A thermal profile of coastal permafrost at Varandey, Russia

Profile thermique du permafrost côtier à Varandey, Russie.

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ABSTRACT:

Soil temperature variation is one of the governing factors to the stability of soil masses in regions affected by permafrost. Understanding of the thermal profile is critical for planning, designing, constructing and maintaining infrastructures which are much needed to sustain industry and/or community in these regions. Studies based on real data of permafrost soils are however rather limited due to the high cost and high risk associated with field investigation in these normally remote areas. This study will contribute to bridge this knowledge gap through an investigation into a typical thermal profile on Pesyakov Island in Varandey, Russia. First, the geological and geomorphological condition of the studied site are described. The paper then discusses the variation of soil temperature measurements at the selected location for study over a period of two years. Finally, a numerical model of the thermal profile calibrated with the measured data at the studied borehole is presented with discussion on important factors influencing the numerical predictions. The numerical models show capability to reproduce quite well the measured data.

RÉSUMÉ: La variation de la température du sol est un des facteurs gouvernants la stabilité des masses de sols dans les régions touchées par le permafrost. La compréhension du profile thermique est essentielle pour la planification, la conception, la construction et la maintenance des infrastructures qui sont très nécessaires au maintien de l'industrie et/ou de la communauté dans ces régions. Les études basées sur des données réelles de sols à permafrost sont cependant plutôt limitées à cause du coût et des risques élevés associés aux investigations sur site dans ces régions normalement éloignées. Cette étude va contribuer à remédier à cette lacune de savoir à travers une investigation dans un profile thermique typique sur l'ile Pesyakov dans le Varandy en Russie. En premier, sont décrites les conditions géologique et géomorphologique de la région étudiée. Ensuite, l'article discute la variation des mesures de température en des endroits choisis pour l'étude sur une période de deux années. Finalement, nous présentons un model numérique du profile thermique calibré par des données mesurées du forage avec une discussion des facteurs importants influençant les prédictions numériques. Les modèles numériques montrent des aptitudes à bien reproduire les données mesurées.

KEYWORDS: permafrost, erosion, coastal, thermal, ground temperature

1 INTRODUCTION

Distribution and variation of ground temperature is one of the key factor influencing soil strength, and hence stability of slopes in arctic coastal regions. The soil masses from these slopes, if become destablized and slide down, can be carried away by waves and ocean currents leading to erosion problems. In such regions, understanding the thermal profile is critically important for constructing and maintaining infrastructure for communities and/or industry.

The Varandey region is located in the north-western part of European Russia adjacent to the south-eastern part of the Barents Sea. This section of the arctic Russian coast has been subjected to noticeable erosion problem over the last decades. The retreat of the coastline becomes a major threat for the existing infrastructure and a challenge to construction of new infrastructure which are needed mostly for oil and gas exploration in Varandey. Understanding the thermal regime of the soils in this region is therefore of strong interest both for academics and engineers.

This study presents some results from two expeditions carried out in Varandey by a team of researchers from the University Centre in Svalbard (UNIS) and the Federal State Budgetary Institution —N.N.Zubov's State Oceanographic Institute (SOI) in Russia. The purpose of the expeditions is to take samples and investigate the permafrost properties and geomorphology condition at the site. The expeditions were carried out around the middle of the summer of two consecutive years (3rd – 20th July 2012 and 9th – 16th Aug 2013). These periods were selected to have optimal weather for the field activities. Two main field activities performed during the expeditions were borehole drilling and installation/monitoring of thermistor strings. The geocryological structure of the permafrost is studied through borehole samples while the thermodynamic state of the soils is observed through thermistor measurements over the studied period.

This paper presents a representative thermal profile of the coastal ground at Varandey. The thermal profile is analysed through field measurements of soil temperature at one borehole and numerical modelling with a finite element code. First, the variation of soil temperature over a two-year period (Aug 2012 – Aug 2014) is presented and discussed. Then, the numerical model ultilizing the commercial code, TEMP/W, is described and used to simulate the measurements of soil temperature for the two years. The numerical results are compared with the actual soil temperature measurements. The study highlights the importance of certain parameters in calibrating numerical model for permafrost soils.

2. SITE DESCRIPTION

2.1. *Geological and geomorphological condition*

The studied location is situated on Pesyakov island in Varandey. Pesyakov is a coastal barrier island with a coastline of around 33 km long, elongated by a spit of 350 m attached to the western end. The island is formed as the result of cross-flow of fine sand sediments from submarine coastal slopes during the period of climatic optimum (i.e. warm period) at the final stage of Holocene transgression (Ogorodov et al. 2014). The topsoil layers are therefore characterised by relatively homogeneous medium to fine sands. Mixed organic grass remains and peaty materials can often be found in soil samples from locations at some distance from the beach (> 100 m).

Figure 1 shows a typical cross-section perpendicular to the coast of Pesyakov island. From the sea to the lagoon, the cross-section can be subdivided into four parts: beach, dune belt, barrier and laida (i.e. low swamped areas formed under the influence of high storm surges). Each part has relatively distinct geological and geomorphological characteristics.

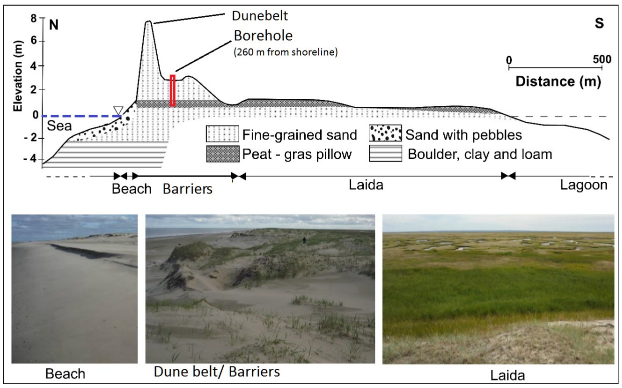

Figure 1. Schematic representation of a typical cross-section showing different morphological parts on Pesyakov island (top figure), and pictures of the ground surface and topsoil at the beach, dune belt/barrier and laida (bottom sub-figures).

2.2 Geocryological and geotechnical characteristics

The elevation of the frozen soil table and the thickness of the active layer are inferred from the borehole profile and some measurements with a steel probe. The average elevation of permafrost table on the barrier terrace is about 1-2 m higher than sea level, with the average thickness of the active layer of approximately 2.2 m. At some locations on the barrier, lenses of frozen soil are found at the depths 1.5 and 2.2 m with thickness varying between 0.3 and 0.6 m. These lenses are attached to the permafrost table in some locations, but there are often layers of unfrozen highly saturated soil interbedded between these frozen lenses and the permafrost table. These lenses are likely to be the remnants of the active layer which were frozen during the previous winter and have not become fully thawed over time. The existence of these frozen lenses interbedded into unfrozen soil layers caused significant difficulties during drilling.

Another special geocryological feature in the middle of the barrier is the presence of cryopegs at the various depths below the permafrost table (Romanovskii et al. 1996) (i.e. between 0 and 7 m below the sea level). Cryopegs are discrete lenses of unfrozen soil saturated with saline pore water. The high salinity of the pore water decreases the frozen temperature of the soil to less than zero degree. This "decreased" freezing temperature leads to situation where the cryopegs stay unfrozen even though the soil temperature drops to zero or negative values, as long as it is still larger than the "decreased" freezing temperature. The existence of cryopegs indicates that the sediments are saline along the Varandey coastline. In addition, the pore water is pressurized in the cryopeg lenses causing the water column to rise up in the borehole when the drilling auger penetrated into the cryopeg lense. The unfrozen state also leads to failure to retrieve the drill columns from the cryopegs lenses. This observation is consistent with the information presented in Ivanova et al. (2008).

Particle size analyses were performed on samples from various depths retrieved from the borehole. For the depth range considered in this study, the particle size distribution analysis shows that the soils at this location are poorly graded (i.e. very little variation in grain size distribution with depth) (Fig. 2). The GSD curves from samples from 4 depths almost coincide (Fig. 2), hence the soils can be considered homogeneous for practical purposes. The samples are dominated by particle sizes from 0.125 to 0.5 mm (96 – 99 % fraction of mass). Within this range, around 30 – 35 % is the "upper" fine fraction of 0.25 to 0.5 mm and the remaining 60 – 65 % is of the "lower" fine sand of 0.125 to 0.25 mm. The coarse fraction (> 2 mm) and the very fine fraction (<0.05 mm) are almost negligible for almost all the samples.

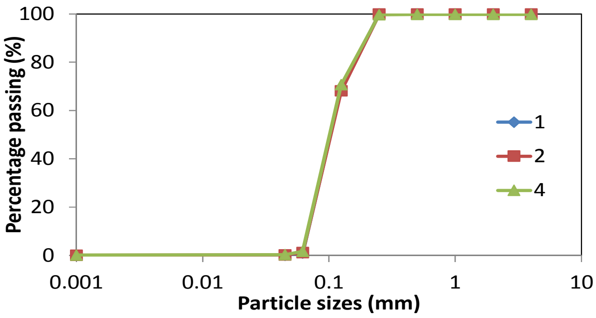

Figure 2: Grain size distribution from borehole samples at 1, 2 and 4 m depth

The gravimetric water content was determined experimentally by weighting the samples immediately after drilling and after drying in the laboratory. The four samples taken at the borehole show water content values ranging between 20 and 38%.

2 SOIL TEMPERATURE VARIATION

The borehole studied in this paper is located approximately 260m from the shoreline, on the barrier between the dune belt and the laida. The borehole is 5.5 m depth, installed with thermistor string up to about 4 m depth. Below 4m, the borehole was flooded with water, hence it was not possible to deploy the thermistor string deeper. The thermistor string (GEOPRECISION GmbH 2016) consists of 20 sensors installed in 50mm diameter plastic pipes filled with sand. The pipes were closed caps at both ends to protect the thermistor strings. Temperature measurements were recorded every 6 hours. Figure 3 shows the variation of soil temperature at different depths recorded by the thermistors. The variation of air temperature over the same two-year period is presented in the same figure to highlight the correlation between air and soil temperatures.

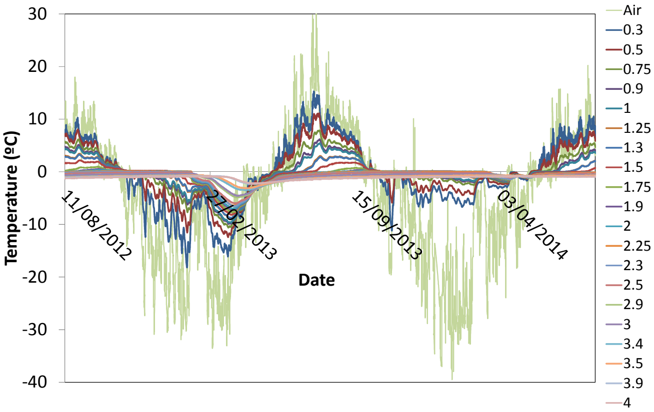

Figure 3: Variation of soil temperature from Aug – 2012 to Aug – 2014. Legends correspond to different thermistor depths.

The soil temperature at this location varies in the same pattern with the variation of the air temperature, but is reduced in magnitude and responses at a delay of 3-8 days (Fig. 3). For example, the air temperature dropped to one of the negative peaks (approximately -32℃) on the 18th Jan 2013. In response to this drop, the soil temperature decreased to -18 ℃ eight days later (on the 26th Jan 2013). Interestingly, even though the coldest air temperature was lower for winter 2013 – 2014 than for winter 2012- 2013, the soil temperatures at the same depth were several degrees higher for winter 2013 – 2014 than for winter 2012 – 2013 (Fig. 3). This could be explained by the thicker snowfall in the latter than in the former year (observed from a meteorological record for the studied period at Varandey) which provided more efficient insulation to the soils. This observation suggests that the proportion of heat emitted from or absorbed in the soils to (or from) the air varies from season to season and years to years. It depends on the complex combined effect of climatic variables (i.e. temperature, snow depth, winds) and geological and geomorphological factors (i.e. soil materials, locations…etc). This must be taken into account in further synthesizing of the data in, for example, numerical modelling or building/construction work at the site.

3. NUMERICAL MODEL

For engineering applications in permafrost, predicting thickness of the active layer is a key task in numerical study because the strength of soils in thawed state (i.e. in active layers) is reduced dramatically compared with the strength in frozen state. This reduction leads to various problems with constructing infrastructure on/in active layers such as, for example, settlement, instability and erosion.

The long continuous records of soil temperature measurements obtained on Pesyakov island provide a valuable opportunity for constructing and calibrating a numerical model for investigating the thermal regime. Such a model can be used, for example, to predict the regional thermal variation in future applications (e.g. designing infrastructure in the region). This study employs the finite element method by using a commercial software, namely TEMP/W (GEO-SLOPE 2012), to model the soil temperature variation at the studied location over the monitored two-year period (Aug 2012 – Aug 2014) in Varandey. Even though the hydrological and mechanical processes might also influence the heat flow besides the thermal processes, there is little information indicating the significance of these processes from the site investigation. Therefore, only thermal processes are modelled in this study while the hydrological and mechanical processes are not included. On the barrier, the ground surface is relatively flat over the large distance. Hence, the dominant direction for thermal transport is vertical. A one-dimensional model is therefore considered to be adequate to capture the thermal processes for a relatively large area on the barrier.

Table 1: Values of soil properties

Parameters	Units	Silty Sand	Clean Sand	Cryopegs
w_g	%	25	15	25
w_θ	%	36	23	36
ρ_d	kg/m^3	1450	1500	1450
ρ	kg/m^3	1813	1725	1813
e		0.83	0.77	0.83
c_s	kJ/kg°C	0.73	0.73	0.71
C_u	kJ/(m$^{3.}$°C)	2577	2038	2548
C_f	kJ/(m$^{3.}$°C)	1816	1565	1787
k_u	kJ / (day m°C)	143	136	143
k_f	kJ / (day m°C)	223	155	223

Three main soil types are found within the 5.5 m depth of borehole. The topsoil layer extends from the surface to 1.3 m depth and is composed of blue grey silty fine sand with some plant residues. From 1.3 to 4 m, the soil becomes yellow grey well-washed clean sand. The soil from 4 m to bottom of the borehole is possibly cryopegs as the soil sample could not be retrieved in the drill column. When using auger to drill, a deposit of blue-grey silty sand with interbedded loam can be observed sticking to the lower auger. This deposit corresponds to the depth interval where the drill column could not retrieve sample, thus is likely to come from the cryopeg lenses. The properties of soils from the three layers (silty sand, clean sand and cryopeg) are presented in Table 1. These parameter values are used in the numerical simulation.

In Table 1, the gravimetric water content (w_g) was measured for a number of samples taken from the site. The dry densities (ρ_d) were not directly measured. The value selected for simulation (Table 1) are based on the typical dry density for three soil types (EVS 2016). The water density (ρ_w) and the solid particle density (ρ_s) are assumed to be constants at 1000 kg/m^3 and 2650 kg/m^3, respectively. The volumetric water content (w_θ) is estimated from the relationship $w_\theta = w_g .\rho_d/\rho_w$. The void ratio ($e$) is also estimated from correlation with solid and dry density $e = \rho_s/\rho_d$-1. The volumetric heat capacity of water (c_w) and ice (c_i) are set to be 4.19 and 2.09 kJ/kg.°C, respectively, adapted from the values given in (Andersland and Ladanyi 2004). The volumetric heat capacity of soil particles (c_s) is assumed to be typical of quartz (0.73 kJ/kg.°C) or similar materials. The frozen (C_f) and unfrozen (C_u) volumetric heat capacities are calculated using the correlations:

$$C_f = \rho_d.(c_s + c_i w_g) \quad [1]$$

$$C_u = \rho_d.(c_s + c_w w_g) \quad [2]$$

The unfrozen (k_u) and frozen (k_f) thermal conductivities are estimated using suggested equations for coarse-grained soils (with less than 20% silt-clay content) (Farouki 1981):

$$k_u = 0.1442(0.7\log w + 0.4)10^{0.6243\rho d} \quad [3]$$

$$k_f = 0.01096.10^{0.8116\rho d} + 0.00461.10^{0.9115\rho d} w \quad [4]$$

The "full thermal model" option (in TEMP/W) is selected for all the three soil materials. This implies the assumption that both the amount of unfrozen water content and the thermal conductivity vary with temperature. These dependencies were not measured for the soils in Varandey, hence the typical functions for similar soil types are adapted from those suggested in the TEMP/W manual (GEO-SLOPE 2012).

An important element which must be taken into account in the numerical models is the difference between the mean annual ground surface temperature (GST) and the mean annual air temperature at each specific location. Various factors contribute to this differences include vegetation, snow cover, thermal property of the topsoil, surface relief and drainage condition. In TEMP/W, this difference is represented by an n_{factor} which fundamentally is a scale to relate the GST to the air temperature. Theoretically, the n_{factor} for freezing condition can be estimated by the ratio between the surface freezing index and the air freezing index. Similarly, the n_{factor} for thawing condition is the ratio between the surface thawing index and the air thawing index (Andersland and Ladanyi 2004). Ideally, the surface freezing and thawing indices should be calculated from the soil temperature measured at the ground surface (1 cm depth). These measurements are however very difficult to obtain accurately and were not performed in this study. Instead, the n_{factor} is estimated by sensitivity analyses with a range of values. The selected values of the n_{factor} are the ones which can best reproduce the temperature variation obtained at the shallowest thermistors at this borehole. In this study, the values og n_{freeze} are 0.6 and 0.2 and the values of n_{thaw} are 1 and 1.5 for 2012 – 2013 and 2013 – 2014, respectively.

Figure 4 shows the comparison between measured and predicted temperature variation at the shallowest and the deepest thermistors. Figures 5 and 6 show comparison of the measured and predicted yearly trumpet curves and the mean temperature curves. The trumpet curves show the lowest and highest soil temperature at different depths over each monitored year. These extreme temperatures together with the mean values are important considerations for design of structures on permafrost.

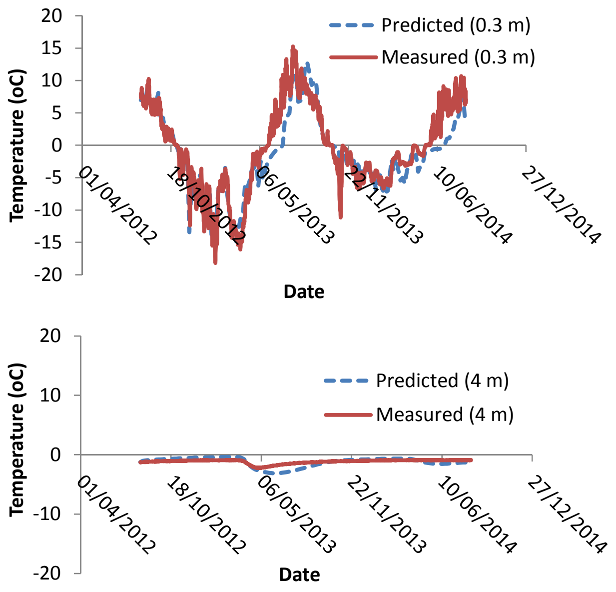

Figure 4: Comparison of the variation of soil temperature between the measurements and the model predictions at the top (0.3 m depth) and bottom (4 m depth) thermistor.

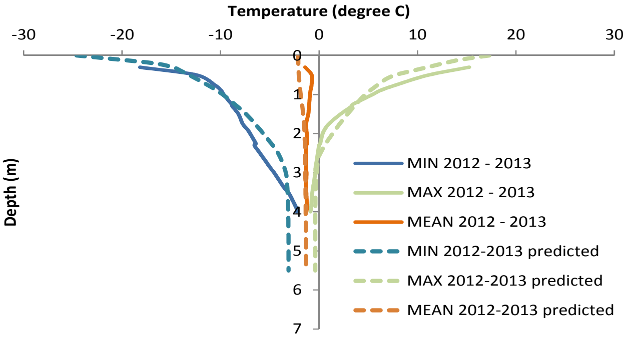

Figure 5: Comparison of the measured and predicted trumpet and mean curves for 2012 - 2013

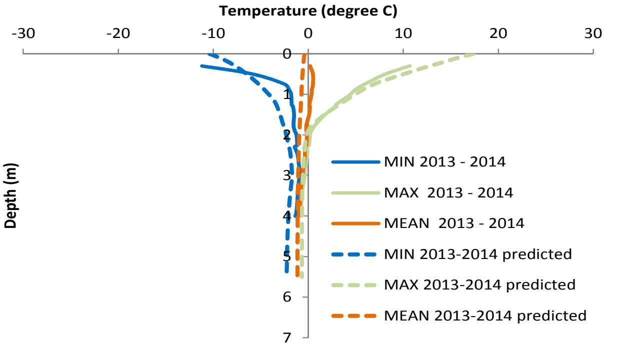

Figure 6: Comparison of the measured and predicted trumpet and mean curves for 2013 - 2014

The 1D model produces good predictions of the first year of temperature measurement (i.e. Aug 2012 – Aug 2013) as shown in Figures 4 and 5. The consistency between predicted and measured curves is better for 2012 – 2013 than 2013 – 2014 (Figs. 4, 5 and 6). The decrease in consistency between the predicted and the measured temperature in the second year is caused by the choices made during calibrating the numerical model. The initial temperatures for the numerical model were calibrated with the first measurements in Aug 2012 – 2013 by the shallowest thermistor, hence the fit between the model and the measurement is perfect at time zero of the simulated two-year period (See Fig. 4). Over time, the predicted temperature fluctuates around the measured temperature with a certain deviation due to various uncertainties (e.g. soil spatial variability, measurement errors, model errors…etc). The overall deviation generally increases with the increasing time lapse from the initial time due to accumulated uncertainty (Fig. 4). For general practical design, the predicted trumpet curves and mean temperature curves for 2013 – 2014 (Fig. 6) can still be considered sufficient close to the measured curves.

4 CONCLUSIONS

A typical thermal profile of permafrost soils on Pesyakov island in Varandey, Russia have been described and discussed in this paper. First, the analyse of real soil temperature measurements (between Aug 2012 and Aug 2014) shows that the response of soil temperature to air temperature varies from year to year, depending significantly on the ground cover. The soil temperature at the studied location generally follows the variation of air temperature in winter, but becomes reduced in magnitude and lagged behind in time. The one-dimensional numerical models of the thermal variation over the monitored period show that the prediction are reasonably closed to the measured data. The deviation between the predicted and the measured values generally increases over time. The numerical results reveals the complexity of the thermal regime at the site. It shows the migration and retreat of the permafrost table over the year and demonstrate the formation of frozen soil lenses/layers within a thawed soil mass and unfrozen soil lenses/layers within a frozen soil mass. The results from the numerical model calibration can be used for future evaluation, assessment and design of infrastructure on permafrost in Varandey or similar regions. In addition, the numerical study can also provide useful tool and reference for design of field investigation, with respect to, for example, borehole locations, number of boreholes, thermistor string depth.

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