



REPORT

# **Norwegian GeoTest Sites (NGTS)**

STANDARDIZATION OF IN SITU TESTS AND FIELD  
WORK

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## Summary

This report presents a brief overview of standards for in situ tests and field work carried out within the NGTS project.

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## Review and reference page

## 1 Introduction

The Norwegian Geo-Test Sites (NGTS) research infrastructure, with funding from The Research Council of Norway, creates a national research test site facility for geotechnical research. The five national test sites are located in Norway and on Svalbard. The research consortium consists of NGI and NTNU, SINTEF/UNIS and NPRA (Norwegian Public Roads Administration). The research project aims at developing five sites as field laboratories for the testing and verification of innovative soil investigation and testing methods. The sites cover the soil conditions of soft clay, quick clay, silt, sand and permafrost. At the end of the project, the test sites will serve as reference sites for the industry, public authorities, research organizations and academia where benchmarked data can be used by several generations of scientists and engineers to develop soil material models, new investigation methods, new foundation solutions and advance the state-of-the-art. The five sites will be operative for at least 10-20 yrs.

To ensure quality of the data generated in the project and to ensure as much uniformity of the results as possible it is important that all partners performing work at the sites follow the same test procedures and standards.

The present report give an overview of the main in situ testing methods and sampling techniques to be used in the NGTS project. Work at the NGTS sites shall be performed according to the referenced standards and requirements listed in the present report.

## 2 Surveying

Prior to surveying, the following are to be done for all boreholes/tests:

- Check availability of cable and infrastructure maps and examine borehole/test locations. If needed the site shall be surveyed by the cable owners.
- Check for previous boreholes/tests in the same location, as they will influence the new tests. Spacing of the boreholes should be more than 2.0 m if this is possible.
- (more)

After testing **each and every single** borehole shall be surveyed, and geodetic coordinates of the borehole recorded with the following accuracy:

- Horizontal accuracy at least 0.1 m or better
- Vertical accuracy at least 0.1 m or better
- Coordinate system EUREG89 UTM with the correct zone for the area e.g. UTM 32 for eastern Norway and Trøndelag, and UTM 33 or UTM35 on Svalbard
- Height system used is NN2000

## **3 In situ testing**

### **3.1 Total soundings**

All total soundings shall be performed according to NGF melding 9 (1). Water is used as a flushing agent during flushing. Air flushing should not be used at the testing sites due to the possibility of disturbances in the soil caused by the air. This disturbance may change the behaviour of the soil in the proximity to the sounding where air has been used as a flushing agent.

### **3.2 Rotary pressure sounding**

All rotary pressure soundings shall be performed according to NGF melding 7 (2).

### **3.3 CPTU**

All CPTUs shall be performed according to NGF melding 5 (3), which is an elaboration on the standard, ISO22476-2:2012 Geotechnical investigation and testing – Field testing – Part 1: Electrical cone and piezocone penetration test, for CPTU testing.

All tests performed shall be of "application class 1" or else the results shall be disregarded for the sensor that is outside of that class.

Slot filters are preferred for the piezocone tests to ensure saturation of the filter system, especially during the penetration of potential dilatant layers. Presaturated porous filters are also allowed, but these are not preferred as the saturation fluid is more easily sucked out of the filter system in dilatant layers.

SCPTU (seismic, e.g. measurements of  $V_s$ ) shall be performed with the same requirements as a normal CPTU. In addition, the shear wave will be recorded as the difference in arrival time for the shear wave between two levels of triaxial accelerometers/geophones in the add-on module.

CPTUs that measure resistivity/conductivity (RCPTU) are performed as normal CPTUs and the resistivity recorded with an add-on module. The module shall be calibrated at the same interval as the CPTU.

### **3.4 Vane testing**

All vane shear testing shall be performed according to NGF melding 4 (4). The use of electromechanical vane devices is encouraged, but traditional vane tests should be performed parallel to the electrical vane shear tests to validate results.

### 3.5 Piezometers

The NGTS project has purchased a large number of electrical piezometers of the type Geotech PVT for use in the project. They are instrumented with remote logging in the project phase. Parallel to the electrical piezometers, hydraulic piezometers can be installed at locations where the pore pressure regime is suitable for this (e.g. hydrostatic pore pressure or less). The purpose for the hydraulic piezometers is to act as control for drift in the electrical sensors over time.

The piezometers are installed according to procedures stated in NGF melding 6 (5).

### 3.6 DMT and SDMT

The NGTS project purchased a flat plate dilatometer (DMT) and a seismic flat blade dilatometer (SDMT). The test is initiated by forcing the steel, flat plate, dilatometer blade, with its sharp cutting edge, into a soil. Each test consists of an increment of penetration (20 cm), generally vertical, followed by the expansion of a flat, circular, metallic membrane into the surrounding soil. The test provides information about the soil's in-situ stratigraphy, stress, strength, compressibility, and pore-water pressure for use in the design of earthworks and foundations.

Various international standards and manuals are available for the DMT. An ASTM Suggested Method was published in 1986. A "Standard Test Method for Performing the Flat Plate Dilatometer" is currently being published by ASTM (2001) (6). The test procedure is also standardized in the Eurocode 7 (1997) (7). National standards have also been developed in various countries (e.g. Germany, Sweden) but not in Norway. A comprehensive manual on the DMT was prepared for the United States Department of Transportation (US DOT) by Briaud & Miran in 1992 (8). Design applications and new developments are covered in detail in a state-of-the-art report by Marchetti (1997) (9). A list of selected comprehensive DMT references is given here below.

The SDMT (seismic dilatometer) makes direct measurements of compression (P-) or shear (S-) wave velocities, or both, in a borehole advanced through soil or rock or in a cone penetration test sounding. A seismic source is used to generate a seismic wave train at the ground surface offset horizontally from the top of a cased borehole. Downhole receivers are used to detect the arrival of the seismic wave train. The downhole receiver(s) may be positioned at selected test depths in a borehole or advanced as part of the instrumentation package on an electronic cone penetrometer (Test Method D 5778). The seismic source is connected to and triggers a data recording system that records the response of the downhole receiver(s), thus measuring the travel time of the wave train between the source and receiver(s). Measurements of the arrival times (travel time from source to sensor) of the generated P- and S- waves are then made so that the low strain (<10–4 %) in-situ P-wave and S-wave velocities can be determined. The calculated seismic velocities are used to characterize the natural or man-made (or both) properties of

the stratigraphic profile. The full procedure for SDMT is standardized in ASTM D 7400-08 with different requirements for energy source, shear beam, recording system, etc.

#### **MANUALS**

Marchetti, S. & Crapps, D.K. (1981). "Flat Dilatometer Manual". Internal Report of G.P.E. Inc.  
Schmertmann, J.H. (1988). Rept. No. FHWA-PA-87-022+84-24 to PennDOT, Office of Research and Special Studies, Harrisburg, PA, in 4 volumes.

#### **STATE OF THE ART REPORTS**

Lunne, T., Lacasse, S. & Rad, N.S. (1989). "State of the Art Report on In Situ Testing of Soils". Proc. XII ICSMFE, Rio de Janeiro, Vol. 4.  
Lutenegger, A.J. (1988). "Current status of the Marchetti dilatometer test". Special Lecture, Proc. ISOPT-1, Orlando, Vol. 1.

### **3.7 Push-in pressure cells**

A Push-in Pressure Cell, also called Spade Cell, is designed to be pushed into the ground where it can measure total earth pressure and pore water pressure within the soil. It can be used as a site investigation tool to determine the in-situ stress state, both vertical and horizontal, depending on the direction of installation. In addition, it can be used to monitor the change in active and passive pressure around structures and other earthworks. Typical installations are in fine grained cohesive soils, including very soft to stiff clays.

The pressure cell and the port for the pore water pressure are connected via stainless steel tubes to two pressure transducers integrated in the cell (typically vibrating wire).

The installation method consists generally in drilling a pilot hole slightly shorter than the planned installation depth, and then to push the pressure cell about 1 meter past the bottom of the pilot hole using standard drill rods or CPT rods that will be left in place or retrieved at a later stage after measurements are completed. Push rods and a push adapter or an inverse thread adapter on the cell can also be used if the cell is to be pushed and left permanently in place with retrieval of the push rods.

The NGTS project has purchased a total of 11 push-in pressure cells and 2 handheld Measuring Device. One measuring device will be placed at the NGI office in Oslo and the other at the NGI office in Trondheim. Eight of the eleven push-in pressure cells have a measuring range of 0-5 bar, two have a range of 0-2 bar and 1 cell has a range of 0-10 bar. The maximum force that can be applied on the cell during installation is approximately 150% times the measuring range.

Additionally, 4 pressure cells from Soil Instruments have been purchased in 2019. They are pressure cells of the type Vibrating Wire Push-In Pressure Cell. A piezometer within the unit allows the measurement of pore water pressure and therefore the derivation of effective pressure. The cell is formed from two sheets of steel welded around the periphery, with the narrow gap between the plates being filled with oil. A Vibrating Wire pressure transducer is connected by a short steel tube, forming a sealed hydraulic system.

A porous filter disc is incorporated in the cell and is connected to a second Vibrating Wire transducer, together forming an integral piezometer. The two Vibrating Wire transducers are mounted in tandem behind the spade-shaped cell and protected within the installing pipe.

### 3.8 Hydraulic fracture test

The NGTS project is presently testing a simple method for *in situ* measurement of the lateral earth pressure in normally consolidated undrained soils. The method is based on the principles of hydraulic fracturing outlined by Bjerrum and Andersen (1972). A vertical crack is initiated in the soil around a piezometer filter. The water pressure at which the crack closes is estimated based on water flow measurements. This pressure is believed to be identical to the total stress across the crack, from which  $K_0$  can be determined.

Figure 3.1 illustrates the field apparatus schematically. The details of the test procedure and interpretation methods are given by Bjerrum and Andersen (1972). In summary, the test procedure consists of two main parts i.e. initiate crack and falling head (close crack). Firstly, water is pumped through a piezometer filter and into the soil. The filter is located close to the piezometer tip. Water is pumped at such a rate that a vertical crack is opened around the piezometer filter. When it is evident that the crack has been opened, the water flow is stopped. Figure 3.2 illustrates a typical pressure head response to crack initiation. The water pressure is allowed to regulate itself freely. When the water pressure has become lower than the total horizontal stress in the soil around the piezometer tip, the crack will close. This critical pressure can then be determined from the water pressure/water flow vs time curve as shown in Figure 3.2.



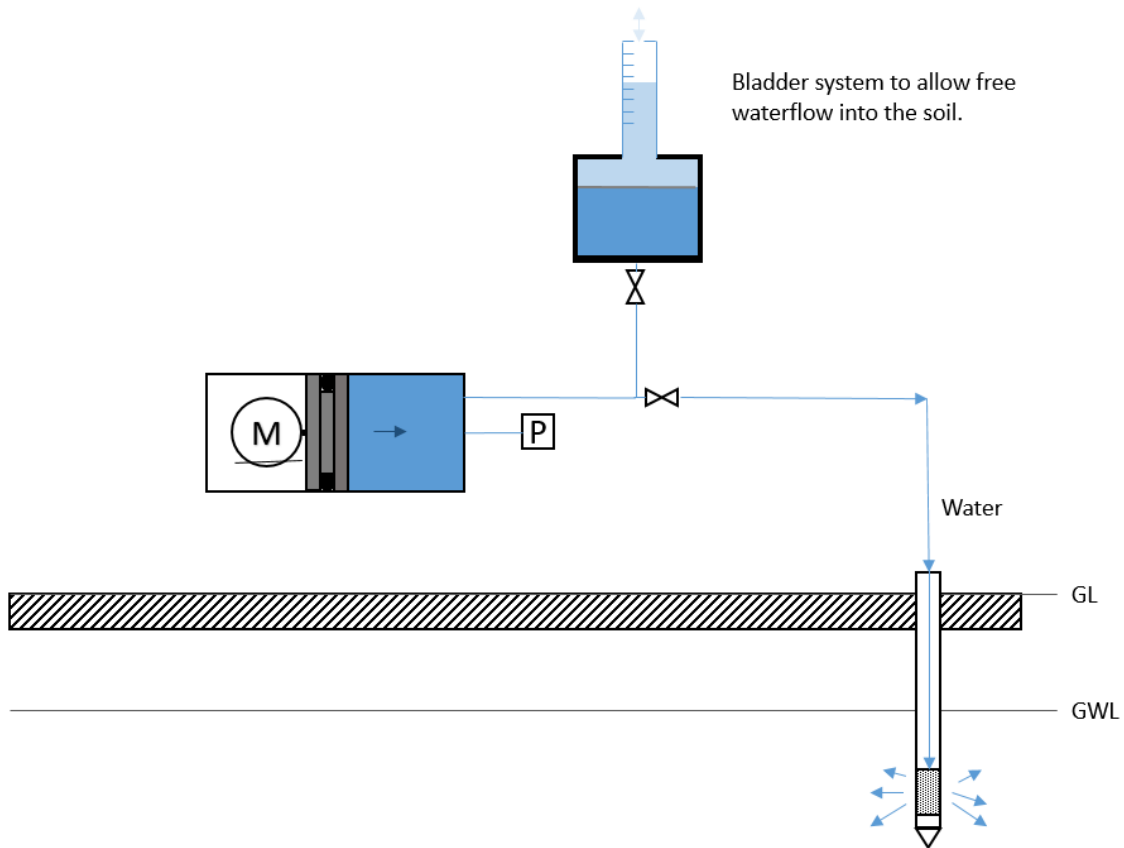


Figure 3.1 Sketch of the field apparatus for hydraulic fracture test

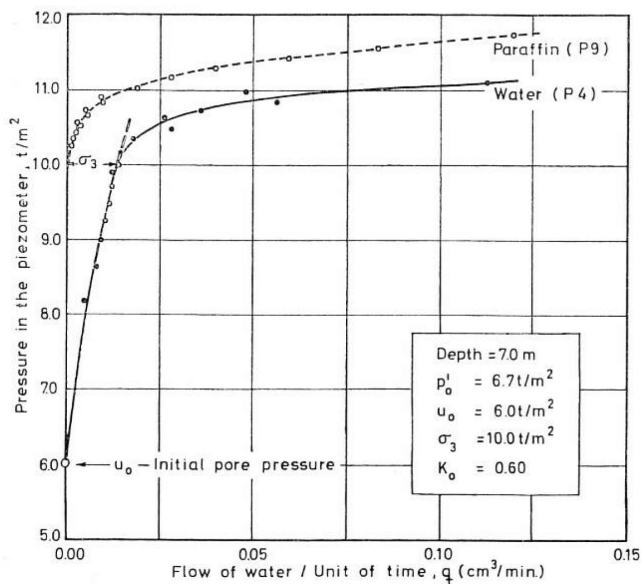


Figure 3.2 Observed relationships between pressures in the piezometer and rate of flow from the piezometer in falling head tests using both water and paraffin (Bjerrum and Andersen, 1972)

A summary of the measured  $K_0$ -values measured by Bjerrum and Andersen (1972) is given in Table 3-1.

*Table 3-1 Average soil properties and measure  $K_0$ -values at different sites (after Bjerrum and Andersen, 1972)*

Site	Soil description	W %	w <sub>L</sub> %	W <sub>p</sub> %	I <sub>p</sub> %	p <sub>c</sub> /p <sub>o</sub> ' -	s <sub>u</sub> /p <sub>o</sub> -	S <sub>t</sub> -	K <sub>0</sub> (virgin)	K <sub>0</sub> (in-situ)
Konnerud	Plastic	52	61	32	29	1.5	0.36	10	0.49	0.60
Konnerud	Lean	30	33	22	11	1.2	0.24	3	0.49	0.50
Drammen River Bank	Lean	34	32	18	14		0.16	6	-	0.60
Sundland	Plastic	58	52	29	23	1.4	0.36	12	0.45-0.53	0.55*
Sundland	Lean	29	33	22	11		0.20	2	-	0.58*
Studenterlunden	Lean	35	35	22	13		0.20	5	0.50	0.60
Ellingsrud	Quick	38	26	21	5		0.09	60	0.52	0.45
Kjelsås	Quick	43	26	20	6		0.12	80	-	0.40-0.50

Notes: \* One test only. s<sub>u</sub> and S<sub>t</sub> were obtained from field vane tests. K<sub>0</sub> (virgin) values obtained from K<sub>0</sub> triax tests loaded above p<sub>c</sub>'.

In connection with the instrumented test fill at Onsøy (Berre 1974 and 2014) Iversen (1974a, b) carried out hydraulic fracture tests at this site. The test results show similar values as the self-boring pressuremeter tests. It is believed that the HFT is one of the most reliable methods for determining K<sub>0</sub> in soft clays.

More information about the results from the current testing will be given at a later stage.

### 3.9 Flow cone

NGI has developed a tool to determine the characteristics of water flow within silts and silty soils for understanding and characterizing the material behaviour. In silts and silty soils, the soil response can be undrained, partially drained and drained during the time of interest. The tool estimates in-situ hydraulic conductivity, in-situ pore pressure distribution and soil type. The standard cone penetrometer test is combined with a filter centred 82 cm above the cone tip. The tool was tested at Øysand (NGTS sand site, (10)) between the 24<sup>th</sup> and 26<sup>th</sup> of September 2018.

Hydraulic conductivity (k) describes the ease with which a fluid (usually water) can move through pore spaces or fractures. It depends on the intrinsic permeability of the material, the degree of saturation, and on the density and viscosity of the fluid. Hydraulic conductivity is sometimes referred to as the permeability. This parameter is important in many design cases.

A flow-controlled pump sends water through a cylindrical filter, radially into the surrounding soil during cone penetration or at specific depths of interest. The resistance generated by the soil is measured and logged.

The flow cone testing at Øysand included two standard cone penetrometer tests and one flow cone test. The standard cone penetration tests were carried out to determine the feasibility before the flow cone testing.

Figure 3.3 illustrates the flow cone test setup. The water pump and acquisition system are placed on top of a euro pallet for stability. The figure indicates the elevation of the pressure sensor. The sensor measures the absolute water pressure. The water pump and acquisition system are hydraulically connected to the water reservoir and the CPTU add-on filter at any time during testing. The pressure sensor outputs the absolute pressure approximately two times per second.

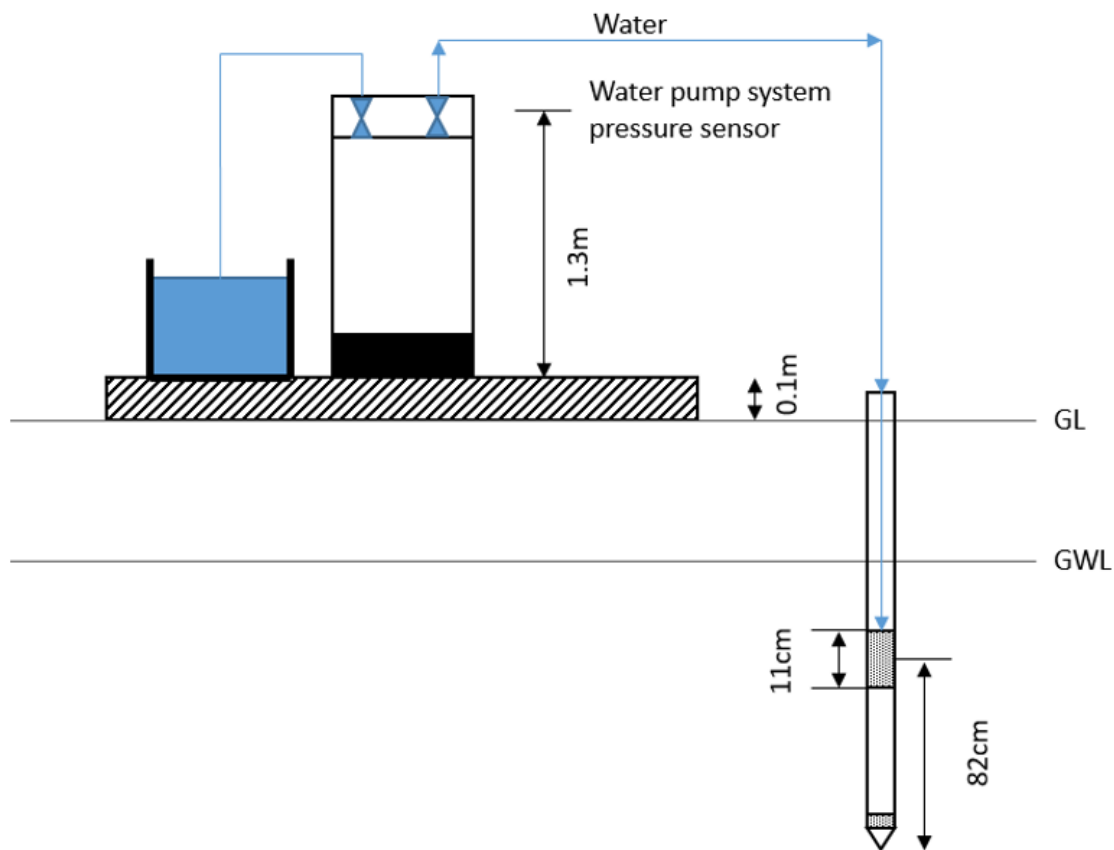


Figure 3.3 Flow cone test setup

Laminar flow is assumed everywhere within the system. The cross section of the tube is constant. The water pressure at filter centre location,  $u_f$ , (inside filter) can be described as follows:

$$u_f = \gamma_w(z_p - z_f) + u_p - H_L$$

Here,  $u_p$  is the water pressure measured by the pump which represents the vertical distance between the pressure sensor and free water surface.  $z_f$  and  $z_p$  are the elevations of filter centre and pump pressure sensor with respect to elevation of ground water level (GWL).  $H_L$  (kPa) represents the system head loss due to friction and is taken as:

$$H_L = \beta q$$

Here,  $\beta$  is a constant and  $q$  is the flow of water per time in millilitre per minute.  $\beta$  is determined from system calibration tests.

If the pore pressure distribution is hydrostatic, the difference between the water pressure at filter location and in-situ pore water pressure can be described as:

$$u_f - u_0 = z_p \gamma_w + u_p - H_L$$

There are generally two test phases, i.e. penetration phase and non-penetration phase. The cone and filter are penetrated to a target depth where further flow testing can be carried out. A constant flow of 50-100 ml/min was applied during penetration phase at Øysand, for example. This was done to keep the system hydraulically connected and to see the pore pressure response. During the penetration phase, the cone penetrometer logs the cone resistance, sleeve friction, pore pressure behind the cone etc. The penetration is stopped at specific depths to do flow testing where the flow of water varies. The testing was carried out with an acoustic cone penetrometer so that all measurements was observed live.

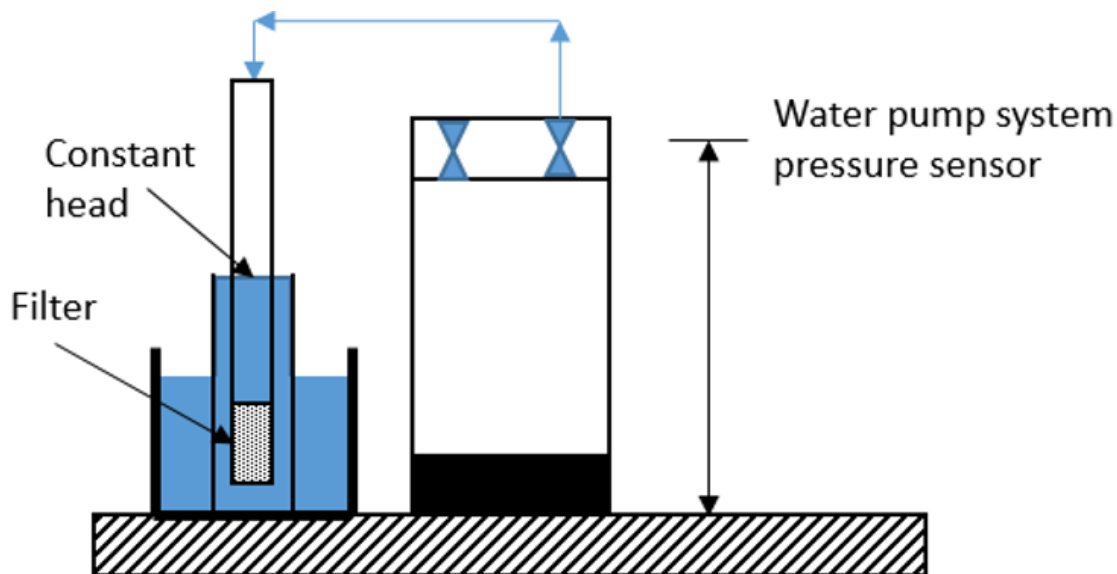


Figure 3.4 Set-up for system calibration

Figure 3.4 illustrates the system calibration setup used in the field. The test starts with a zero reading with no flow which corresponds to the water level marked as constant head in the figure. Subsequently, different flows are specified to the pump and the corresponding head loss is measured.

## 4 Boreholes - Sampling

### 4.1 Sampling in clay

All sampling shall be performed according to NGF melding 11. In NGTS the use of larger diameter samples are preferred to get less disturbed samples.

Samplers in the order of preference for the clay sites is listed below:

1. Block sampling Ø250 mm
2. Block sampling Ø160 mm
3. Ø72 mm fixed piston
4. Gel push sampler
5. Ø95 mm
6. Ø54 mm, steel cylinders
7. Ø54 mm, composite cylinders.

At each site one reference borehole with Ø250 mm block samplers with the Sherbrooke shall be executed. For comparison one 160 mm miniblock sampling borehole should be executed.

Fixed piston samplers of the diameter Ø72 mm – Ø76 mm is the preferred sampling of tube sampling due to lower disturbance of the mechanical properties of the sample in both plastic and sensitive soils. The sampling tubes should have an area ratio lower than 15% and use a cutting angle less than 10°. There shall be no inner clearance in the cylinder.

### 4.2 Sands and silts

In sands and silts undisturbed sampling is more difficult to achieve. To assess the best method of sampling for each site several samplers should be used. The best method may perhaps reach down to specific layers at the site.

Samplers in the order of preference for the silt and sand sites is listed below:

1. Block sampling ( $\varphi$  250 mm and  $\varphi$  160 mm)
2. Gel push sampler
3. Ø72 mm fixed piston

4. Ø72 mm push samplers
5. Ø54 mm with composite liners
6. Sonic drilling
7. Auger sampling
8. Percussion sampling

Block sampling has been performed several times in silty soils and can be successful if the material has enough cohesion to stay intact in the sampler. However, block sampling might be difficult to achieve at the sand sites.

### 4.3 Sampling in permafrost

Different methods are, in general, used for sampling of frozen fine-grained and coarse-grained soils. Some methods are, however, applicable for both types of soils. Special coring systems can be used for coring ground ice. Drilling and sampling in rock permafrost material is not presented in this document.

Systematic reviews on drilling in permafrost (including coring) is presented in (11), (12) and (12).

#### 4.3.1 Sampling in fine-grained soils

Sampling of fine-grained soils is presented in details in (10), (11) and (13).

The following sampling methods can be implied:

- Coring with or without fluids with conventional double-wall core barrel or wire-line core barrels.

Standard diamond reaming shells shall be used. Core bits suitable for frozen soils must be used: tungsten and surface-set diamond bits with kerf as thin as possible. Bits shall provide full face cutting. Face discharging bits are preferable, mostly in coarse-grained soils. Core catcher of "split-ring" type shall be used. Compressed cold air can be used as an agent transporting reworked soil material from the borehole.

High core quality can be provided with this method. Cores are suitable for visual description, testing for index properties, and for mechanical testing.

- Coring with CRREL coring auger or modification of this corer (for instance the modified SINTEF corer).

When coring with CRREL coring auger – compressed air is needed for transport of "chips" of frozen soil on the surface. Compressed air is not needed when coring with the SINTEF modified corer.

The core retained in the core barrel due to "dry-blocking", no core catcher is incorporated in the construction of the corer. Corer retrieval from the corer shall be performed with a piston pusher.

High core quality can be provided with this method. Cores are suitable for visual description, testing for index properties, and for mechanical testing.

- Single-tube core barrels with tungsten or diamond core bits. No core catcher is normally incorporated in such barrel, dry-blocking of the core is used.

Cores can be suitable for visual description and testing for index properties.

- Driver sampling: with modified Shelby tube or percussion sampler for moraine sampling.

Samples can be suitable for visual description (at some degree) and testing for index properties.

- Rotary sampling (grab samples of cuttings from augering).

Samples can be suitable for identification of material type and testing for some index properties.

- Chopping of block samples.

Samples can be suitable for visual description, testing for index properties. Samples can be machined in order to produce of samples of specific shape for mechanical testing.

Sampling of material from active layer with a corer can be a challenging task, especially when some gravel is present. Single piece of gravel may destroy PCD inserts (if any are used in corer construction).

The following methods can be used for sampling from active layer:

- Coring.
- Rotary sampling (grab samples of cuttings from augering).
- Chopping.
- Sampling from a soil pit in summer time, procedures from (14) can be suggested for adoption.

### 4.3.2 Sampling of coarse-grained soils

Surface casing is important for drilling in coarse-grained material, hence this installation usually needs to be done.

Methods for sampling of coarse-grained soils:

- Coring. Core sampling of coarse-grained material is a demanding task due to fragile behaviour of ice bonds between the soil grains. Samplers of large diameter are required for this operation. Large diameter of a sample provide sufficient rotational resistance of frozen material during drilling, hence a core will be strong enough against disintegration during drilling.

Diamond drill bits shall be used. The bits should be designed and operated in a manner comprising that gravel and stones are cut and not torn out of the frozen matrix.

High core quality can be provided with this method. Cores are suitable for visual description, testing for index properties, and for mechanical testing.

- Rotary sampling (grab samples of cuttings from augering).

Samples can be suitable for identification of material type and testing for some index properties.

- Chopping of block samples.  
Samples can be suitable for visual description, testing for index properties. Samples can be machined in order to produce samples of specific shape for mechanical testing.

## 5 Geophysical methods

### 5.1 Seismics

#### 5.1.1 Method

Seismic waves are acoustic waves which correspond to small elastic displacements in the ground. The waves travel with a velocity which depends on the material's density and elastic moduli. By deploying a grid of seismic sensors (geophones) and optionally generating acoustic signals, seismic data can be recorded and analysed in order to assess the ground's elastic properties. Depending on the method applied, information about sediment and bedrock interfaces, rock quality and soil shear strength can be obtained.

There are two main types of seismic waves: Body waves, which travel through the bulk of the materials, and surface waves, which travel at interfaces between materials of different elastic properties.



The techniques named "Seismic reflection" and "Seismic refraction" both analyses the travel times of body waves. Waves may be either P (pressure) waves or S (shear) waves or a combination of the two, and they may be generated by a P-wave (hammer, explosives) or a S-wave (vibrator) source, respectively. In a certain material, all frequencies travel at the same velocity (no dispersion).

The technique named "MASW" (Multiple analysis of surface waves) analyses surface waves, which might be either "Rayleigh waves" or "Love waves". Surface waves are dispersive, i.e. the travel velocity is a function of the wave frequency. In MASW, the frequency dependence of the velocity (the dispersion relation) is analysed.

Calculation of the shear wave field may be used to obtain valuable geotechnical information. The fundamental relationship between shear wave velocity  $V_s$ , maximum (small-strain) dynamic shear modulus  $G_0$  and bulk density  $\rho$  is given by:

$$V_s = \sqrt{\frac{G_0}{\rho}}$$

## 5.1.2 Seismic reflection and refraction

### 5.1.2.1 Data acquisition

In seismic reflection and/or refraction surveys, a set of geophones (called spread) is distributed evenly along a line, and seismic waves generated by a source at various positions along the line are recorded simultaneously by all the geophones. The source may be a sledgehammer, a weight drop, explosives or a vibrator plate. The frequency range of vibrator sources is normally in the range of 15-1000 Hz. The waves travel either directly along the terrain surface (first arrivals), or they are reflected and critically refracted at interfaces in the ground, before they arrive the various geophones and are recorded.

The geophones may be designed to acquire displacement in only one direction (vertical) to record P-waves, or in two or three directions (vertical and horizontal) to additionally enable recording of S-waves.

### 5.1.2.2 Data processing

Processing of reflection/refraction data may include

- Interpretation of first-arrival travel times, which are picked (often manually) on the seismic record.
- CMP analysis of refractions from a two-layer model
- Tomographic inversion of seismic velocities from refraction data
- Stacking of reflected signals.

Figure 5.1 (right) illustrates the path of the seismic waves with source and receivers at the surface to map the sediments/bedrock “refractor” and estimate a mean velocity of the sediment layer.

The final product of a reflection/refraction seismic survey is a two-dimensional section along the survey line that may contain stacked reflections, distribution of seismic velocities or a CMP-curve showing the transition between two assumed layers.

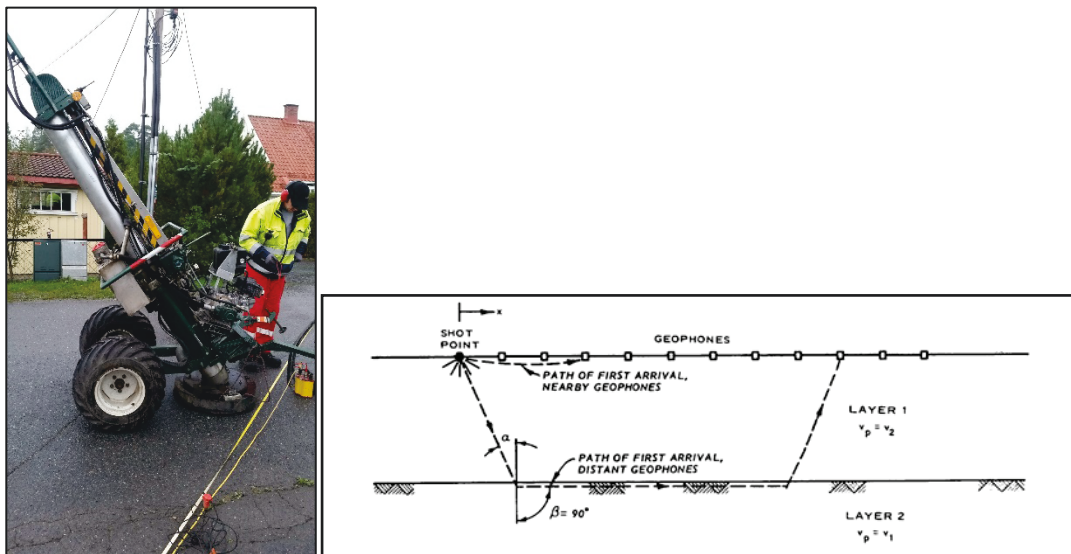


Figure 5.1 Refraction seismics. Vakimpak accelerated weight drop source (left) and corresponding seismic wavepaths (right, figure taken from US Army Corps of Engineers, 1995).

### 5.1.2.3 Resolution and penetration depth

Recording of refracted waves require a relatively long geophone spread (shot-reciever offset 3 to 5 times the investigation depth) but recording of reflected waves does not require a large offset. For long profiles, a powerful source is preferred (an accelerated weight drop or explosives).

The resolution is commonly defined as  $\frac{1}{4}$  of the wavelength (velocity divided by frequency). Therefore, low velocities (and/or high frequencies) contribute to better resolution.

#### 5.1.2.4 Applications

- Depth to bedrock. Requires a significant impedance contrast across the bedrock surface. Very shallow depths (smaller than the geophone spacing) may be difficult to resolve.
- Rock quality. Changes in the velocity field may be used to evaluate potential weakness zones.
- Soil shear strength. May be evaluated from shear wave velocity analysis. Requires calibration with CPT soundings.
- Internal layers. Interpreted sections in the seismic velocity distribution can lead to high-resolution internal stratigraphy of soil deposits that may help locating preferential leaching paths building a more realistic ground model.
- A sharp increase of velocity can be used to differentiate between frozen and unfrozen material. Hence, the technique is applicable in locating the top of permafrost table

#### 5.1.2.5 Limitations

Refraction seismic requires that the velocity increases with depth. As a consequence, the method is unable to detect low-velocity layers at depth (so-called *hidden layers*).

The velocity contrast between clays, silts, gravel and sand is normally small.

Elastic discontinuities may not be related to geological changes (e.g. water table crossing geological layers) and changes in lithology may not produce velocity contrasts (soft clay versus quick clay).

### 5.1.3 MASW

In the Multichannel Analysis of Surface Waves (MASW) method, the velocity of surface waves travelling at impedance contrast interfaces are analysed. Surface waves penetrate about half to one wavelength (shear waves) into the sub-surface. The frequency range is therefore normally lower (e.g., 1–30 Hz) than for refraction surveys. It provides shear-wave velocity ( $V_s$ ) information of near-surface materials, and the data collection procedure in field is relatively simple.

#### 5.1.3.1 Data collection

Data may be collected passively (recording only seismic signals generated by the surroundings) or actively (by using a P- or S-wave source, preferably the latter). Signals are recorded by normal two- or three-component geophones.

### 5.1.3.2 Data processing

In conventional seismic exploration, surface waves are often referred to as ground roll and removed by filtering. However, in MASW processing, the complete wavefield is kept, and the travel group velocities will be a complicated function dependent on frequency,  $V_s(\omega)$ . In vertically heterogeneous media, wave equations for dispersive surface waves have multiple solutions at given frequencies. In other words, multiple propagation modes will exist. Ultimately, deriving shear wave velocity profiles versus depth requires inversion of the dispersion curves extracted from the data.

MASW processing of seismic data includes:

- 2D wavefield transformation of the data.
- Extraction of dispersion curves.
- Inversion of 1D  $V_s$  profile,
- Assembling of multiple 1D profiles to make a 2D seismic section.

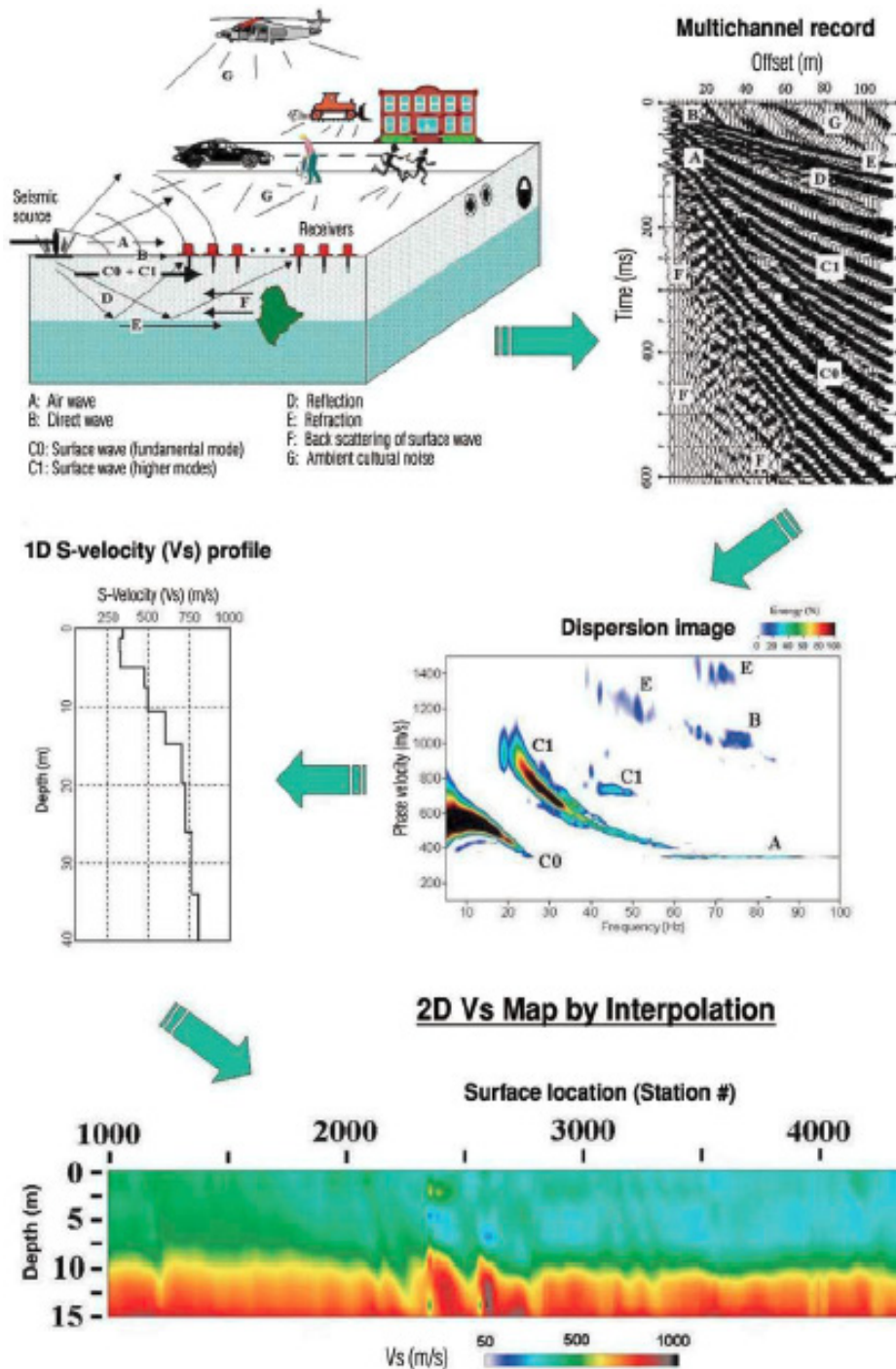


Figure 5.2 Illustration of the overall procedure of the MASW method. Complicated nature of seismic waves is carried over into the measurement (multichannel record). Figure from Park et al., 2007.

#### 5.1.4 Limitations

- Vertical resolution is limited because the Vs profiles are extracted by means of one-dimensional models. The spacing may vary from a few to several tens of meters.
- Processing may be time consuming (The multiple propagation modes should be taken into account in inversion in order to obtain a more accurate geophysical model of the shallow sub-surface.)
- Preliminary tests prior to data acquisition is required. For example, a certain minimum offset, which is site-dependent, is necessary to move away from near-field effects.
- The spacing between the receivers  $\Delta x$  on the other hand determines the maximum wavenumber that can be recorded, controlled by the Nyquist sampling theorem or Nyquist wavenumber as:

$$k_{Nyquist} = \frac{\pi}{\Delta x}$$

- Energy associated with wavenumbers beyond the Nyquist wavenumber will be aliased, indicating undersampled data in spatial dimensions. However, some energy can be recovered after unfolding of the wavenumber axis.

#### 5.1.5 Applications

- Surface waves are of particular interest for geotechnical applications, as their behaviour can be used to assess shear wave velocity which provides direct insight in soil stiffness.
- As for the refraction method, the obtained velocity contrast may not be related to geological changes (e.g. water table crossing geological layers) and changes in lithology may not produce velocity contrasts.
- However, large double layer induces weak bonding of clay particles that could potentially lead to S-wave velocity decrease in leached clays. Shear-wave velocities for quick-clay, measured using the MASW approach, appear to be slightly less than those measured for non-quick-clay and may help to discriminate in case of ambiguities.
- Vs sections can lead to high-resolution internal stratigraphy of the deposits that ultimately may help locating preferential leaching paths building a more realistic geological model.

## 5.2 Resistivity / Induced polarization (ERT/IP)

### 5.2.1 Method

Electrical Resistivity Tomography (ERT) and Induced Polarization (IP) are two closely related near-surface geophysical methods that uses direct current to measure the earth's electrical properties.

The electrical potential is measured while the current is turned on. This parameter is used to calculate the resistivity model (ERT). Right after the current is turned off, the potential field will decay gradually, and the amount, duration and shape of this decay is related to the polarizability of the ground (IP).

Subsurface resistivity is highly varying and is mainly governed by the sediments and rock types (lithology) in the area. ERT / IP thus enables us to distinguish different materials, ranging from low resistivity clay to high resistivity hard rock.

### 5.2.2 Data acquisition

A spread of electrodes (usually 40 cm steel bars) is installed into the ground with fixed intervals and connected to an instrument through multi-channel cables. The current is injected into the subsurface through two electrodes at a time (marked C in the figure 3), and the resulting potential field in the ground is measured along a profile by two other electrodes (marked P). The selection of C and P electrodes runs automatically through a specified protocol.

### 5.2.3 Data processing

Data processing usually includes topography correction and masking / filtering of bad data points. Thereafter, inversion is carried out, applying measured standard deviations and the correct regularization technique (smooth, blocky etc) appropriate for the data and the ground conditions. The result is a two- or three-dimensional resistivity / IP model of the subsurface.



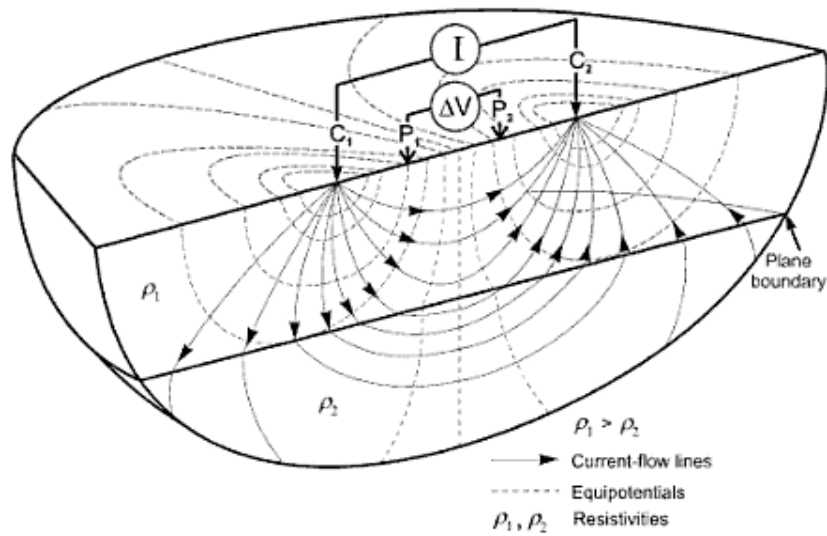


Figure 5.3. Basic principle of electrical resistivity imaging (top). It is possible to determine earth resistivity  $\rho$  by driving a current  $I$  into the ground and measuring the resulting potentials  $\Delta V$  (Figure from Knödel et al., 2007). Electric resistivity tomography (ERT) with field instrument linked to electrodes planted in the ground using electrical cables (lower).



## 5.2.4 Resolution / penetration depth

The resolution is governed by the electrode spacing: The resolution is about half the spacing between the electrodes at the surface and decreases gradually with depth.

The depth of investigation is dependent on the simultaneous spread length (the length of the cable layout used during a measurement), as well as the ground resistivity. A general estimate for depth of investigation is 10-20% of the simultaneous spread length.

An electrode switch box and an additional power source can be applied to give both high resolution and increased penetration depth.

Increased data coverage along the line direction is accomplished by using roll-along measurements.

## 5.2.5 Applications

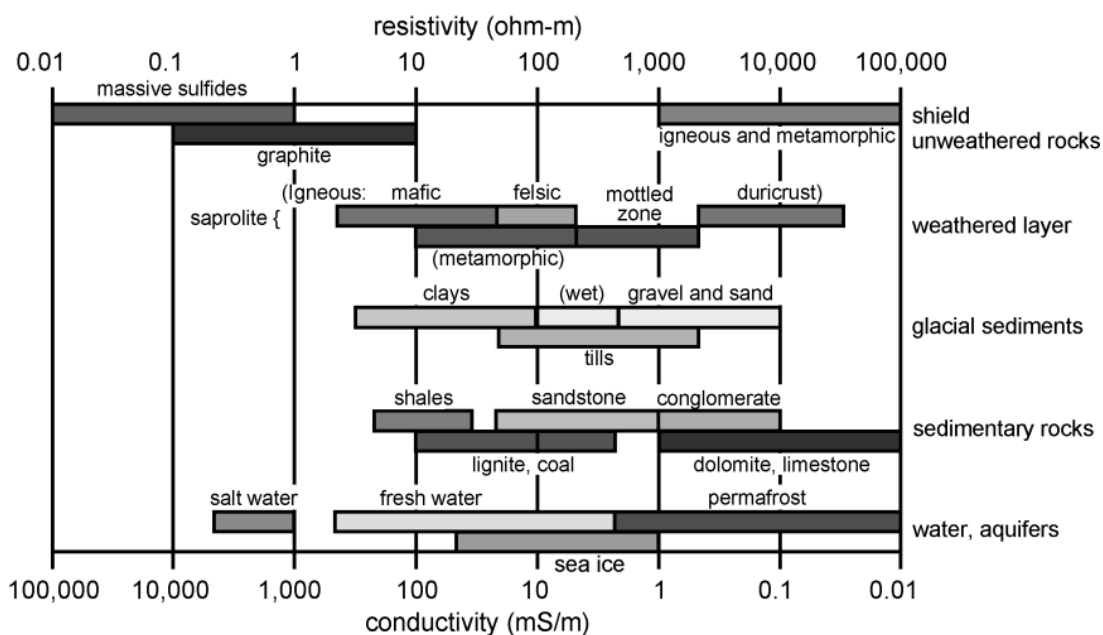


Figure 5.4. Typical ranges of electrical resistivities of earth materials after Palacky (1987).

Soil resistivity is mainly dependent on the soil minerals, the grain size distribution, degree of water saturation and the chemistry of the pore water.

Rock resistivity is largely dependent on the rock minerals, but also on rock quality and ground water saturation and mineralization.

A broad classification of the resistivity of various rock and soil types is given in Figure 5.4.

Resistivity mapping can distinguish water-saturated silt from drained, coarse moraines, making the method applicable for some drainage problems, i.e. related to railway embankment investigations. The stratigraphic interpretation from ERT results alone is limited but one can take advantage of the wide range of resistivity values between clays, silts, gravel and sand.

Resistivity variations within clay layers could reflect the variation of salt concentration in the pore water and/or the variation in grain size. Electrical resistivity may therefore be a suitable indicator for leached and possibly quick clay if calibrated to sparse conventional site investigation soundings and laboratory tests.

ERT can be used for mapping horizontal and vertical distribution of permafrost, including distinction between permafrost and non-permafrost areas, detection of massive ice and monitoring of temporal evolution of permafrost, quantifying/comparing ice content. The best results with this method are obtained in ground with sharp electrical contrast, for instance when dense ice-cemented soil is located next to loose soil with a large unfrozen water content (16).

### 5.2.6 Limitations

It is important to judge the area to be investigated and thoroughly evaluate the suitability and possible outcome of electrical methods. The following points should be evaluated:

- The resistivity contrast between the target and the surrounding materials should be evaluated and the cable layout designed accordingly.
- Good contact between the ground and the installed electrodes lowers the signal-to-noise ratio of the measurements and will help to improve penetration depth and lower the model uncertainty.
- Buried electrical cables and other man-made infrastructure may cause noise in the measured voltages.
- Large variations in geology/topography perpendicular to the cable layout may cause erroneously mapping of 3D structures onto the 2D inversion model.
- The inversion results are based on a nonlinear mathematical problem and the solution has therefore intrinsic non-uniqueness. Consequently, interpretation should be done with a critical mind.
- The choice of regularization introduces some degree of smoothness to the inversion model, resulting in an inability to detect sharp layer interfaces.

## 5.3 Ground Penetrating Radar

### 5.3.1 Method

Ground Penetrating Radar (GPR) uses electromagnetic waves reflected on discontinuities (dielectric contrasts) after emission from radar antennas positioned along the earth's surface. These discontinuities correspond to changes of electromagnetic impedance  $\eta = \mu c$  where  $\mu$  is the magnetic permeability and  $c = (1/\epsilon\mu)^{1/2}$  is the velocity of electromagnetic waves,  $\epsilon$  being the electric permittivity. The electromagnetic wave velocity  $c$  decreases in general with depth. As in seismic, the higher the frequency, the better the resolution, but the lower is the penetration depth. In addition, the penetration capacity is better in resistive materials (e.g., granite, dry sand, ice) than in conductive layers (e.g., clay, saturated soils). GPR is widely used thanks to light and portable equipments (Figure 5.5), the “easy” processing, and its high resolution (from a few cm to a few m, depending the soil and antennas). In conventional systems, both the emitting and receiving antennas are moved keeping a fixed distance (offset) between them, this in a profiling mode. Though this acquisition mode allows the quick visualization on field of ground reflectors and diffractors, the intrinsic lack of velocity information prevents proper depth conversion (users usually assumes a mean velocity of 0.1 m/ns to get a rough estimate of depth on field or use diffractors - if any - to estimate an equivalent velocity). It is therefore highly recommended to acquire a few Common Mid-Point (CMP) gathers at key locations, a technique inherited from seismic acquisition/processing and assuming locally horizontal reflectors. This is done by moving away emitter and receiver from a given location, thus increasing the offset step by step. In GPR, the lower the frequency is, the longer the antennas are, which may complicate the acquisition on difficult terrain (steep, rough, etc) as the whole antenna surface should be lying on the ground. A more recent development is the use of towed systems which greatly facilitates the acquisition in such cases.



Figure 5.5 GPR technology: the instrument can be easily rolled over even ground.

### 5.3.2 Limitations

First, GPR utilization in Norway is limited due to the usual presence of clay materials and water saturated layers which absorb electromagnetic energy. Second, the high level of diffractions in complex 3D structures may yield poor imaging. Finally, GPR surveys are only feasible on even ground (not boulders or vegetation). In comparison to seismic, a major drawback of GPR surveys is also the lack of reliable velocity information to constrain the scattering structures in depth as the acquisition is performed in a constant-offset mode, i.e., with fixed distance between emitter and receiver. Without CMP information at different locations, a proper velocity models cannot be derived, and only rough estimates are obtained by searching for diffractions patterns to determine mean velocities.

### 5.3.3 Applications

Generally, GPR is used for mapping soil and rock stratigraphy. Even though GPR does not have the sufficient depth penetration to image clay deposits, it can be used to mapped in details the coarse grain material cover.

GPR amplitude variation within clay layers could reflect the variation of salt concentration in the pore water and/or the variation in grain size. Grain size variation could be interpreted from GPR amplitude variation.

The applications win permafrost studies include:

- Detecting the position of thermal interfaces, for instance the depth to the top of permafrost and the depth of active layer (17).
- Detection of massive ground ice, distribution of ice wedges (17).
- Determination of spatial variations of water content in the active layer (41).
- Measurements of snow and ice thicknesses (44), and for glaciological studies (mapping of bedrock beneath glaciers, for instance). The method can be used for mapping of ice thickness.

## 6 Permafrost

Terminology related to permafrost and ground-ice is presented in (15). Detection and characterization of permafrost is commonly performed by using combination of geophysical methods and in situ tests.

At NGTS sites, field investigations included drilling, core and sample retrieval, casing of boreholes, installation of temperature sensors, and CPTU. Several drilling methods were employed to retrieve samples for laboratory testing and install the casings for thermistor strings. Bag samples of cuttings were collected using a soil auger and down-the-hole (DTH) drill. Core sampling in frozen soil was conducted by SINTEF using a drill rig equipped with a core barrel with flights and poly-crystalline diamond composite bit inserts. This core barrel is used without drilling fluids and obtains samples with a 47 mm diameter. Core sampling in the unfrozen, cryopeg zones was done using a 54 mm piston sampler from Geonor AS.

Boreholes were cased with plastic pipes ( $\varnothing = 50$  mm) and instrumented with thermistor strings (GeoPrecision M-Log5W). Collaboration with Pagani Geotechnical Equipment provided access to a CPTU rig (TG63-150). Measured parameters include cone resistance ( $q_c$ ; given in MPa), sleeve friction ( $f_s$ , given in MPa), penetration pore pressure ( $u_2$ , given in kPa), temperature, depth, rate of penetration, and inclination. Seismic piezocone penetration tests (SCPTU) and standard penetration tests (SPT) can also be performed using this rig. Additional field activities, included electrical resistivity tomography (ERT) surveys, conducted in collaboration with the Norwegian Geotechnical Institute.

Standards and guidelines for many of geophysical methods (if not all) are not elaborated due to various ground conditions and broad spectrum of goals of investigations. Hence one may be encouraged to follow existing case studies if ground conditions and goals of investigations comply to previously research done.

### 6.1 Geophysical methods

Geophysical surveys provide opportunities to define distribution of permafrost and determining its properties (16). Permafrost distribution can be divided into two groups (17):

- Definition of horizontal limits (mapping);
- Definition of vertical limits (sounding), which involves determination of upper and lower boundaries of permafrost distribution, and the position of thawed zones within a permafrost section.

As Svalbard is located in the continuous permafrost zone (18), mapping problems are related to determining the shape and the size of taliks (16). One should, however, bear in mind that distribution of frozen ground near water bodies (i.e. at coastal zone, near rivers) can be complex and difficult to determine. In addition, determining parameters

and patterns of groundwater flow with geophysical means could be also of practical interest.

Implementation of geophysical methods for detection and characterization of permafrost is based on contrast of values of physical properties from those of thawed ground (or unfrozen ground). The relevant geophysical properties are the electric resistivity, the dielectric permittivity and the velocity of seismic waves, (19). The latter causes that electrical and electromagnetic methods, and seismo-acoustic methods are the most commonly methods used to study permafrost. Mentioned geophysical methods do not give information on thermal regime.

In addition, several miscellaneous methods, however, are also widely used (gravity, radiometric, magnetic, thermal logging).

Geophysical methods include airborne, surface (contact and non-contact), and borehole methods. All methods have characteristic effective depth of penetration, some methods can be used only for qualitative determination of one of the vertical limits (17).

Some geophysical methods can be complementary, for instance in cases when two different geophysical methods and a ground truthing method (based on coring, for instance) are used.

Review of geophysical methods for the study of permafrost for the period from 1973 to 1990 is presented in (17). The latter reference also provides a flow chart (modified from (20)) for assessment of the geophysical methods and their applicability. Brief overview of geophysical methods for resource and infrastructure development is presented in (16). Introduction to applied geophysics in periglacial environments is presented in (21). Concise overview of characteristics of geophysical techniques is presented in (19).

Some geophysical methods which seems to be beneficial and applicable to conditions of field sites of NGTS project in Svalbard are outlined below.

### 6.1.1 Electrical techniques

These techniques are based on the measurement of electrical resistivity (or its reciprocal, electrical conductivity), (19).

The following methods are commonly used: (i) direct-current (DC) electrical measurements, (ii) self-potential measurements (SP) and induced-polarisation methods (IP), including spectral-induced polarisation (SIP), (21).

DC resistivity method is most applicable. General applicability – studying of horizontal and vertical distribution of permafrost ( (17)), including distinction between permafrost and non-permafrost areas, detection of massive ice and monitoring of temporal evolution of permafrost, quantifying/comparing ice content (19).



The best results with this method are obtained in ground with sharp electrical contrast, for instance when dense ice-cemented soil is located next to loose soil with a large unfrozen water content (16).

Most applicable variants of the method are **Electrical Resistivity Tomography (ERT)**. This method may provide results with fine resolution. The essential feature of this technique is electrode arrays, which are introducing/detecting current into/in the ground.

Examples of applicability (based on case studies) of different variants of DC method (based on electrode arrays placed in the ground) are presented below:

- Thawed zones associated with surface and/or groundwater flow (22).
- Small scale features within the valley bottoms, like distribution of relict permafrost as highly resistive ice-rich material, local permafrost degradation and shallow ice-wedge polygons (23).
- Thickness of shallow permafrost and permafrost aggradation (24).
- Ice features in permafrost terrain (25) and (26).

Another variety of DC method is **Capacitively-Coupled Resistivity (CCR)**. This method is less applicable than ETR in practice but becomes more common. The method provides results of coarser resolution than ETR, but much faster pace of work.

The method is very useful for detection of thawed zones in permafrost terrain. The method can be used to the depths of approximately 20 m.

Survey is performed by the means of capacitively-coupled resistivity system "OhmMapper" (CCR). OhmMapper is designed to be pulled along the ground as a streamer and thereby provide almost continuous resistivity profile (27). Description of the method is given in (28). Thawed zones can be obtained by interpretation of CCR data.

Examples of CCR applicability: delineation between frozen vs. thawed materials, and ice-rich vs. ice-poor materials can be conducted with CCR solely ( (29), (30)), or in combination with GPR ((30), (31)).

## 6.1.2 Electromagnetic Methods

These methods are based on variations in the dielectric permittivity.

### 6.1.2.1 Inductive electromagnetic methods

Techniques include frequency-domain EM systems (FEM), time-domain electromagnetic systems (TDEM), systems using very low frequencies (VLF), including radiomagnetotelluric method (RMT) (32).

EM systems are used less frequent than electrical resistivity systems. However, they have been widely used in studies of arctic permafrost ( (33), (34), (35), (36) and (37)).  
Applicability, (19):

- FEM and VLF systems – mapping of isolated ice occurrences, mapping of boundaries of periglacial phenomena, mapping horizontal differences in the active layer thickness, determining the degree of heterogeneity to assess the representativeness of single point measurement.
- TEM systems – determining thickness of permafrost layer (vertical sounding).

Examples of applicability:

- Mapping of shallow permafrost occurrence (in the upper 6 m) and depth of active layer was performed with instruments EM31 (Geonics, Inc.) or GEM-300 solely (37), or in combination with DC resistivity survey (38).
- Thickness of shallow and thin permafrost features was determined by using GEM-2 instrument (Geonics, Inc.) (24).
- Permafrost depth (down to 100–300 m) was determined with the time-domain system PROTEM (37).
- Thickness of deep (approximately 500 m) permafrost was defined with frequency-domain electromagnetic sounding (39).
- Mapping of permafrost distribution with airborne instruments was performed in discontinuous permafrost zone, for instance, by (23) and (40).

### 6.1.2.2 Ground Penetrating Radar (GPR)

Ground Penetrating Radar is an EM method employing short radio waves in the frequency range 10–1000 MHz. Overview of the method is, for instance, presented in (41). The core information of the method is summarized in (42) and (43). The method is applicable on landscape scales (several kilometres).

Applicability of the method:

- Mapping soil and rock stratigraphy ((17), (19)).
- Detecting the position of thermal interfaces, for instance the depth to the top of permafrost and the depth of active layer (17).
- Detection of massive ground ice, distribution of ice wedges (17).
- Determination of spatial variations of water content in the active layer (41).



- Measurements of snow and ice thicknesses (44), and for glaciological studies (mapping of bedrock beneath glaciers, for instance). The method can be used for mapping of ice thickness.
- Use of the method in fine-grained material is greatly restricted, with the greatest penetration depth obtained in sands and gravels. GPR does not penetrate through saline water.

Applicability of this method can be illustrated by defining the following features:

- The depth of active layer ( (45), (46)).
- Thaw depth beneath small streams ( (47), (48)).
- Detection of frozen and unfrozen interfaces in river bed over ice cover (49).
- Locating/recognition ice wedges ( (46), (50)), massive ground ice (51) and 3D visualization of ice wedges networks (52).
- Sub-bottom sediment profiling in lakes (53).

### 6.1.3 Seismic techniques

The method is based on analysis of seismic wave velocities, and sharp increase of velocities can be used to differentiate between frozen and unfrozen material. Hence, the technique is applicable in locating the top of permafrost table (19).

Overview of techniques is presented in (17). Detailed discussion on application of method in periglacial environments is presented in (54).

### 6.1.4 Miscellaneous methods, (17).

Magnetic method was used for determining ice wedge distribution. Gravity surveys were used for estimations of excess ice. Radiometric techniques were used for rapid logging (in boreholes) of density and ground-ice content of ice-rich permafrost.

## 6.2 In situ testing

### 6.2.1 Monitoring of ground temperatures

The following operations shall be performed:

- Monitoring of Ground Surface Temperature (GST).
- Thermal monitoring of active layer.
- Thermal monitoring of permafrost.

### 6.2.1.1 Monitoring of Ground Surface Temperature

"The ground surface temperature is defined as the surface or near-surface temperature of the ground (bedrock or surficial deposit), measured in the uppermost centimetres of the ground," (55). The depth of measurements should be 2 cm ( (56), (57) and (58)).

Measurement technique and procedures for data analysis can be adopted from (55). Devices to monitor shallow ground temperatures is described in (59) and (60), ground surface temperature was also monitored with miniature data loggers (iButtons) (61).

### 6.2.1.2 Monitoring of temperatures in active layer and in permafrost

Monitoring of temperatures in active layer and in permafrost (hereafter, "monitoring of ground temperatures in permafrost") is usually combined when one uses a thermistor string. Thermistor strings is a standard equipment used for these purposes.

Monitoring of ground temperatures only in the active layer can be of specific interest, but such task is beyond the scope of this manual.

It can be suggested to monitor ground temperatures in permafrost in several locations within one field site. Six locations can be recommended in order to provide basis for statistical analysis of spatial variability of ground temperatures.

Methodology for monitoring can be adopted from (55): Section "Thermal monitoring of active layer", Section "Thermal monitoring of the permafrost."

Main suggestions for the monitoring setup (suggestions are partly based on (55)):

- Depth of boreholes – 30 m;
- Boreholes should be drilled with air as flushing agent if any flushing agent to be used.
- Monitoring shall be performed with thermistor strings. A thermistor string includes a data logger. Data is sent on web-server via GMS modem. Data must be stored on data logger until the moment when it safely (with some standard back-up solution) can be saved on a server.
- Thermistor strings shall be calibrated (with ice-bath method) prior to deployment.
- Boreholes can be equipped with casing. Positive experience of using casing is given for instance in (62).

Several aspects related to cased boreholes for thermal monitoring:

- Reasons for equipping boreholes with casing are the following: (i) to prevent hypothetical frost heave action on the string; (ii) to be able to retrieve the string for recalibration purposes or in case of malfunction.
- Suggestions for casing: (i) PEHD pipes with flushed threaded joints. Each casing must be equipped with bottom and end cap/well cover; (ii) plastic one-piece pipe.
- It is suggested to avoid using the following types of casing: (i) metal casing in order to avoid any possible thermal perturbation or (ii) PVC casing of socket type (with glue or without glue assembling) in order to avoid work with glue in cold conditions, casing without glue does not resist to frost heave action (string can be torn due to action of frost heave). However, steel casing (with liquid filling) was widely used in practice.
- There is no need to fill the casing (63), but experience with liquid-filled casing, casing filled with dry sand does exist.
- At the same time there is a credible opinion that installation of thermistor strings without casing provides most accurate data. However, references on such studies were not identified.
- Additional monitoring of ground surface temperatures in several locations (at least six) is suggested.
- Installation: precautions shall be taken in order to have a precise measurement of the elevation of thermistors.

## 6.2.2 Measurements of the active layer thickness

It is suggested to estimate active layer thickness on the basis of temperature measurements. At the same time, the CALM site, located next to the Adventdalen site provides yearly data obtained with permafrost probe.

## 6.2.3 Piezometers in permafrost

One can suggest to perform installation of electrical piezometers in permafrost within the depth of active layer: one piezometer can be installed at the bottom of the active layer, while another piezometer can be installed in the middle of active layer.

It is recommended to do total sounding prior to installation of piezometers to get an overview of sediment types. To prevent freezing a frost protection fluid should be used to saturate the filter tip. In case of coarse material the installation of piezometers must be performed in pre-drilled holes; either made by total sounding or auger. The piezometers with rods are lowered in the hole with the drillrig and pushed approximately 10 cm into virgin sediments. The cavity between the piezometer rods and the wall of the hole is filled with sand. In case of fine-grained soils like clay/silt the piezometer is installed by the drillrig from the surface.

The electrical piezometers can either be read continuously with GSM transfer or data can be downloaded at given intervals by PVT reading device.

#### 6.2.4 Inclinerometers in permafrost

Study done by Savigny and Morgenstern (1986) (64) can be used as a reference for description of inclinometer installation in permafrost conditions.

#### 6.2.5 Total sounding in permafrost

The standard method for total soundings, as specified by the Norwegian Road Authorities (NPRÅ 2014), is performed by rotating a drill bit into the ground at constant rotation and speed of penetration while recording the soil resistance. Increased rotation speed, flushing and drill hammer is used to penetrate hard layers or rocks. In frozen soils, the resistance is too high to facilitate the required penetration rate, i.e. increased rotation is used at all time and valuable information is lost. Based on this, a modification to the total sounding procedure has been developed by SINTEF which allows for obtaining detailed information of the soil profile while maintaining the effectiveness of sounding. The modified total sounding is performed with constant force while logging the penetration rate. Hammering and flushing (usually sea water) is performed continuously.

The modified total sounding procedure is found to be a valuable tool in permafrost soil investigation. The method procedure achieves enough pressure to penetrate through the frozen ground while still producing detailed data on the soil profile. The tested procedure works well in frozen soil, but in saline clay, the conventional Norwegian total sounding procedure is preferred.

#### 6.2.6 Cone penetration test in permafrost

Experience of the cone penetration tests (CPT) in permafrost is limited. It has to be decided if this section should be elaborated in details or not. The following studies illustrates implementation of CPT in permafrost:

- Deep static cone penetration test was suggested by (16) (for verification of creep parameters), detailed description of the instrument is presented in (65).
- Andersland and Ladanyi (16) suggested to use static or incremental-loading CPT for soil strength determination within a given soil layer (for obtaining creep parameters), and (ii) for soil profile determination down to a given depth.
- Rate-controlled penetration rates were used for identification of permafrost stratigraphy.

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