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Research article

Field investigations at the NGTS permafrost site: Methodologies, experiences, and results

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Abstract: This paper presents the results of field investigations conducted during the establishment of the permafrost site of the Norwegian GeoTest Sites (NGTS) project. The soil investigation methods used include total sounding, drilling, and sampling with a conventional auger and core and piston sampling. The installation methods for measuring ground temperatures with thermistor strings are also presented. Field investigations and instrumentation have allowed the characterization of continuous soil profiles under rather challenging geotechnical conditions at the site, with layers that include cryopegs. The quality of the retrieved core samples is sufficient for proper characterization of the presence of ground ice and determination of the soil composition and provide specimens that can be used for uniaxial compression tests. The chosen methodologies and results of this field investigation may be of interest to other investigators who are planning work under challenging conditions at sites with saline soils and/or permafrost settings, where the soil is a few degrees below the freezing point and unfrozen soils are present in the strata. In addition, to complete the geocryological characterization of the site, measurements of permafrost temperatures at the site from 2018 to 2024 are presented.

Keywords: permafrost; permafrost investigation; coring; drilling; total sounding; cryopeg

1. Introduction

The Norwegian GeoTest Sites (NGTS) infrastructure project, funded by The Research Council of Norway, was established to develop a set of national research test sites to facilitate geotechnical research. The project developed five sites to serve as field laboratories for testing and verifying innovative soil sampling and soil testing methods, including solutions for foundations. The five sites cover various soil conditions, such as soft clay, quick clay, silt, sand, and permafrost [1]. The permafrost site is near the town Longyearbyen in the Svalbard Archipelago, i.e., in the Arctic. The site consists of two subsites: (1) *Adventdalen* and (2) *UNIS East*, which are located as shown in Figure 1 (B). A description of the sites, the soil conditions (indexes and thermal properties), the results of laboratory investigations, and general information about the field investigations performed are presented in [2]. The ground conditions are saline permafrost with ground temperatures at a 10 m depth of −4.0 °C at *Adventdalen* and from −3.6 °C to −3.7 °C at *UNIS East* [2]. Unfrozen pockets of saline soils (known as cryopegs) were encountered at *Adventdalen.* A cryopeg is a layer of unfrozen ground in permafrost soil, usually of marine origin, where freezing is prevented by a freezing-point depression caused by dissolved salts in the pore water [3].

The field campaigns were performed in the spring of 2017 and 2018 [4,5]. The main objectives were 1) to obtain samples for describing the soil conditions at the sites and 2) to deploy plastic casings for the installation of thermistor strings. These objectives correspond to the following research questions: How can credible and reliable soil data be obtained under challenging soil/ground conditions, and what are the practical methods that can work?

This paper presents information about the chosen investigation methods and reports and describes experiences from practical work; it also presents some soil sample results, ground temperature data, and temperature development until 2024. Some of the findings and experiences may be valuable for planning investigations in other permafrost regions. The paper is based on internal notes from field campaigns and two field reports [4,5]. Complementary investigations have been carried out at the *UNIS East* site using cone penetration testing (CPT) equipment and electrical resistivity tomography (ERT) scanning [2]. These investigations have provided complementary information on site conditions, especially CPT tests, which have provided valuable findings regarding the presence of unfrozen and plastic frozen clays.

2. Methods

2.1. Sampling and drilling

2.1.1. Practical considerations

Methods for permafrost sampling and drilling were selected on the basis of the expected soil conditions and experience from earlier sampling activities under similar conditions in Svalbard [6]. The soil conditions in *Adventdalen* were presumed to be sand and silt at a mean annual ground temperature (MAGT) at a 10 m depth of approximately −5 °C [7]. The hypothesis that cryopegs could be encountered in *Adventdalen* was based on observations from a previous project at the

University Centre in Svalbard (UNIS) [8]. It was expected that drilling could be performed under dry conditions, i.e., with no free ground water in the boreholes. The use of a large-diameter steel borehole casing was considered a backup solution for enabling drilling through and stabilizing cryopeg zones. The ground conditions at *UNIS East* were presumed to be clay. The soil temperatures were expected to be approximately −4 °C, which was slightly warmer than that at *Adventdalen*. The possible presence of cryopegs at *UNIS East* was presumed on the basis of ground investigations performed prior to construction of the UNIS building (1990s, Figure 1D) and experience from other ground investigations in the area.

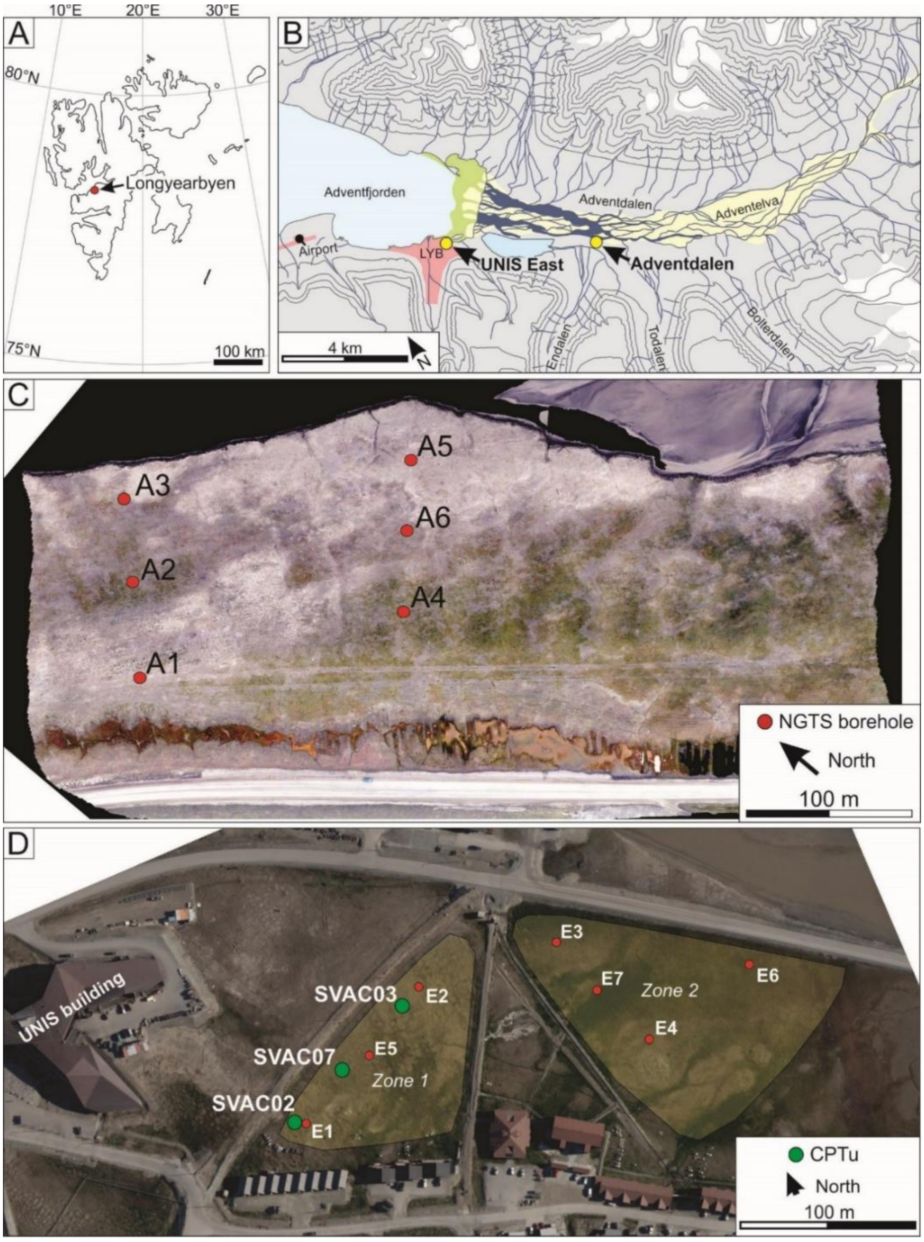

Figure 1. A) Location of Longyearbyen in Svalbard. B) Locations of the *Adventdalen* and *UNIS East* sites in relation to Longyearbyen. C) Details of the *Adventdalen* site. D) Details of the *UNIS East* site. Map data from the Norwegian Polar Institute. Figure: Gilbert et al. (2019) [2].

Experience in sampling unconsolidated permafrost in Svalbard with different techniques is reported in the literature [6,9,10]. As the soil and permafrost conditions were uncertain and challenges were expected, various types of equipment for sampling/drilling were prepared: 1) rods and drill bits for total sounding, 2) 75 mm and 120 mm augers with auger bars, 3) Stiftelsen for industriell og teknisk forskning (Norwegian), “The Foundation for Industrial and Technical Research” SINTEF-modified Cold Regions Research and Engineering Laboratory CRREL coring augers and sample pusher for retrieving samples from the corer, 4) conventional 54-mm piston sampler, and 5) steel casings with an outer diameter (OD) of 159 mm. To ensure that the fieldwork could be performed as planned, a double set of most types of critical equipment was brought to Longyearbyen. Soil sampling and total sounding were performed using the purpose-built Geotech 504 drilling rig of SINTEF. This rig is equipped for different types of drilling and sounding, including CPTs, permafrost coring, and conventional piston sampling. Figure 2 shows the rig in operation in *Adventdalen*. Field campaigns for sampling and drilling were conducted during late winter/spring, as snow cover and frozen surfaces eliminated the negative impacts of the investigations on sensitive tundra vegetation. Additionally, ambient negative air temperatures eased the handling of the retrieved core samples, and the daylight conditions were good.

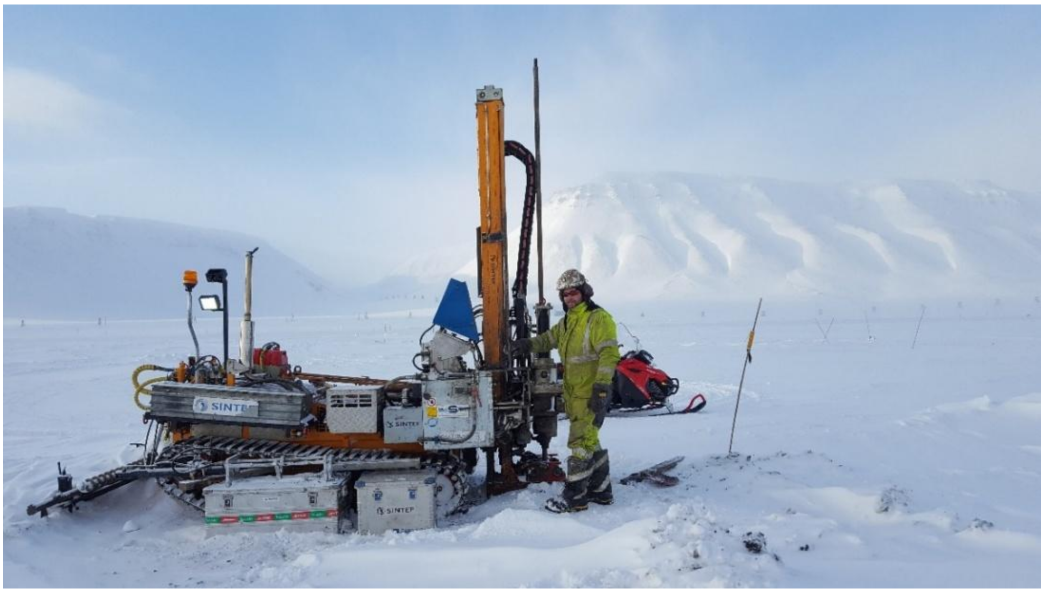

Figure 2. Geotech 504 drilling rig of SINTEF during operation in *Adventdalen*.

2.1.2. Spatial planning of sampling

Bulk soil and core samples were obtained from each site from the depth interval between the ground surface and a depth of 30 m. Each borehole location was sampled as follows: 1) Augering was performed between the ground surface to a depth of approximately 1 m, with soil being collected from the auger flight; 2) continuous coring was performed between depths of 1 m and 10 m; and 3) bulk soil samples were collected continuously between depths of 10 m and 30 m, with one meter of core interval at each of the following depths: 15 m, 20 m, 25 m, and 30 m. Several sampling locations were selected to document the spatial heterogeneity of the soil and permafrost conditions. The spacing and placement of the sampling locations included consideration of fluctuations in the geotechnical properties of the soils (20–50 m spacing was used), and the sampling locations should have been outside bodies of wedge ice identified from aerial images [11]. The sampling locations were organized along two transects across the sites. All boreholes were equipped with casings for the installation of thermistor strings. The advantages of using borehole casings for thermistor strings are discussed in 2.1.7. Overall, the plan was to sample to a depth of 30 m at a minimum of one location at each subsite and install several thermistor strings at both sites.

2.1.3. Preliminary investigations using modified total sounding

The standard methods for total sounding ([12]) and modified total sounding for permafrost ([13]) are both aimed at detecting soil layering. Standard total sounding is performed by rotating a drill bit into the ground at constant rotation and speed of penetration while the soil resistance is recorded. An increased rotation speed, flushing, and a drill hammer are used to penetrate hard layers or rocks ([12]). The modified total sounding for permafrost is performed at a constant sounding force while the drilling time per meter is logged (sec/m, [13]). Husdal [13] pointed the potential for determining layering with this method but noted that the method is not suitable for consultancy purposes. We therefore aimed to use modified total sounding by hypothesizing that layering could be qualitatively evaluated on the basis of observed changes/anomalies in drilling time and parameters such as the required hammering, which could provide some indication of frozen and unfrozen layers. It is generally difficult to define layering in permafrost soil on the basis of readings, as both the drilling time and penetration force may vary significantly under seemingly homogeneous soil conditions. In addition, the characteristics of the curve of the penetration force are usually similar to those of a spiky curve despite variations in the soil type (sand, silt, or clay), which is not the case for unfrozen soils. Hence, the collection of soil material during modified total sounding should be performed to support the classification of layering, which is performed by visual inspection of core samples and index tests in the laboratory. When soil material is collected during modified total sounding, it is assumed that the sample debris collected at the top of the borehole originates from depths close to the drill bit as the compressed air continuously blows the material up to the surface.

From a technical point of view, the following considerations are important when performing modified total sounding in permafrost: The penetration force is defined and manually set by the operator to an upper limit. Depending on the resistance in the soil, the force fluctuates near the preset value. When the resistance in the frozen soil becomes too high, increased rotation, hammering, and flushing are required to maintain sufficient progress, which makes interpretation of the soil properties difficult. The drilling time here is an indicator of weak and strong layers.

Usually, modified total sounding can be performed in permafrost to a depth of approximately 25 m with the chosen equipment. Testing to greater depths is restricted by the capacity of the air compressor to effectively transport soil out of the borehole and by the stability of the borehole in the case of saline permafrost. Drilling with modified total sounding may be an effective method for making boreholes for thermistor strings with or without casings in the boreholes.

In the project, site investigations with modified total sounding were initiated prior to further coring, as it was expected that it could provide valuable preliminary information on the soil profile.

The overall aim was to obtain information about soil layering on the basis of field work and the collected material to identify unfrozen zones and possibly detect rock surfaces.

2.1.4. Drilling and sampling with conventional augers

A conventional auger with a diameter of 75 mm and length of 1.5 m was used together with extension rods. To begin, it was used for sampling. In this case, the soil was collected from auger flights. With the equipment used, sampling can be performed down to depths of approximately 30 m. Deeper sampling is limited by the accumulation of soil above the auger and the clogging of the borehole. Similar to that of total sounding, the stability of a borehole in the presence of saline permafrost is a limiting factor. When the SINTEF-modified CRREL coring auger is used, the conventional auger is normally used for drilling/sampling through the active layer ([3]) of the permafrost to avoid damaging the cutting bits in the drill crown of the corer from gravel often present in this layer. The 75 mm-diameter auger is also used to drill and sample between the coring depths and clean the borehole from the soil cuttings before coring from a given depth and/or clean the borehole before the deployment of the casing for a thermistor string. If desired, a 120 mm-diameter auger can be used to deploy a stabilizing casing in the active layer to prevent loose material from falling into the borehole and water from entering.

2.1.5. Core sampling

Core samples of good quality were important in the project. A comprehensive evaluation of available techniques was therefore performed. The recommendations of several state-of-the-art reviews ([14–16]) formed the basis for the selection of the permafrost corer. Details on sampling and drilling in fine-grained soils were found in [14,15,17], and those in coarse-grained soils were reported in [14,15,18,19]. Historically, sampling (of cores and loose material) in fine-grained soils has been conducted by applying several methods, including drive sampling using a modified Shelby tube [15]; coring with various core barrels with or without fluids; coring with a hollow stem auger (acting as a casing in unstable conditions); coring with a standard core barrel [20]; and collecting samples from auger flights. Coarse-grained material can be sampled by coring, using the rotary method, and grabbing cuttings from auger flights or retrieving/cutting block samples. Artificial freezing can be used to strengthen the soil for sampling purposes, but this method was not an option in the project.

Several types of core barrels were considered: 1) double-tube, swivel-head core barrels of the “M” type with bottom discharge bits (or face-discharge core bits), which are recommended for core drilling in frozen soils with temperatures normally encountered in the field [14]; 2) single-tube core barrels; 3) triplex systems [21]; 4) CRREL coring augers; 5) SINTEF- modified CRREL coring augers; and 6) wire-line core barrels. The following core barrels were considered most suitable because of the available drilling rigs: 1) a single-tube core barrel as a reliable and relatively inexpensive method for shallow and deep sampling in fine-grained soils ([9,10,22]); 2) a double-tube core barrel, where several options are found in the literature and available on the market ([10,14,21]); and 3) a SINTEF-modified CRREL coring auger. The latter was chosen, mainly because of earlier experience and success in using this corer to sample fine-grained sediments in *Adventdalen* ([6]).

The following technical details of the core barrels and other relevant equipment were also considered: 1) Dimensions of the core barrel (diameter, length) versus the type of soil material (fine- or coarse-grained); 2) system used for core retrieval (e.g., core catcher); 3) coring bits used for various core barrels depending on the type of soil material and ground temperature ([10,21,22]); 4) configuration and dimensions of the casing through the active layer; 5) particularities and challenges in drilling through the unfrozen layers/cryopegs; 6) technical specifications of drilling rigs; and 7) capacities and availability of compressors (air volume and temperature).

The SINTEF-modified CRREL coring auger used for permafrost is shown in Figure 3. The corer consists of a thick-walled hollow core collecting auger with specially designed cutting bits in the front. The outer diameter is 76 mm, and it is approximately 80 mm at the cutting bits. The inner diameter of the corer cylinder is 45 mm, and the length enables 0.4 m-long soil samples. Hardened polycrystalline diamond (PCD) bit inserts ensure penetration in most materials. The bits are very durable and can be used to sample, even in weak/weathered rock. The corer has proven to be effective in collecting cores in fine-grained frozen soils. The core barrel is used with compressed air as a drilling fluid, which is an advantage when operating in cold climates where environmentally toxic additives would otherwise be required to prevent the drilling fluid from freezing. Typically, sampling is performed without thawing the soil samples. A custom-built rod system is used to push the cores out from the core barrel.

The retrieved core samples were visually inspected and photographed to assess the degree of sample disturbance and quality (deformation, cracking, etc.). Pictures of core samples are available at [4,5] and [23].

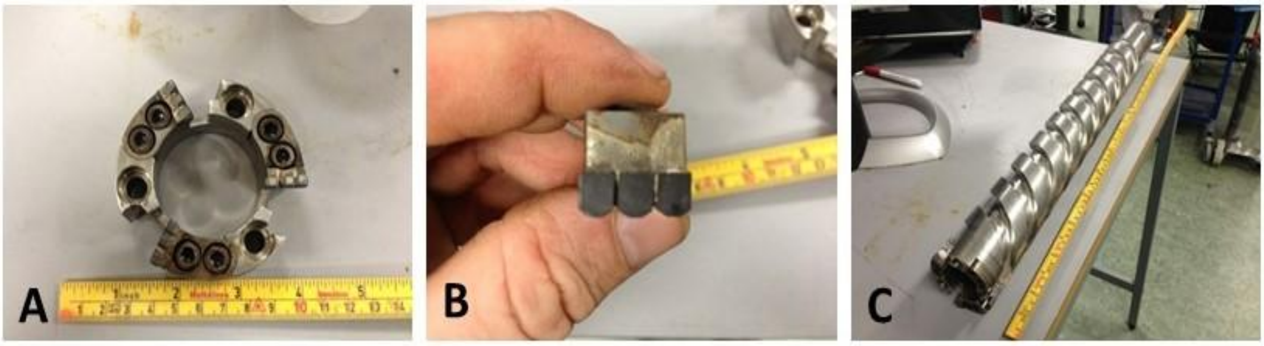

Figure 3. SINTEF-modified CRREL coring auger used for permafrost: (A) drill crown; (B) PCD inserts; (C) assembled corer.

2.1.6. Piston sampling

A conventional piston sampler was used to obtain undisturbed samples of unfrozen fine-grained soils in the cryopeg zone. A Geonor thin-walled stationary 54 mm piston sampler with cylinders of steel was used. The typical length of the samples was 0.8 m.

2.1.7. Monitoring of permafrost temperatures

The technology used for monitoring ground temperatures is described in [24,25]. The most common method is to use thermistor strings installed in boreholes at the desired depths. Thermistor strings are flexible wires with sensors placed at different depths connected to a data logger. The thermistor strings are either lowered inside a casing pipe [24,26] in the borehole or placed directly in the borehole. Thereafter, the borehole may be filled with a sand slurry [27]. There are concerns regarding thermal disturbances from the use of metal casings in such boreholes. Nevertheless, metal casings have been widely used. In earlier installations (15 years ago or earlier), diesel was used as a fill liquid. Unfilled casings (air gaps around strings) are normally equipped with top and bottom lids, which prevent water from entering and reduce air convection inside the casing. Thermistors installed directly in filled boreholes without casings have direct contact with the surrounding soil. As argued by Ladanyi et al. [27], the latter may provide the most accurate ground temperature data. However, there is a risk of abrasion of the string during installation in the borehole and a risk of rupture by frost heave of the string during the operation. In addition, the thermistor string cannot be extracted.

For designs with thermistor strings inside unfilled casings, air convection and temperature disruptions are normally assumed to be prevented by using small-diameter casings (25 to 50 mm) and inserting diaphragms between the sensors in the upper region of the casing [28]. Such designs normally allow the thermistors to be retrieved, recalibrated, and reused.

2.1.8. Installation of thermistor stings at the sites

In the project, the thermistor stings were installed in plastic casings, some in boreholes drilled with conventional augers and some inside steel casings in larger boreholes (see Sect. 2.1.9). The chosen thermistor strings have temperature sensors with a digital chip with a 0.01 °C resolution and a +/− 0.1 °C base accuracy. The strings were designed with sensors distributed over a total length of 30 m, with spacings of 0.25 m in the upper part and 1 m toward the bottom of the borehole. The thermistor strings were connected to Global System for Mobile Communications GSM modems for continuous data transfer, but data were downloaded manually only once per year because of the power consumption of the modems. The factory calibration of the temperature sensors was used, as it was expected to provide satisfactory accuracy.

For the thermistor strings installed in plastic casings and then in steel casings, the space between them was filled with dry sand. It was assumed that the steel casing would not influence the permafrost regime significantly, except perhaps for the uppermost part, due to exposure to air at the surface.

2.1.9. Use of steel and plastic casings

The walls of a borehole in permafrost may be unstable because of the presence of unfrozen soil layers, such as cryopegs or taliks (layers of unfrozen ground in permafrost areas), or simply because of lateral pressure at greater depths in the frozen soil. In such cases, a casing is usually deployed to a depth somewhat deeper than the unfrozen layers to permit further sampling. Installation of large-diameter casings is normally performed by large industrial drilling rigs. In our field campaigns, steel casings with a diameter of 159 mm were used. Installation was performed by applying a heavy industrial drilling rig with an Odex casing system and a down-the-hole hammer (DTH hammer). This permitted the collection of bag samples at desired depths during drilling. Such drilling rigs are commonly used for drilling boreholes for pile foundations of residential housing and other needs.

In general, boreholes should be equipped with casings for thermal measurements in permafrost zones for the following reasons: 1) Casing protects the wire of the thermistor string from rupture if frost heave occurs at the site (this was not known for *Adventdalen* at the time of the casing/thermistor string's installation); 2) casing protects the borehole from collapsing if cryopegs are encountered; and 3) casing provides an opportunity to replace the thermistor string if some sensors malfunction during exploitation or for recalibration. The plastic casing used in the project was of the Polyethylene high-density PEHD-type and 50 mm in diameter with threaded joints, and the sections were 1 and 2 m long. Sealing tape was used in the threaded coupling between the casing sections to prevent water from entering the casing, as recommended by the producer. The plastic casing was deployed in the boreholes after total sounding (cleaned with auger), coring, or augering. In steel-cased boreholes, it was backfilled with dry sand.

3. Results and discussion

Fieldwork was performed at site *Adventdalen* in the spring of 2017 and 2018. Two transects were established at the site (Figure 1C and Table 1): three sampling locations (A1–A3) along the first profile and three sampling locations (A4–A6) along the second profile. The distance between the sampling locations was approximately 100 m, and the distance between the profiles was 200 m. The work at *UNIS East* was performed in the spring of 2018. The sampling locations were organized in one profile with three boreholes (E5–E7). Four additional boreholes, E1–E4, were established to install the thermistor strings (Figure 1D). The distance between the sampling locations was between 100 m and 200 m. Details on the borehole locations, depths, casings, and sampling methods are summarized in Table 1.

3.1. Sampling and drilling

3.1.1. Preliminary investigations with modified total sounding

At *Adventdalen*, total sounding was performed at boreholes A1–A3 to a depth of approximately 25 m. Debris from total sounding was collected for each meter and stored in plastic bags. Total sounding was performed with one 25 m-deep borehole per day. The total sounding results are presented in Figure 4. Several changes/anomalies in the drilling time and other parameters, such as decreased force and short drilling time, are summarized in Table 2 in columns B–E and marked in Figure 4. The observation of changes/anomalies was performed by the operator, not on the basis of a numerical criterion. The intention was to capture a general picture of the conditions.

Table 1. Borehole locations.

Location	Site Id.	Longitude	Latitude	Elevation, m (NN2000)	Coring depth, m	Plastic casing depth, m	Steel casing depth, m	Sampling methods	Monitored (thermistor string (TS)) depth, m
Adventdalen	A1	78.2009°N	15.8333°E	4	10.0	–	–	Auger, total sounding	no TS
	A2	78.2012°N	15.8350°E	4	27.0	22.7	–	Auger, core sampler, total sounding	no TS
	A3	78.2016°N	15.8364°E	4	30.0	23.0	–	Auger, core sampler, total sounding	No TS
	A4	78.2000°N	15.8389°E	4	29.0	19.5	29.0	Auger, core sampler	29
	A5	78.2005°N	15.8420°E	4	28.0	19.5	–	Auger, core sampler	no TS
	A6	78.2003°N	15.8397°E	4	29.5	29.0	29.0	DTH hammer, auger, core sampler	29.5
UNIS East	E1	78.2215°N	15.6580°E	7	30	30	30	DTH hammer	30
	E2	78.2220°N	15.6615°E	6	30	30	30	DTH hammer	TS frozen, no DATA
	E3	78.2218°N	15.6655°E	2	30	30	30	DTH hammer	TS frozen, no DATA
	E4	78.2213°N	15.6661°E	3	30	30	30	DTH hammer	TS frozen, no DATA
	E5	78.2218°N	15.6601°E	6	26.1	26.1	–	Auger, core sampler	28
	E6	78.2215°N	15.6659°E	2	11.1	10	–	Auger, core sampler	no TS
	E7	78.2214°N	15.6695°E	2	11.7	14	–	Auger, core sampler	no TS

Table 2. Identification of cryopegs at *Adventdalen*.

	Readings of total sounding						
	A	B	C	D	E	F	G
Site Id	Visual observation of saline liquid during total sounding	"Decreased penetration force"	"Short" drilling time	No flushing	No hammer	Sampling with a 54 mm sampler	Coring
A1	-	7.0–9.0 12.0–13.2	7.9–8.8 12.0–13.6 18.6–20.7	12.0–13.2	8.5–9.5 11.0–13.3 14.8–15.1	–	–
A2	12.0–16.0	12.0–16.0	12.0–17.0 18.5–22.2		5.6–6.2 12.0–16.0 18.0–18.6	–	–
A3	14.0*	14.2–17.2 19.0–21.0	14.2–17.2 19.0–22.0		14.2–17.2	14.5–16.8	0.8–14.1
A4	NA	–	–	–	–	Ca. 14.0–ca. 17.0	1.3–12.9 (4.1–4.9–unfrozen samples) 20.2–22.6 24.2–28.0
A5	NA	–	–	–	–	15.2–16.5	1.5–10.3 (9.1–9.5–unfrozen sample) 12.2–13.0
A6	NA	–	–	–	–	–	–

* – water in the borehole was observed the next day after coring to 14.1 m.

Cryopegs were discovered during total sounding and subsequent coring and piston sampling in all boreholes at depths ranging from 12 m to 16 m (Table 2). The cryopegs were encountered by saline water and transported to the surface by compressed air (Table 2, Column A). In some cases, the presence of cryopegs coincided with weaker soil zones. These weaker soil zones were identified on the basis of the co-occurrence of the following: 1) shorter drilling time (approximately 20%); 2) lower penetration force; and 3) no use of a hammer (Figure 4). This can be seen for some layers at boreholes A2 and A3 (identified with blue circles in Figure 4). For other cases, the weaker zones did not contain liquids, as in boreholes A1 and A3 (identified with violet circles in Figure 4). Additionally, in some cases, the reasons behind the lack of hammer use, such as at depths of approximately 6 m and 18 m at A2, are not clear—this could be attributed to the intention of the operator (we inclined to assume this reason) or possibly to technical issues in drilling. In any case, short drilling time was achieved *without* hammering at depths of approximately 6 m and 18 m at A2, which points out the presence of a weaker zone/cryopeg.

Visual observations of saltwater, which is lifted by compressed air, are helpful for defining the upper boundary of a cryopeg layer. Defining the lower boundary of cryopegs by such observations seems to be problematic, as water from a cryopeg layer may continue to drain into the borehole and consequently be lifted to the surface after the total sounding drill bit has advanced below the lower boundary.

On the basis of the obtained results, one may suggest the identification of cryopegs and their boundaries on the basis of total sounding readings. The identification should be based on anomalies in the readings, where a cryopeg layer is significantly weaker than the frozen soil. This results in faster drilling; less need for hammering, flushing, and high rotation; and leads to decreases in the preset and intended constant penetration forces. Observations of several anomalies at the same depth in adjacent boreholes strengthen the conclusion of the presence of a cryopeg layer. However, in saline soils at ground temperatures close to the freezing point, the cementing effect of pore ice on the mechanical strength of frozen soil may be low, and the soil strength may be much the same in the frozen and thawed state. Here, the detection of unfrozen layers using total sounding is difficult.

The potential presence of cryopegs was not excluded at the preparatory stage of the field investigation; however, it was not expected that they would be widespread in the field. Observations of cryopegs at locations A2–A3 in *Adventdalen* suggested that the extent of the cryopeg lenses in the plane was at least on the order of 100 m and that they could underline the entire test site and extend beyond its boundaries.

The total sounding graph of penetration force vs. depth, shown in Figure 4, is relatively smooth in the upper part (down to 3–4 m) of the soil profile for boreholes A1 and A2. The graph for borehole A3 shows more variation in the upper part. The reason for smooth graphs for A1 and A2 may be the presence of an ice-rich zone at locations A4–A6. This was verified by soil laboratory investigations [2]. Also, the graphs at A1–A3 are smoother in the lower part than the middle part, where clay and sand were correspondently reported from the laboratory analyses of samples from boreholes A4–A6 [2]. Therefore, total sounding may also be suggested for preliminary identification of zones with high ice content, and to some extent, predicting the distinction between frozen sand and clay.

Performing a pre-investigation with total sounding prior to the main fieldwork in the spring of 2017 would have been useful. This would have provided a basis for designing the sampling campaign while considering the cryopeg features at the sites and sampling from soil below the cryopeg layers. It could also have guided the selection of the sampling methods, given time to mobilize the necessary equipment, and help estimate the required effort and duration of the work. Furthermore, geophysical investigations or analysis of existing geophysical data for *Adventdalen* would have been useful prior to the geotechnical investigation, which could have helped provide information about the probability of cryopegs existing

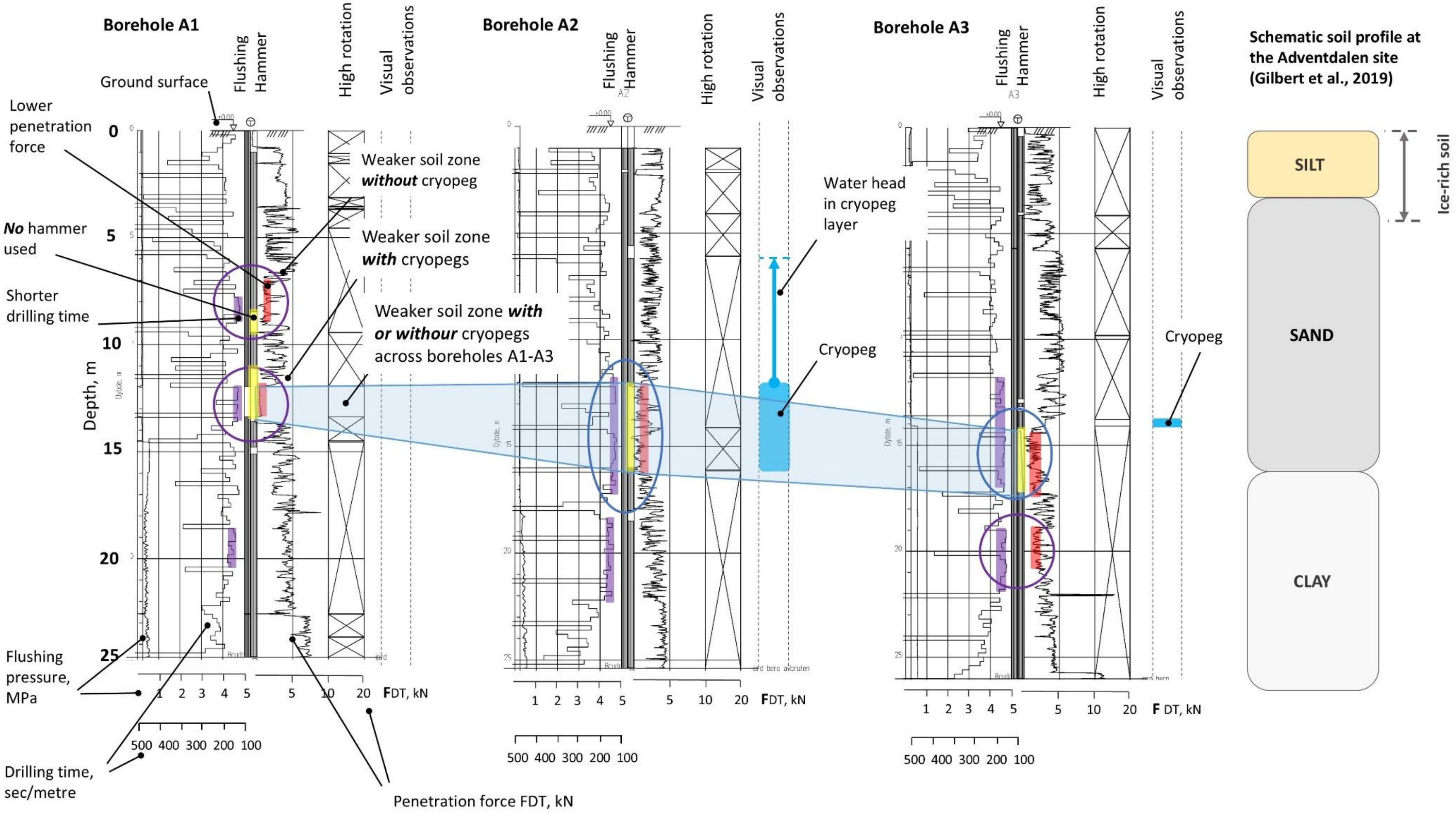

Figure 4. Results of modified total sounding at locations A1–A3 in *Adventdalen*; FDT—penetration force, violet fill—faster drilling, red fill—lower penetration force; yellow fill—no use of hammering; blue fill—outline of the weaker zone with the cryopeg (on the basis of visual observations and total sounding). The purple circles depict where readings from modified total sounding suggested cryopegs, and the blue circles depict where cryopegs were observed (see Table 2).

3.1.2. Drilling and sampling with conventional augers

At *Adventdalen*, sampling with an auger was performed at depths of 0–1 m, with continuous augering performed from the bottom of the cryopegs down to 28–30 m. Augering and collection of soil were performed between the coring intervals below the cryopegs when the steel casing was installed (spring of 2018). Augering below the cryopeg zone appeared to be challenging yet possible, even without an installed steel casing. A challenge was the saline water from the cryopeg zone, which filled part of the borehole below the cryopeg with the subsequent contraction (within approximately 30 minutes for depths of 20–30 m) of the borehole. Another use of the auger was to reach the sampling depth for piston sampling and cleaning boreholes before coring and the installation of a plastic casing for the thermistor strings. At *UNIS East*, sampling with an auger was performed at a depth of 0–2 m and, in a few cases, between sampling depths for coring and cleaning the borehole between coring operations and before the installation of the plastic casing.

3.1.3. Core sampling

At *Adventdalen*, in spring of 2017, core samples of frozen soil were obtained between depths of 1 m and 12–14 m, i.e., to the top of the cryopeg layer. Coring within the cryopeg zone was challenging because of 1) the unfrozen state of the soil, which led to the collapse of the borehole, and 2) challenges caused by the presence of water filling the corer. The construction of the corer permitted pushing out the water while obtaining the core, but the efficiency of the drainage was not clear. Importantly, most of the core samples obtained were frozen, with only a few exceptions (Table 2, Column G.)

In spring of 2018, to solve the issue of collapsing boreholes, a steel casing was deployed by a subcontractor to a depth of approximately 3 m below the unfrozen zone, i.e., at a depth of 20 m at location A2 (borehole A2–2). The casing was supposed to remain empty; however, it filled with saline water up to ca. 6 m below the ground surface. The reasons are unclear; one might suggest incomplete welding in the casing joints and hence some drainage of the water. The water level was used to estimate the water head in the cryopeg layer (see Figure 4). With the upper layer of the cryopeg at a depth of 12.0 m (see A2 in Table 2), the excess water head is 6 m.

Installation of the second casing at location A4–2 was successful, which permitted almost continuous sampling down to 28 m. No cryopegs were detected at depths of 20–30 m. Many of the core samples were of very good quality (see examples in Figure 5) and were well suited for soil characterization and uniaxial compression tests.

At *UNIS East*, an almost continuous coring profile was obtained at location E5 down to a depth of 26.1 m and to a depth of 11.1–11.7 m at E6 and E7. The reason for the shallower depths for the latter two boreholes was that the boreholes were shrinking after the drilling column was retrieved. This can occur in relatively weak soil, which may be due to the ground temperatures, salinities, and physical properties of the soil. The retrieved samples were of very good quality and suitable for laboratory tests. Weaker soil conditions at this site were identified at a later stage by CPT tests [2]. On the basis of these tests, unfrozen or plastic frozen clays were suggested for depths below 3 m, and cryopegs were suggested for depths between 5 and 15 m.

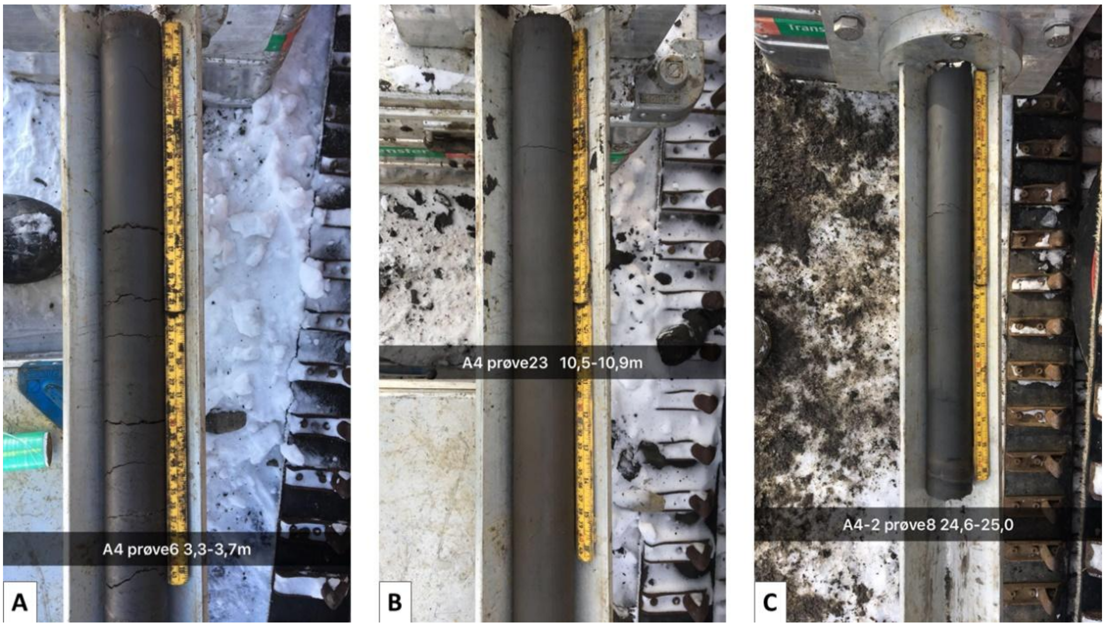

Figure 5. Core samples from borehole A4. Depths: (A) 3.3–3.7 m; (B) 10.5–10.9 m; (C) 24.6–25 m.

3.1.4. Piston sampling

Piston sampling was performed to sample soil from the cryopeg zones in *Adventdalen* (Table 2). The relevant depth (14–17 m) was determined from the total sounding and core sampling results. A borehole was first augered to the defined depth, and piston sampling was subsequently performed down to the interface to the frozen soil below, which was recognized by a higher pushing resistance. Some of the tubes with samples from the bottom of the unfrozen zone were slightly deformed. Saline fluid was retrieved from the unfrozen zones (interval 14–16.3 m, [4]) of boreholes A3–A5. The salinity of the fluid measured with a salinity refractometer was 7% NaCl. This finding shows that cryopegs are present in *Adventdalen* and that piston sampling may contribute to confirming such conditions.

3.1.5. Concluding remarks on identification techniques for cryopegs

Certain disagreement exists in defining the limits of the cryopeg zone on the basis of visual observations during total sounding, interpretation of total sounding, and the results of sampling (core and piston sampling). Observations for boreholes A1–A3 are as follows: Observations revealed an upper boundary of cryopegs at depths of 12–14 m, and the results of total sounding suggested weaker soil between 18 and 22 m for boreholes, whereas piston sampling suggested a cryopeg layer between approximately 12 and 17 m. Unfortunately, no coring or piston sampling was performed at borehole A2, where excessive water head was observed, and the water head was not monitored at A3–A5, where sampling with a corer and piston samplers was performed at high density. Planned monitoring of the water head at boreholes would provide a better characterization.

A few hundred meters to the northwest of the *Adventdalen* test site, a CO_2 test project was performed in 2010 [7], with presumably similar geomorphological settings. Continuous sampling was performed down to depths of some hundred meters with a triplex coring system. Interestingly, [8] described particularities in drilling, and blowouts were attributed to the presence of unfrozen, pressurized mud. Instead, this could have been caused by the cryopegs.

3.1.6. Sample storage

The retrieved samples were sealed and stored in a shaded container at an ambient air temperature below −5 °C during the sampling days in 2017 and below 0 °C during the field campaign in 2018. The samples were subsequently stored in a freezer at a constant temperature of −18 °C. The core samples were later used for determining standard index properties of the soil. The best solution would probably have been to store the samples in a controlled environment at their natural temperature, i.e., approximately −5 °C. Varying temperatures and freezing may have caused some redistribution of water across the diameter of the core samples. This should, however, not result in significant errors when determining index properties such as total water content w_{tot}, bulk density ρ, and submerged unit weight γ', as these samples were taken as short cylinders cut from 0.8 m-long cores.

3.1.7. Use of steel and plastic casings

At *Adventdalen*, steel casings were installed at locations A2–2, A4–2, and A6 to depths of 20 m, 20 m, and 30 m, respectively. Bag samples were collected for each meter during installation. The deployment technique ensured the exact depth for sample collection. The plastic casing, 50 mm in diameter, was installed at a later stage, and the space was filled with dry sand. Thermistor strings were subsequently installed in the plastic casings. A plastic casing was installed at locations A2–A5 to depths between 19.5 m and 23 m. These installation depths were approximately 10 m less than the actual depths of boreholes drilled with the auger because the lower parts of the boreholes collapsed or shrunk. There may be several reasons for such collapse. The soil in the cryopeg layers is weak because of the absence of stabilizing ice-cement between the soil particles. The borehole wall is also affected by interactions between the saline water from the cryopegs and the surrounding frozen soil, where thawing of ice-cement may occur in the borehole walls above and below the cryopeg layers because of decreased freezing-point depression by saline water.

A drilling rig was used to carefully push the plastic casing into the collapsed part of the boreholes. This probably damaged the casing at two locations (A3 and A5). The presence of saline water, likely from the cryopeg zone, was observed during the installation of the thermistor strings at these sites. This allowed for judgement of the water head in the cryopeg layer, which was estimated to be approximately 6 m for the cryopeg at A3 (at depths of 14 to 17 m). Issues encountered during installation of plastic casing may probably be solved by using casings of other types. For example, Polyvinyl chloride PVC pipe roll could be considered as an alternative solution. In this case, weaker points, i.e. joints between the sections, would be avoided. It could also be recommended to avoid push of the plastic casing by drilling rig into the collapsed part of the boreholes.

At *UNIS East*, large-diameter steel casings were installed at a depth of 30 m at four locations (E1–E4). Bag samples were collected, and plastic casings were installed as explained above. Plastic casings were also installed in three boreholes (E5–E7) directly after coring was completed. Sediments falling into the boreholes were removed with an auger. The deepest installation depth was at E5, at 27 m, whereas it was 12 m at E6 and 16 m at E7. Signs of the probable intrusion of saltwater were observed during thermistor string installation, indicating the presence of water on the string wire at E6 and E7.

3.1.8. General soil description based on visual observations during sampling

The active layer at *Adventdalen* has a thickness of approximately 1 m. This layer was frozen during the field campaigns. The sediments above the cryopeg layer seem to consist mainly of silts and sands, which can be observed from the samples taken with the permafrost corer. Some 54 mm piston samples were successfully taken from the cryopeg layer (see Table 2, Column F), which indicated that the material consisted of soft, fine-grained material in this layer. Visual inspection of the samples confirmed that silts and sands dominated below the cryopeg layer down to depths of 22–23 m. Below this depth, the sediments seemed to be more fine-grained. These observations agree with those of later laboratory tests [2], which revealed sandy, clayey silt for the top layer down to a depth of 3 m, silty sand at a depth of 13 m, and clay or silty clay at depths of 16–30 m. The laboratory tests revealed salinities of up to 72 ppt for the soil at depths of 11–18 m, which agrees with what could be expected in a cryopeg zone.

At *UNIS East*, coarse-grained silty material was observed down to depths of 2.4–2.7 m in the soil profiles. The material below this layer seemed to be fine-grained, but some coarse-grained layers with thicknesses of 8–10 cm were encountered at depths of approximately 8, 10, and 12 m. A thin ice layer was observed at a depth of approximately 3 m. The field observations also coincided with the results of later laboratory material tests [2], which revealed gravelly, silty sand in the top layer down to 3 m and silty clay below.

Table 3. Permafrost data at *UNIS East*, from 2018−2024.

Location	Period	MAT, °C	MAGST, °C	MGT, °C	ALT, cm
UNIS East, borehole E1	2018–2019	−2.5	−2.0	−3.4	97
	2019–2020	−4.7	−3.8	−3.3	100
	2020–2021	−1.3	−0.5	−3.4	103
	2021-2022	−3.8	n/a	−3.4	100
	2022–2023	−1.6	n/a	−3.4	n/a
	2023–2024	−3.0	−2.0	−3.4	117

3.1.9. Ground temperature at the site from 2018−2024

The ground temperatures at *UNIS East* are presented in a temperature heatmap plot in time-depth space in Figure 6 and by temperature profiles in temperature-depth space in Figure 7, the latter showing both average values (broken lines) and envelopes for maximum and minimum values (full lines). The permafrost data are summarized in Table 3. The variation in the mean annual ground-surface temperature (MAGST) from 2018–2024 was between −3.8 °C and −0.5 °C, whereas the mean air temperature (MAT) ranged from −4.7 °C to −1.3 °C. The active layer at the site (annual thawing and freezing thickness at the surface, (ALT)) remained at a thickness of 97 cm to 117 cm. The permafrost data for *Adventdalen* were collected during the same period, similar to earlier data (reported for the Old Aurora station, [29]). The mean ground temperature (MGT) remained practically constant during the six-year period, with a temperature of −3.4 °C.

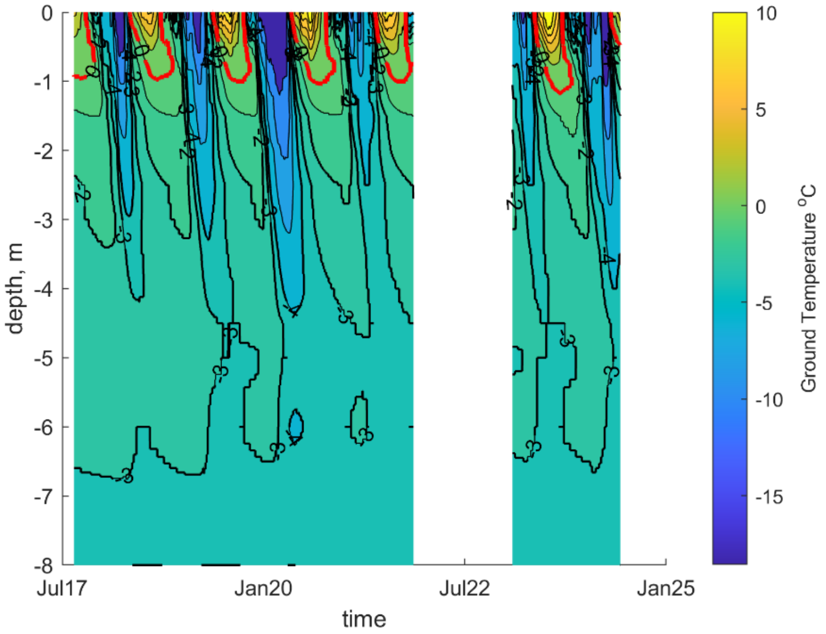

Figure 6. Ground temperatures at *UNIS East*, location E1, from 2018–2024. The white areas in the plot are due to missing data, and the red curve represents 0 °C.

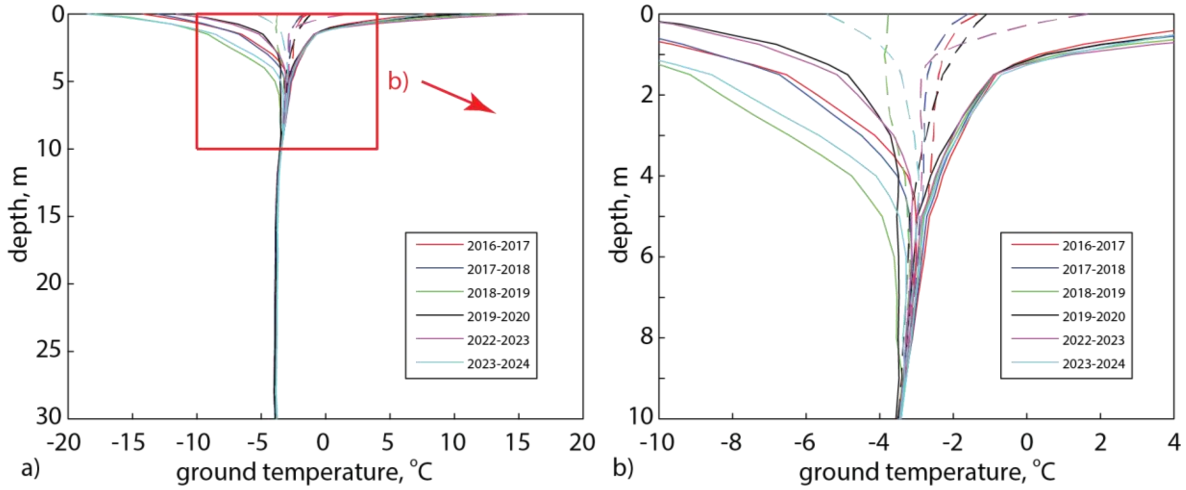

Figure 7. Trumpet curves for ground temperatures at *UNIS East*, location E1.

4. Conclusions

Overall, the applied set of methods provided successful sampling under challenging conditions of saline permafrost with temperatures close to the freezing point and with the presence of cryopegs. Sampling was performed to the desired depths through varying soil conditions. The quality of the core samples from all parts of the soil profile was sufficient for site characterization and mechanical testing of the frozen soils. Hence, the applied methods are recommended for geotechnical investigations under similar geological conditions in coastal permafrost areas and comparable site conditions in cold regions.

Modified total sounding may be recommended for preliminary investigations at the site. In particular, the results from total sounding can be useful for determining sampling techniques at a site. For example, total sounding may be applied to perform a quick check in permafrost if there is concern about unfrozen zones or cryopegs. A conventional auger can be used for the following operations: 1) drilling and sampling in the active layer, especially when it contains coarse inclusions that may damage the coring bits of more sophisticated corers; 2) drilling and sampling of permafrost at deeper depths, although the presence of cryopegs limits the applicability of this method, as boreholes in saline permafrost or those filled with saltwater tend to contract; and 3) assisting operations such as reaching sufficient sampling depth for piston sampling and coring and cleaning boreholes before coring and the installation of plastic casings for thermistor strings. Total sounding may also be suggested for preliminary identification of zones with high ice content and, to some extent, detecting a boundary between materials as frozen sand and clay.

The SINTEF-modified CRREL coring auger is useful for sampling frozen clay, silt, and sand when these materials have a high degree of saturation (80–100%). Sampling such soil types under unfrozen conditions is challenging. Piston sampling can be used to obtain samples from unfrozen layers within permafrost, for example, from cryopegs. A DTH hammer is suitable for installing steel casings and obtaining bag samples. A steel casing installed with a DTH hammer can be a practical solution when installing thermistor strings in saline permafrost, with or without cryopegs, and with ground temperatures close to the freezing point. In such cases, the string should be installed in a plastic casing, and the borehole should be filled with sand. Other solutions, such as drilling boreholes for thermistor string installation with conventional augers, can be challenging, as boreholes under these conditions tend to contract shortly after completion. The issues experienced with the installation of plastic casings to depths of 20–30 m in saline permafrost highlight the need for improvements in the applied methods.

The applied method with piston sampling from the cryopeg zone may also be applicable to soil material in talik zones in permafrost areas, which may be more common in the future because of the increasing impact of global warming.

The existence of cryopegs with an excess water head may limit the use of the *Adventdalen* test site for general testing of deep pile foundations, as the adfreeze strength may be affected by saline ground water.

The temperature measurements at *UNIS East* revealed variations in the MAGST, whereas the thickness of the active layer remained largely constant. These findings support earlier conclusions that ground warming is a relatively slow process due to the thermal properties of ice-rich permafrost. However, ongoing monitoring is essential for becoming aware of local conditions and revealing long-term trends.

Author contributions

Anatoly O Sinitsyn: Conceptualization, Data curation, Investigation, Methodology, Project administration, Visualization, Writing–original draft, Writing–review & editing; Stein O Christensen: Data curation, Methodology, Writing–original draft, Writing–review & editing; Graham L Gilbert:

Writing–review & editing; Trond E Larsen: Data curation, Investigation; Kjartan Følke: Data curation, Investigation; Arne Aalberg: Writing–original draft, Writing–review & editing; Aleksey Shestov: Data curation, Investigation, Writing–review & editing.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Data availability

Data such as drill logs and drill logs from modified total sounding can be provided upon request. Pictures of core samples are available at: https://zenodo.org/records/16792571 ([23]).

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Conflicts of interest

The authors declare that they have no conflicts of interest.

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