Thermal modelling of erosion protection with Gesoynthetic containers in combination with Light Clay Aggregate

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Des défis du Nord au Sud

Magne Wold[1, 2], *Arne Instanes*[1,3],, *Arnstein Watn*[1,2], Lars Vollmert[4], *Katja Werth*[4]

[1)] *Sustainable Arctic Marine and Coastal Technology (SAMCoT), Centre for Research-based Innovation (CRI), Nowegian University of Science and Technology, Trondheim, Norway*
[2)] *SINTEF Building and infrastructure, Trondheim,Norway*
[3)] *Instanes Polar AS, Bergen, Norway*
[4)] *NAUE GmbH & Co KG, Espelkamp-Fiestel,Germany*

ABSTRACT
The main objective of this study has been to investigate the possibility of using special types of Geosynthetics Clay Liners in combination with Geotextile Soil-filled Containers (GSC) to insulate the slope to reduce the thickness of the active layer and freeze-thaw action on the slope. In this manner the thermo-denudation process can be slowed down and the erosion of the slope can be reduced to acceptable levels during a coastal structure or landfall service lifetime.

The numerical model has been extended in order to investigate the possibility of using similar erosion protection techniques in more fine graded soil (silt). The prediction and modelling of coastal erosion in fine-grained, ice-rich continuous permafrost can be more challenging than in coarser soils, due to the presence of ground ice. Under these conditions, the rate and location of erosion can be highly variable from year to year. The results from the analysis must, therefore, be used with care.

RÉSUMÉ
L'objectif principal de la modélisation thermique a été d'étudier la possibilité d'utiliser *Naue Geosynthetics* pour protéger le talus et ainsi réduire l'épaisseur de la couche active affectée par le mécanisme gel-dégel. De cette façon, le processus de thermo-dénudation peut être ralenti et l'érosion de la pente peut être réduite à des niveaux acceptables pendant la durée de vie de service d'une structure côtière ou d'un glissement de terrain.

Le modèle numérique a été extrapolé afin d'étudier la possibilité d'utiliser des techniques similaires de protection contre l'érosion, sur des sols plus fins comme le limon par exemple. La prédiction et la modélisation de l'érosion côtière dans du pergélisolt à grains fins peut être plus délicate que pour des sols plus grossiers, du fait de la présence de la glace. Sous ces conditions, autant la localisation que le taux d'érosion peuvent subir d'importantes variations d'une année à l'autre. Les résultats de l'analyse doivent donc être utilisés avec prudence.

1 INTRODUCTION

The potential exploitation of natural resources and need for infrastructure in the high Arctic has led to an increased interest in permafrost engineering and understanding from oil companies and contractors. In turn this has led to a demand for retrieving reliable data and development of new construction methods in permafrost areas.

Permafrost is present in most areas in the high Arctic including the coastal regions. Sea water and higher global temperatures are warming the permafrost, which reduces the stability of the shoreline and makes it more vulnerable to erosion from waves and sea ice interaction.

This erosion presents a problem for near costal infrastructure and harbour structures in Arctic regions.

There is a need to develop erosion protection structures which withstands forces from ice and waves and reduces the effect on degradation of permafrost. Conventional erosion protection structures are often made of bedrock and concrete. The availability of high quality bedrock is scarce in many Arctic regions and transport costs are high. Construction techniques using local soils and alternative materials such as geosynthetics and expanded clay light weight aggregates (expanded clay LWA) are therefore beneficial in many situations. Some initial investigations and test projects on erosion protection with geosynthetics and local soils have already been carried out (Bæverfjord et al, 2014).

The combination of expanded clay LWA and geosynthetics give the possibility to manipulate the thermal properties of the erosion protection embankment and hence obtain a structure less vulnerable to thermal abrasion. This paper presents a thermal model showing the effects of insulating the bluff front with geosynthetic bags filled with local soils and expanded clay LWA.

2 EROSION PROTECTION EMBANKMENT DESIGN

2.1 General

Erosion protection embankments built of geosynthetic bags have been installed in Svea, Svalbard archipelago, Norway, in 2007 and 2009 (Finseth, 2009).

Studies of these embankments show that the constructions are able to withstand influence from ice and wave actions over several years (Wold et al, 2013).

In erosion affected coastal areas worldwide the use of geotextile sand-filled containers provides an effective construction element (Dassanayake, 2013).
The schematic cross-section design is shown in figure 1. The basic protection scheme is to place a GCL-sandmat composite on the embankment surface for avoiding of hydraulic exchange between water table and subsoil. Geotextile soil-filled containers (GSC) are protecting the embankment slope against wave attack. Both geosynthetic elements together form the protection scheme.

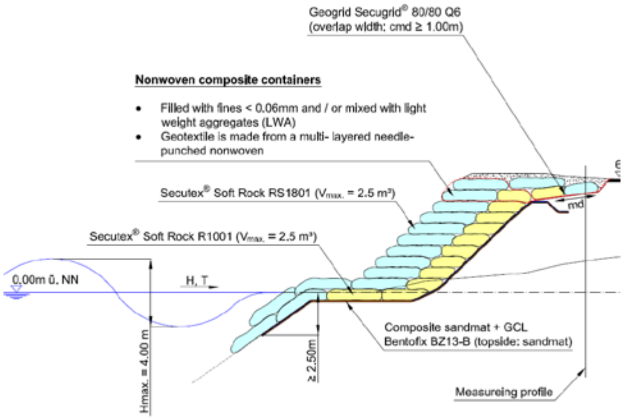

Figure 1 Cross-section with GSC and GCL-sandmat

2.2 Geosynthetics

A cross-section of this GCL-type is shown in Figure 2. In practice a composite of geosynthetic Clay Liner and sandmat on top is considered for underwater installation. GCLs are characterised by a low hydraulic conductivity in a range of $k = 2 \times 10^{-11}$ m/s.

Geotextile soil-filled containers and bags are robust and versatile construction elements against erosion and scouring. They are made typically from needle-punched nonwoven with fill volumes between 1 and max. 2.5 cubic metres limited by dry filling method. For exposed applications (UV, ice, debris) it is recommended to use double-layered needle-punched nonwoven composite with a mass per unit area of 1200 g/m^2. Further information on materials and design is given in Dassanayake (2013).

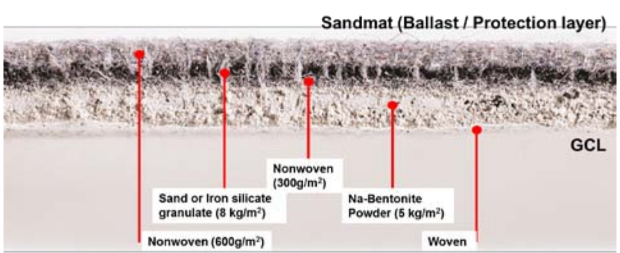

Figure 2 GCL-sandmat composite


Figure 3 Typical GSC coastal protection revetments

2.3 Expanded clay LWA

Expanded clay LWA is produced by expanding natural clay in rotating ovens at high temperature thus producing a granular material with low weight and strength properties comparable to granular materials. The material can be produced in different grading and with different properties but the most common grading is 10-20 mm. This material has a loose bulk density of 200-300 kN/m^3 (dependent on the specific product) and can be installed by blowing equipment. An overview of characteristic properties and geotechnical application areas are given in (Watn, 2008).

The physical mechanical and thermal properties of the expanded clay LWA may vary dependent on the properties of the clay raw material and the production process. Some typical characteristics for two grades of expanded clay LWA are given in Table 1.

Table 1 Physical properties of expanded clay LWA

Characteristics (%)	Grading 10-20	Grading 0-32
Compact density , ρ_k	2600 kg/m^3	2600 kg/m^3
Pellet density , ρ_k	750 kg/m^3	800 kg/m^3
Internal pore volume in pellets	71%	69%
Dry bulk density before compaction, ρ_d	280 kg/m^3	335 kg/m^3
Volume reduction by compaction, P	10%	10%
Dry density after compaction $\rho_{d,f}$	310 kg/m^3	370 kg/m^3
Porosity of the fill, n	54 %	49 %

The lightweight clay aggregates has very good insulation properties. Based on laboratory investigations and field measurements the thermal conductivity related to the water content is presented in Figure 4 (Watn et al, 2000).

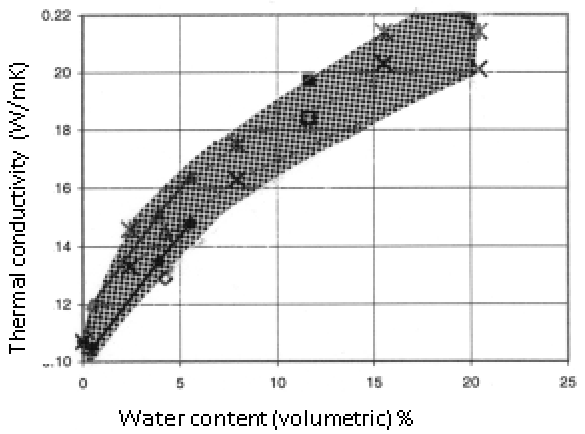

Figure 4 Thermal conductivity of lightweight clay aggregate (Furuberg et al, 2000).

3 THERMAL MODEL

Finite element software, TEMP/W version 8.0, has been used to model the permafrost coastline (Geo-Slope, 2012). TEMP/W can model thermal changes in the ground due to changing temperature or heat flux boundary conditions. The software is often used in practical engineering applications and gives good results at point locations given that the model is validated by observational data (Instanes and Anisimov, 2008). The TEMP/W model accounts for the effects of temperature dependent thermal conductivity, volumetric latent heat of fusion, and soil unfrozen water content.

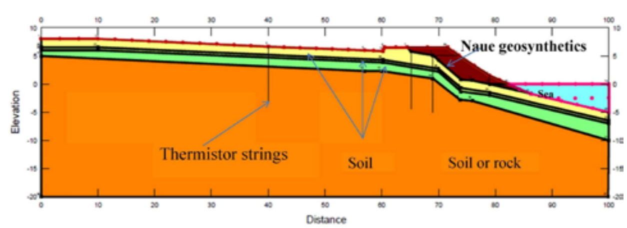

Figure 5 Thermal model

In this study simplified soil profiles and geometry from Vestpynten, Svalbard, was used, to develop a 2-dimensional thermal model, see Figure 5. Soil parameters used in the analyses are presented in table 1. Thermal conductivities and unfrozen water contents were adjusted to changing ground temperatures between -10°C and 0°C using simplified empirical relationships. The soil profiles were modelled using iso-parametric 8-nodes quadrilateral finite elements. The baseline case was "tuned" to temperature measurements on the site Vestpynten. The soil parameters were then varied to take into account:

- Coarse material with high ice/water-content.
- Silty soils with high ice/water-content in the top layers.

Table 2 Soil parameters used in the thermal model.

	Case	0-1,5 m	1,5–2,0 m	>2,0 m
Water content (%)	Coarse	10	17	25
	Coarse (ice-rich)	16	33	56
	Silt (ice-rich)	40	30	20
Thermal conductivity T < -10°C (W/mK)	Coarse	2,0	2,2	2,7
	Coarse (ice-rich)	2,0	2,2	2,7
	Silt (ice-rich)	1,1	1,3	1,6
Thermal conductivity T > 0°C (W/mK)	Coarse	2,0	2,2	2,7
	Coarse (ice-rich)	2,0	2,2	2,7
	Silt (ice-rich)	1,1	1,3	1,6
Volumetric heat capacity (frozen) (MJ/(m^3 K))	Coarse	1,5	1,6	1,8
	Coarse (ice-rich)	1,6	1,9	2,2
	Silt (ice-rich)	2,0	1,9	1,9
Volumetric heat capacity (unfrozen) (MJ/(m^3 K))	Coarse	1,8	2,2	2,5
	Coarse (ice-rich)	2,1	2,8	3,5
	Silt (ice-rich)	3,1	2,8	2,6

The analysis was carried out for the different soil profiles with identical geometries and temperature boundary conditions:

- Coarse soil - according to soil conditions at Vestpynten. Depth to bedrock less than 4 metres.
- Coarse soil - taking into account ice-rich surface layers. Depth to bedrock less than 4 metres.
- Silty soil - taking into account ice-rich surface layers. Depth to bedrock more than 20 metres.

The preliminary design suggested here as scour protection in Arctic regions is shown in Figure 1 and Figure 5. It is indicated that the nonwoven composite containers may be filled with fines mixed with expanded clay LWA. The volumetric relationship between local materials and imported expanded clay LWA, affects the thermal behaviour of the scour protection system. In the numerical model, the thermal conductivity of the composite containers has been assumed to be constant in each model run. In different model runs, the scour protection thermal conductivity has been varied from 0.25 W/(mK) to 2.0 W/(mK). The water content has been kept constant at w=5%.

Mean monthly air temperatures for the time period 2014-2050 were applied to the surface boundary of the finite element mesh, see Figure 2. The mean monthly air temperatures are based on climate scenarios for Svalbard (Benestad and Engen, 2009; Hanssen-Bauer et al., 2005). The scenario from Hanssen-Bauer et.al (2005) is considered to be a moderate warming scenario and is in good agreement with recent warming trends. The analyses were carried out for the time period 2014-2050.

It is assumed that the service lifetime of the scour protection system is in the order of 10 to 20 years.

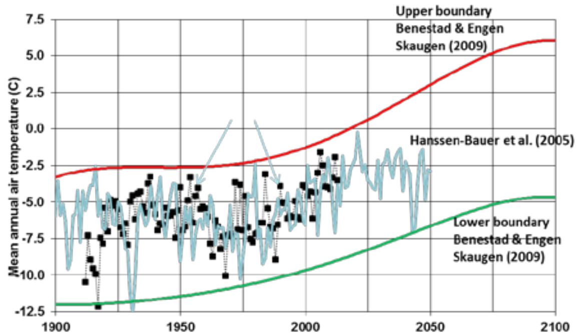

Figure 6 Svalbard mean annual air temperature observations and climate models.

It should be noted that n-factors of 1.0 was used in the analysis presented in this paper. Andersland and Ladanyi (2004) suggest that n-factors between 1.0 and 2.0 would be appropriate for thawing of natural terrain surfaces containing turf, sand and gravel.

4 RESULTS

4.1 Coarse soil

Figures 7 to 11 present the initial model run with the coarse ice-rich soil material. The blue area in the figures show the 0°C-isotherm during the period 2014-2050. It is an indication of the maximum thaw depth (active layer thickness). Figure 7 indicates that the active layer thickness is approximately 1.5 m. In the following figures (Figure 7 to 10) composite containers have been placed on the slope. The thermal conductivity in the analysis has been decreased from 2.0 W/(mK) in Figure 7 to 0.25 W/(mK) in Figure 11. This means that the insulation effect of the containers is increasing from Figure 8 to Figure 11. It can clearly be observed from the figures that the thaw depth decreases with increasing thermal conductivity of the containers. It can also be observed that there is some thawing at the toe of the slope that needs special attention. In this area thermo-abrasion will also be active, so toe protection will be necessary.

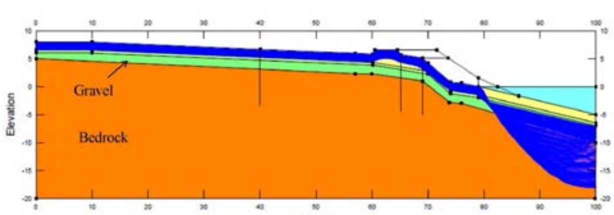

Figure 7 Vestpynten thermal model with coarse material without gesoynthetic containers. 0° isotherm 2015-2050

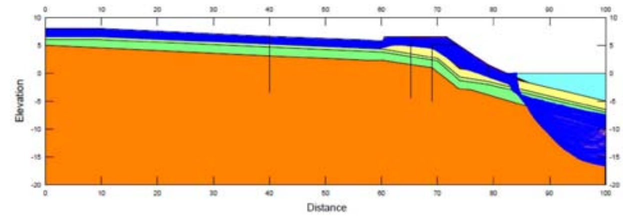

Figure 8 Vestpynten coarse material with gesoynthetic containers. (k=2 W/mK). 0° C- isotherm 2014-2050.

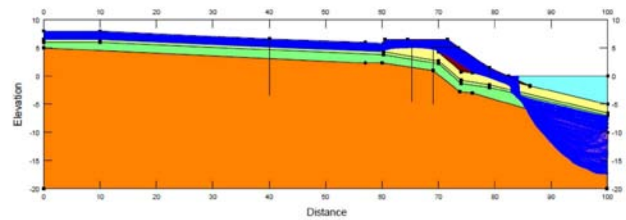

Figure 9 Vestpynten coarse material with gesoynthetic containers. (k=1 W/mK). 0° C- isotherm 2014-2050.

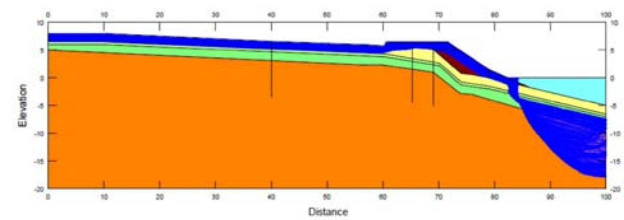

Figure 10 Vestpynten coarse material with gesoynthetic containers. (k=0.5 W/mK). 0° C- isotherm 2014-2050.

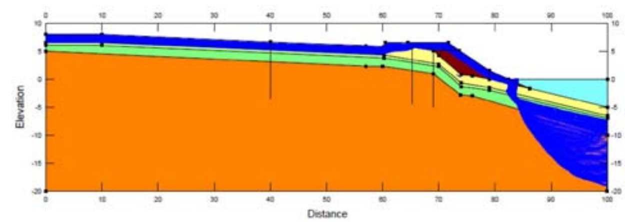

Figure 11 Vestpynten coarse material with gesoynthetic containers. (k=0.25 W/mK). 0° C- isotherm 2014-2050.

4.2 Silty soil

Figures 12 to 17 present the results from the analysis with ice-rich silty soil. Figure 12 indicates that the active layer thickness is approximately 1.1 m. The decreased active layer thickness compared to the coarser soil, is due to higher water content/ice content in the surface layers. In Figure 13, the extreme climate warming scenario from Benestad and Engen (2009) has been applied to the analysis. The result is that the active layer thickness increases from 1.2 m in the moderate climate warming scenario to over 8 meters.

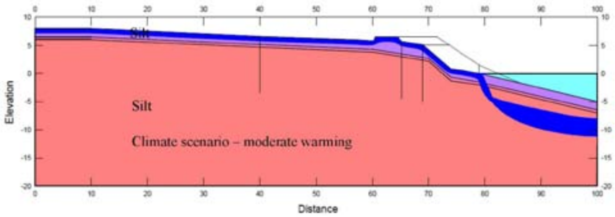

Figure 12 Silty soils without composite containers. 0˚ isotherm 2014-2050. Moderate warming scenario.

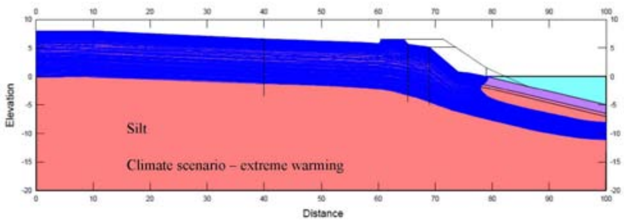

Figure 13 Silty soils without composite containers. 0˚ isotherm 2014-2050. Extreme warming scenario.

In the following figures (Figure 14 to 17) composite containers have been placed on the slope. The thermal conductivity in the analysis has been decreased from 2.0 W/(mK) in Figure 10 to 0.25 W/(mK) in Figure 17. It can clearly be observed from the figures that the thaw depth decreases with increasing thermal conductivity of the containers. It can also be observed from the figures that there is still a toe problem that needs to be solved. Figure 18 shows the thaw depth during an extreme warming scenario with container thermal conductivity of 0.25 W/(mK). The figure illustrates that the containers are not capable of protecting the slope during a worst case scenario. In this case, the solution should be combined with artificial cooling of the slope.

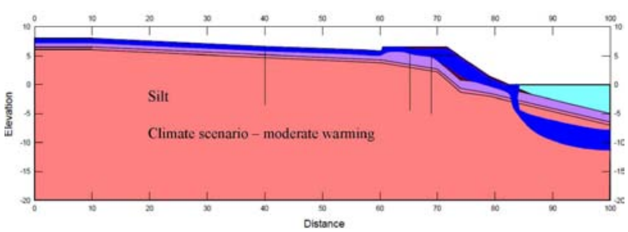

Figure 14 Silty soils with composite containers (k=2.0 W/mK). 0˚ isotherm 2014-2050.

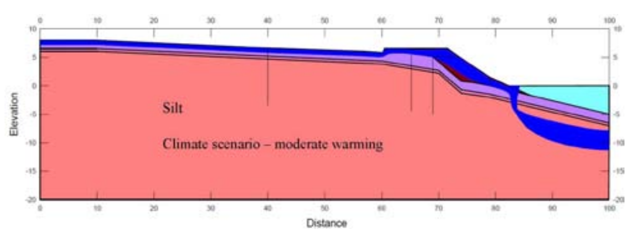

Figure 15 Silty soils with composite containers (k=1.0 W/mK). 0˚ isotherm 2014-2050.

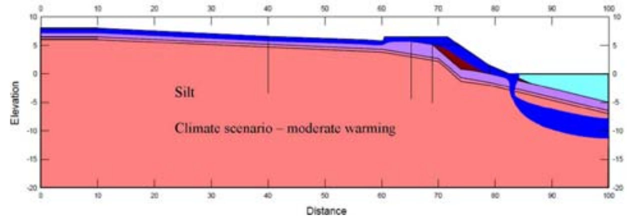

Figure 16 Silty soils with composite containers (k=0.5 W/mK). 0˚ isotherm 2014-2050.

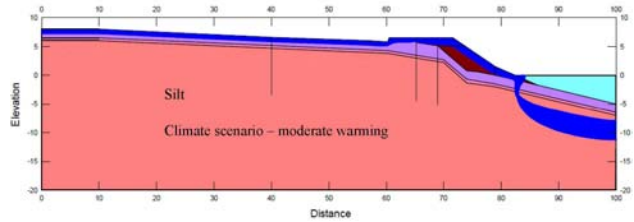

Figure 17 Silty soils with composite containers (k=0.25 W/mK). 0˚ isotherm 2014-2050.

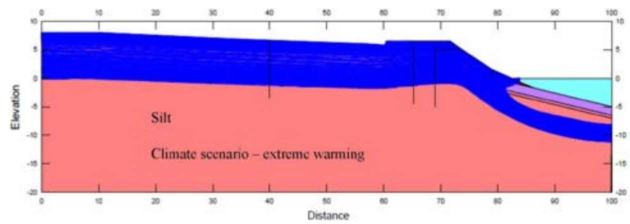

Figure 18 Silty soils with composite containers (k=0.25 W/mK). 0˚ isotherm 2014-2050. Extreme warming scenario.

5 SUMMARY AND CONCLUSION

Thermal analysis of erosion protection of a permafrost coastline utilising *Naue Geosynthetics* has been carried out. The analysis shows that:

- Insulating the slope using composite containers filled with fines mixed with light weight aggregates (LWA) will effectively decrease the thaw depth in the slope.
- The same effect of reduced thaw depth is found for slopes containing coarse material (gravel and sand) and fine material (silty soil).
- Increased volumetric content of light weight aggregates in the composite containers will improve the thaw mitigation capability of the scour protection.
- The toe of the erosion protection system requires special attention due to the combined effect of thermo-abrasion and thermo-denudation.
- In the extreme worst case climate scenario, the erosion protection system is not sufficient to avoid thaw occurring in the permafrost below. In this case the technical solution should be combined with artificial cooling systems.

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