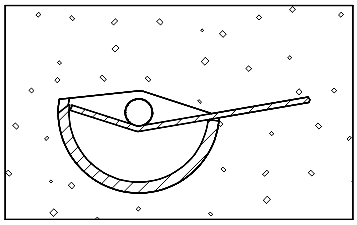
3. Turn the blade to fully seal off the gouge. The blade's protruding side should cover the flat, non-cutting edge of the gouge.

4. Insert the sampler vertically, without rotating it, into the soil or into the water to a chosen depth. The blade seals off the gouge so as to prevent it from filling up. The massive cone pushes the soil aside. The cutting edge cuts through the soil.

While augering, hold the auger by its synthetic handle. It is fully insulated should you hit an electricity cable.

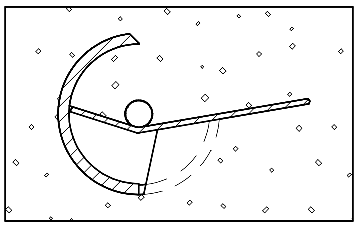
Do not force, or pound on, the peat sampler. The use of a hammer may cause serious damage. Force may cause torsion of the blade, which may bend or snap.

5. At the chosen depth, give the auger a half turn clockwise. The gouge will make a half circle, pivoting on the blade's hinges. Resistance will cause the blade to remain in position, whereas the gouge cuts through the soil and upon completion of a half circle is fully filled with sample material (see figures below). The blade seals off the sample inside.

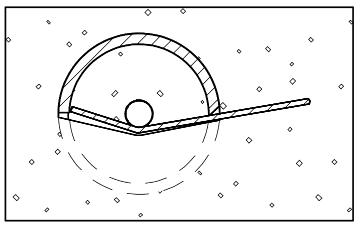


6. Hoist the auger vertically; keep your back straight and your knees bent to prevent injuries. The blade fully seals off the gouge, so the sample will not mix with upper soil layers. If necessary, use the push/pull handle to ensure a full grip at a comfortable position.

In very weak soils or open water, hoist the sampler while gently rotating it to ensure that the blade remains in position. In addition, in open water the current may cause the gouge to open. Turn the sampler to ensure that the current pushes against the blade.



7. Upon withdrawal, lay the sampler flat on the ground, the blade on top of the gouge. Turning the blade a half circle in a horizontal position will clean the gouge, presenting a hardly disturbed sample laid out on the blade.



Augers over 4 m should be handled in parts. This will prevent damage to the rods and reduce the risk of being hit by augers tipping over. This applies to inserting and hoisting the auger.

Be cautious during a thunderstorm. Lightning strokes often occur in the open field, in particular when one holds a metal auger.

Some remarks:

- ❒ It is possible to auger at any chosen depth to take a sample (a depth-specific sample). Usually, pre-augering to a chosen depth will not be necessary.

- ❒ To determine the sampler depth (in particular in open water), it is recommended to apply variable grade marks to the extension rods (an elastic band or sleeve).

- ❒ Coarse, fibrous or stony soils may cause the blade not to seal off the gouge well. This may result in loss of sample.

- ❒ Resistance incurred upon insertion of the massive cone and of the blade may hamper sampling in stiff soils. The resistance may cause torsion of the auger body, or the blade to bend. In that case, it is advised to pre-auger using the Edelman auger (see paragraph 3.2).

3.2 Edelman auger, combination type

1. Hold the auger by its handle and rest it vertically on the ground (see figure).

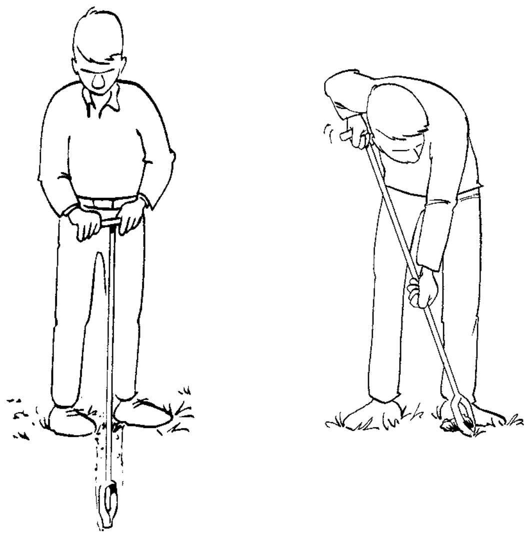
2. Upon 2¼ rotations (360°), the auger should have dug 10 cm. The auger body will be filled up to its bracket with slightly disturbed soil material. Depending on the type of soil additional rotations may be necessary.

☞ **Always rotate clockwise.**

3. Cut off the sample rotating a full turn (360°) without pressing down, and hoist the auger while gently rotating it.

4. To release the cohesive material hold the auger askew on the surface (see figure), rotate the auger 180° while pressing it into the ground. The sample should detach itself and can be taken out by hand or by lightly tapping the auger. Moderately cohesive material will detach itself immediately.

5. After pre-augering, the peat sampler can be used for sampling (see figure and paragraph 3.1)



Caution:

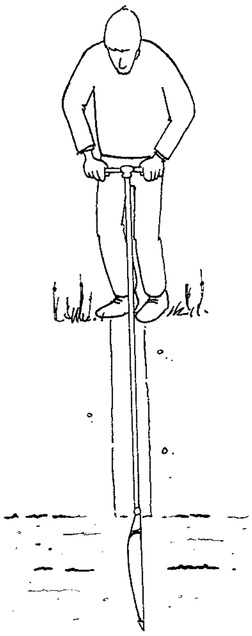
- ❒ Do not overfill the auger body. Superfluous material will coat the auger hole, which hinders pulling out subsequent soil samples. When augering under the water table an overfilled auger acts like a plunger, which hampers hoisting the auger and results in loss of sample material.
- ❒ Loss of sample material. Hoist the auger with sample while lightly rotating it, do not pull it straight out.

4. Applications

The peat sampler is suitable for use in weak, cohesive soils such as swampy, peaty soils and in subaqueous soils ('sediment'). It may also be used for sampling of powder and granule-like material held in big-bags, lorries and drums. The standard set allows sampling to a depth of 10 m.

The peat sampler can be used for sampling at any chosen depth without pre-augering. In the case of stiff soils (such as clay), pre-augering using the Edelman combination type should precede sampling with the peat sampler.

The peat sampler is applied to take semi-disturbed samples in:
- ❒ Environmental studies.
- ❒ Soil research in peat (structure, composition of profiles).
- ❒ Aquatic botany.
- ❒ Paleontological and pollen research.
- ❒ Sampling of powder and granule-like materials.
- ❒ Filter beds with sand and activated carbon.



5. Troubleshooting

- ❒ The peat sampler incurs considerable resistance upon insertion into stiff soil layers (such as clay, sand or gravel) or into coarse fibrous and stony soils. If these layers are top layers, the Edelman auger can be applied for pre-augering.

- ❒ Loss of sample occurs during hoisting the peat sampler, caused by the blade badly sealing off the gouge. Coarse, fibrous structures or gravel stuck between the blade and the gouge may be the reason. In this situation, no sampling is possible.
  Very weak soils or open water may also have caused loss of sample. Hoist the sampler, gently rotating it to ensure that the blade seals off the gouge. In addition, in open water the current may cause the gouge to open. Turn the sampler to ensure that the current pushes the blade against the gouge.

- ❒ Sampling may be unsuccessful when the blade incurs insufficient resistance. The peat sampler is not suitable for sampling in weak soils offering insufficient resistance to cut off the sample. In that case, the Multisampler is recommended (available from Eijkelkamp Soil & Water).

6. Maintenance

- ❒ It is recommended to keep the equipment in good condition by rinsing it during use. Use a stainless steel brush to clean the conical thread connections.

- ❒ Clean the augers after use with tap water and dry them well. Stow away the equipment in the carrying bag after drying.

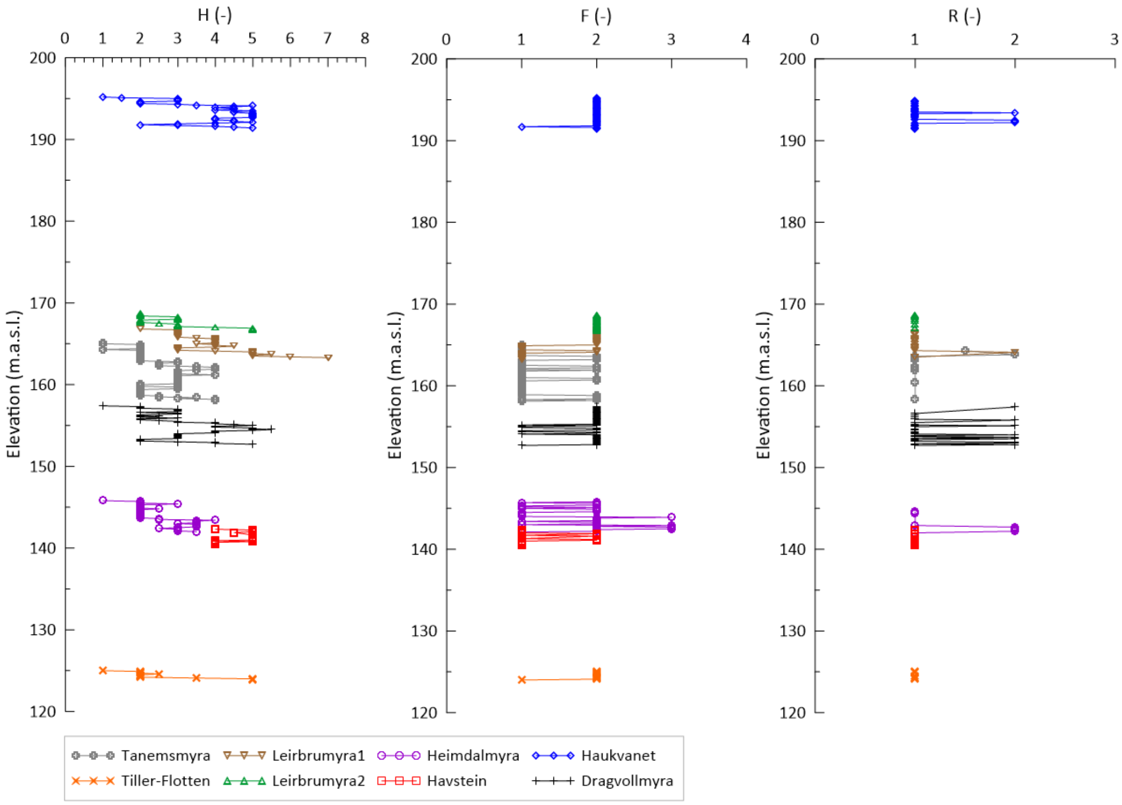
- ❒ The Edelman auger body needs no whetting, use keeps it sharp-edged. Under normal conditions oxidation is not detrimental to the auger and will vanish upon use. To avoid excessive oxidation when storing the Edelman auger body, apply Vaseline.

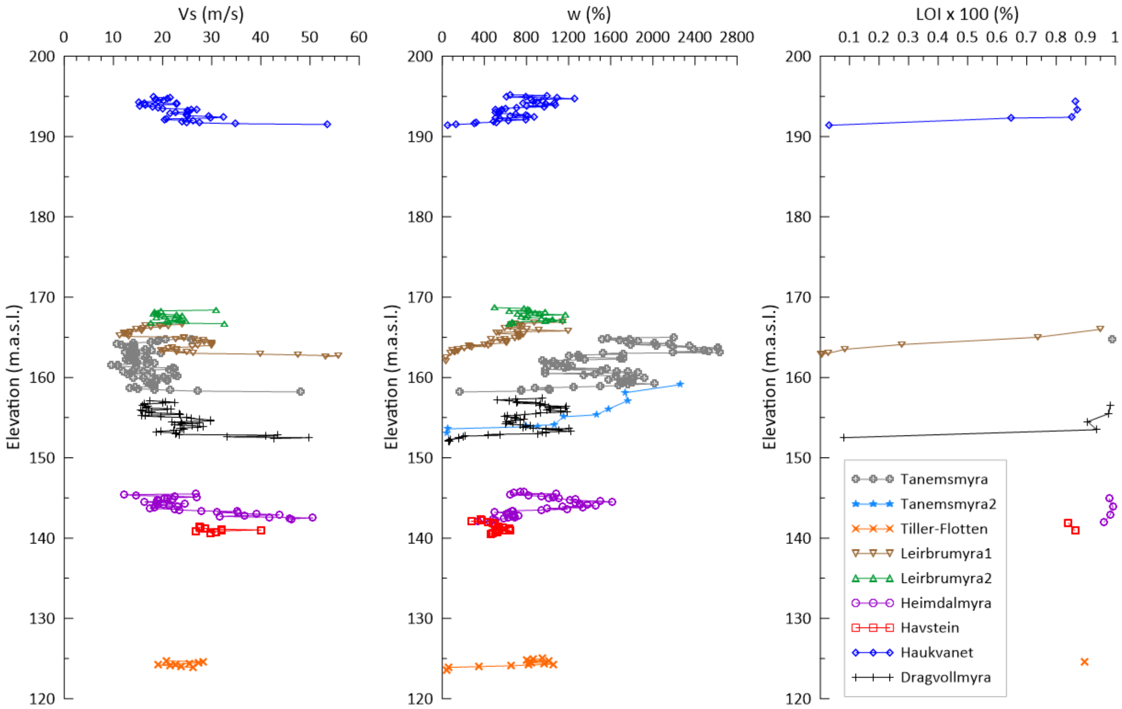
Appendix C

COLLECTED DATA OF VON POST CLASSIFICATION, WATER CONTENT, SHEAR WAVE VELOCITY FOR 2019 FIELDWORK SITES

Contents

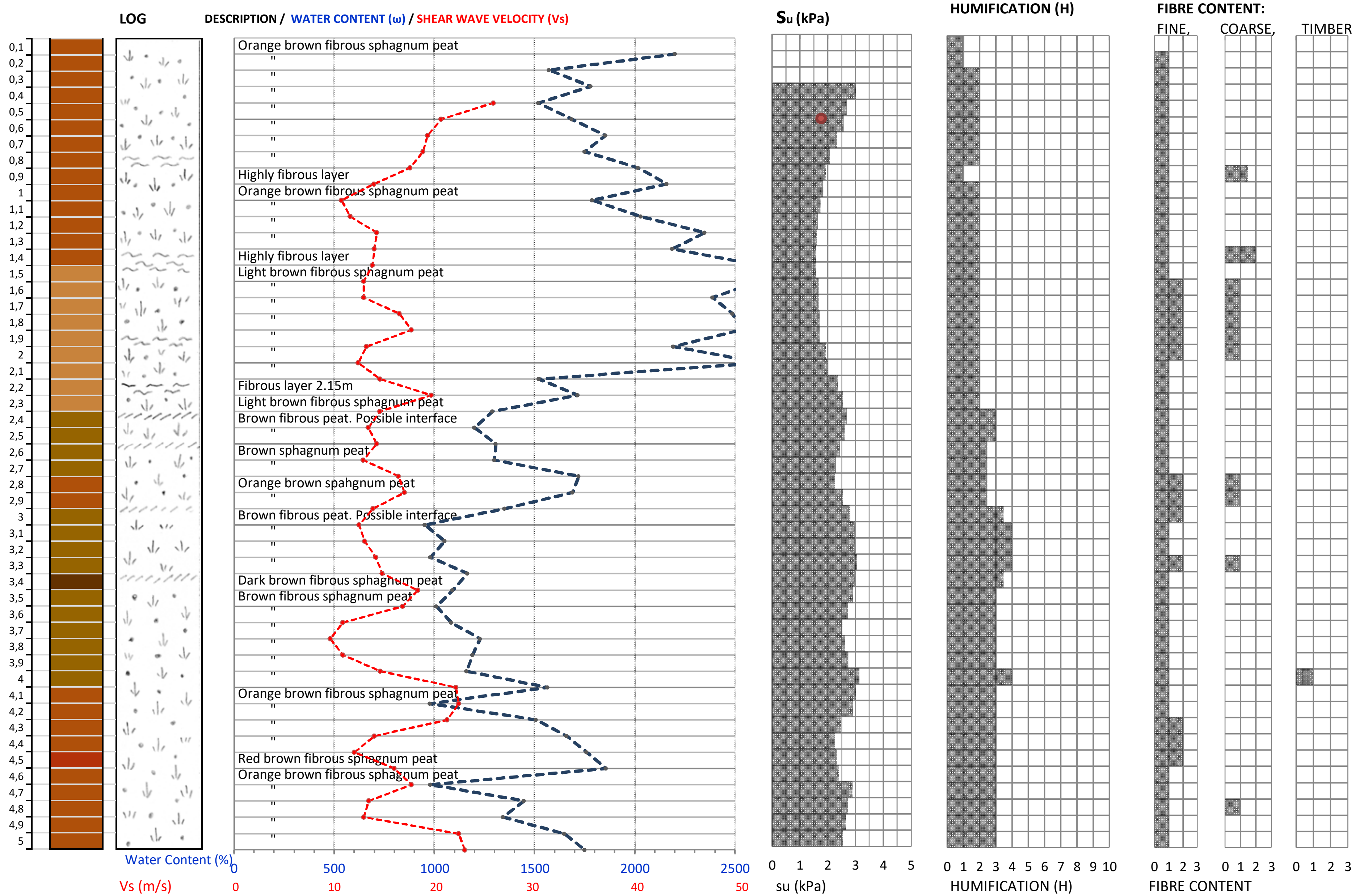
C1 Summary of values varying with elevation





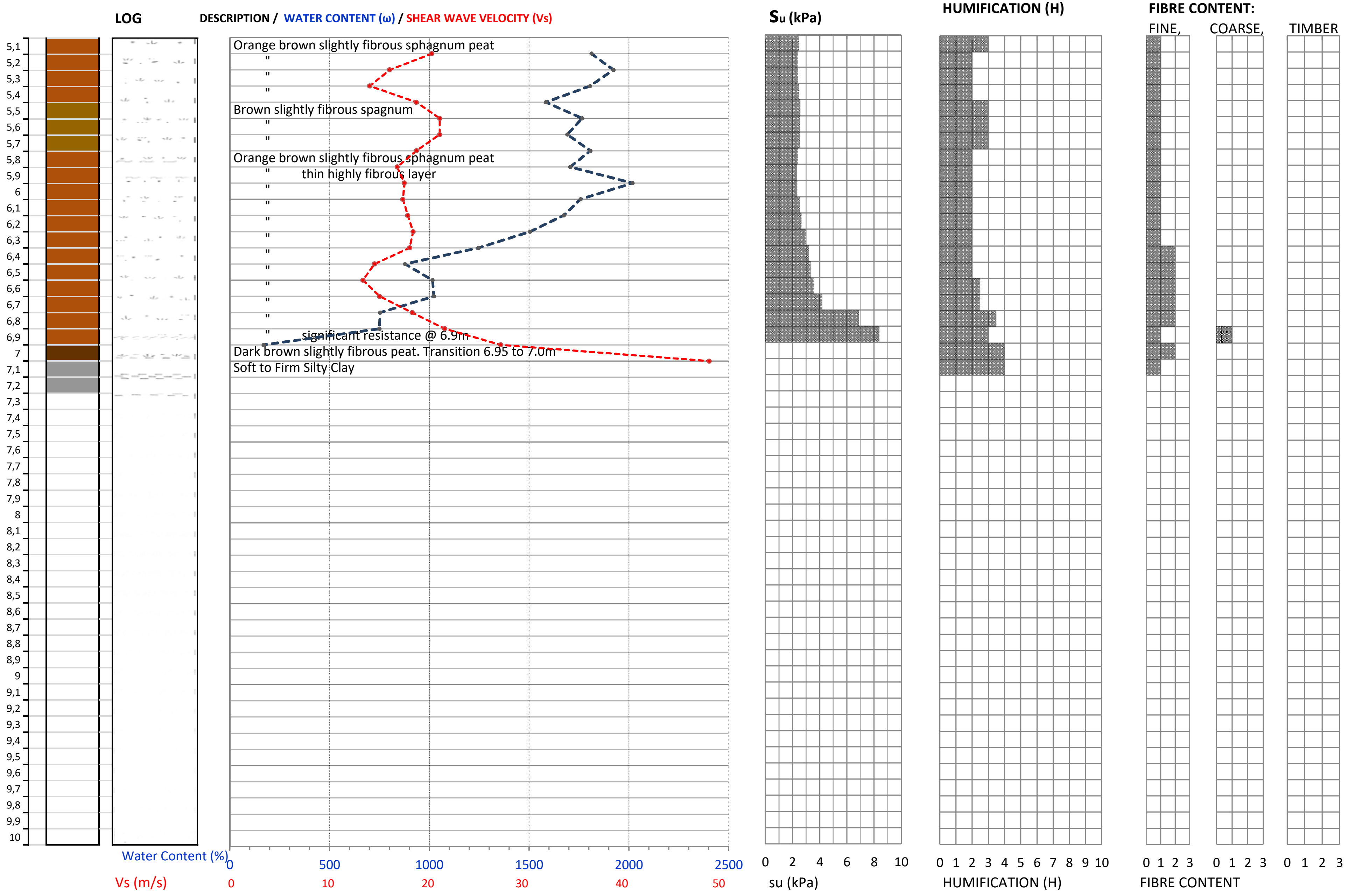
VON POST LOG - Tanemsmyra VSWP

PROJECT:	TRAFF19003	**EASTING (ING):**	63°18,780'	**COMMENTS:**
LOCATION:	Klæbu, Trondheim, Norway	**NORTHING (ING):**	10°25,912	Tanemsmyra
CLIENT:	NGI	**ELEVATION:**	165,2 m.a.s.l.	
DATE:	24.07.2019	**LOGGED BY:**	A Trafford	



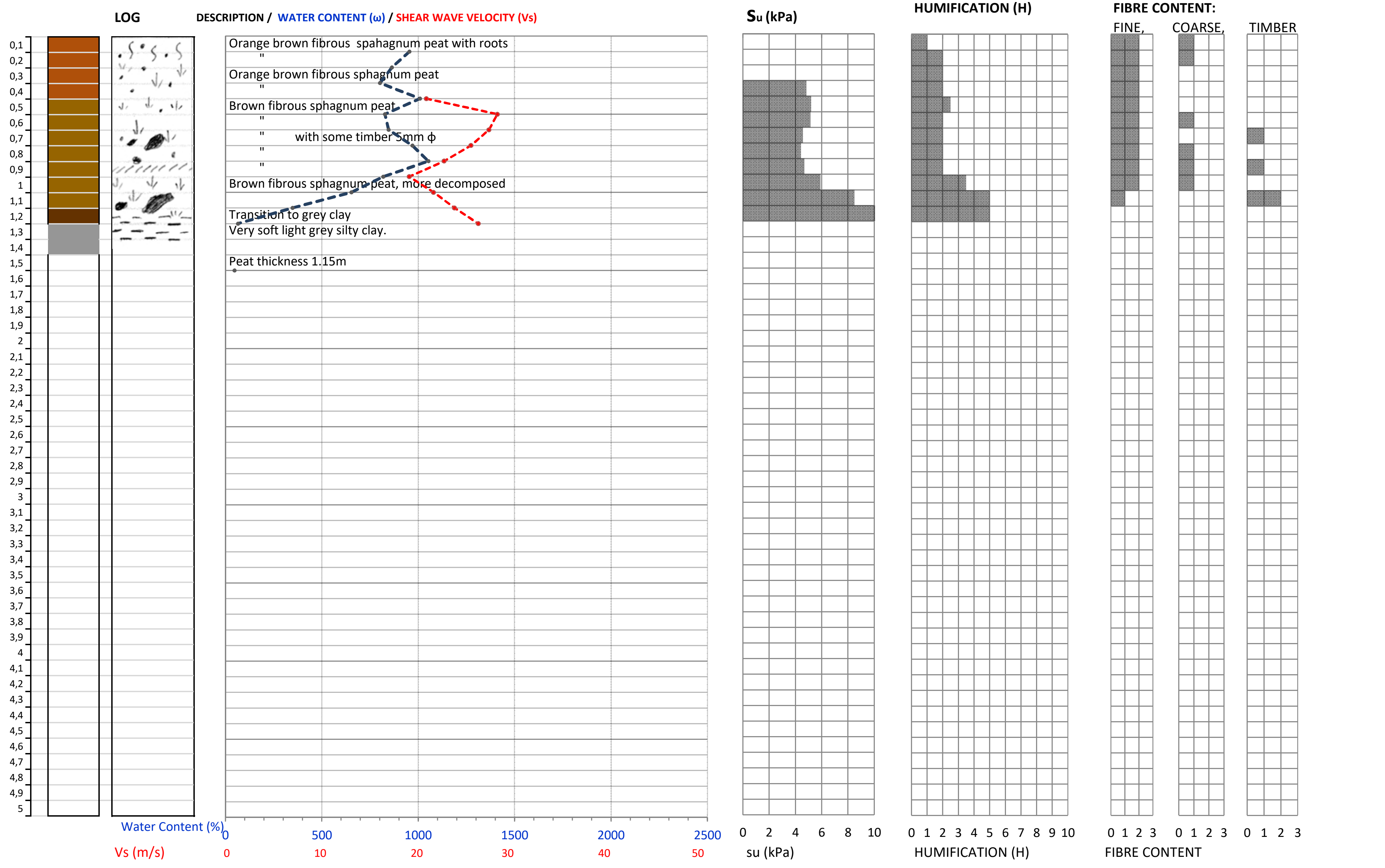
VON POST LOG - Tanemsmyra VSWP

PROJECT:	TRAFF19003	**EASTING (ING):**	63°18,780'	**COMMENTS:**
LOCATION:	Klæbu, Trondheim, Norway	**NORTHING (ING):**	10°25,912	Tanemsmyra
CLIENT:	NGI	**ELEVATION:**	165,2 m.a.s.l.	
DATE:	24.07.2019	**LOGGED BY:**	A Trafford	



VON POST LOG Tiller-FlottenVSWP

PROJECT:	TRAFF19001	**EASTING (Long):**	63° 20.250'	**COMMENTS:**
LOCATION:	Flotten, Trondheim, Norway	**NORTHING (Lat):**	10° 20.0470'	Forrested area with relatively stiff upper peat
CLIENT:	NGI	**ELEVATION (masl):**	125,1 m.a.s.l.	Relatively poor data quality due to noise
DATE:	25.07.2019	**LOGGED BY:**	A Trafford	

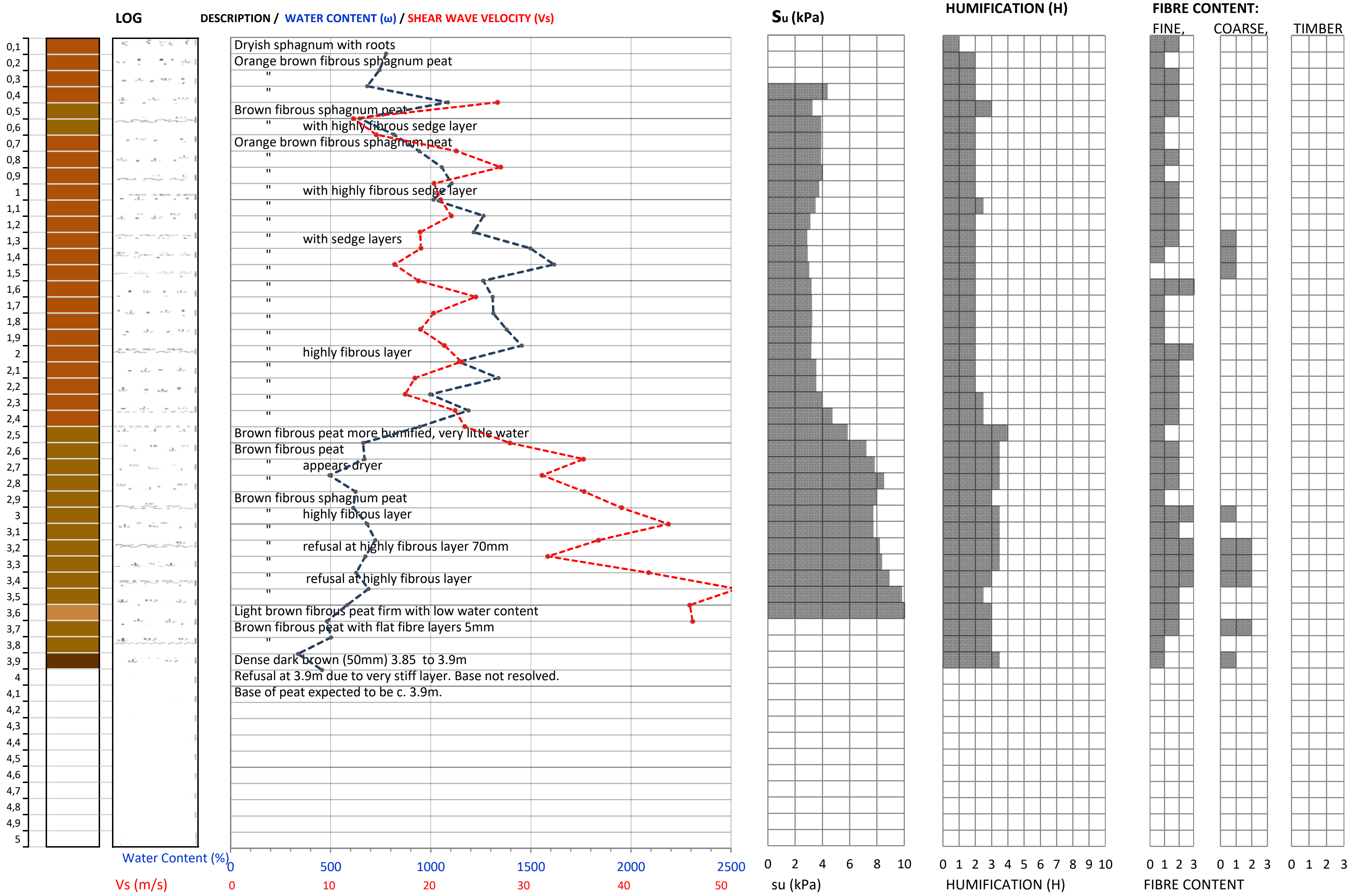


VON POST LOG - Heimdal VSWP

PROJECT: TRAFF19003
LOCATION: Heimdal, Trondheim, Norway
CLIENT: NGI
DATE: 27.07.2019

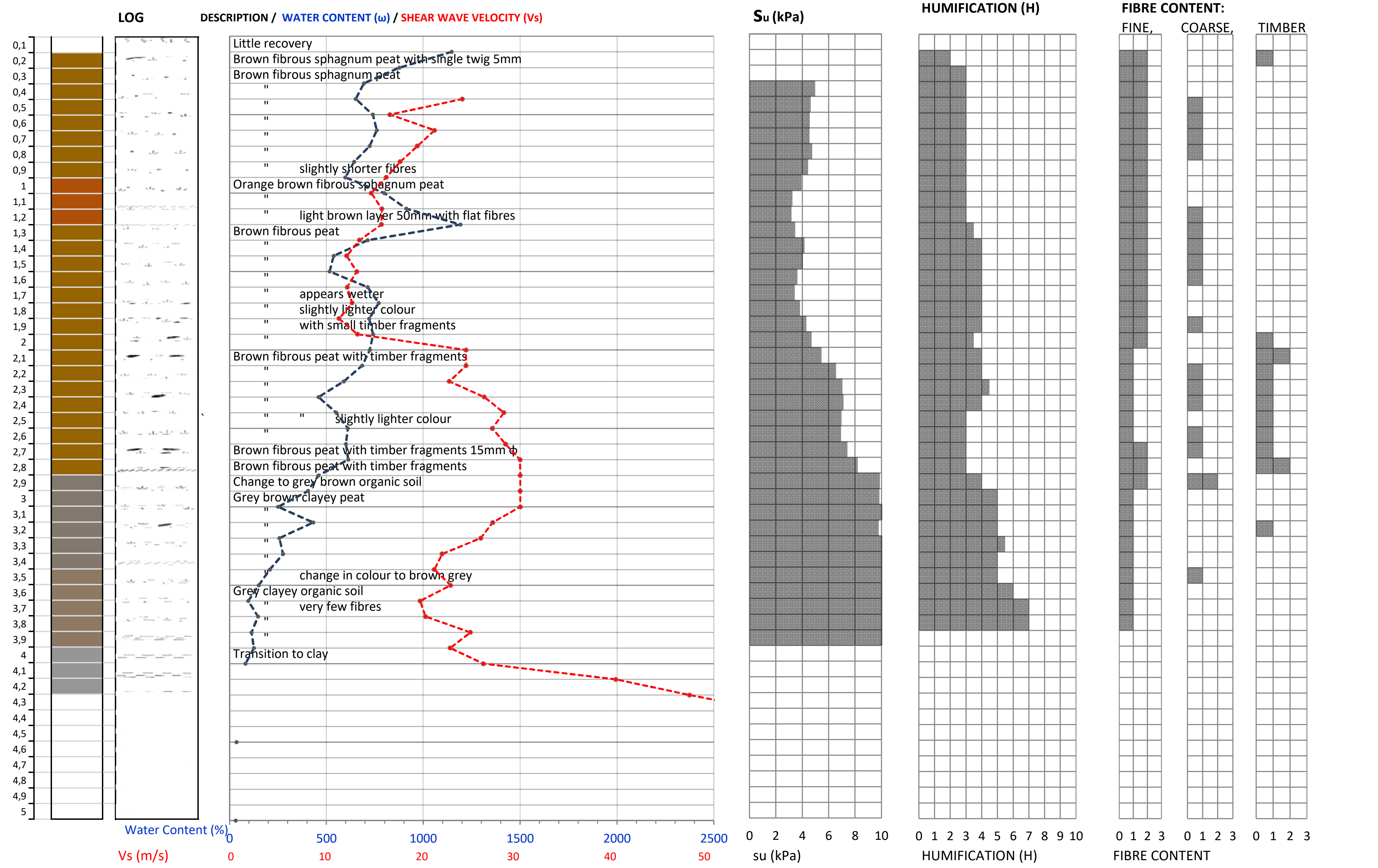
EASTING (ING): 63°21,529'
NORTHING (ING): 10°23,527'
ELEVATION: 145,9 m.a.s.l.
LOGGED BY: A Trafford

COMMENTS:



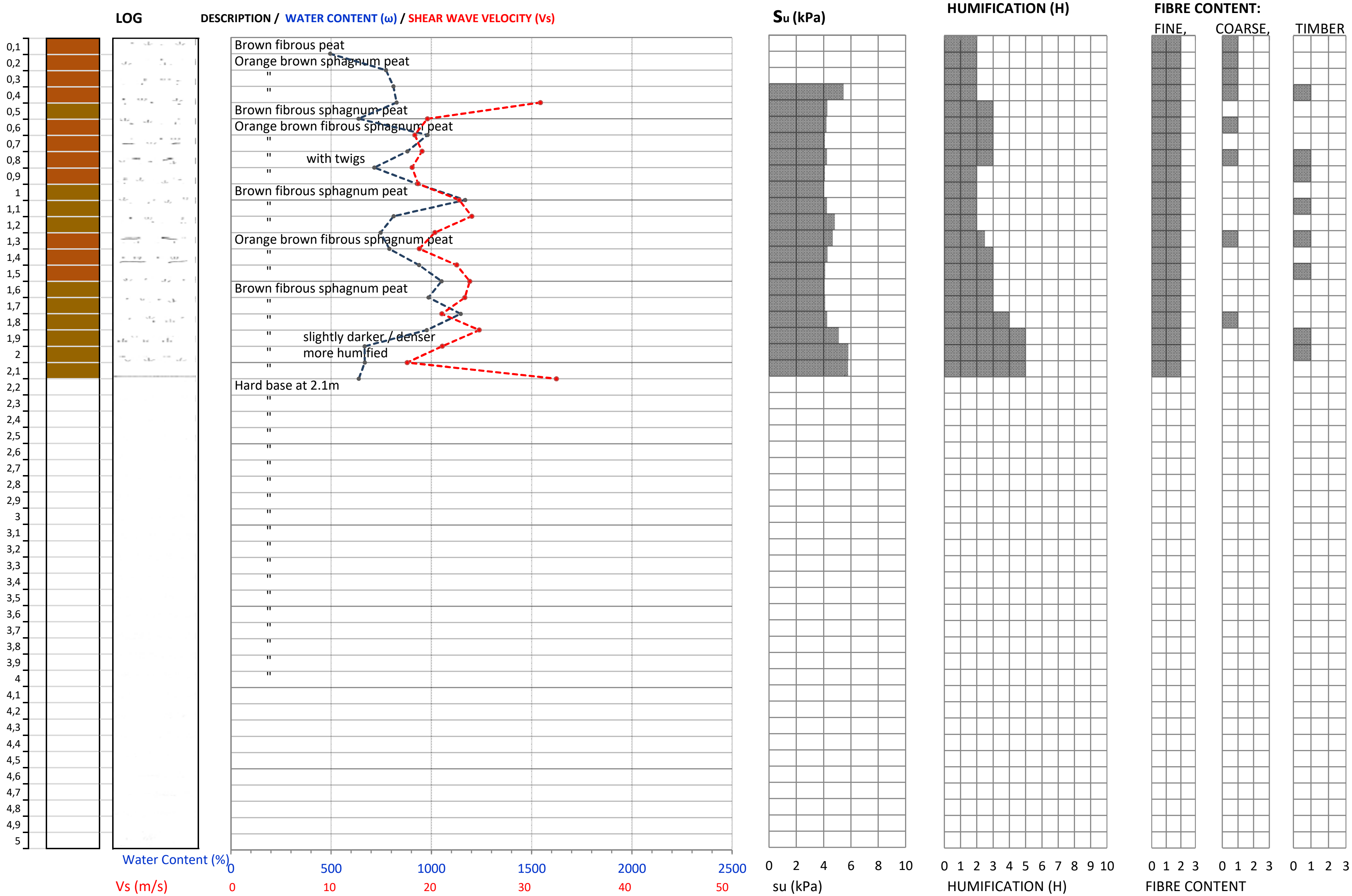
VON POST LOG - Leirbrumyra1 VSWP1

PROJECT:	TRAFF19003	**EASTING (ING):**	63° 22.857'	**COMMENTS:**
LOCATION:	Leirbrumyra 1, Trondheim, Norway	**NORTHING (ING):**	10° 18.727'	
CLIENT:	NGI	**ELEVATION:**	167,0	
DATE:	26.07.2019	**LOGGED BY:**	A Trafford	



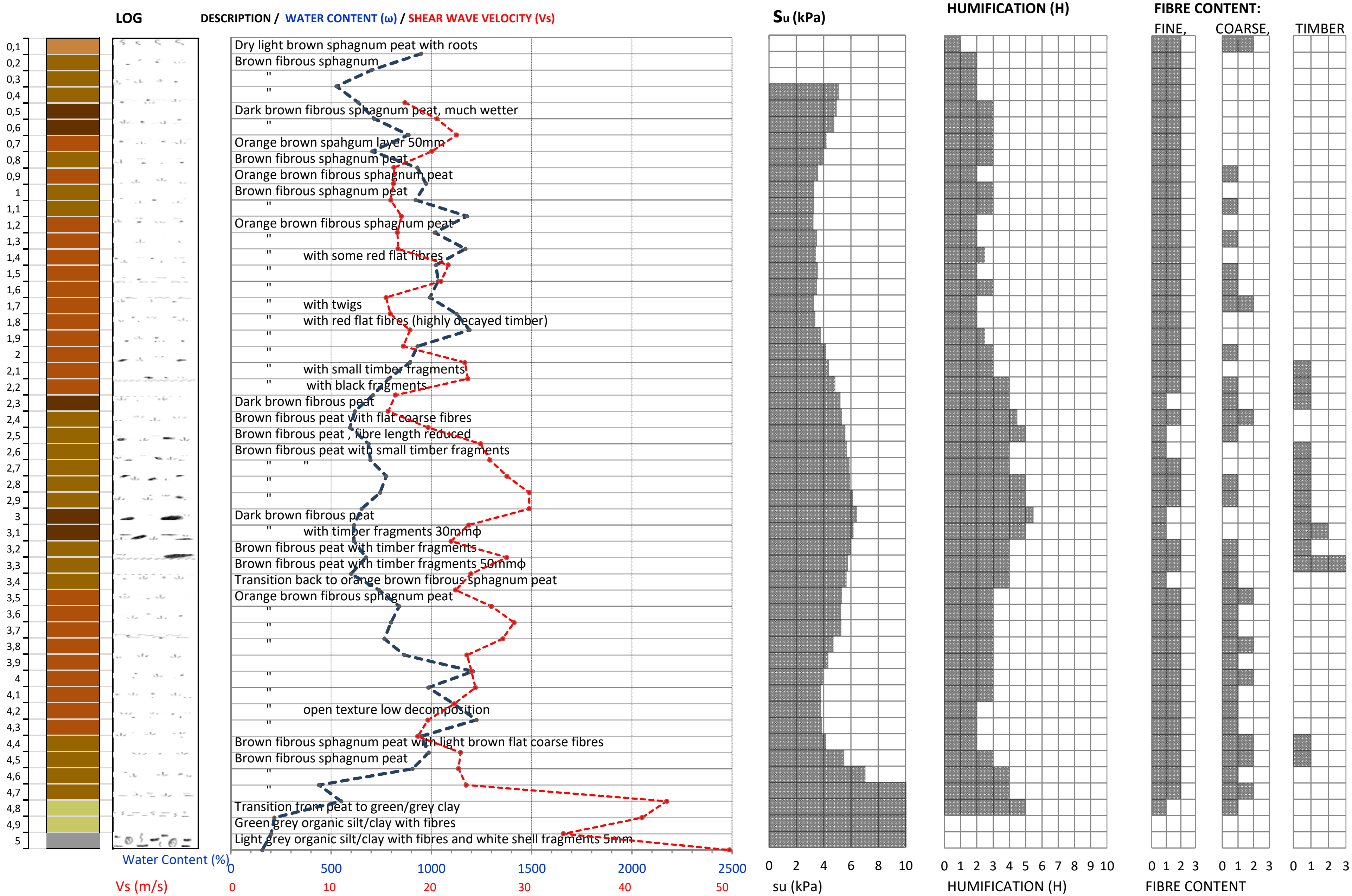
VON POST LOG - Leirbrumyra2 VSWP

PROJECT:	TRAFF19003	**EASTING (ING):**	63° 22.843'	**COMMENTS:**
LOCATION:	Granasen, Trondheim, Norway	**NORTHING (ING):**	10° 18.865'	Hole 2 close to main road/track
CLIENT:	NGI	**ELEVATION:**	168,8	Hole terminated @ hard base @ 2.1m (timber or rock). Base not fully resolved
DATE:	26.07.2019	**LOGGED BY:**	A Trafford	



VON POST LOG - Dragvoll VSWP

PROJECT:	TRAFF19003	**EASTING (ING):**	63°24.340'	**COMMENTS:**
LOCATION:	Dragvoll, Trondheim, Norway	**NORTHING (ING):**	10°28.233'	Peat thickness 4.75m. Transition into grey quick clay at 5.2m.
CLIENT:	NGI	**ELEVATION:**	157,5 m.a.s.l.	Fibres in all clays above 5.2m depth.
DATE:	27.07.2019	**LOGGED BY:**	A Trafford	

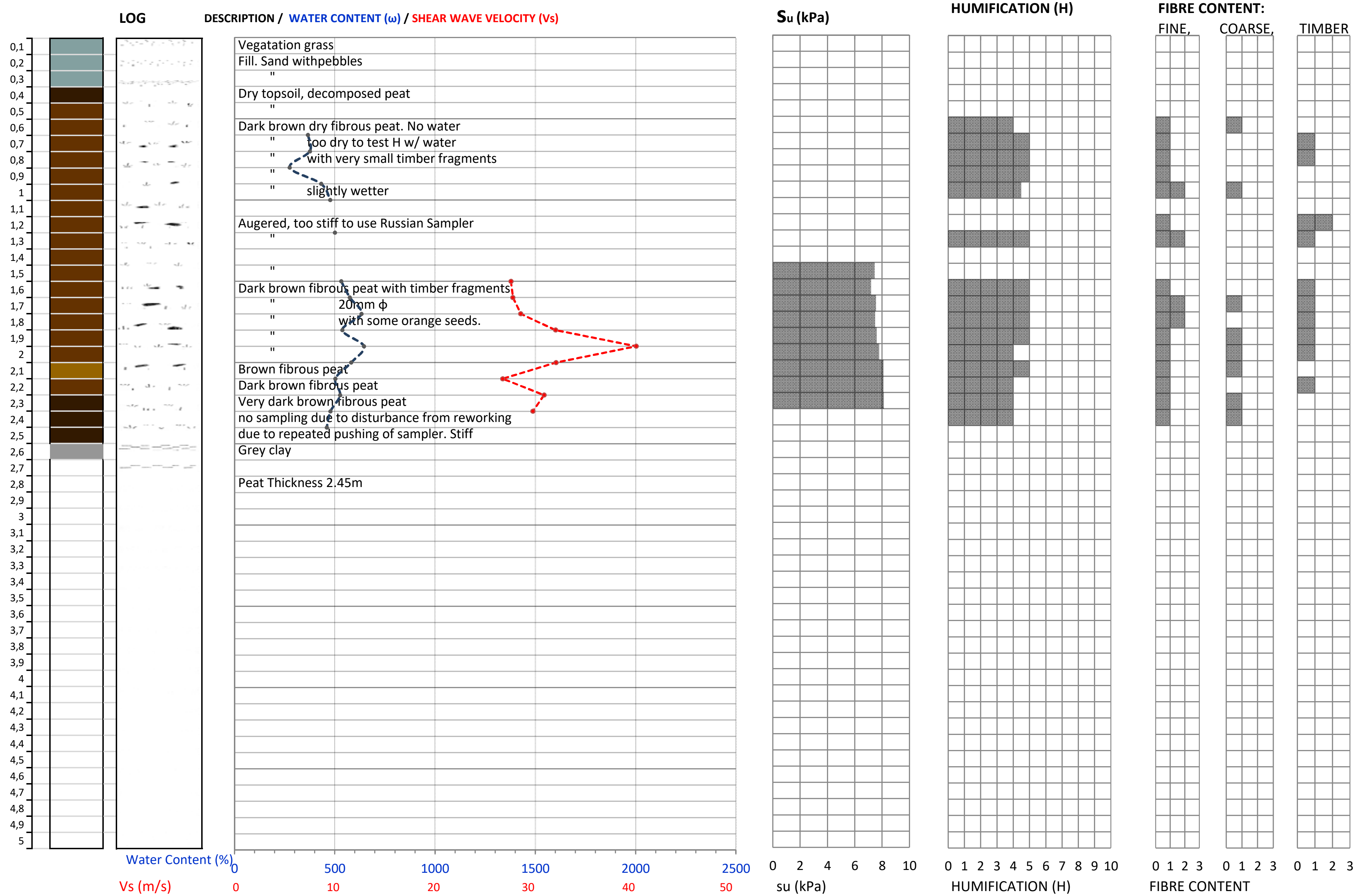


VON POST LOG - Havstein VSWP

PROJECT: TRAFF19003
LOCATION: Havstein, Trondheim, Norway
CLIENT: NGI
DATE: 25.07.2019

EASTING (Long): 63°24,378'
NORTHING (Lat): 10°21,222'
ELEVATION (masl): 142,9 m.a.s.l.
LOGGED BY: A Trafford

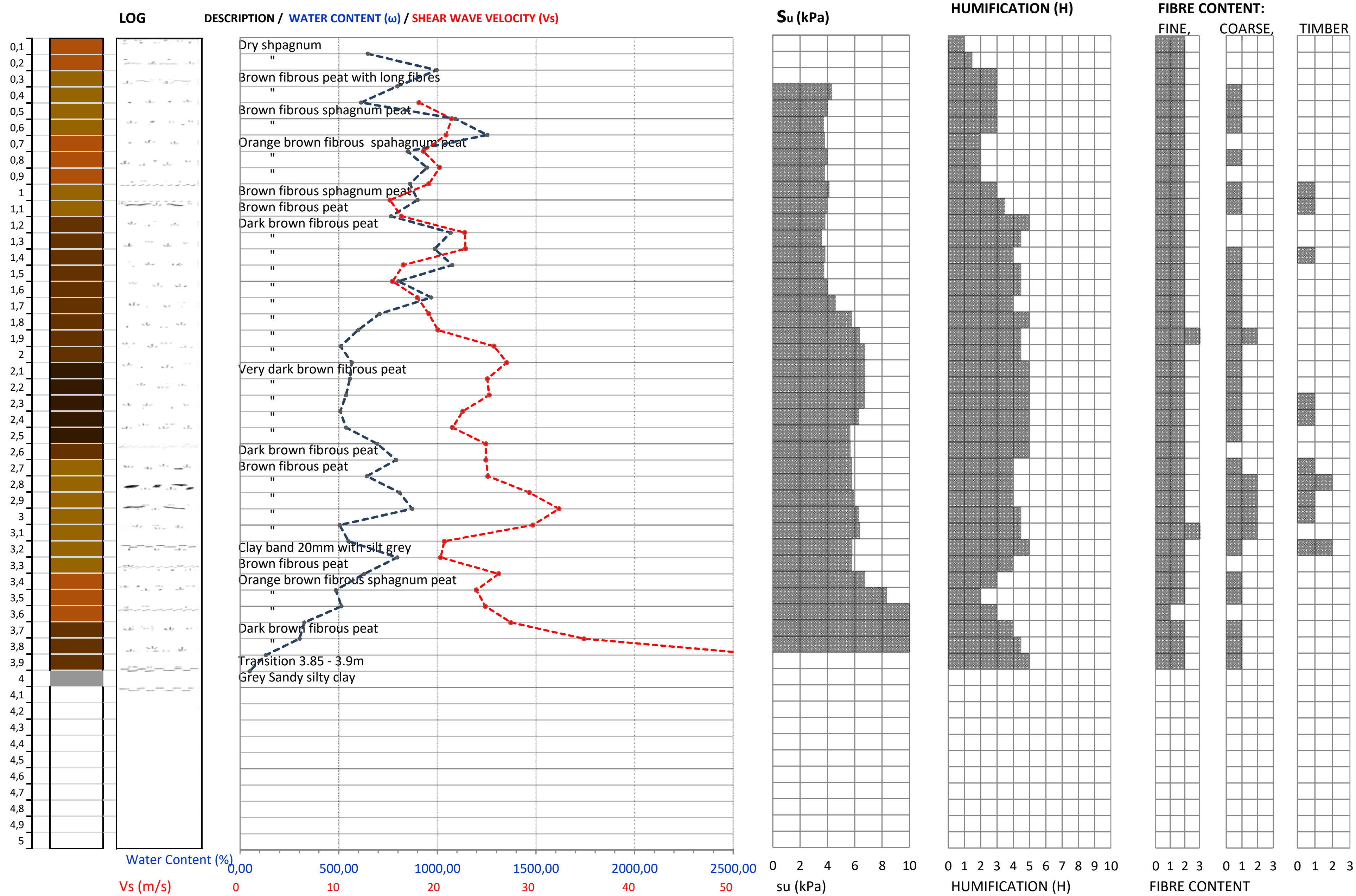
COMMENTS:
Location in grasssed area at side of road. Area scanned prior to probing.
Very stiff / dry fill / topsoil. Poor quality VSWP data
Augered 0 -1.5m. Russian sampler below 1.5m.



VON POST LOG - Haukvanet VSWP

PROJECT:	TRAFF19003	**EASTING (ING):**	63°23,740'
LOCATION:	Haukvanet, Trondheim, Norway	**NORTHING (ING):**	10°19,162'
CLIENT:	NGI	**ELEVATION:**	195,3 m.a.s.l.
DATE:	25.07.2019	**LOGGED BY:**	A Trafford

COMMENTS:
Adjacent to road. Previous proposed overflow car park location.

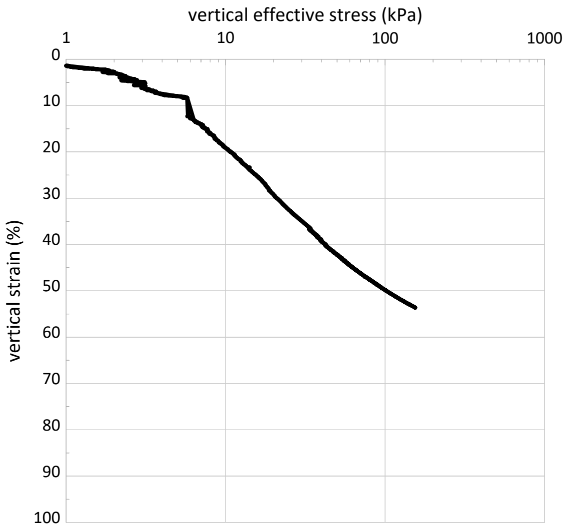


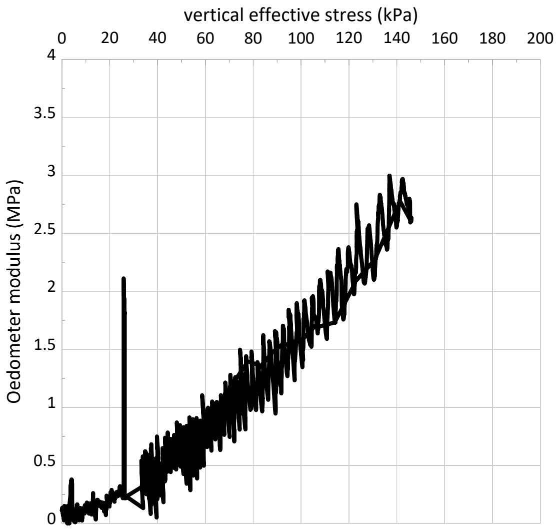
Appendix D

CRS TESTS RESULTS FOR 2019 FIELDWORK SITES

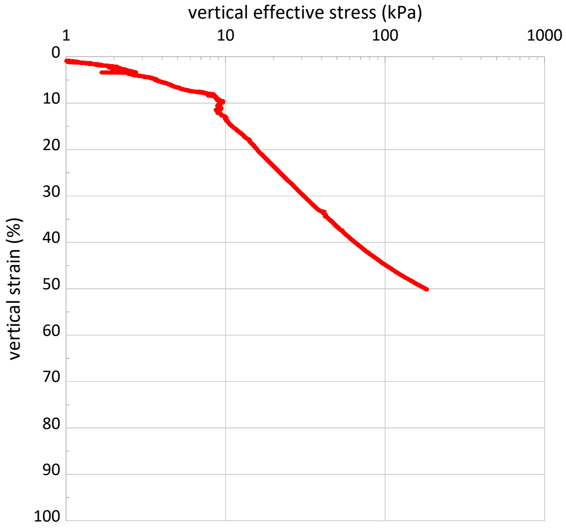
Contents

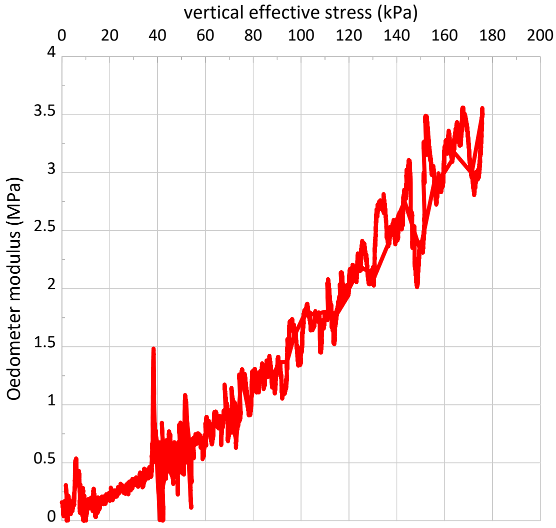
D1 Dragvollmyra



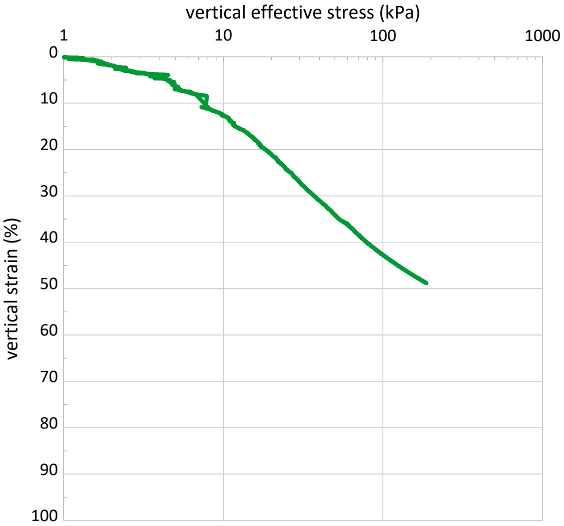


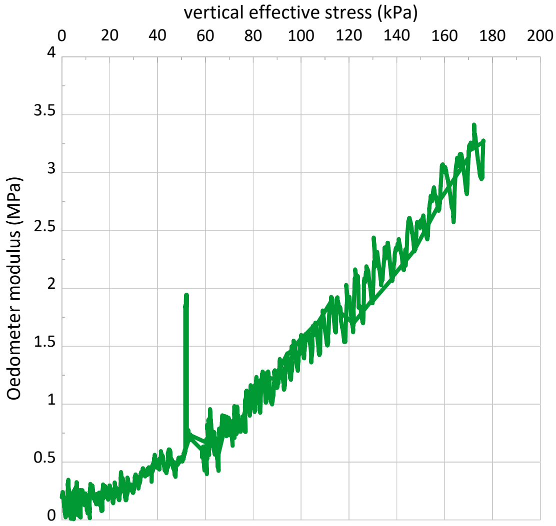
D2 Haukvanet



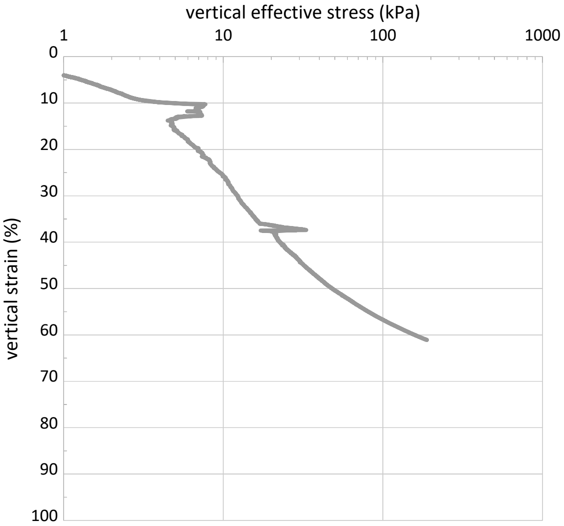


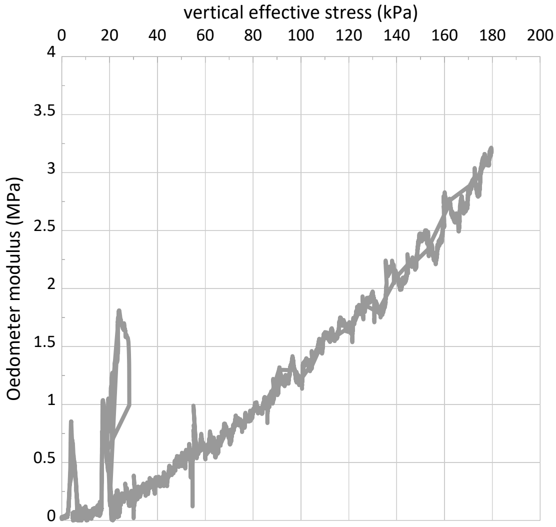
D3 Leirbrumyra



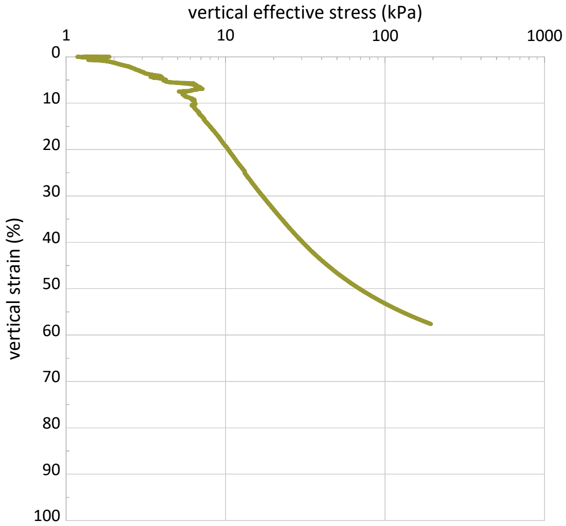


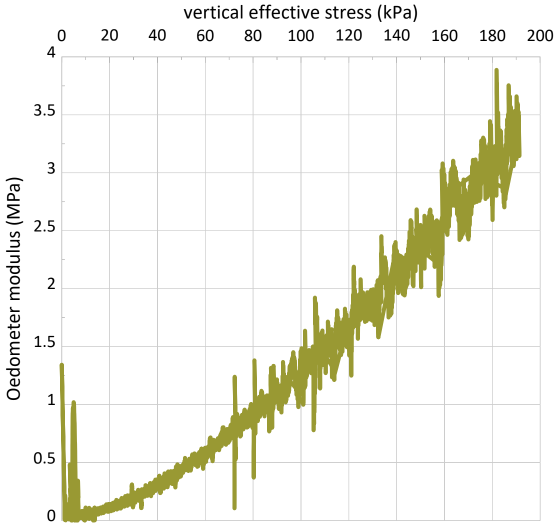
D4 Tanemsmyra 1



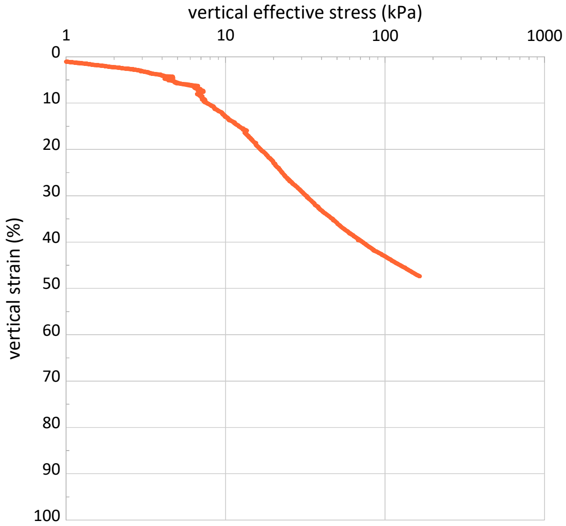


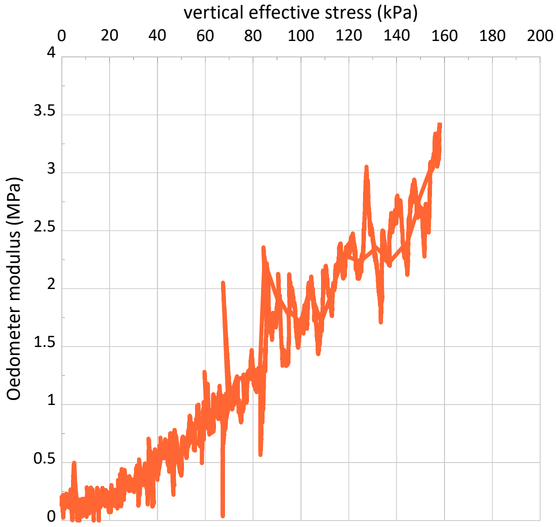
D5 Tanemsmyra 2



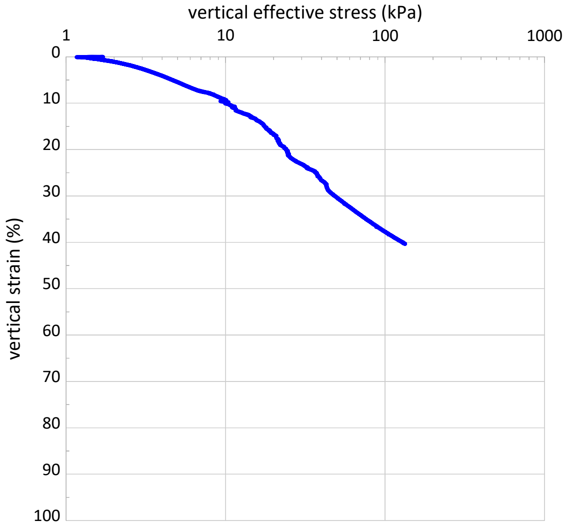


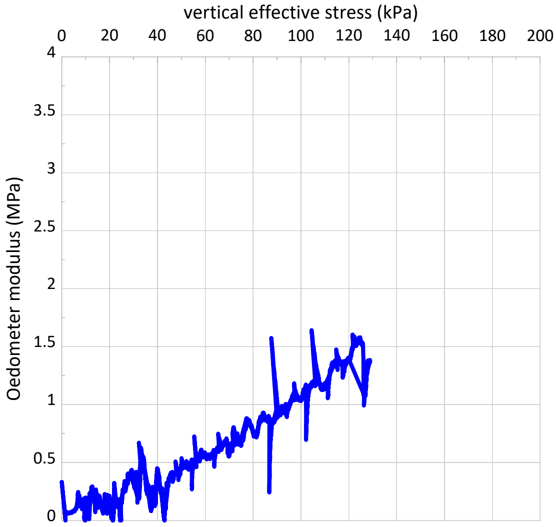
D6 Tiller – Flotten



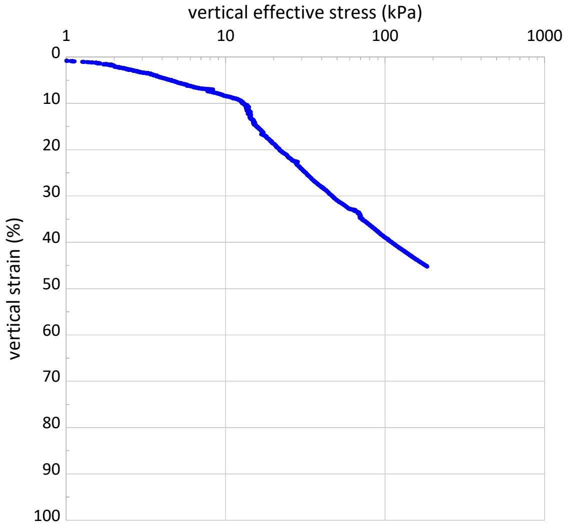


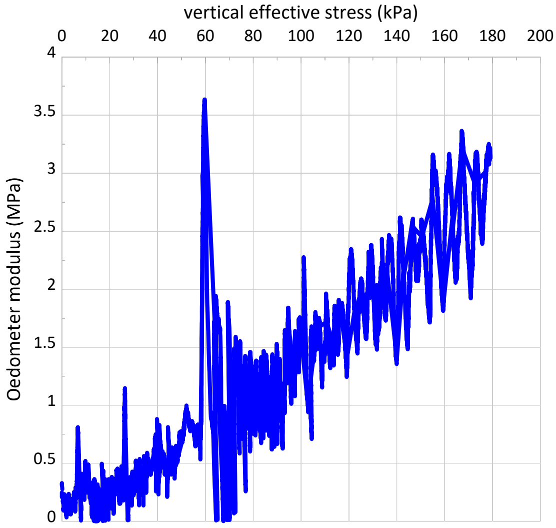
D7 Heimdalmyra-4





D8 Heimdalmyra-2-turned sample





Appendix E

PEAT ODOMETER TESTS RESULTS FOR 2019 FIELDWORK SITES

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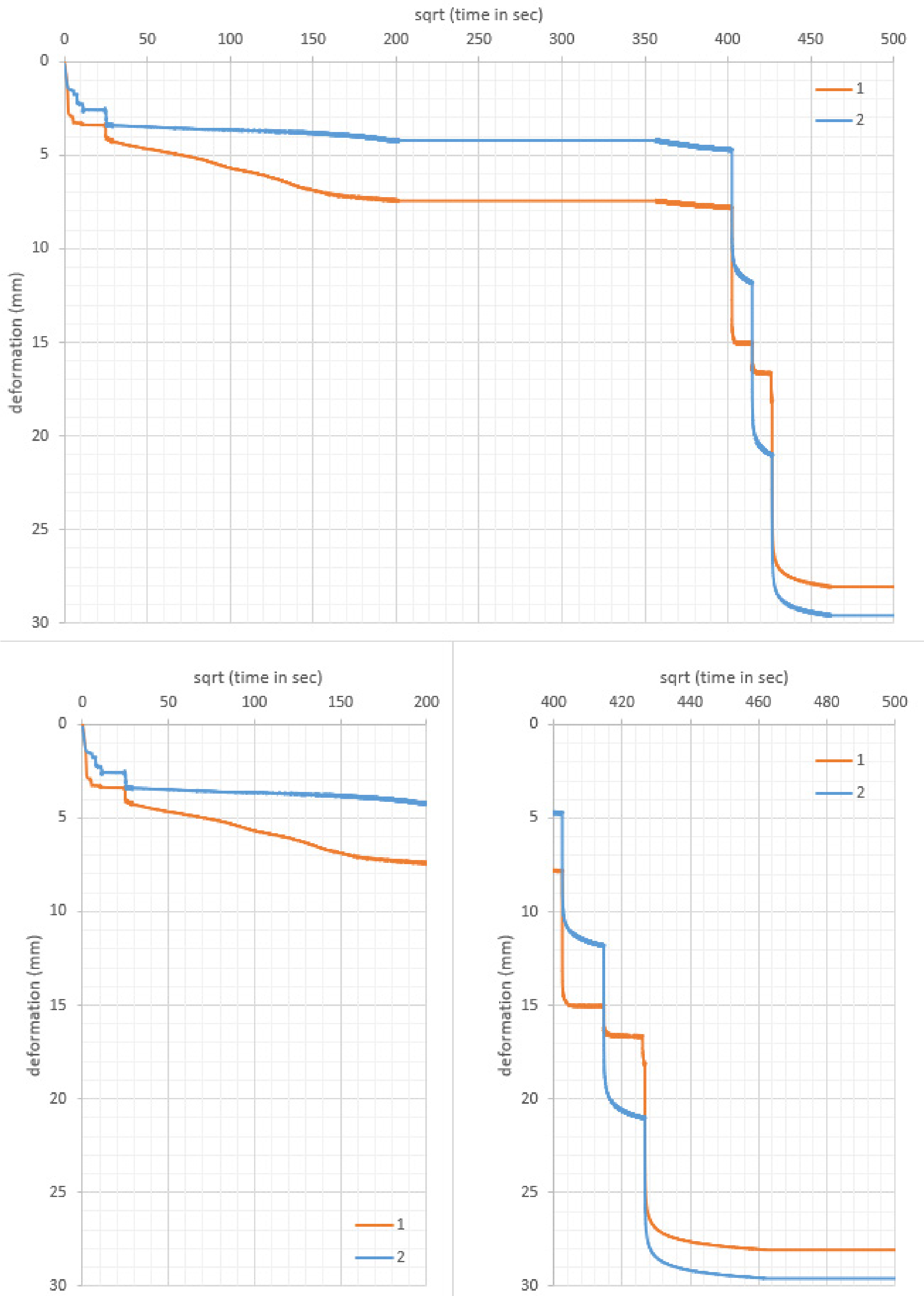

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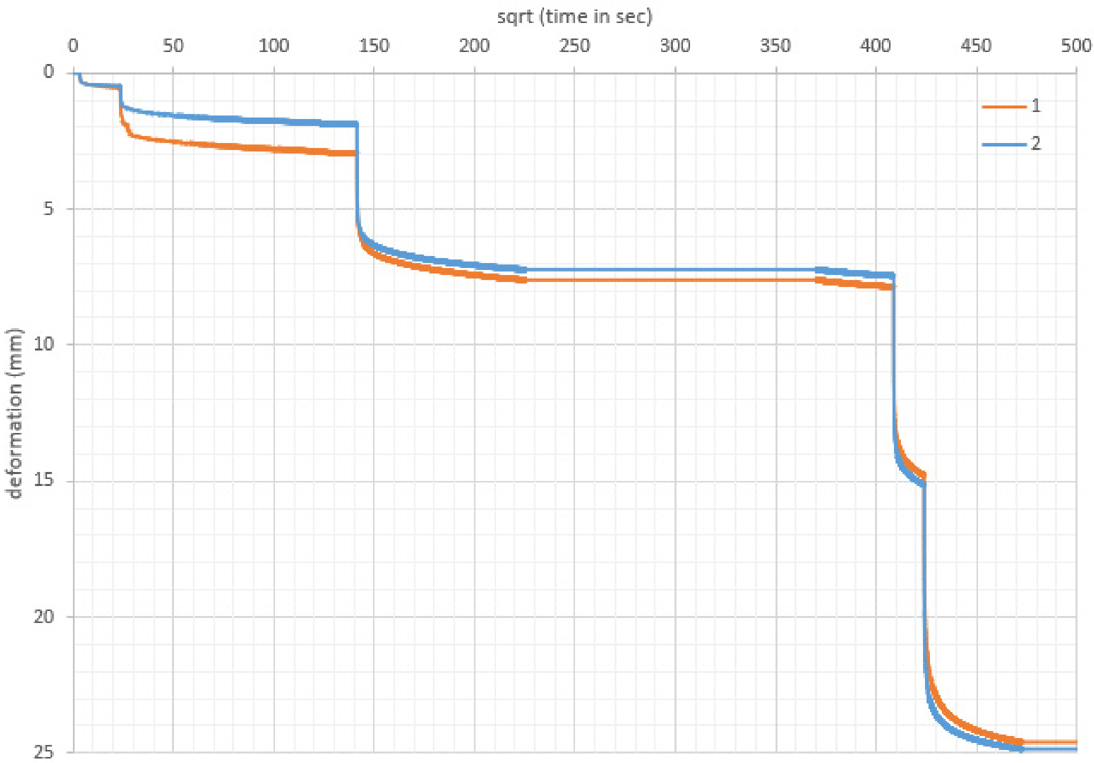
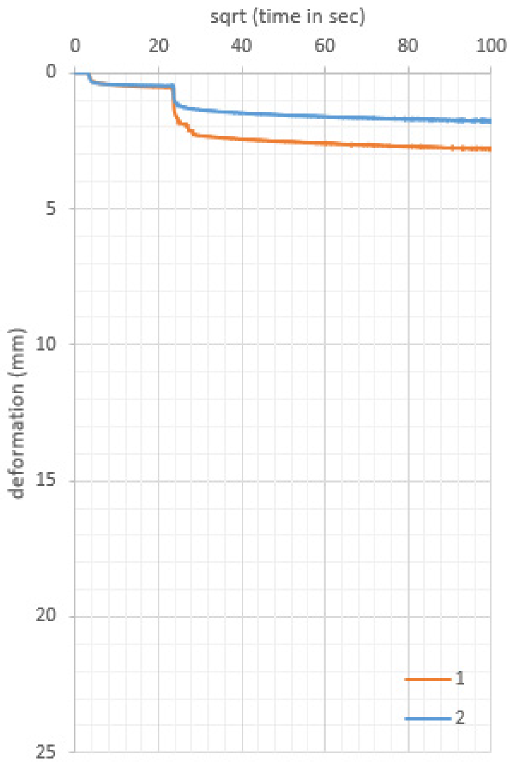
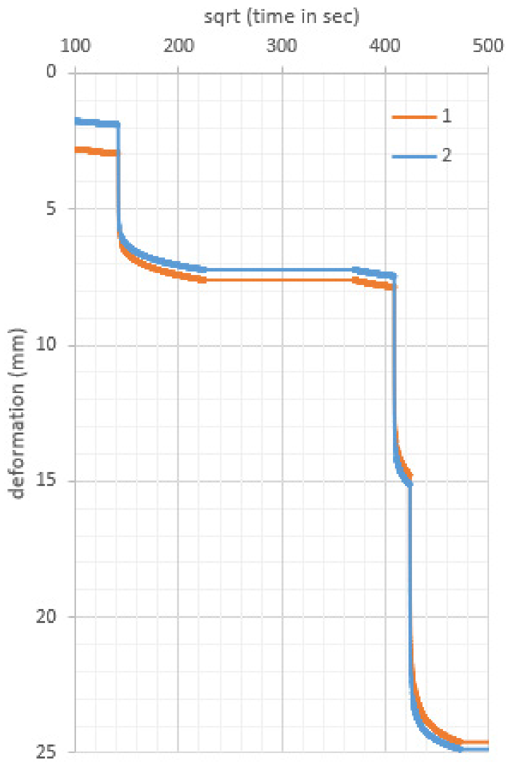
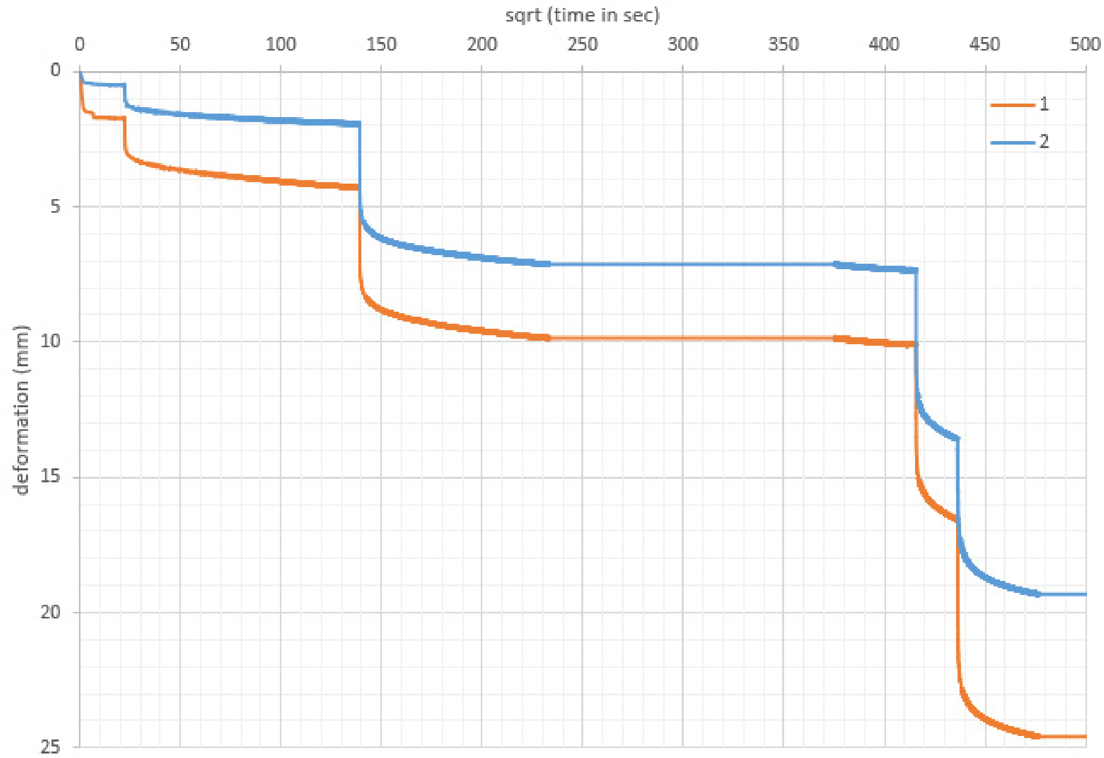
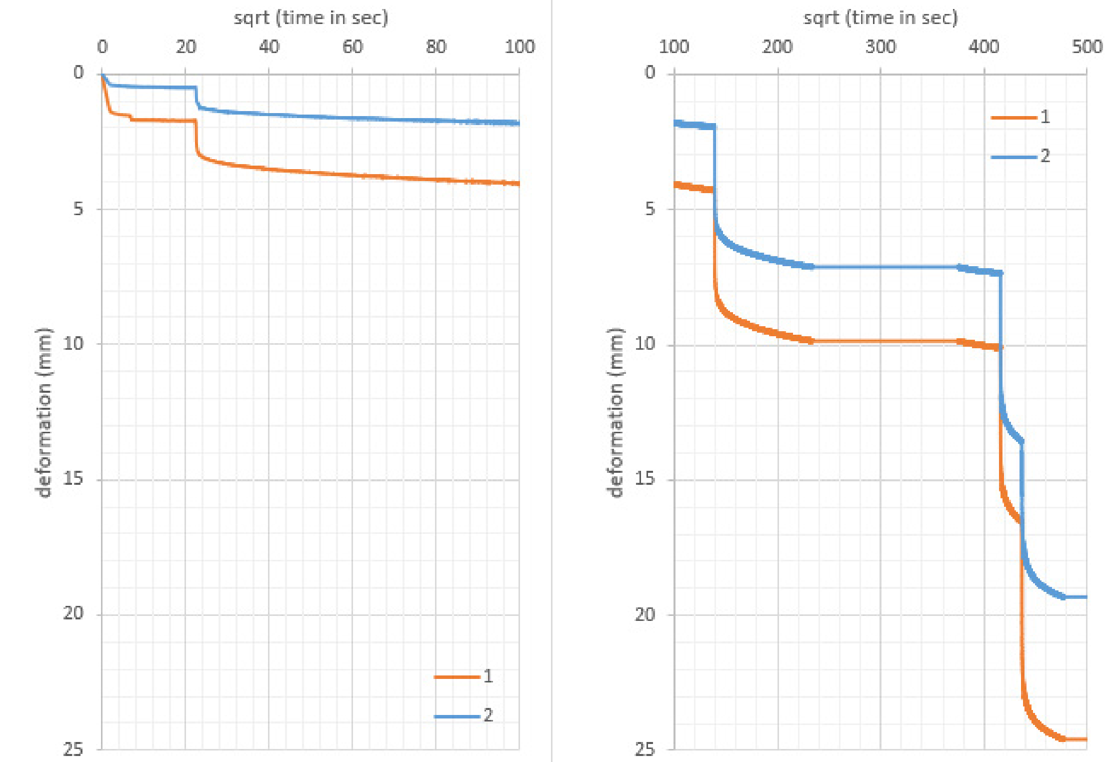






E3 Leirbrumyra





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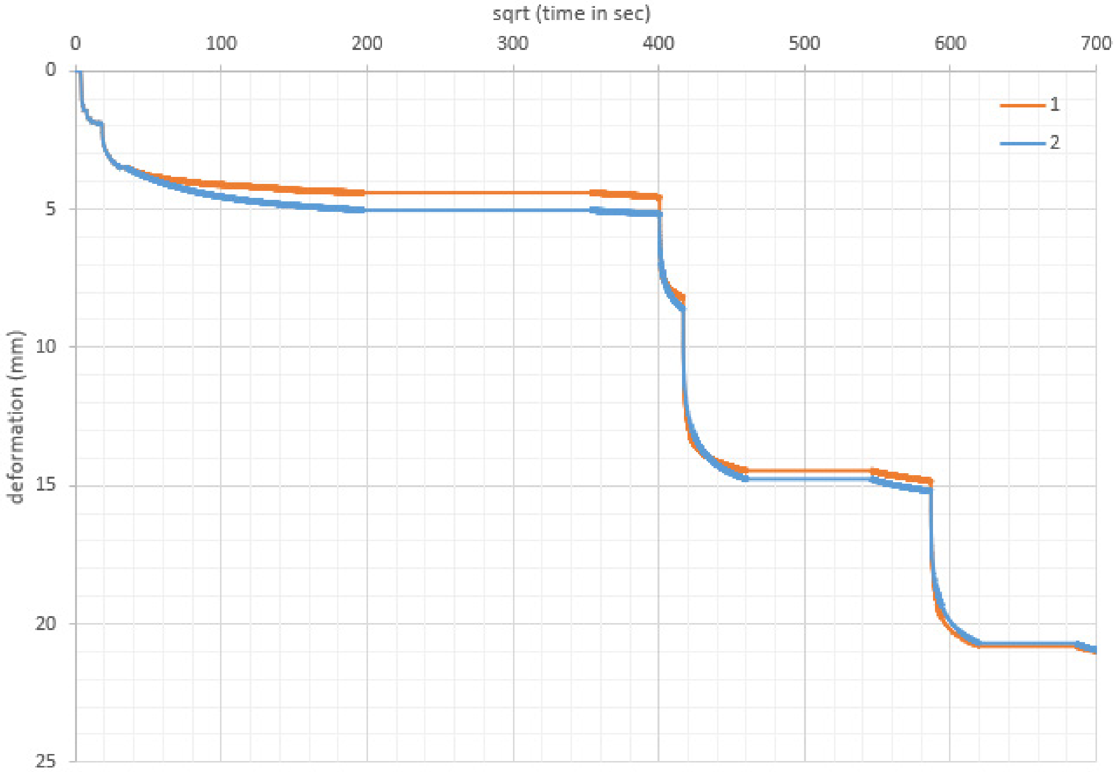
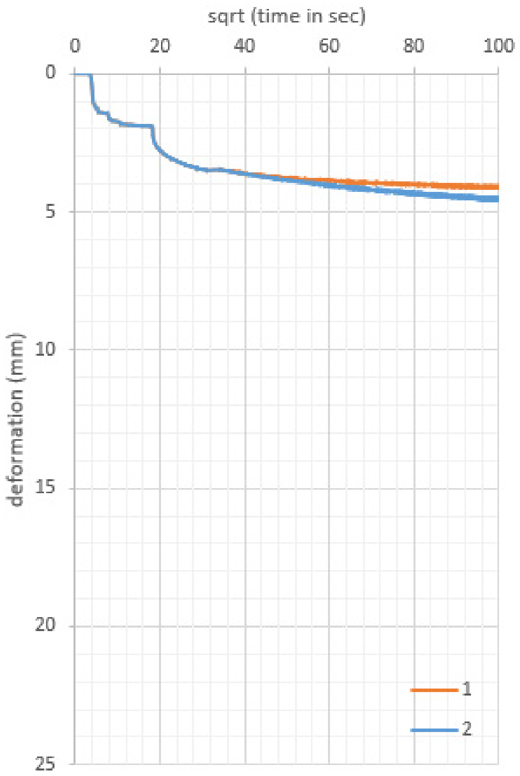
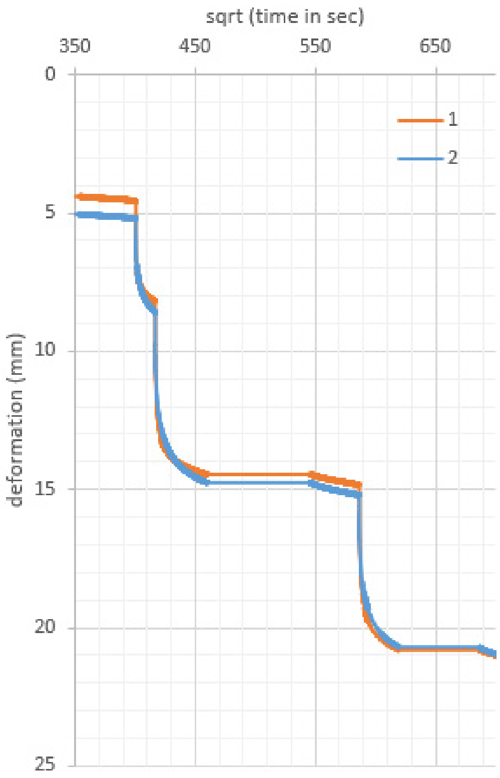
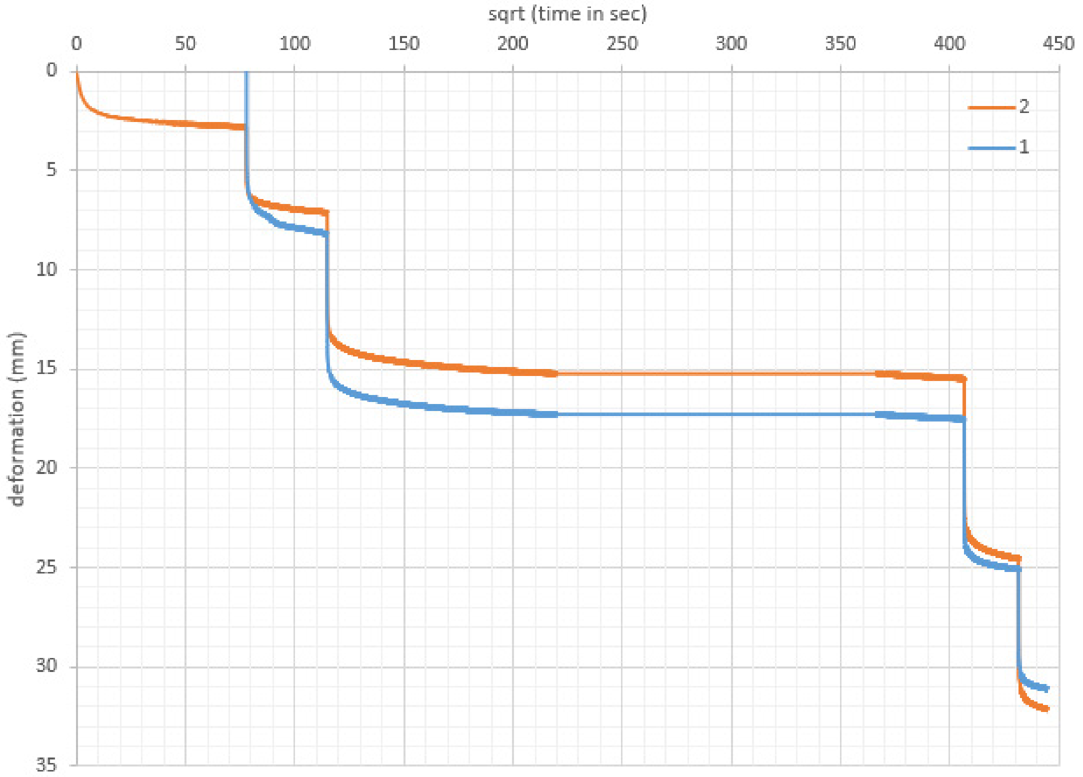
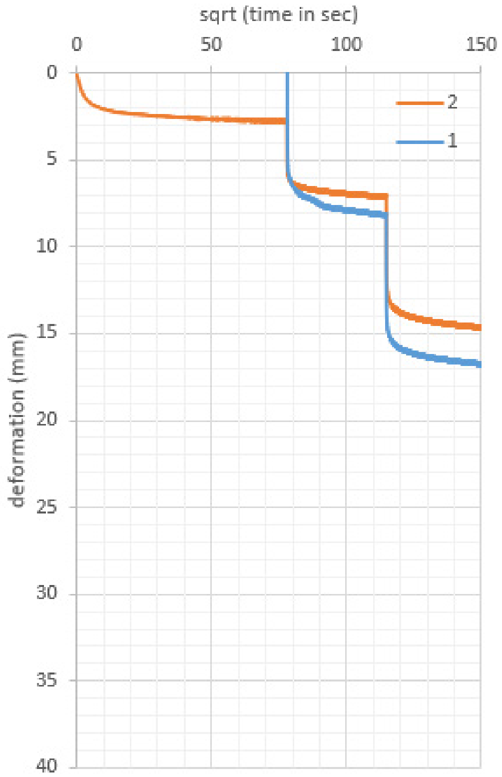


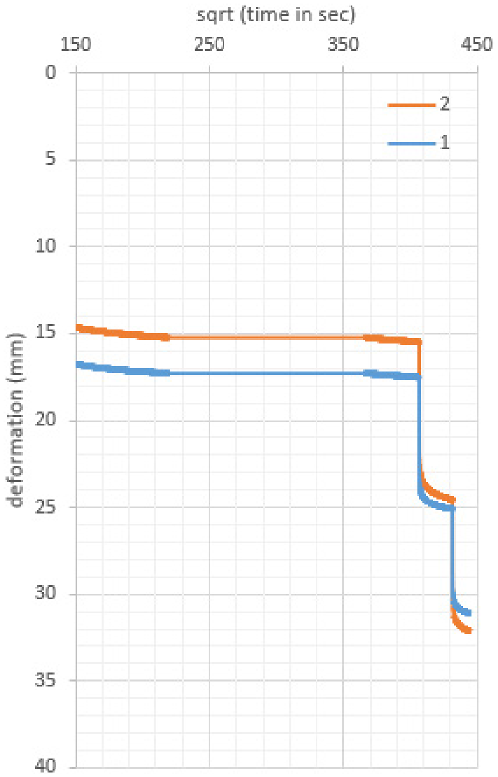




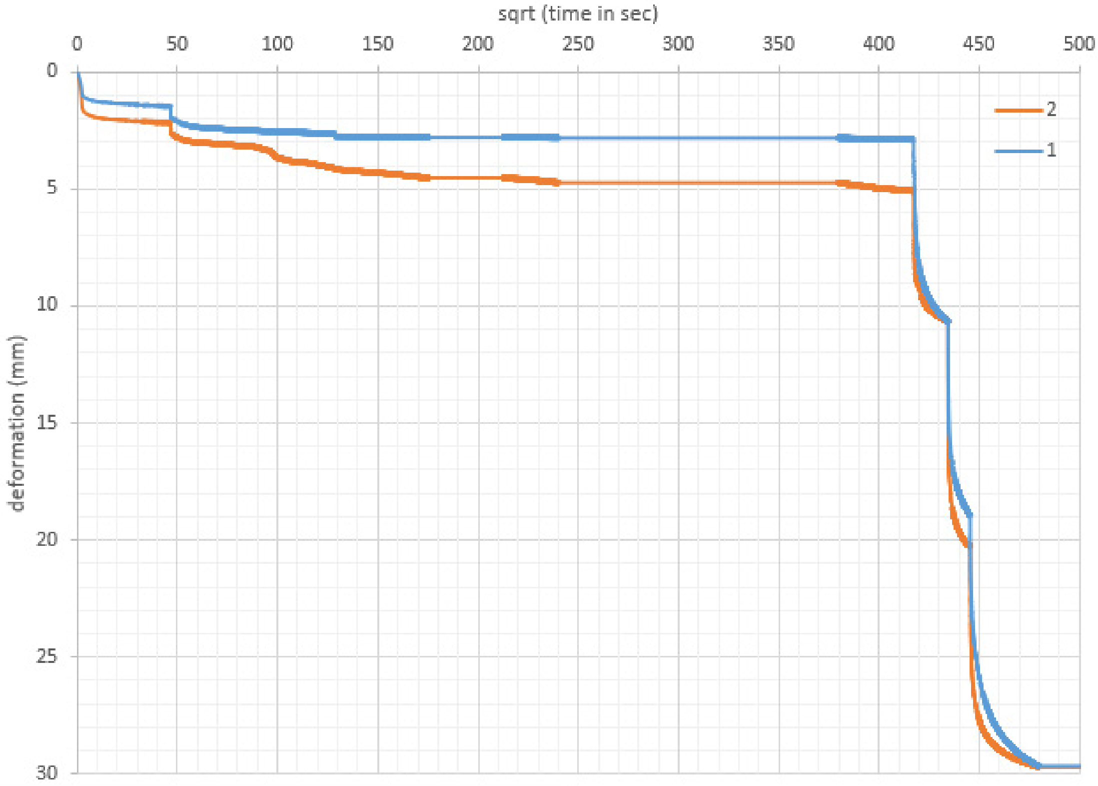
E5 Tanemsmyra

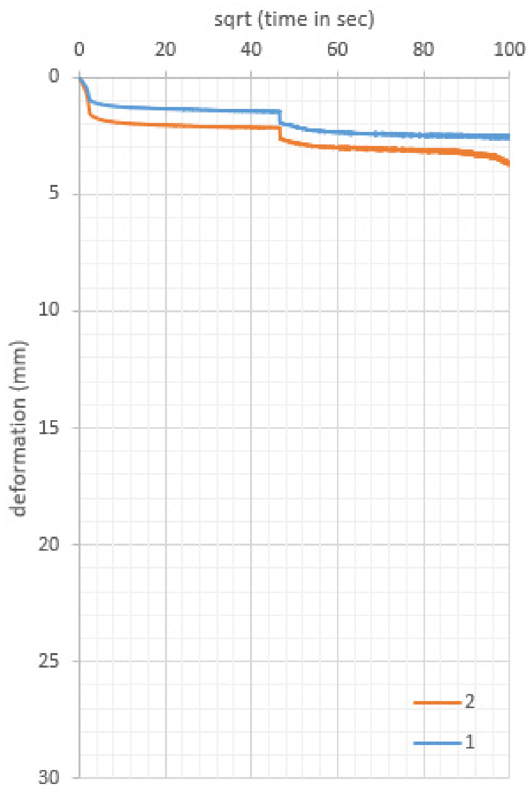


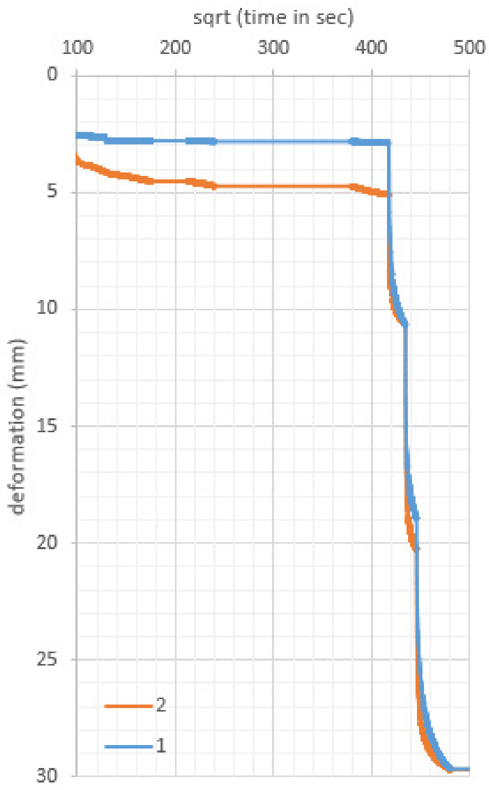




E6 Tiller – Flotten







Vedlegg F

DSS TESTS RESULTS FOR 2019
FIELDWORK SITES

TEST 1 - Dragvollmyra

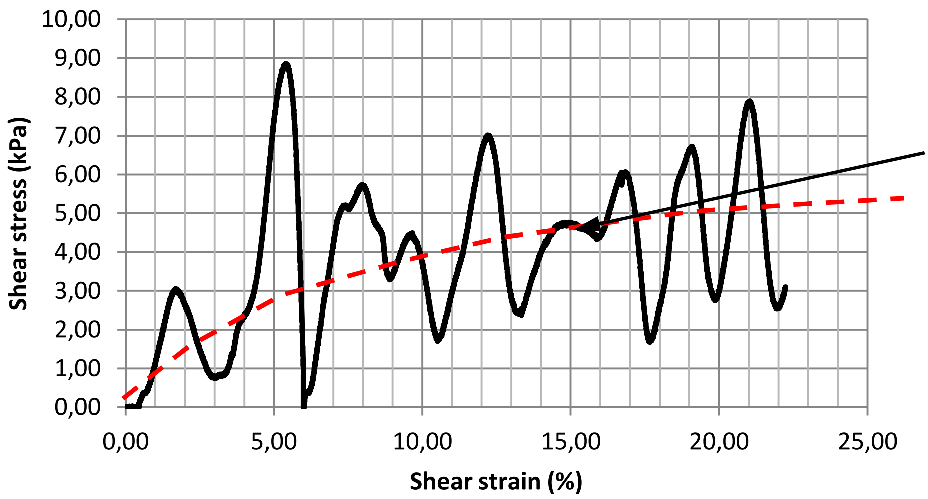
DIRECT SIMPLE SHEAR TESTING LOG

Undrained test - sheared at 4% horizontal strain per hour with constant sample height maintained.

Peat Sample	Dragvollmyra	Date Tested	23.09.2019
Location	Trondheim	Sample Diameter (mm)	80
Date Collected	-	Cross Section Area (m^2)	0,00496
Depth	0.6m	Density (Mg/m^3)	1,003
Humification	3/4	Load Applied (N)	19,9
		Consolidation Stress (kPa)	4,02

Shear Stress / Horizontal Strain.

Undrained shear strength interpreted at peak stress / stress at 15% shear strain.



S_u (kPa)	4,75

Additional Testing	Value	Results
In Situ Water Content	886 %	Site 5 Dragvollmyra VSWP.xlsx
In Situ Vs	23m/s	Site 5 Dragvollmyra VSWP.xlsx
DSS Water Content	772 %	-

Peat sample taken from wooded area adjacent to car park.

TEST 1 - Haukvanet

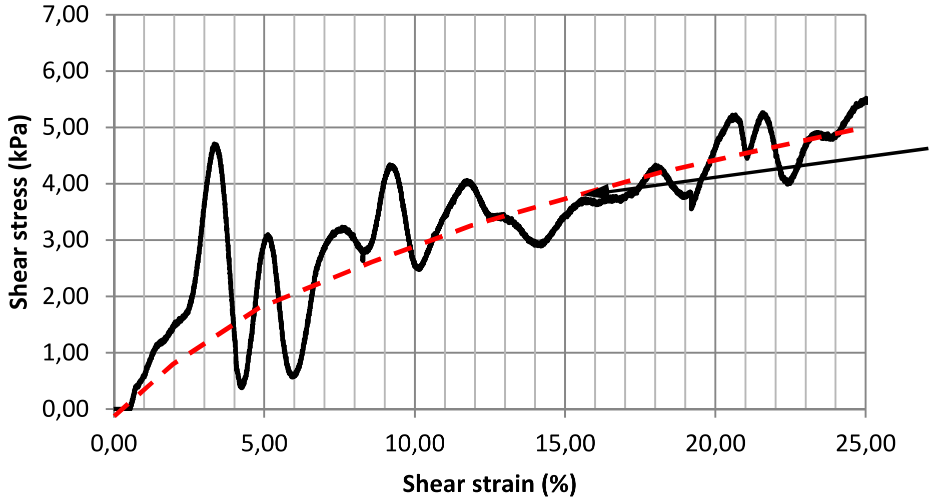
DIRECT SIMPLE SHEAR TESTING LOG

Undrained test - sheared at 4% horizontal strain per hour with constant sample height maintained.

Peat Sample	Haukvanet	Date Tested	24.09.2019
Location	Trondheim	Sample Diameter (mm)	80
Date Collected	-	Cross Section Area (m^2)	0,00496
Depth	0.6m	Density (Mg/m^3)	0,936
Humification	3	Load Applied (N)	16,2
		Consolidation Stress (kPa)	3,27

Shear Stress / Horizontal Strain.

Undrained shear strength interpreted at peak stress or stress at 15% shear strain.



S_u (kPa)	3,75

Additional Testing	Value	Results
In Situ Water Content	1250 %	Site 7 Haukvanet VSWP.xlsx
In Situ Vs	20m/s	Site 7 Haukvanet VSWP.xlsx
DSS Water Content	1183 %	-

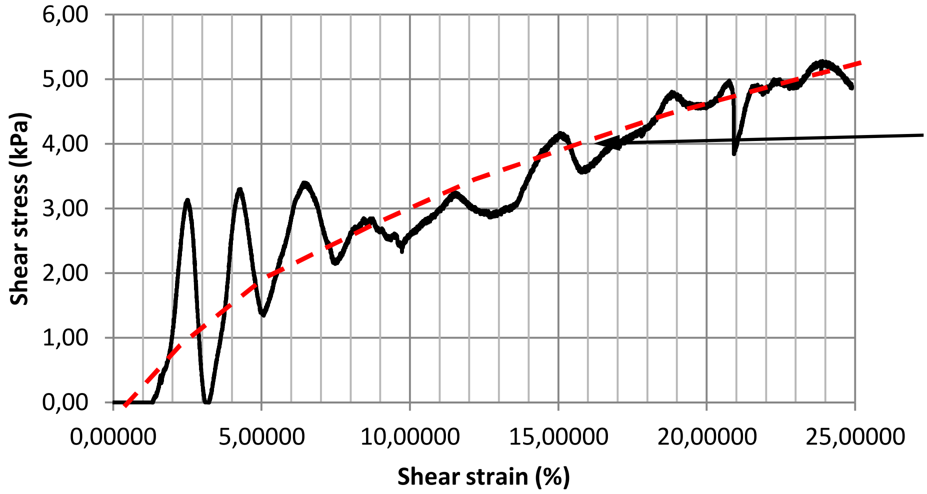
DIRECT SIMPLE SHEAR TESTING LOG

Undrained test - sheared at 4% horizontal strain per hour with constant sample height maintained.

Peat Sample	Heimdalmyra	Date Tested	23.09.2019
Location	Trondheim	Sample Diameter (mm)	80
Date Collected	-	Cross Section Area (m^2)	0,00496
Depth	0.6m	Density (Mg/m^3)	0,919
Humification	2	Load Applied (N)	19,9
		Consolidation Stress (kPa)	4,00

Shear Stress / Horizontal Strain.

Undrained shear strength interpreted at peak stress / stress at 15% shear strain.



S_u (kPa)	4

Additional Testing	Value	Results
In Situ Water Content	818 %	Site 3 Heimdalmyra VSWP.xlsx
In Situ Vs	20m/s	Site 3 Heimdalmyra VSWP.xlsx
DSS Water Content	943 %	-
Bender Element WC	886 %	At start of VS consolidation test
Bender Element Vs	28m/s	-

TEST 1 - Leirbrumyra1

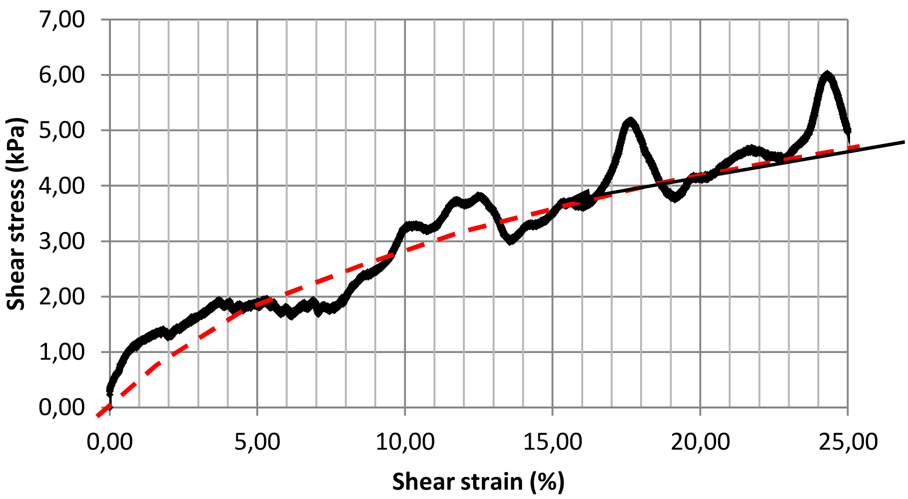
DIRECT SIMPLE SHEAR TESTING LOG

Undrained test - sheared at 4% horizontal strain per hour with constant sample height maintained.

Peat Sample	Leirbrumyra1	Date Tested	15.02.2017
Location	Trondheim	Sample Diameter (mm)	80
Date Collected	-	Cross Section Area (m^2)	0,00496
Depth	0.6m	Density (Mg/m^3)	1,050
Humification	3	Load Applied (N)	21,0
		Consolidation Stress (kPa)	4,23

Shear Stress / Horizontal Strain.

Undrained shear strength interpreted at peak stress / stress at 15% shear strain.



S_u (kPa)	3,6

Additional Testing	Value	Results
In Situ Water Content	760 %	Site 4 Leirbrumyra1 VSWP.xlsx
In Situ Vs	20m/s	Site 4 Leirbrumyra1 VSWP.xlsx
DSS Water Content	664 %	-

Ski jump site. Sample taken from 1st location.

TEST 1 - Tanemsmyra

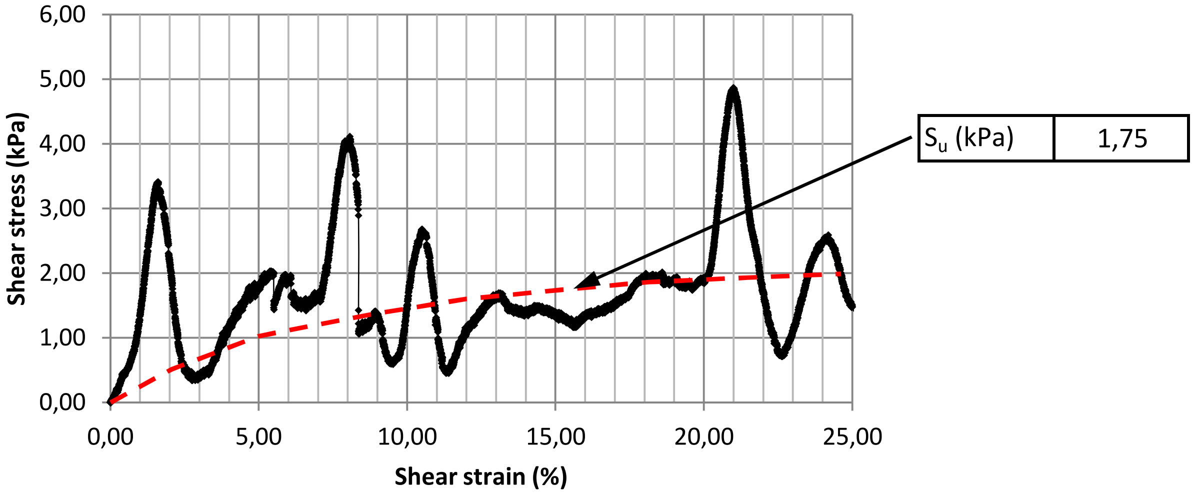
DIRECT SIMPLE SHEAR TESTING LOG

Undrained test - sheared at 4% horizontal strain per hour with constant sample height maintained.

Peat Sample	Tanemsmyra	Date Tested	06.11.2019
Location	Trondheim	Sample Diameter (mm)	80
Date Collected	25.07.2019	Cross Section Area (m^2)	0,00496
Depth	0.6m	Density (Mg/m^3)	0,901
Humification	2	Load Applied (N)	16,0
		Consolidation Stress (kPa)	3,22

Shear Stress / Horizontal Strain.

Undrained shear strength interpreted at peak stress / stress at 15% shear strain.



Additional Testing	Value	Results
In Situ Water Content	1855 %	Site 1 Tanemsmyra VSWP.xlsx
In Situ Vs	19m/s	Site 1 Tanemsmyra VSWP.xlsx
DSS Water Content	1576 %	-
Bender Element WC	1696 %	At start of Vs consolidation test
Bender Element Vs	25m/s	-

TEST 1a - Tiller-Flotten

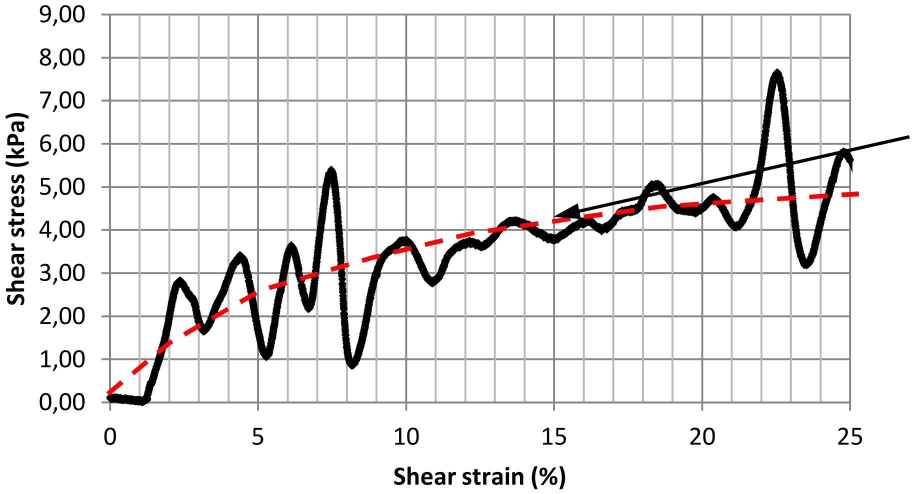
DIRECT SIMPLE SHEAR TESTING LOG

Undrained test - sheared at 4% horizontal strain per hour with constant sample height maintained.

Peat Sample	Tiller-Flotten	Date Tested	16.09.2019
Location	Trondheim	Sample Diameter (mm)	80
Date Collected	25.07.2019	Cross Section Area (m^2)	0,00496
Depth	0.6m	Density (Mg/m^3)	0,987
Humification	2/3	Load Applied (N)	21,5
		Consolidation Stress (kPa)	4,33

Shear Stress / Horizontal Strain.

Undrained shear strength interpreted at peak stress / stress at 15% shear strain.



S_u (kPa)	4,25

Additional Testing	Value	Results
In Situ Water Content	846 %	Site 2 Tiller-Flotten VSWP.xlsx
In Situ Vs	27m/s	Site 2 Tiller-Flotten VSWP.xlsx
DSS Water Content	829 %	-
Bender Element WC	873 %	-
Bender Vs	28m/s	Flotten 1 vs Consolidation Test.xlsx

Peat sample taken from Flotten (NGI Test Site) Trondheim

TEST 2 - Tiller-Flotten

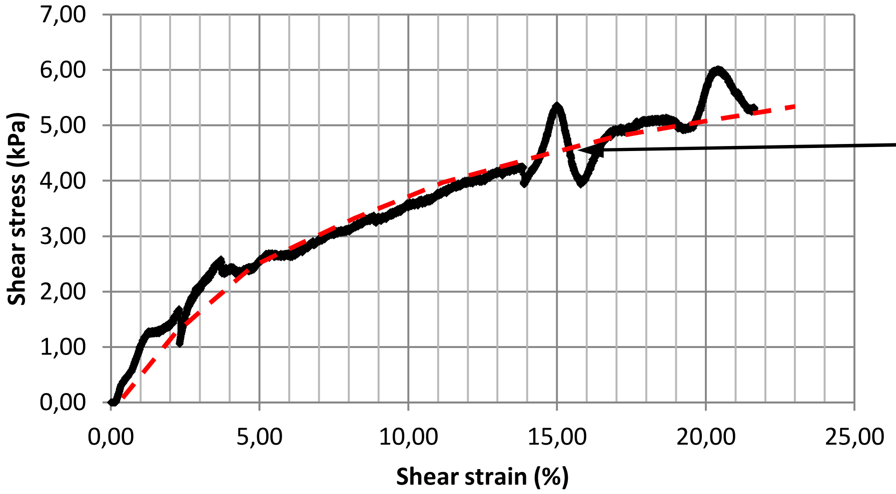
DIRECT SIMPLE SHEAR TESTING LOG

Undrained test - sheared at 4% horizontal strain per hour with constant sample height maintained.

Peat Sample	Tiller-Flotten	Date Tested	15.02.2017
Location	Trondheim	Sample Diameter (mm)	80
Date Collected	25.07.2019	Cross Section Area (m^2)	0,00496
Depth	0.6m	Density (Mg/m^3)	0,975
Humification	2/3	Load Applied (N)	22,6
		Consolidation Stress (kPa)	4,55

Shear Stress / Horizontal Strain.

Undrained shear strength interpreted at peak stress / stress at 15% shear strain.



S_u (kPa)	4,5

Additional Testing	Value	Results
In Situ Water Content	846 %	Site 2 Tiller-Flotten VSWP.xlsx
In Situ Vs	27m/s	Flotten 1 vs Consolidation Test.xlsx
DSS Water Content	887 %	-
Bender Element WC	873 %	-
Bender Vs	27m/s	Site 2 Tiller-Flotten VSWP.xlsx

Peat sample taken from Flotten (NGI Test Site) Trondheim

Vedlegg G

MSC PROJECT WORK: BACK-CALCULATION FOR A PEAT SLIDE AT TANEMSMYRA

On Slopes and Excavations in Norwegian Peat Soils – Tanensmyra Case Study

Omar Berbar[1]

[1] Msc. Geotechnics & Geohazards, Norwegian University of Science and Technology, Trondheim, NO
[2] In partnership with the Norwegian Geotechnical Institute (NGI)

E-mail: omarb@stud.ntnu.no
o.berbar@outlook.com

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Abstract

Peat soils are a geotechnical challenge worldwide. The presence of fibers and the lack of a straightforward method to quantify strength reinforcements from fibrous content continue to pose as challenges. A brief review of some peat failure incidents as well as a back analysis of an excavation failure in Klæbu, Norway is discussed in this paper. It is found that a minimum peat undrained shear strength of 8.1 kPa was required in the Klæbu case. This however does not conform with field and laboratory testing results of the peat soils in the area and arises questions on the methodology of peat modelling. An anisotropic model that considers peat fibers should be developed to properly model peat failure mechanisms.

Keywords: Norway, peat, excavation, slide

1. Introduction

Geotechnical engineering practice worldwide is frequented with the challenge of peat soils. Peat soils are difficult to deal with and have been usually subject to excavation or removal. As such, peat behaviour and strength characteristics haven't been as thoroughly researched compared with other soils. However, with a greater focus on environmental preservation globally, jurisdictions are tending towards peat preservation rather than excavation. Norwegian practises are tending towards leaving peat soils untouched on advice from the Environment Directorate. As such, research into Norwegian peat soils is necessary. This study will focus on a peat excavation failure in Klæbu, and will attempt to asses the failure mechanisms and governing strength parameters. The research questions that will be answered are: (1) what were the apparent failure mechanisms of the excavation (2) what strength properties could be assumed for in-situ peat. To answer these questions, a back-analysis using a variety of techniques of the failure was completed as well as a geotechnical site and laboratory investigation. The results of which are discussed in this paper.

2. Peat Background Theory

Peat grows in flatland areas where water accumulates. It forms from organic materials (such as dead leaves and forest litter) that over time accumulate and given the correct biochemical conditions, degenerate into a soft soil. It grows at a rate of 1000 mm per year. Although peat is more frequently found in northern regions around the world, it can grow anywhere where the conditions allow (Huat et al., 2014).

2.1 Geotechnical Properties

Peat is notably different from other types of soil: it has elevated moisture contents (sometimes up to 1500%) and typically a high organic content. Peat soils are highly compressible and have markedly low shear strength characteristics (Huat et al., 2014). In addition, peats have varying levels of decomposition, a characteristic that can affect the soils strength values. Peats are classified geotechnically into three general types: fibrous, semi-fibrous, and amorphous (Huat et al., 2014). Fibrous peats, typically a fresher and less decomposed variant, can contain a multitude of fibers that can inflate strength values. These fibers which often range in size, are a function of the soil's overall decomposition, slowly humifying from fibrous to amorphous over time. As such, the classification of peat strength is not as straightforward as with homogeneous mineral soils.

The presence and inconsistences of fibres in peat has proved to be a challenge for accurate soil strength characterization. The amount of fibers in peat is a result of the level of decomposition the soil has undergone – with undecomposed peat more likely to have a fibrous content and therefore additional fibrous strength. Considering its effect on strength, it's imperative that the level of decomposition be measured. Over the years, several classification systems have been proposed to classify peat. One of the earliest is the von Post index method.

The von Post method classifies peat based on its levels of humification, ranging from an H1 to an H10. This index method, originally proposed by the Swedish Geotechnical Institute in 1921, although useful geotechnically, requires some botanical knowledge to be applied, and can be subjective depending on the experience of the soil logger. Despite the drawbacks and due to a lack of any clear alternatives, the index method as been adopted into several standards worldwide, including the American Standard Testing Methods (ASTM)'s standard practise for estimating the degree of humification of peat and other organic soils (ASTM D5715-14).

Table 1 below presents a description of humification ranging from H1 to H10 according to the von Post index:

Table 1 Von Post Humification Classification System (ASTM D5715-14)

H1	**Completely undecomposed peat** that, when squeezed, releases clear colorless water. Plant remains are intact and easily identifiable. No amorphous material is present.
H2	**Almost completely undecomposed peat** that, when squeezed, releases yellowish water. Plant remains are still relatively intact. No amorphous material is present.
H3	**Very slightly decomposed peat** that, when squeezed, releases turbid brown water, but in which no amorphous peat passes between the fingers.
H4	**Slightly decomposed peat** that, when squeezed, releases dark brown water. No peat passes between the fingers but the plant remains are somewhat visibly altered and less distinct. The residue left in hand appears slightly pasty.
H5	**Moderately decomposed peat** that, when squeezed, releases very turbid water containing a small amount of amorphous granular peat through the fingers. The residue remaining in hand is strongly pasty in consistency and the tissues of the original source plants are difficult to recognize.
H6	**Moderately decomposed peat** that, when squeezed, releases through the fingers about one-third of the peat. The residue remaining after squeezing is strongly pasty. Very little plant structure is visible before squeezing; but, some small amount of intact debris becomes more visible after squeezing.
H7	**Strongly decomposed peat** that, when squeezed, releases through the fingers about one-half of the peat. The water released, if any, is dark and. The residue remaining after squeezing is primarily composed of amorphous material with little recognizable plant tissue.
H8	**Very strongly decomposed peat** that, when squeezed, releases through the fingers about two-thirds of the peat. The residue remaining after squeezing is primarily composed of amorphous material with very little intact plant tissue.
H9	**Almost completely decomposed peat** that, when squeezed, almost entirely releases through the fingers as a fairly uniform dark paste. Almost no recognizable plant structures are evident in the residue.
H10	**Completely decomposed peat** containing no discernible plant tissues. When squeezed, all of the peat releases through the fingers as a uniform dark paste.

Since peat is nearly always found beneath the groundwater table, the undrained shear strength is an important parameter for geotechnical design. Peat soils are known for their high compressibility and low shear strengths (Huan et al, 2014). Although a fibrous peat will likely have a higher shear strength compared with a more humified peat (Culloch, 2006), the additional shear strength gained from fibers is often anisotropic, and not applied uniformly through the soil body. The strength behaviour of the peat is modified.

Fibers in the peat act as a reinforcement in the direction of the load. This is important to note as it means peats are anisotropic both in strength and in strain (Huat et al., 2014). A peat may have different apparent and operational shear strengths depending on the direction of fibers with respect to the direction of loading. Although notable, it is however very difficult in today's practice to quantify the exact influence of fibres on a peat's shear strength (Long and Boyland, 2013).

An alternative way to characterize peat strength is to consider a normalized strength ratio; that is undrained shear strength over the vertical effective stress (Su/σ_v'). This method considers the stress history of the peat (Long et al., 2013). In addition to the water content and the degree of decomposition, peat strength is affected by its stress history, likely due to its high compressibility. This has been proven in both the field and laboratory testing of peat (Long et al., 2013). Surficial peat tends to have a different stress history compared with deeper samples due to surface loading and seasonal water table fluctuations. A normalized shear strength ratio is able to classify a peat's strength using its vertical effective stress history. Soft organic soils such as peat typically have a large normalized strength ratio (Long et al., 2013).

2.2 Laboratory Testing and Field Investigations

Insitu field testing and sampling of peat can be challenging. Usually found in soft marsh lands and mires, peatlands can be hard to access with traditional testing apparatus such as heavy drill rig machinery or excavators. If a drill rig can be accessed, cone penetration testing (a common method in geotechnical site explorations) can be used to obtain soil strength data. However, this does not allow for undisturbed sampling. Due to the often-rudimentary methods of sampling peat, complications arise in keeping samples undisturbed. Peat shear strengths are found to vary significantly as a result of sample disturbance. As such, it is important to ensure peat samples are kept undisturbed. Due to the nature of peat, this is a difficult. (Shogaki and Kaneogo, 1994).

Field Vanes are a common way of assessing in-situ peat shear strengths. Includes penetrating the ground surface with a multi-pronged tool and shearing until the soil ruptures, field vanes can give both peak and remoulded shear strengths. However, due to the presence of fibres amongst other factors, the values can be distorted. Long et. al (2011) found that field vane results in peats are usually grossly underestimated and should be corrected (Long et. al., 2011).

Another method is using shear wave velocities and correlating data to obtain geotechnical parameters such as undrained shear strengths based on empirical and theoretical calculations. This method required some sampling to be carried out to measure moisture levels and can be an efficient way to estimate insitu shear strengths. This method however does not consider the effects of fibers, which can sometimes be significant.

The most common laboratory test methods for evaluating peat drained shear strengths is the direct shear test. This test requires an undisturbed block sample of peat to be sheared. An undrained consolidated-undrained triaxial test is often used for undrained shear strength characterizations. Undisturbed samples are preconsolidated to the desired stress history, and loading is applied.

Due to the inconsistencies and difficult of sampling and testing peat in undisturbed environments, a combination of different testing techniques should be used to decrease uncertainties and provide a clearer image of a peat's strength behaviours (Zwanenburg and Erkens, 2019).

2.3 Brief Review of Back-Analyses Conducted for Peat Failure Incidents

Failures in peat soils have a long history in places like Ireland where peat is widespread in population centres. Long et al., (2011) details a host of events with peat failures that occur from 2006 to 2010. Most if not all involve an outside factor such as excessive rainfall or nearby construction. Long chronicles an overall increase of peat related incidents over the last century. However, this may be as a result of increased development and a greater practise of data and a record keeping.

The Ballincollig Hill slide in 2008 was used as an example of peat failure back-analysis. The slide occurred following a period of heavy rain. In addition,

Figure 1 Before and After Photos of the Excavation Failure, Tanensmera, Klaebu 2018

some of the top 1 m layer of the peat had been mechanically cut in preparation for extraction for domestic turf-cutting purposes. Despite the slope angle having a relatively shallow relief 3°, the peat failed with a peeling action. The slide eventually continued for 3 km.

Prior to the main slide accident, locals encountered "a ripple effect" in the surrounding marchlands. This hints at non-constant levels of pore pressure. Back-analysis was completed using the Infinite Slope Method (further discussed in Section 3.4.1). It was found in this case that the laboratory direct simple shear (DSS) test results correlated well with the expected failure strength values estimated from the back-calculation.

Boyland et al. (2008) identifies the most important factors in peat failure events as: (1) intense rainfall, (2) loading of peat surface, (3) Excavation, (4), Morphology, (5), Geomorphology, (6) Hydrology, (7) Geology. In most failure incidents, Long et al. identify a combination of elevated rainfall with another factor, such as construction.

Zwanenburg et, al. (2019) conducted a study and back analysis on a variety of peat sites in the Netherlands in an attempt to classify the operational undrained shear strengths of fibrous and amorphous peats. Employing a variety of testing techniques with back-analysis, they found that although the operational undrained shear strengths of the modelled peat conformed well with the field and laboratory data, the failure mechanisms did not match what was observed. A Tresca-model deformation analysis was used. They suggest a more advanced model that considers the rupture effects of fibers to be developed (Zwanenburg, 2019).

3. Tanensmyra Slide

The Tanensmera slide occurred in Klæbu roughly 20 km southeast of Trondheim, in Norway's Trøndelag district. The Klæbu region is situated in lacustrine clay region below the marine limit. The site lies in an area consistent with glaciofluvial deposits and overlain by peat and marshlands. Surficial soils are consistent with marine clays and other organics. The site sits below the marine maximum extent, and as such contains sensitive clays**.**

Figure 2 Augured Peat run At Tanensmyra, July 2019 (Photo taken by Omar Berbar)

3.1Excavation Failure

In late summer 2016, construction work was ongoing for the upgrade of a road and intersection in the Tanensmyra are of Klæbu. As part of the works, a large trench was excavated in the surficial peat and left standing 12 hours overnight. Crews continued excavating the next day, where the failure occurred after the next lift excavation. To reiterate the research questions, *We will seek to analyze what the failure mechanisms and strength properties of the peat.*

3.2 Field Investigation

A field investigation was conducted at the Tanensmyra site in July 2019. This was carried out as a part of a Norwegian peat classification program by the Norwegian University of Science and Technology (NTNU) and the Norwegian Geotechnical Institute (NGI). A hand-auger was drilled, approximately 15 m south of the now filled and paved excavation location. A hand auger was advanced to a nominal depth of 10 m below ground surface. Soil in 0.5 m intervals were logged and sampled in accordance with the von Post classification system. Two holes were drilled at this location. The full detailed geotechnical borehole logs and descriptions are appended to this paper.

Following the completion of the soil logging, shear wave velocities were measured. These values were then correlated to estimate in-situ undrained shear strengths. The shear strengths are compared with moisture contents and von Post humification in Figure 3 below. The results of the shear wave test are appended to this paper.

Moisture contents and humification levels appear to be negatively correlated, with higher moisture in the shallower, less decomposed soil. Moisture decreases while humification increases with depth. Shear strengths appear to be failure constant, with slight jumps that appear to correlate with an increase in decomposition. The shear wave method in classifying undrained shear strengths appears to be limited in that it does not

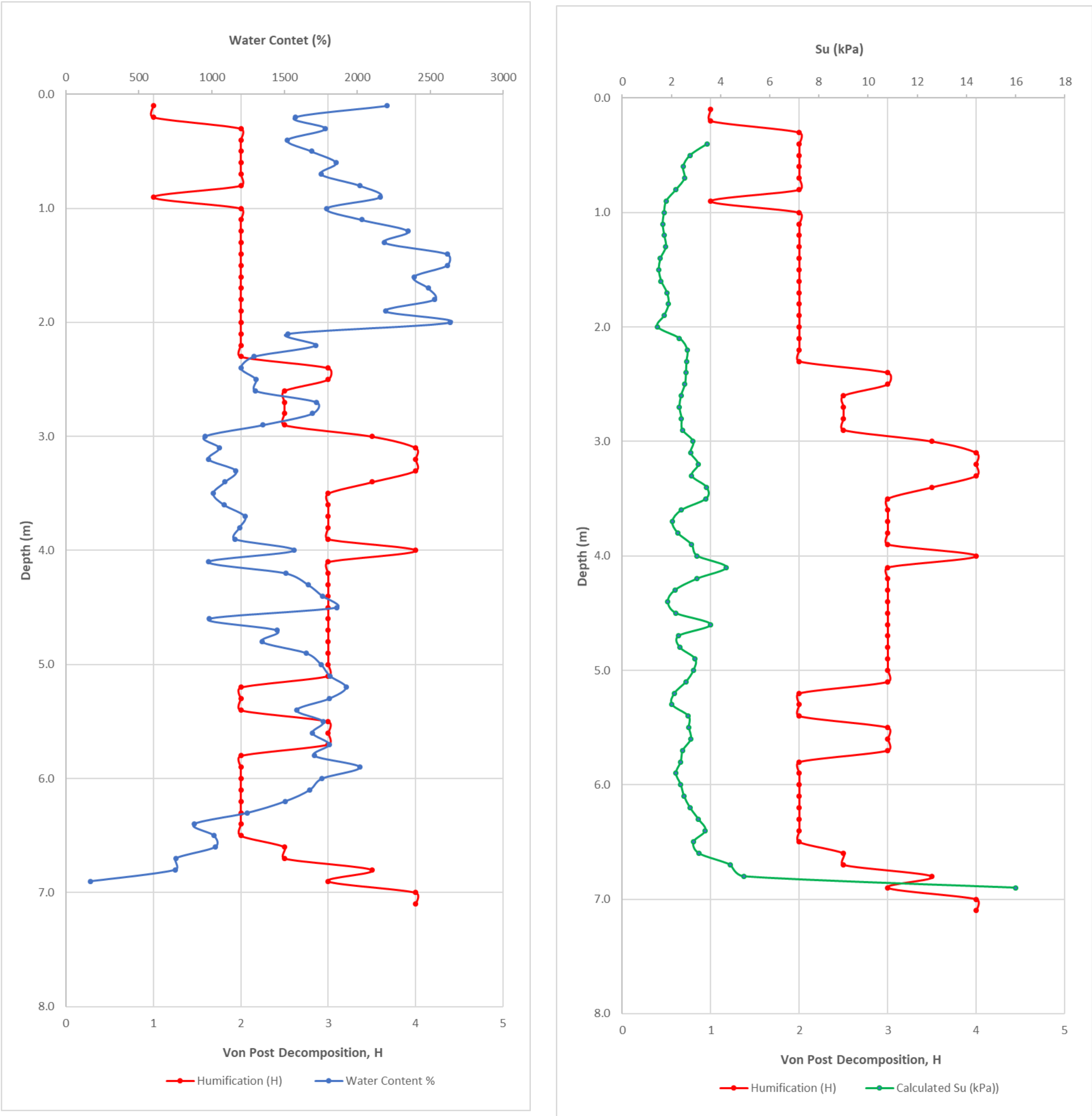

Figure 3 Depth vs. von Post Humification, Moisture Content, and Estimated Undrained Shear Strength (Su).

consider the effects of fibrous reinforcement in the peat. Fibrous peats. are associated with lower von Post H values, which should provide a jump in operational Su in the shallow soils. This is not reflected.

3.3 Laboratory Test Results

Laboratory testing focused primarily on the peat. As part of the program, peat samples were taken from seven different sites around the greater Trondheim area. This study will only comment on the findings from the Tanensmyra site. The laboratory testing was completed in Trondheim, Norway, as well as in Dublin, Ireland. In addition to moisture contents and index testing, the following tests were performed on peat:

- Direct Shear Test (DSS)
- CRS Triaxial

Block samples were taken at shallow depths, wrapped, and stored for testing. Every effort was taken to ensure samples were undisturbed, however due to travel and other factors, some levels of disruption may have occurred. The samples were preconsolidated to the required vertical effective stress history to emulate in-situ conditions. The full results of the tests are appended to this report. Figure 4 below presents undrained shear strength of a sample at 0.6 m depth, with and Su of 1.75. The sample was interpreted at peak stress with a 15% strain.

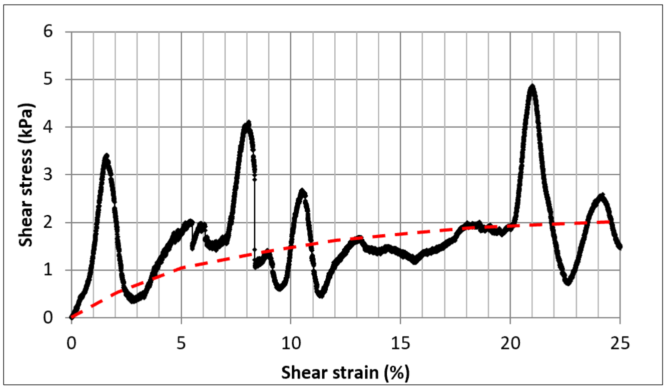

Figure 4 Undrained shear strength of a Tanensmyra sample retrieved at 0.6 m depth; interpreted at peak stress with 15% strain.

3.4 Preliminary Analyses

Back analysis is a method to delineate actual in-situ soil strength conditions based on a known failure. These have been done historically with trial pit failures, as discussed previously, but are faced with limitations. For instance, significant assumptions on geometry and drainage conditions are required (Long, 2005). The extent of which these assumptions limit or control the failure is unknown. As a result, a sensitivity analysis will also be performed to get to limit uncertainty.

3.4.1 Infinite Slope Method

To narrow the scope of the back-analysis, an infinite slope approach was performed as a preliminary investigation technique. Peat slides and excavation failures have typically been translational instead of rotational in the past. It is suspected that a translational slide took place at the Tanensmyra slide. An infinite slope method can be used to calculate factor of safety (FoS), this equation is presented below.

$$\mathrm{FOS} = \frac{s_u}{\gamma_b z \sin\beta \cos\beta}$$

Where Su is the undrained shear strength, γ_b is the bulk unit weight, and β is the angle of the slope.

3.5 Fine Element Analysis

A deformation back-analysis was undertaken using the finite element method in PLAXIS 2D (PLAXIS, 2018). This was performed to see what soil strength and stiffness parameters would theoretically be required to induce a failure as observed in the field. The following section discusses the methodology of the analysis.

3.5.1 Geometry

Model geometry was constructed based on a Statens Vegvesen memorandum dated to 2016 (Hove, 2016). The excavation is recorded to have extended roughly 5.5 m below nominal ground surface, extending 10 m – 12 m laterally. The excavation began at a slope of 1:1.5, later turning to 1:2. Exact measurements were not specified.

As such, to account for the uncertainty in the geometry, three different slope angles were modelled: are (1) the base case, a combination of 1:1.5 and 1:2 slope switching at roughly 3m depth; (2) 1:1.5 slope, and (3) 1:2 slope.

Modelling the three geometries also allow for an assessment of the significance the slope angle may have on the failure.

3.5.2 Geotechnical Input Parameters

Choosing the correct soil model is imperative in a back analysis. For simplicity, a Mohr-Coulomb model was selected. Mohr-Coulomb assumes that all strains are elastic until a failure envelope is reached (NTNU,2019). Although it is advantages in that it is simple in it's use, Mohr-Coulomb can be a flawed approach when it comes to peat soils as peat hardily ever behaves in a perfectly linear manner (Long, 2005). The Mohr-Coulomb failure criterion is normally linear for non-organic soils, behaves in a curved manner for peat (Long, 2005). Further, this model does not consider anisotropic strain behaviour.

Due to the short-term nature of the failure, an undrained approach was used. Undrained analysis assumes water is trapped in the pores which prevents a change in volume (NNTU, 2019). For this analysis, the peat was modelled with *Undrained B*. This considers "short-term material behaviour in which stiffness is defined in terms of effective properties and strength is defined as undrained shear strength" (PLAXIS, 2018).

"Stiffness is assumed to be constant in the simple linear elastic-perfect plastic models. In reality, stiffness varies with the stress level and how close we are to failure" (NTNU, 2019). Selecting a stiffness was therefore imperative. Stiffness information can be estimated from shear wave velocities (L'Heureux, 2016). Based on these correlations, stiffness values were estimated as presented in Table 2. Geotechnical parameters for the underlying silty clay were chosen from previous site investigation data from the area.

Input geotechnical parameters are presented in Table 2 below.

Table 2 Input Geotechnical Parameters

	Peat	Silty Clay
E' (kN/m)	500	3000
ν	0.3	0.4
γ (kN/m)	9	19
Su (kPa)	-	45

* γ_{sat} is assumed to equal γ_{unsat}

3.5.3 *Flow Conditions*

Groundwater flow was modelled using open boundary conditions. Flow is assumed to run from into the excavation.

3.5.4 *Construction Phases*

The excavation is modelled with four construction phases, with ~1.3 m excavated in each phase. The model also allows for a consolidation phase, where the effects of consolidation over the 12-hour period are considered. Finally, a c-phi reduction phase is carried out at the end to delineate minimum factor of safety required to meet equilibrium. The consolidation phase is applied after the first three lifts are removed. A final lift is removed after the 12-hour consolidation period. Figure 5 below displays the phases chosen for this analysis.

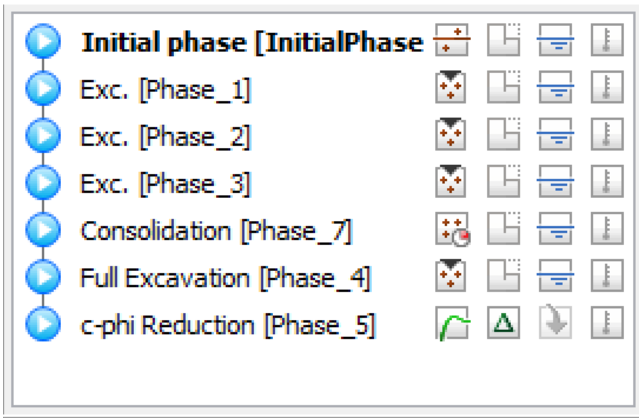

Figure 5 Deformation Analysis Construction Phases

4. Results

The results of the analyses are summarized in the following section.

3.6 Infinite Slope Method

This method yielded undrained shear strengths of 20 kPa with a 1:2 slope. This does not conform with the expected values of peat or based on the results of the field and laboratory investigations. This is not a reliable method in that it does little to consider the outside effects of the excavation.

3.7 Finite Element Analysis

The aim of the back-analysis was to estimate an undrained shear strength of peat that allowed for the excavation to fail given the specified geometries. After careful analysis, an overall best estimate of **Su was determined to be 8.1 (kPa)**. Since the exact depth at which the excavation slope angle changed, a sensitivity analysis was completed to assess the weight of the geometry on the excavation. A minimum peat strength difference of 8% is observed by simple geometry from a 1:1.5 to 1:2 slope. Consolidation appears to have no effect on the undrained model. The results are presented in Table 3 below. The failure mechanisms are shown in Figures 7 and 8.

Table 3 Back-Analysis Results

Case	**Peat Su (kPa)**
Base Case	8.1
Base Case w/ consolidation	8.1
1:2	7.6
1:1.5	8.3

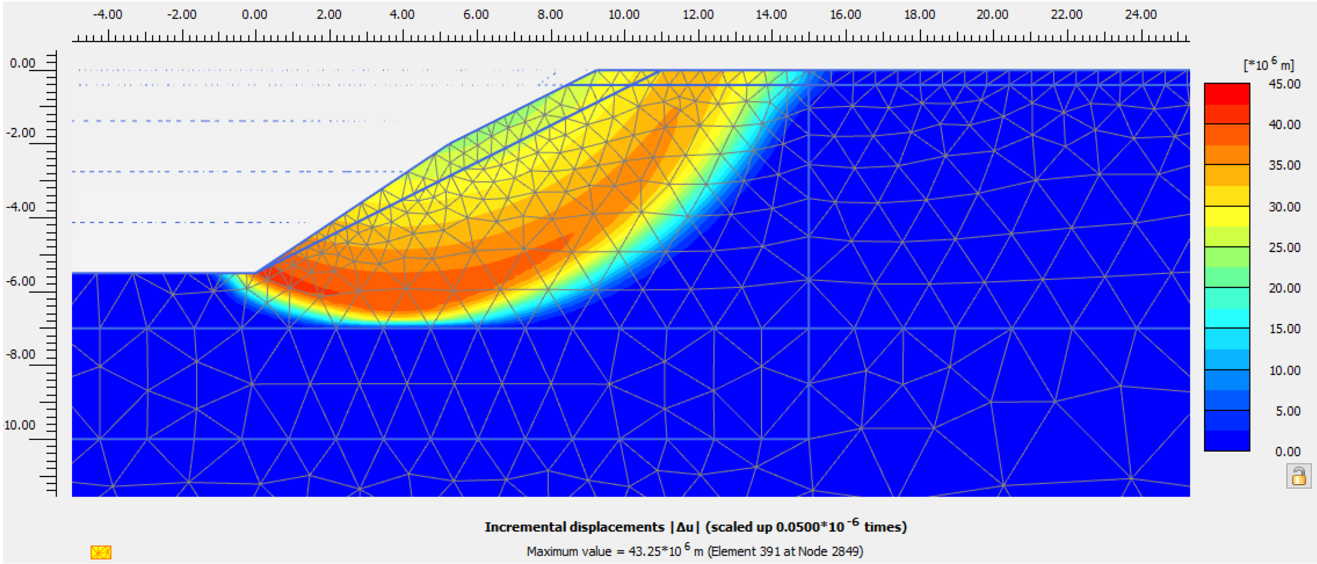

Figure 7 Undrained Analysis Incremental Displacements of Full Excavation

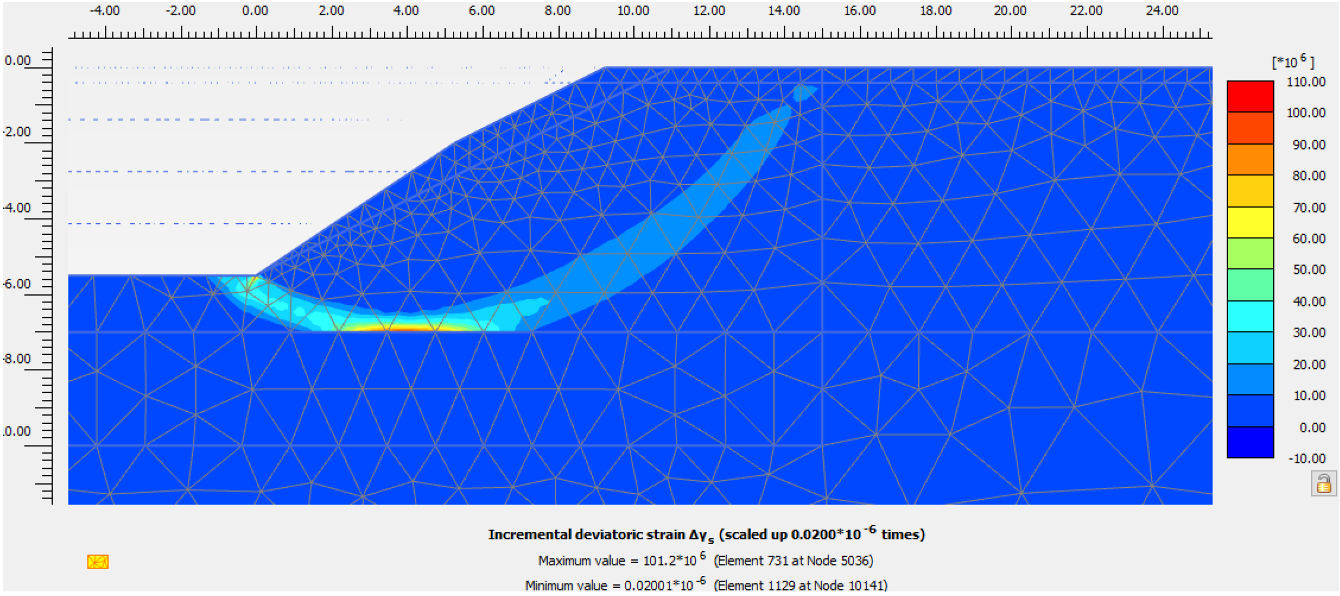

Figure 6 Undrained Analysis Incremental Deviatoric Strains of Full Excavation

5. Discussion

A change between a 1:2 slope and a 1:1.5 slope produces an 8% difference in minimum Su required for failure. The failure mechanism from the back analysis projects a circular failure, intersecting the peat-silty clay interface. In reality, the failure type has not been thoroughly documented, but observations point towards a shallower failure. Therefore, the failure mechanisms modelled are inconsistent with what was observed in the field.

The peat undrained strength from the back analysis is significantly larger than what was estimated from the shear wave velocity correlations and the laboratory testing (roughly 250% higher). This can be a result of several reasons: (1) either the field and laboratory testing underestimated shear strengths, or (2) the model overestimates the minimum required strength values. The following two scenarios are discussed below.

(1) As discussed earlier, the shear wave correlation is not an adequate way to consider the reinforcement strength generated by fibers in peat. Further, any slight disturbance to the sample may have skewed and underestimated the results from the DSS test.

(2) The finite-element model fails prior to the excavation completion with a lower Su. The model may also be limited due to the nature of a

two-dimensional deformation analysis, these failures could be a result of shallow sloughing and not overall failure. Tolerance of shallow failures may vary case to case.

In addition, the three-dimensional nature of the actual excavation likely plays a role in elevating shear strengths. The three-dimensional slope geometry can act as a toe-berm for the slope and increase the excavations factor of safety. This may play a role in the elevated minimum shear strength estimated by the back analysis. In real life, the Su is likely lower than what was modelled in the two-dimensional space, and possibly conforms with the field and laboratory testing results. As such, three-dimensional effects may have a significant role in stability of peat excavations.

6. Recommendations for Future Work

An approach that considers anisotropy in strain could be considered in the future. An example could be a model similar to the NGI-ADP, that has three different strain inputs (NTNU, 2019), or perhaps an independent model derived specifically for peat and the fibrous reinforcements of peat. Such a model would be better suited to model failure mechanisms in peat soils. This solution was also proposed by Zwanenberg et. al., (2019) Such a model has not yet been developed in conventional deformational analysis practice.

Stiffness assumptions should be tested to see if they hold true. Poisson ratios for unloading can be significantly lower (i.e. 0.1) (NTNU, 2019). This may affect the outcome of the model.

An analysis considering drained parameters should be run to check the consolidation results. A time vs. factors of safety chart could be developed.

Finally, a further analysis utilizing different methods such as a three-dimensional finite element analysis, or a limit equilibrium approach may yield better results in dealing with the failure mechanism and handling shallow sloughing failures.

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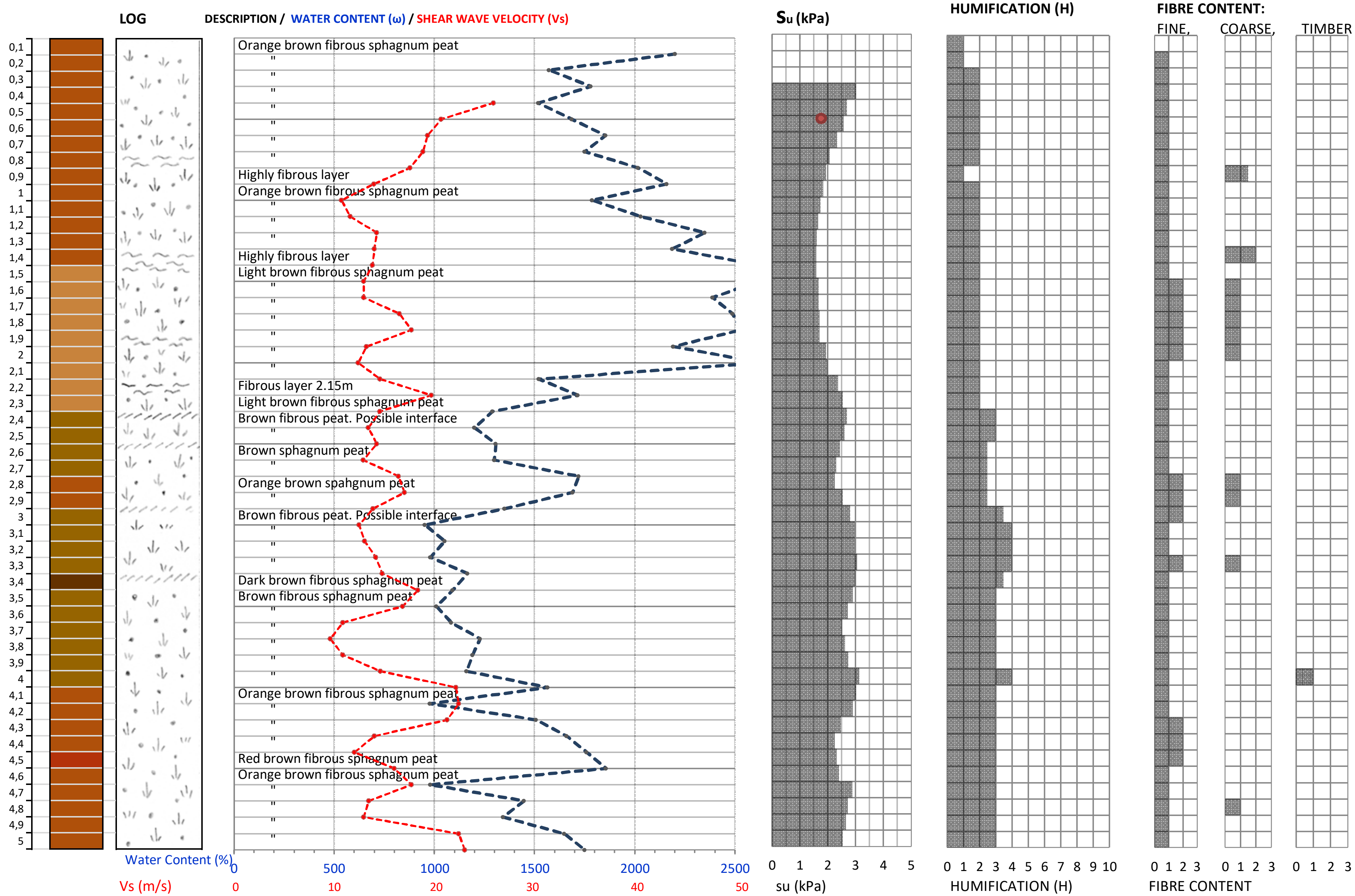

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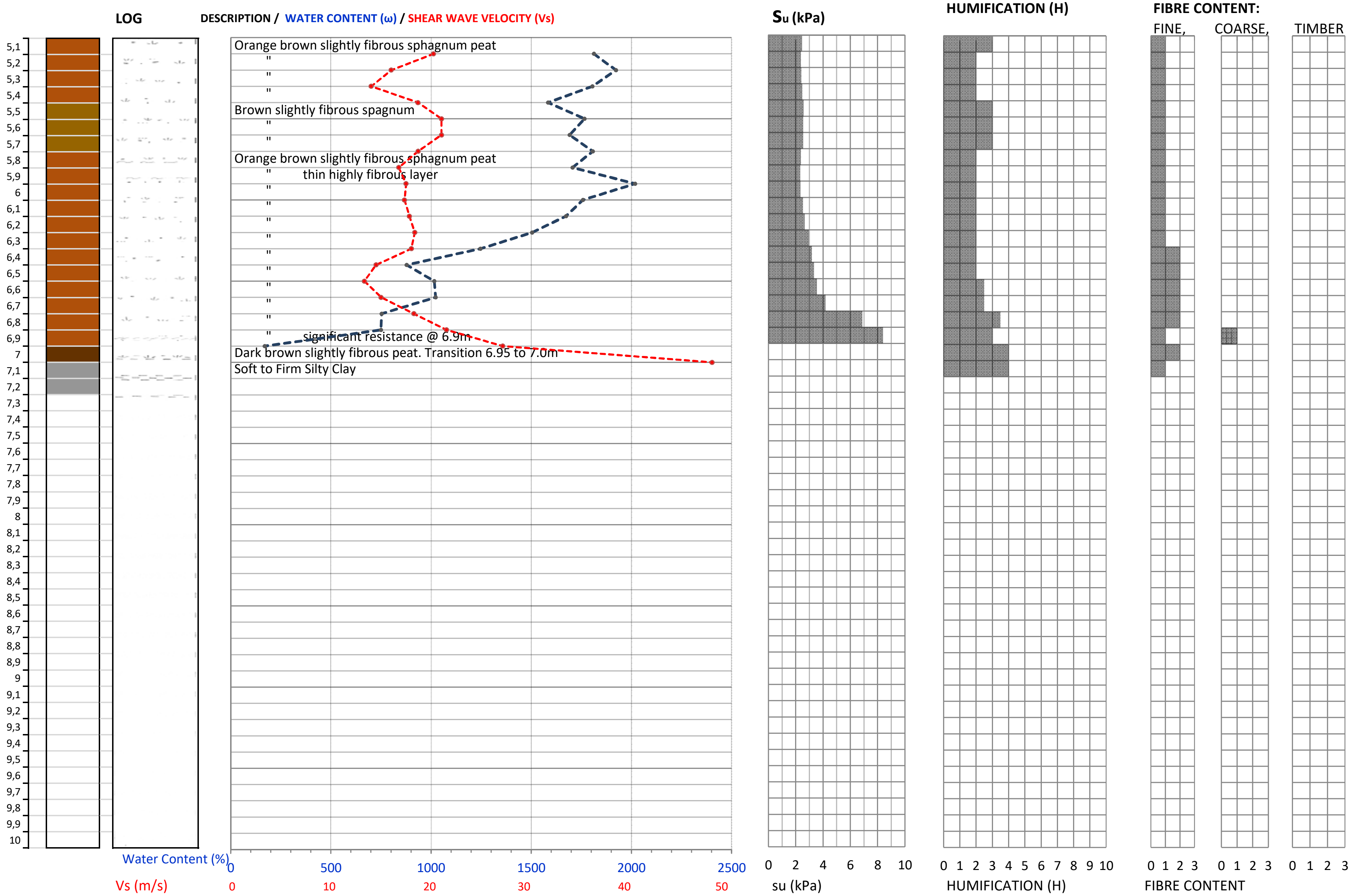

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NORWEGIAN GEOTECHNICAL INSTITUTE
NGI.NO

Main office
PO Box 3930 Ullevaal St.
NO-0806 Oslo
Norway

Trondheim office
PO Box 5687 Torgarden
NO-7485 Trondheim
Norway

T (+47)22 02 30 00
F (+47)22 23 04 48
NGI@ngi.no

BIC NO. DNBANOKK
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