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Anne Tuomela

ENHANCING THE SAFETY AND SURVEILLANCE OF TAILINGS STORAGE FACILITIES IN COLD CLIMATES

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Abstract

The mining industry is at the base of much of developed society worldwide. It is a major part of the economic well-being of many countries but has the significant drawback of the large amounts of waste it generates. One of the by-products of mining are tailings, a generic definition for the left-over materials after the process of separating the valuable elements from the economically unexploitable ore. Sustainable mining tends to reduce waste generation and find new ways to use these by-products. Arctic mining is a notable part of the mining industry. When mining in these cold climates, the presence of snow and ice must always be considered at every stage. The main aim of this thesis was to enhance mine tailings performance in cold regions by studying the monitoring and safety of tailings disposal from a geotechnical point of view.

The study included four metal mines in artic or sub-artic regions and gathered valuable knowledge on frost susceptible manners of tailings, which was known to correlate with the damages induced by frost. Based on the results, tailings frost performance was found to be similar than in natural soils. Therefore, an analogous characterization system can be adopted for tailings and the framework developed can help to evaluate the frost susceptibility of materials. The in-situ frost measurements were used to validate the developed one-dimensional thermal regime model. The findings showed a strong agreement between the modelled temperature in the tailing regime and the in-situ data. This study provides knowledge which can be used to improve the management of tailings storage facilities (TSFs) and avoid failures resulting from freezing.

UAV measurements were used as a practical tool for monitoring and gathering the large amounts of topographical data from TSF with an accuracy range of a decimetre. The subsidence maps created were beneficial for mapping the settlements and observing the erosion patterns in the pond. The method provided several ways to improve the process, like helping with planning a disposal strategy and following the volume capacity of the pond.

Much of the tailings cannot be utilised and therefore must be safely disposed of. The literature review showed that geomembrane lined TSFs can decrease harmful effects on the environment. The framework developed for identifying the lined tailings ponds as important for the mine project will increase the quality of the construction of the TSFs and thus reduce environmental impacts over the entire life cycle of the mining operation. The results obtained in this work can be exploited at various stages of mining design.

Keywords: drones, frost simulation, frost susceptible, geomembrane, geotechnic, mining, tailings, UAV

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Tiivistelmä

Kaivosteollisuus on tärkeä perusta kehittyneelle yhteiskunnalla. Se on osa myös maiden hyvinvointia, mutta toiminnan kääntöpuolena syntyy suuria määriä jätteitä. Yksi syntyvä sivuvirta on rikastushiekka. Se on yleisnimitys materiaalille, jota muodostuu rikastusprosessissa ylijäämänä, kun malmista on erotettu taloudellisesti hyödynnettävissä oleva osa. Kestävä kaivostoiminta pyrkii vähentämään syntyviä jätteitä ja löytämään uusia keinoja hyödyntää sivuvirroissa syntyviä materiaaleja. Arktinen kaivostoiminta on jokapäiväistä, jonka toiminnassa on huomioitava lumen ja jään läsnäolo. Työn päätarkoitus oli lisätä tietoa rikastushiekan käyttäytymisestä kylmissä ilmastoissa parantamalla seurantaa ja turvallisuutta geoteknisestä näkökulmasta.

Tutkimuksessa saatiin tietoa neljän metallimalmikaivoksen rikastushiekan routimisherkkyydestä, jonka tiedetään korreloivan syntyvien routavaurioiden kanssa. Tulosten perusteella rikastushiekat käyttäytyivät jäätyessä kuten luonnonmateriaalit. Sen vuoksi luonnonmateriaaleille käytettäviä routivuusluokitteluja voidaan käyttää myös rikastushiekoille. Työssä kehitettiin menetelmä, jonka avulla materiaalien routivuustestausta voidaan ohjata. Kentällä tehtyjä routa-/lämpötilamittauksia hyödynnettiin yksidimensionaalisen routamallin validoinnissa. Mallilla voitiin simuloida tarkasti lämpötiloja rikastushiekassa eri ajanjaksoilla. Tulosten avulla voidaan välttää jäätymisestä aiheutuvia ongelmia rikastushiekkaa läjitettäessä.

Lennokkimittauksien (UAV) todettiin olevan käytännöllinen työkalu monitoroimaan ja keräämään maanpinnan korkeustietoa rikastushiekka-altailta desimetrin tarkkuudella. Luodut painumakartat olivat hyödyllisiä painumien seurannassa ja eroosiokohtien havaitsemisessa. Menetelmällä todettiin olevan useita käyttömahdollisuuksia ja sitä voidaan hyödyntää esim. läjityksen suunnittelussa ja altaiden täytön optimoinnissa.

Kaikkea rikastushiekkaa ei voida hyödyntää ja sen vuoksi sitä tulee voida varastoida turvallisesti. Tutkimuksessa saatiin tietoa, että varastoaltaan pohjarakenteissa käytettävällä yhdistelmärakenteella voidaan vähentää rikastushiekasta aiheutuvaa haitallista kuormaa ympäristöön. Työssä laadittiin kirjallisuuskatsauksen perusteella ehdotus toimintamalliksi, jonka avulla voidaan parantaa rikastushiekka-altaiden rakentamisprosessia, sekä saavuttaa laadullisesti parempia rakenteita, jotka vähentävät läjityksestä aiheutuvia ympäristövaikutuksia toiminnan elinkaaren aikana. Työssä saatuja tuloksia voidaan hyödyntää kaivossuunnittelun eri vaiheissa.

Asiasanat: geomembraani, geotekniikka, kaivos, lennokit, rikastushiekka, routamallinnus, routiminen, UAV

To My Family

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Oulu, April 2022 Anne Tuomela

List of symbols and abbreviations

Abbreviations

AMD	Acidic mine drainage
CQA	Construction quality assurance
DEM	Digital elevation map
DoD	DEM of difference
EIA	Ethylene interpolymer alloy
EPDM	Ethylene propylene diene monomer
GNSS	Global navigation satellite system
GPS	Global positioning system
Grad$T$	Temperature gradient
HDPE	High-density polyethylene
LiDAR	Light detection and ranging
LLDPE	Linear low-density polyethylene
LVDT	Displacement transducer
NAPP	Net acid-producing potential
NIR	Near infrared spectrometer
PP	Polypropylene
PVC	Polyvinyl chloride
RTD	Riverine tailings disposal
SAR	Synthetic-aperture radar
SP	Segregation potential
SfM	Structure from motion
STD	Submarine tailings disposal (STD)
RADAR	Radio detection and ranging
TIR	Thermal infrared spectroscopy
TSF	Tailings storage facility
UAV	Unmanned aerial vehicle

Symbols

C	Volumetric heat capacity for the soil mixture
k	Thermal conductivity for the tailings mixture
L'	Volumetric latent heat
m_s	The dry mass of the sample
m_w	Mass of water
t	Time
T	Temperature
v	Water intake velocity
w	Water content
x	Depth from the tailings surface
$Z_{ij,1}$	Elevation of pixel ij during time t_1
$Z_{ij,2}$	Elevation of pixel ij during time t_2

List of original publications

This thesis is based on the following publications, which are referred to throughout the text by their Roman numerals:

I Tuomela, A., Ronkanen, A.-K., Rossi, P. M., Rauhala, A., Haapasalo, H., & Kujala, K. (2021). Using geomembrane liners to reduce seepage through the base of tailings ponds – A review and a framework for design guidelines. *Geosciences*, *11*(2), 1–23. https://doi.org/10.3390/geosciences11020093

II Tuomela, A., Pekkala, V., Rauhala, A., Torabi Haghighi, A. & Leviäkangas, P. (2021). Frost susceptibility of Nordic metal mine tailings. *Cold Regions Science and Technology*, *192*, Article 103394. https://doi.org/10.1016/j.coldregions.2021.103394

III Knutsson, R., Tuomela, A., Rauhala, A., Knutsson, S., & Laue, J. (2021). Geothermal study of a tailings deposit: Frost line modelling and comparison to field data. *Journal of Earth Sciences and Geotechnical Engineering*, *11*(3), 15–32. https://doi.org/10.47260/jesge/1133

IV Rauhala, A., Tuomela, A., Davids, C., & Rossi, P. M. (2017). UAV remote sensing surveillance of a mine tailings impoundment in Sub-Arctic conditions. *Remote Sensing*, *9*(12), Article 1318. https://doi.org/10.3390/rs9121318

The author's contribution to publications I–IV:

I Designed the study with the co-authors. Was responsible for collecting the data, analysis and writing the paper. Received critical comments on the manuscript from the co–authors.

II Designed the study with the co-authors. Was responsible for collecting the data, analysis and writing the paper. Wrote the paper with the co-authors.

III Designed the field study with Rauhala. Conducted the field work and analysed the results with Rauhala. Wrote the paper with the co-authors.

IV Designed the study with co-authors. Performed the field work and analysed the results with Rauhala. Wrote the paper with the co-authors.

Contents

1 Introduction

The mining of metals and minerals is critical to the development of modern society, having a huge impact on the economy of many countries. Globally, China, Indonesia and India are known to produce the greatest volumes of coal, potash and copper (Statista, 2021). When comparing dominant mining companies based on market capitalization, the leaders come from Australia, the United Kingdom, the United States, China, Canada, and South Africa, respectively (Statista, 2021). The Arctic is an area where a great deal of global mining takes place, but mining in the Arctic is recognized to come with several challenges. Haley et al. (2011) has reviewed the effects of Arctic mining on local communities and gives a good overview of the regions where mining operations take place. The drivers for Arctic mining are the same as in other regions, global markets and the presence or prospect of major ore deposits (Haley et al., 2011; Heininen et al., 2015; Tolvanen et al., 2019). In Nordic countries, especially in Finland, many new mines have been recently opened, the driving force being the higher prices of metals and opportunities of interest, e.g., the battery industry. The need for minerals and metals has increased yearly, with rare earth mineral production doubling in the 2000s (Kanazawa & Kamitani, 2006; Reichl & Schatz, 2021). This is due to these minerals being essential for production in computing, smartphones, and cleaner new technologies, such as solar panels, lasers, lenses, and electric car batteries, among others (Chakhmouradian & Wall, 2012; Jordens et al., 2013).

Minerals are mined all over the world, even in very harsh, extreme conditions. The need to mine in severe conditions is the consequence of all the easily accessible deposits being extracted. In general, weather and climate can cause challenges due to high or low temperatures, heavy rains, long drought seasons, evaporation, wind, lightning, or the presence of permafrost (e.g., Alakangas et al., 2013; International Commission on Large Dams [ICOLD], 2001; Liu et al., 2016; Yilmaz et al., 2014). Where one mine in a warm arid climate may suffer from the lack of processed water, another located in cold rainy regions, will have a highly positive water balance. The operation conditions of mines vary widely depending on the region in which the mine is situated. These climatic demands must be handled, with the side effects of the climate being mitigated during the life cycle of mining (Rico et al., 2008).

Another major issue for mining is the huge amount of untapped materials generated, irrespective of the operating conditions. Globally, millions of tons of ore are mined every year, more than 95% of this is disposed of as waste rock or tailings (Falágan et al., 2017). In Finland, 75% of the yearly disposed of waste materials is generated by mining (Official Statistics of Finland, 2022). Lottermoser (2003) has estimated that the number of tailings created is around 25 billion tons/year worldwide and around 88 million tons/year in Finland (Official Statistics of Finland, 2022). Tailings are created during the enrichment process, are rarely reused, and are mainly disposed of as slurry in tailings storage facilities (TSFs). The storage of tailings is known to pose one of the most significant environmental risks in the mines (Azam & Li, 2010; ICOLD, 2001; Rico et al., 2008; Wang et al., 2014). The presence of water is known to be one of the most challenging factors, causing seepage problems and internal erosion of the structures of the facility. Overtopping and errors in the decanting or spillway systems have also caused issues (ICOLD, 2001; Rico et al., 2008).

Recently, due to social debate, tighter legislation and enhanced corporate environmental awareness, a variety of disposal options have been studied in more detail. The disposal of tailings in a thickened, paste or dry form has become much more common (Davies, 2011; Dixon-Hardy & Engels, 2007; Fourie & Jewell, 2015; Robinsky, 1975; Robinsky, 1978; Yilmaz & Fall, 2017). The disposal of the thickened tailings, rather than the traditional slurry form, requires more knowledge on the rheological properties of tailings (Boger, 2006; Roussel 2007). The so-called paste technique has been successfully used in surface disposal, mainly in warm, arid conditions (Adiansyah et al., 2015; Dixon & Hardy, 2007; Fourie, 2009; Theriault et al., 2003;). The Geotechnical and rheological properties are well documented, with a good deal of literature available (e.g., Amoah et al. 2018; Hu et al., 2017; Sofrà & Boger, 2011). Still, the effects of cold climate are much less known as there is a shortage of the needed design parameters. Scientific discussion is clearly lacking in this area, considering the frequency of tailing disposal in frigid zones. Therefore, more scientific based knowledge of tailing performance and disposal in cold regions is urgently needed.

1.1 The characterization and surface disposal of tailings

Tailings consist mostly of crushed and milled rock, with some chemicals from the enrichment process (Lottermoser, 2003). Tailings is used as a general definition for all residues from the extraction process. Therefore, tailings have several different qualities depending on the type of mining and the process used. Thus, an understanding of the makeup of tailings plays a vital role. There are some properties common to all tailings, like a level of angularity, a consequence of the crushed rock (Kossoff et al., 2014). There are also, however, many differences between types of tailings, like grain size distribution, which is known to vary and is difficult to generalize (Hu et al., 2017; Kerry et al., 2009; Kossoff et al., 2014). The characterization of tailings will give specific information about the short- and long-term behaviour of tailings (Hu et al., 2017; Kossoff et al., 2014). The document, Best Available Techniques Reference Document for the Management of Waste from Extractive Industries, in accordance with Directive 2006/21/EC, describes thoroughly the best process for characterizing tailings (Garbarino et al., 2018). Several of the geochemical and geotechnical behaviours of tailings must be determined, such as the amounts of trace elements, leaching properties, density, grain size distribution, rheological properties, friction angle, mineralogy, etc. (Garbarino et al., 2018; Hu et al., 2017; Martín-Crespo et al., 2020). Kossoff et al. (2014) have given some examples of the chemical characteristics of tailings and remind us that chemical activity continues after disposal, possibly changing the tailings' behaviour, e.g., forming more harmful compounds through oxidation.

Environmentally, the most critical challenge for tailings disposal arises from their acidity, alkalinity, and susceptibility to leaching (Fourie & Jewell, 2015; Park et al., 2019; Shu et al., 2001). If tailings include sulphur, there is the potential for oxidization, which may have significant effects on the quality of the waters leaching into the surrounding area (Kuyucak, 2002; Lange et al., 2010; Martin-Crespo et al., 2020; Palmer et al., 2015) this is known as acidic mine drainage (AMD). There is theoretical balance between tailings' capacity to generate acid and to neutralise it, known as net acid-producing potential (NAPP) (Jewell & Fourie, 2015). If the calculated NAPP value is higher than zero, tailings are classified as potentially acid forming and, if the value is smaller than zero, they are classified as non-acid forming (Shu et al., 2001). One of the most important tasks is to prevent the formation of AMD, but this has major challenges (Demers et al., 2008; Nyquist & Greger, 2009; Park et al., 2019). Therefore, in some cases authorities have demanded the building of impermeable ponds for the disposal of tailings (Fig. 1). The cross-section of Fig. 1 shows the simplified water balance of a conventional tailings storage facility with an impermeable basal structure in the active mining phase. Even with geomembrane-lined low-permeable basal structures, the challenge of AMD still persists (Finland Times, 2015; Harmon, 2017; Safety Investigation Authority, 2014).

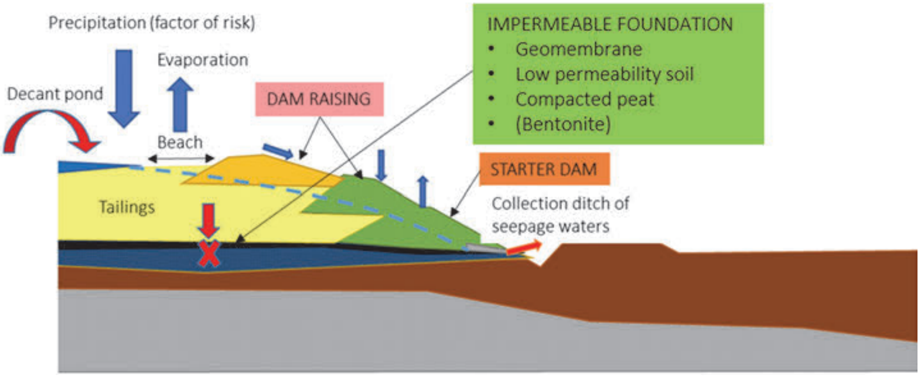


Fig. 1. A conventional method of disposing of mine tailings, as slurry in a tailings pond. In some cases, regulations demand the use of a geomembrane liner at the pond base to achieve low permeability and keep seepage waters away from the surrounding environment during the active phase of disposal (Under CC BY 4.0 license from Paper I © 2021 Authors).

Historically, tailings were pumped directly into the nearest possible watercourse (Vick, 1990). Nowadays, this is a much less common practice, with 16 mine sites using riverine (RDT) or submarine tailings disposal (SDT) methods in 2012 (Adiansyah et al., 2015). The most conventional method of storage of tailings is hydraulically, as slurry with a solids content of 20–40% by weight relative to the total weight (Fig. 2).

Fig. 2. A conventional method is hydraulically disposing of tailings as slurry into the wide tailings storage facilities using spigots or other pumping systems.

Using the conventional disposal method, tailings storage facilities are expensive to build, they occupy a great deal of space, and the environmental impact, depending on the quality of the tailings, can be high due to the potential of seepage. In addition, there is a risk of dam failures, allowing the slurry to run out into the environment, causing widespread destruction. Examples of this issue can be seen at the Baia Mare in Romania in 2000, at the Mount Polley mine in Canada in 2014 or, latest in 2022 at Shanxi Daoer Aluminum Co. in China, to mention just a few (Byrne et al., 2018; Fourie, 2009; ICOLD, 2001; Kossoff et al., 2014; Lye et al., 2019; Rico et al., 2008; Wise Uranium Project, 2022). The dams around the facility are raised during the operation. The main raising methods are downstream, upstream or centerline (Vick, 1990). The most cost-effective method is through raising upstream and using tailings or waste rock as construction materials. Still, the upstream method is known to create challenges, slurry tailings may segregate and form unstable areas (Azam & Li, 2010; Davies, 2002; Rico et al., 2008; Vick, 1990; Walsh et al., 2021). According to Rico et al. (2008), statistically the frequency of failures is around 20 events/decade.

To lower the risks of conventional slurry-based disposal, newer techniques are available, such as thickened tailings, tailings paste, and dry tailings (cake) (Davies, 2011). In thickening, the water content of the tailings is reduced, with the composition of the tailings changing from a slurry to a dough-like paste. The excess water can then be directed back into the process and does not have to be stored in ponds (Henriquez & Simms, 2009; Sofrà & Boger, 2011; Theriault et al., 2003). In addition, the disposal of tailings in a firmer form takes up less space than conventional disposal (Fitton, 2007; Seddon & Fitton, 2011). This avoids the need for large amounts of water and high dams and reduces the potential of leaching water flowing into the environment. Nevertheless, there are still issues connected with these techniques. A lack of knowledge and experience, e.g., of using the techniques in rainy (Liu et al., 2016) or cold climates (Alakangas et al., 2013), has limited the use of these techniques. The main obstruction to the uptake of tailings thickening is that it requires mining companies to invest more capital annually (Schoenberger, 2016).

1.2 Effects of cold climate on disposal conditions

The Earth can be divided into climate types, usually done using the Köppen-Geiger system (Geiger, 1954). Cold climates can have several sub definitions, like polar climates, ice cap climates, tundra climates, sub-Arctic climates, and continental climates. Fig. 3 shows the Earth classification based on the Köppen-Geiger system, with the sites of existing mines visible. The presence of snow, ice and freezing temperatures creates special boundary conditions for mine operation, such as employee safety, the durability of the machinery, and environmental impacts.

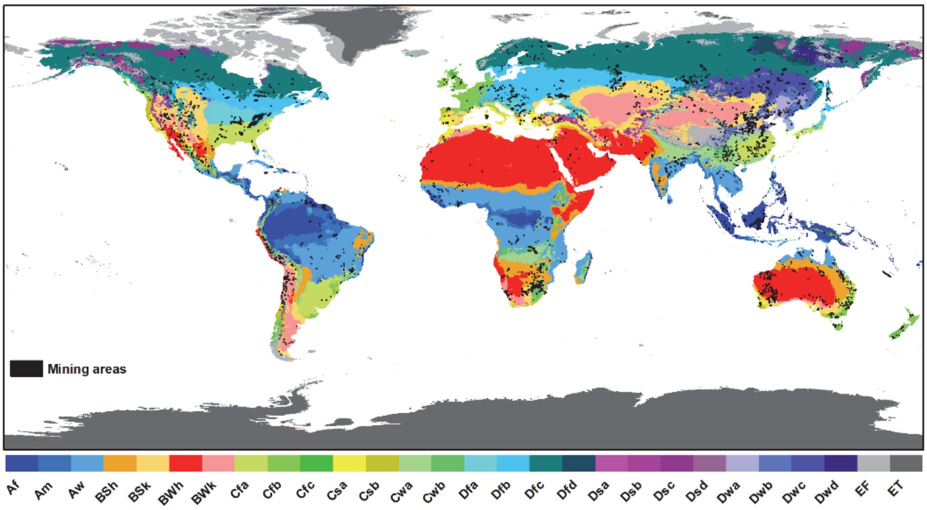


Fig. 3. Visible mine locations globally and climate divisions according to Köppen-Geiger classification of the five main groups: A (tropical), B (dry), C (temperate), D (continental), and E (polar), with several subclasses. Regions starting with D and E are areas where the temperatures may be under 0 °C for at least part of the year (Figure: Anssi Rauhala, climate zone data under CC BY–NC 4.0 from Beck et al., 2018, mining area data under CC BY–SA 4.0 from Maus et al., 2020).

Soil frost occurs in Arctic or sub-Arctic areas when the temperature stays below 0 °C for several months, causing the ground water to change from liquid to ice. Freezing causes the water to expand and, thus, may cause changes in the soil body. This phenomenon, known as frost action, has an impact on the structures' performance. Frost penetration and frost heave are the main results of frost action. Frost action may increase the seepage or consolidation of materials by affecting the permeability or density of the soil (Dagli, 2017; Peppin & Style, 2013; Robertson & Clifton, 1987). The generation of frost heave needs 1) cold temperatures, 2) the material involved to have frost susceptible properties and 3) free available water (Dagli, 2017; Konrad & Morgenstern, 1981). Some results of frost action can be beneficial, but some are harmful for the structure. For example, in the construction of infrastructure, there may be severe economic losses due to frost heave (DiMillio, 1999; O'Neill & Miller, 1985; Xu et al., 2019). Damage caused by frost action are known to correlate with the frost susceptibility of material (Dagli, 2017). Therefore, soil frost and the sensitivity of material to the frost must be investigated and acknowledged when designing structures (Adajar & Zarco, 2013; Dagli 2017).

Effects of surface disposal of tailings

Above is discussed the environmental impact of the disposal of slurry tailings, with dewatering given as an option for decreasing the effects on the environment. Under cold climates, specific challenges are known to arise, e.g., due to the lower water content of tailings as this complicates the transportation of tailings dramatically. When there is a smaller amount of water, the tailings freeze quicker, which can easily clog the transport and pumping system (Alakangas et al., 2013; Kam et al., 2011; Knutsson et al., 2018). One of the major positives of disposing of tailings as paste or cake was the need for smaller embankments around the facility. In snow-rich places, the amount of released water from thawing snow can be high during the melting period. The melting water must be forwarded safely out of the facility. If the facility has a lower embankment, the capacity for storing melting waters can be limited or low. If there is a potential for overflow, there is a higher likelihood of stability problems or failures.

The permafrost situation around the facility also poses challenges. The deposition rate of tailings is known to affect the generation of permafrost (Knutsson et al., 2018). When deposited in layers of tailings, some frozen tailings do not have time to melt during the summer. This is something that needs to be considered, especially around dams or under the raised dam. If the permafrost melts later (e.g., as a consequence of climate change), the pore water pressure may increase, which reduces effective stress and increases the water content, thereby weakening dam safety or causing more undesired settlements (Glotov et al., 2018; Knutsson et al., 2018; Kääb, 2008). Therefore, the presence of snow and ice create challenges for the technology (Fig. 4) and more research from the field is needed (Alakangas et al., 2013; Knutsson et al., 2016).

Fig. 4. The presence of snow and ice causes issues for the design and operation of tailings storage facilities (Photo: Johanna Holm Boliden Kevitsa).

However, the disposal of tailings should not be the only factor to consider. Circular economy solutions should be promoted in the case of tailings. There has been an increase in discussions around finding new ways of utilizing the left-over material produced by mining (Dong et al., 2019; Mahmood & Elektorowicz, 2018a). Even now, tailings are already being used as road construction materials (Mahmood & Elektrowicz, 2017, 2018b) or on-site filling materials (Deng et al., 2017; Fall et al., 2008). Park et al. (2019) have found the recycling of mine waste to be one potential strategy for lowering AMD generation. In cold areas, where the distances can be markable, tailings could offer one promising construction material if the material requirements are fulfilled. Though this requires a full understanding of the tailings mechanical and chemical behaviour. Factors like soil frost performance and the presence of snow would still need to be taken into consideration when recycling tailings.

1.3 Geotechnical monitoring in mine tailings

Geotechnical engineering as a field of science can be described in several ways. It can be seen as a sub-discipline of civil engineering and can be defined as “the use of earth material (soil and rock) for improving and defending society and life” (Alderton & Elias, 2020). The other explanation is that “Geotechnical engineering is the systematic application of techniques which allows construction on, in, or with geomaterials, i.e., soil and rock” (Eslami et al., 2019). According to Eslami et al. (2019), geotechnics cover several professional fields, like Geology, Structural Engineering, Mechanical Engineering, Hydraulic Engineering, Earthquake Engineering, Environmental Engineering, Construction Engineering, Transportation Engineering and Structural Engineering. In turn, the word monitor is explained as “to watch and check a situation carefully for a period of time in order to discover something about it” (Cambridge dictionary, 2021). Through their combination, geotechnical monitoring can observe and perform several monitoring tasks (Dunnicliff, 1993). In the case of monitoring mine tailings, potential risks in the operation phase have been identified as i) the leaking of the tailings slurry pipeline, ii) geotechnical failure, iii) TSF overflow, iv) seepage through containment walls, v) seepage infiltration into ground water, vi) dust or gas emission, vii) the interaction of wildlife or livestock with tailings and viii) mine acid pollution into the ground and surface water (Adiansyah et al., 2015). After the closure of the tailings site, the continued risks include the erosion of containment walls, spillway failure, overtopping by rainfall run-off and the failure of the land cover system on the tailings’ surface (Adiansyah et al., 2015; Laurence, 2001). In addition, it is important to monitor sites at the construction phase, this is known as construction quality assurance (CQA) (e.g., Darilek & Laine, 2001). Generally, there are three main reasons for monitoring: a) safety assurance, b) the validation of design assumption, and c) scientific experimentation and research (Ding & Qin, 2000).

Traditionally, data has been collected manually on site. Recently, automatization has offered advanced possibilities, like the inclusion of early warning systems in parts of the on-line monitoring system (Carri et al., 2021; Clarkson et al., 2021; Hui et al., 2018). In practice, several sensors and methods are used for monitoring tailings storage facilities and similar structures (Caduff et al., 2014; Ding & Qin, 2000; Dunnicliff, 1993; Hui et al., 2018). The methods can be divided into two group, geodetic (surveying) methods and geotechnical methods. The geodetic survey offers multiple options for monitoring deformations, the most typical solution being the use of a Global Navigation Satellite System (GPNSS), with the most used system being the global position system (GPS). In the field, the most typically monitored parameters are hydraulic head or pore water pressure with piezometers or pore water gauges, displacement with an inclinometer, settlement cells, vertical extensometers, radio detection and ranging (RADAR) and light detection and ranging (LiDAR), temperature sensors and weather stations, and the measuring of vibration. However, in the case of TSFs, sampling and water chemistry is at the centre of monitoring.

Furthermore, remote sensing offers an enhanced possibility of improving monitoring (Caduff et al., 2014; Colombo & MacDonald 2015). Compared with traditional in-situ measurements, remote sensing efficiently maps larger areas at a low cost. There are several applications developed for monitoring subsidence (e.g., Eyers & Mills, 2004; Necsoiu & Walter, 2015; Samsonov et al., 2013), slope stability (e.g., Agliardi et al., 2013; Herrera et al., 2010; Salvini et al., 2015) or environment (e.g., Riaza et al., 2011; Swayze et al., 2000; Zabcic et al., 2014). Recently, further technological development has made new approaches available, like IOT-based (Carri et al., 2021) or deformation controlling based methods using Intelligent Optimal Algorithms (Feng & Liu, 2019). Tolvanen et al. (2019) have pinpointed some cornerstones for future research, such as the impact of climate change and sustainable standardized monitoring in Arctic mining. However, the most important aspect is to ensure that monitoring is designed and implemented in a way which minimizes risk during the life cycle of the monitored structure.

1.4 Research objectives

The main objective of this thesis was to increase knowledge around mine tailings' performance under cold climate and to study the safety and monitoring of tailings disposal from a geotechnical perspective (Fig. 5). The thesis was focused broadly onto improving the safety of tailings storage facilities, not purely focussing on dam safety, which is often the only focus. Two frameworks were developed (Papers I and II) to improve the construction quality of tailings storage facilities and to address tailings' frost behaviour and enhance the utilization possibilities of tailings. The thermal regime simulation was used as a tool for predicting the frost penetration in the tailings regime and helping the management of safe tailings storage. In the final stage, the capability of drones was tested as a surveillance method in order to find cost-effective methods of producing data for stakeholder use. The research is divided into four main parts, these parts are focused on in detail in Papers I–IV.

I **By sealing the bottom of tailings ponds with geomembranes, is it possible to improve the safety of tailings disposal?** Where the main aim was to identify design requirements, guidelines, or recommendations for the use of geomembrane structures in the tailings storage facility. In addition, the goal was to improve the project management of the building of tailings storage facilities and built a framework to continue this work.

II **Do tailings show a similar freezing performance to natural soil material?** The frost properties of four different metal mine tailings were tested and the results were compared with natural soil testing assessment. Based on the results, a framework was proposed for assessing the frost behaviour of metal mine tailings.

III **Can we influence the presence of freeze layers through the modelling of a tailings disposal technique?** The developed one-dimensional geothermal simulation model was tested and evaluated using the field data gathered from Laiva mine. This simple model was used to predict temperatures and frost front positions on the tailings' surface. The intention was for the method to help predict the temperatures and frost lines during disposal and avoid generating permafrost layers in the heaps.

IV **Does the use of drones improve tailings storage management?** The main aim here was to research the potential of the use of UAV monitoring when observing the movements of the surface in a Nordic tailings storage facility. Four UAV campaigns were performed between the years 2015–2017. Digital elevation maps (DEMs) and point clouds were generated from the data. The settlements were estimated with DEMs of Difference (DoDs) and the accuracy of the method was clarified.

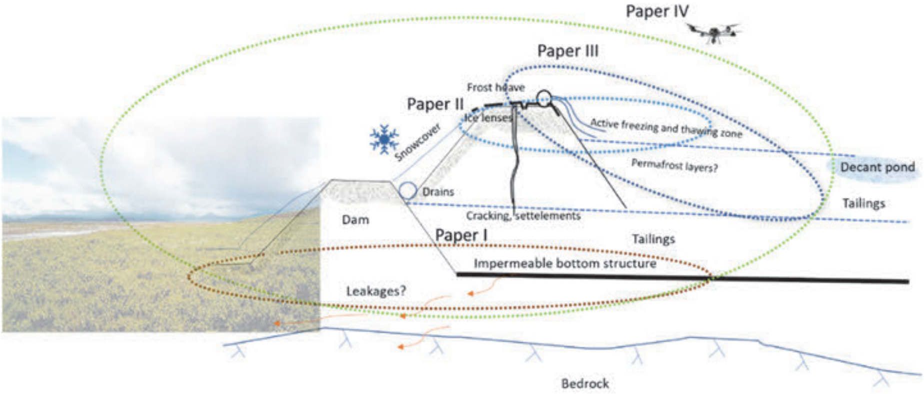


Fig. 5. Conceptual cross-section of a typical tailings pond with the areas of focus for each paper shown (Papers I–IV).

2 Materials and methods

This chapter introduces the materials and methods used to answer the research questions (see Section 1.4). First the study sites are described. Next the field measurements and data acquisition are outlined. Finally, the methods used are explained. Review-based analysis was used for detecting the main findings for the sustainable use of geomembrane lined bottom structures (Paper I), the material characteristic of knowledge acquisition of tailings frost susceptible behaviour (Paper II), thermal regime simulation (Paper III) and remote sensing (Paper IV) for improving the management of tailings disposal.

2.1 Description of study sites

The field studies were carried out in four different mine sites in northern Finland and Sweden (Fig. 6). The study in the Laiva mine Raahe tailings storage facility was focused on understanding the geotechnical phenomena at different time slots, and the data collected was used further in the freezing studies and settlement analyses (Papers II, III and IV). The studies at the Kevitsa mine in Sodankylä, the Aitik mine in Jälliware and the Sotkamo silver mine in Sotkamo were used to compliment the data from the Laiva mine (Paper II).

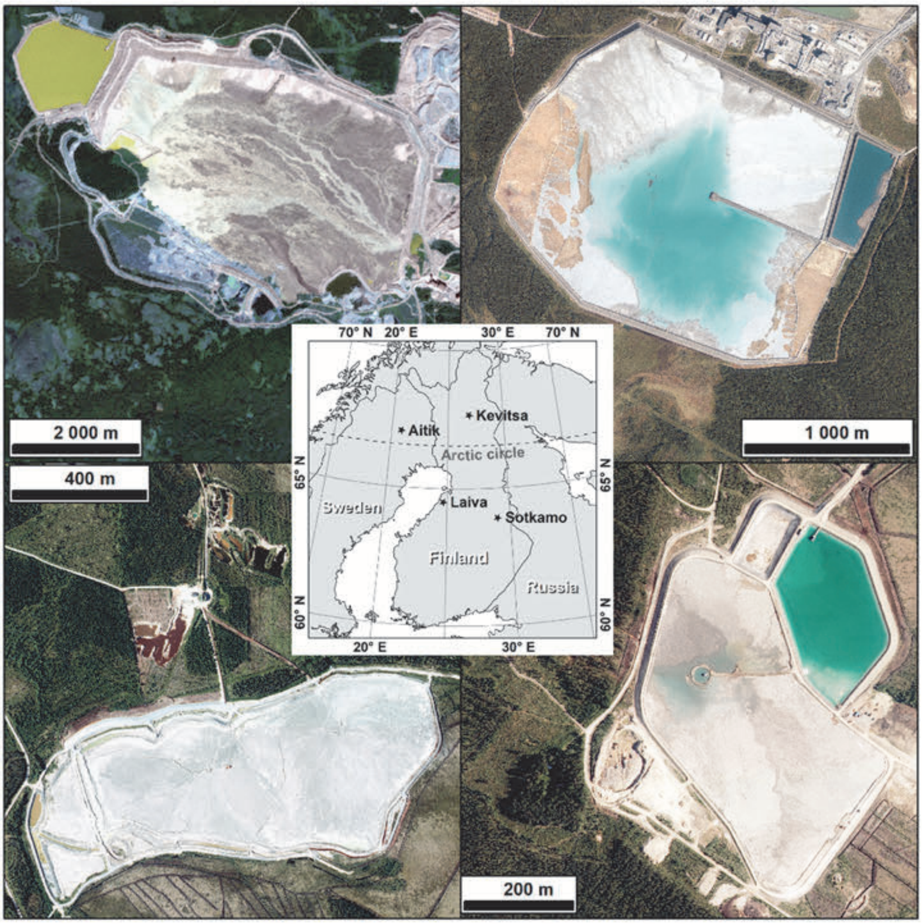


Fig. 6. The research study sites, in the upper left is the Aitik mine tailings storage facility (TSF), the upper right is the Kevitsa mine TSF, the bottom left is the Laiva mine TSF, and the bottom right is the Sotkamo Silver mine TSF, which was opened after the research studies were conducted (Satellite image data under CC BY-SA 3.0 IGO licence from European Space Agency, 2020; Aerial image data under CC BY 4.0 license from National Land Survey of Finland, 2020; Central map under CC BY 4.0 license from Paper II © 2021 Authors).

Every mine site was unique, but subjects were overarching. All mines were in the Arctic region near the Arctic Circle where the distance between mines varies from 60 to 320 km. Three of the mines were in Finland and one in Sweden. The mines produced metal minerals, mainly focusing on gold, nickel, copper, and silver. The mean temperatures varied from −9.3 to −14.6 °C in January; the coldest temperatures where at the Aitik mine. The mean permanent snow cover duration in the region lasted around 5–7 months, lasting longer in the North (Pirinen et al., 2012; Sveriges meteorologiska och hydrologiska institut [SMHI], 2019). Therefore, all selected study sites had the potential for soil frost, man-made permafrost or even natural permafrost. The tailings composition and the disposal methodology used varied from mine to mine. The thickened tailings disposal method was used in the Laiva mine, while the other three mines used the more convention slurry-based method. The selected disposal method was known to affect several geotechnical aspects in the tailings storage facility, such as the segregation of tailings, which meant that the properties of the tailings could change even within the same facility. The mines are described in greater detail in Papers II–IV.

2.2 Field measurements

2.2.1 Soil sampling (Papers II, III)

All samplings were carried out between 2014–2017. The sampling methods differed between the mines. In the Laiva mine and Kevitsa mine, samples were excavated from the pond areas (Fig. 7), while the sample from the Aitik mine was taken from the outlet delivery pipe of the tailings pond. At the soil sampling period, the Sotkamo Silver mine had not yet started major production, consequently, the sample was gathered from the pilot process instead. After the sampling, the samples were stored in vessels in dark conditions and retained in the refrigerator (+4 °C) in the geotechnical laboratory at the University of Oulu.

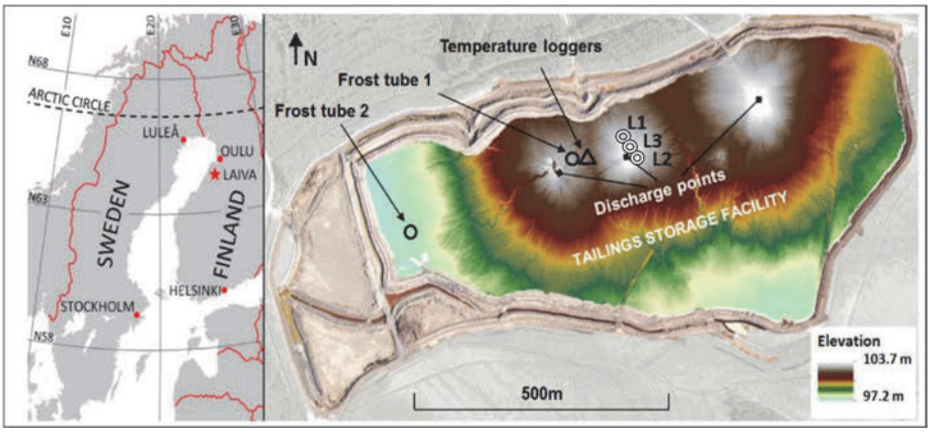


Fig. 7. The main samplings and in-situ measurements were gathered from the Laiva mine's tailings storage facility (Under CC BY 2.5 license from Paper III © 2021 Authors).

Geotechnical measurements were carried out in the Laboratory of Oulu. For each sample, initial water content was determined by drying a portioned sample in the oven at 105 °C. Water content was then calculated using the equation

$$w = \frac{m_w}{m_s} \times 100\%, \tag{1}$$

where m_w is the mass of water and m_s is the dry mass of the sample. The grain size distribution was measurement by sieving according to a standard SFS-EN ISO 17892-4:2016. A SAHI capillary meter was used to measure the capillary rises of the samples, with a tube width of 52 mm.

2.2.2 Thermal field measurements (Paper III)

The thermal field measurements were conducted in the Laiva mine from 2016–2017. The temperature distribution of the tailings was monitored using one set of temperature sensors and two frost tubes (Fig. 8). The frost tubes, known as Gandahl frost depth indicators, were installed in the autumn of 2016. The Gandahl method is described in detail by Gandahl (1963), and the accuracy of the method is discussed more closely by Andersland and Ladanyi (2004). The main principal of the method is that horizontal heat transfer can be used to monitor freezing conditions from an indicator column which correspond with the freezing level in the ground (Gandahl, 1963).

In addition, at one study point, temperature data loggers with Onset HOBO UA-001-08 were installed. In the datalogger was a set of 11 loggers, which were located below the tailings cover at intervals of 0.2 m. Fig. 8 shows the data loggers. Inside a plastic pipe, the foam rubber insulated loggers were attached into hollowed cavities.

Complimentary data, such as air temperature and snow cover depth, was taken from the Raahe Lapaluoto (temperature profile) and Siikajoki (snow depth observations) weather stations of the Finnish Meteorological Institute (FMI, 2017). The municipality of Siikajoki is located approximately 25 km to the north-east and Raahe, 21 km to the west of the mine site. Although these locations were slightly different from the studied area, they were close enough for the purpose.

The data from the frost tubes was collected once a week with the help of Laiva mine personal. The readings were read from the pipe column. According to Andersland and Ladanyi (2004), the reading accuracy is about 5 mm. An issue with the method was the lack of a temperature profile and impossibility of measuring thaw penetration (Iwata et at., 2012). Because of this, temperature sensors were installed, and data was collected every fourth hour to get a continuous temperature profile from the tailings. The accuracy of the specification was set to be ±0.53 °C and a sensor resolution to 0.14 °C. The combination of methods complemented each other.

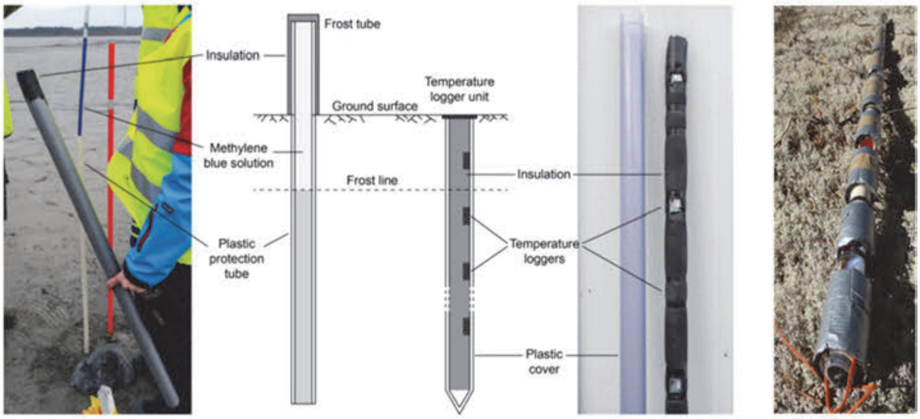


Fig. 8. Left: Frost depth measurements using a frost tube. Right: Temperature loggers (Under CC BY 2.5 license from Paper III © 2021 Authors).

2.2.3 UAV campaigns (Paper IV)

Remote sensing with unmanned aerial vehicles (UAV) was conducted to study possible cost efficiency enhancements for the environmental monitoring of tailings storage facilities. The UAV campaigns were carried out during the summers of 2015–2017. Detailed information about the campaigns, such as the drones used, operator, type of camera, flight height and speed, number of photos, achieved ground resolution, number of ground control points (GCPs) and the measurement device used, is collected in Table 1. The flight operator was changed once because it was deemed unnecessary to use an operating company from Norway. The flight height varied from 150 to 300 meters. In addition to drone flights, 12 to 20 ground control points (GCPs) were measured to improve the accuracy of later produced digital elevation maps (DEMs) by using an RTK GNSS receiver (Fig. 9).

Table 1. The details of UAV flights during the summers of 2015–2017.

Detail	Year and Month			
	2015 August	2016 July	2017 June	2017 August
Drone	a fixed wing aircraft (Cryowing Scout)	a fixed wing aircraft "Observer" developed by Aranica	an Aerotekniikka M-017 fixed-wing UAV	an Aerotekniikka M-017 fixed-wing UAV
Operator	Norut	Norut	Maailmasta Oy	Maailmasta Oy
Camera	a 12-megapixel (MP) Canon Powershot SX260 HS	an 18 MP Canon EOS M camera with a 22 mm lens (~35 mm full-frame equivalent)	a professional-grade mirrorless camera (Sony Cyber-shot DSC-RX1R II) with a 42 MP full frame sensor and 35 mm fixed lens	a professional-grade mirrorless camera (Sony Cyber-shot DSC-RX1R II) with a 42 MP full frame sensor and 35 mm fixed lens
Flight height (m)	~300	~150	~150	~150
Flight ground speed (m/s)	~20	~15	~14	~14
Total number of photos	664	376	894	711
Ground pixel resolution	10 cm/pixel	3 cm/pixel	2 cm/pixel	2 cm/pixel
Number of GCPs	12	15	20	18
Measurement device	a Topcon GR-5 RTK GNSS receiver	a Topcon GR-5 RTK GNSS receiver	a Satlab SLC multi-purpose RTK GNSS receiver	a Satlab SLC multi-purpose RTK GNSS receiver

Fig. 9. Starting the fixed-wing UAV flight (left) and measuring the ground control points using a GNSS receiver (right).

In addition to the GPCs measurements, the collection of ground-truth data was performed around the tailings storage facility in the year 2016 (Fig. 10). The more stable landmarks, the service road and dams, were measured as 189 GNSS ground checkpoints. The data collected was better in terms of accuracy than the data produced later in the SfM (Structure from motion) approach.

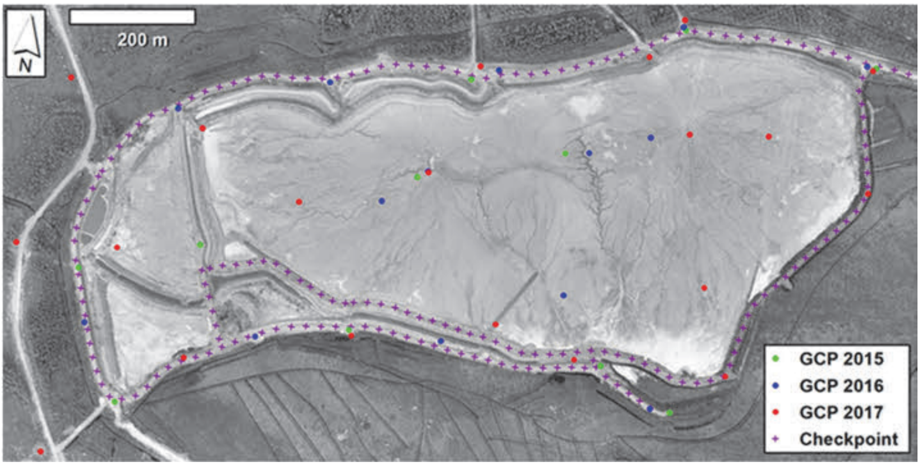


Fig. 10. Orthomosaic of the tailings storage area for the Laiva mine generated from the images gathered during the 2015 survey. Different colored circles indicate ground control points (GCPs) gathered over different campaigns. Purple crosses indicate the locations of the 189 ground checkpoints gathered in 2016 using a Trimble R8 RTK GNSS device (Under CC BY 4.0 license from Paper IV © 2021 Authors).

2.3 Traditional review (Paper I)

A traditional review was applied to study the area distribution of geomembrane-lined basal structures in the mining industry worldwide (Fig. 11). It was used to identify design requirements, guidelines, and recommendations for the use of geomembrane-lined pond structures. Based on a synthesis of the literature review, we outlined the most important structural requirements for the design of geomembrane-lined pond structures. Finally, the framework for an improved design process for geomembrane-lined tailings storage facilities was presented, and limitations and prospects were discussed.

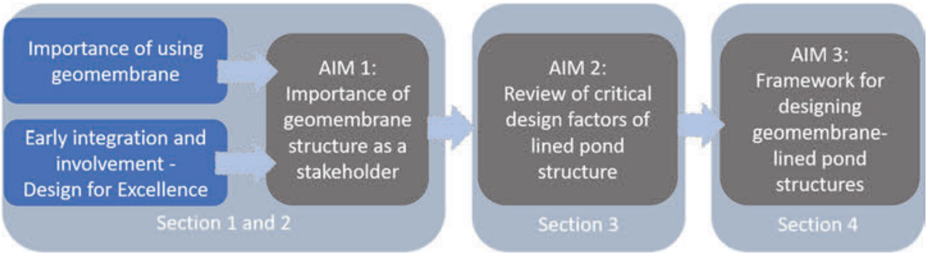


Fig. 11. Flowchart of the work performed in this study (Under CC BY 4.0 license from Paper I © 2021 Authors).

2.4 The frost susceptibility of tailings (Paper II)

The frost susceptibility was potentially determinable using several different methods (Dagli, 2017; Peppin & Style, 2013) if the standardized method was not available. According to International Society of Soil Mechanics and Foundation Engineering Technical Committee on Frost (ISSMFE-TC8, 1989), a rough material frost susceptibility estimation was done by comparing the grain size distribution to the limit boundary lines drawn in Fig. 12. The results were presented in a visual graph. If the draw grain size line crossed the other boundary lines or the curved line was in region 1, the soil was classified as frost susceptible. When the curved line was in region 1L, the soil was classified as having low frost susceptibility. Soils were estimated to be non-frost susceptible when curved line was in area 2, 3 or 4.

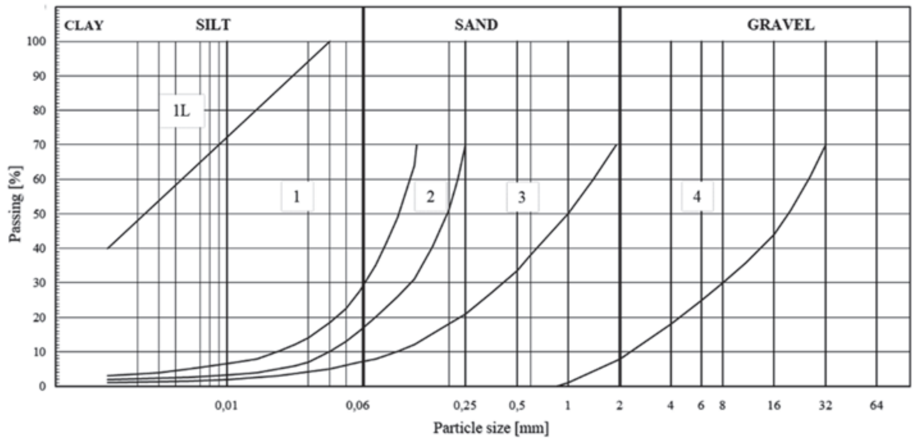


Fig. 12. A rough empirical estimation of soil frost susceptibility can be done using grain size distribution. If the drawn grain size distribution lies in region 1, soil is categorized as frost susceptible, in 1L low frost susceptible and in regions 2, 3 and 4 non-frost susceptible. If the line crosses a regions border, soil is estimated to be frost susceptible (ISSMFE-TC 8, 1989).

A more advanced method was measuring the generation of frost heave using one-dimensional frost heave testing. The disturbed samples were conducted using the frost heave test equipment in the geotechnical laboratory University of Oulu (Fig. 13). The testing method was not standardised, but its use is widely accepted. Dagli et al. (2018) have described the methodology thoroughly and our study corresponded closely to their methodology. The test was mainly conducted in a cold storage room where a constant temperature of +3 °C to +4 °C was maintained. A sample was compared to the 10 cm × 10 cm cylindrical cell to match the conditions in the field. The compaction was done in five layers, using a hand hammer to approximately correspond to the density and moisture in the field. Next, the thermocouples were installed inside the sample to depths of 0 mm, 15 mm, 35 mm, 55 mm, 75 mm, 95 mm, and 100 mm, respectively. The installed sensors measured the temperature data from the sample. After preparation, the cylindrical cell was set into the test equipment. To simulate field conditions, a load was added above the sample. During the test and settling phase (at least 20 hours), deionised water was allowed to flow freely around the sample via a porous plate set below the sample. Before the test was started, the sample was thermally insulated. The minimum time for the test run was 96 hours. Displacements were monitored with a displacement transducer (LVDT) from the top of the sample during the test. The cooling unit kept the upper part of the sample at a stable temperature of −3.5 °C and another cooling unit maintained the temperature at the bottom at +3.5 °C.

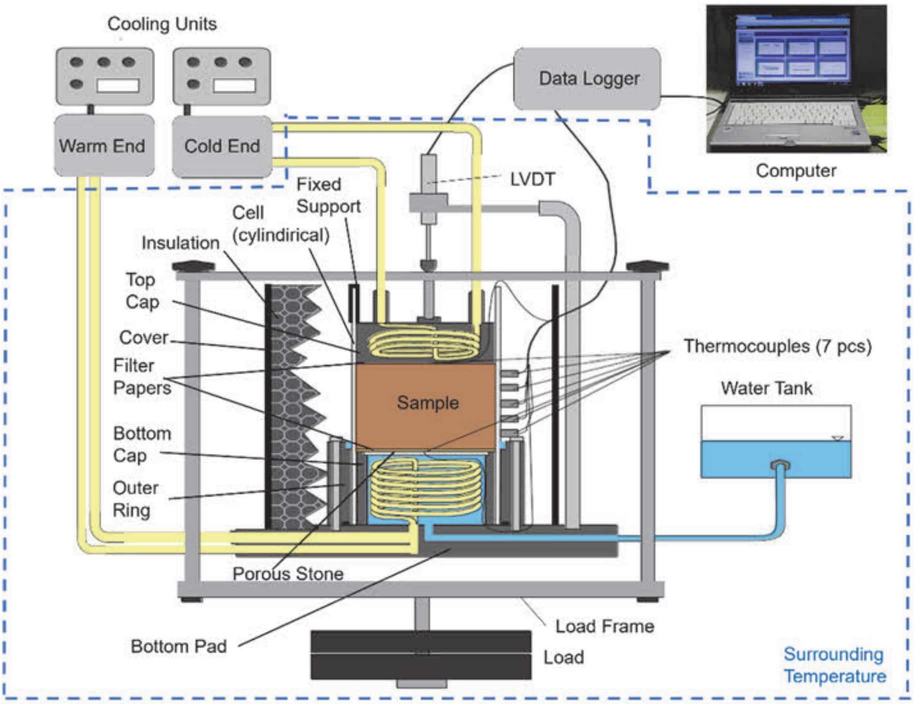


Fig. 13. Schematic representation of the equipment used in frost heave tests (Adapted, with permission, from Dagli et al. 2018 © 2017 Elsevier B.V.).

The segregation potential of the sample was calculated from the collected data using an equation (Konrad & Morgenstern, 1981; Slunga & Saarelainen, 2005)

$$v = SP \times \mathrm{Grad}T, \tag{2}$$

where v is the water intake velocity (mm/h), SP (mm^2/Kh) is the segregation potential matter under calculation and Grad$T$ is the temperature gradient (K/mm) in the frozen fringe by a proportionality constant. A segregation potential calculation was used to estimate frost heave and to classify material according to the frost susceptibility of material. In Table 2, the classifications based on SP values and amount of the capillary rise is shown (Beskow, 1951; Konrad & Morgenstern, 1981).

Table 2. Determination of the frost susceptibility class of a soil type based on segregation potential (SP) value and capillary rise (ISSMFE-TC8, 1989).

Frost susceptibility class	Segregation potential SP (Konrad & Morgenstern, 1981) [mm^2/Kh]	Capillary rise (Beskow, 1951) [m]
Negligible	< 0.5	< 1.0
Low	0.5–1.5	1.0–1.5
Medium	1.5–3.0	1.5–2.0
Strong	> 3.0	> 2.0

2.5 Geothermal modelling (Paper III)

A one-dimensional MATLAB based heat conduction simulation method has been developed by Knutsson et al. (2018) for estimating the geothermal regime in tailings. The input data for the simulation was collected from the Laiva mine (see Section 2.2.2). The model was needed as a boundary condition for air temperature during the simulated time, tailings deposition rate speed and tailings properties. The one-dimensional heat conduction equation is

$$C\frac{\partial t}{\partial t} \pm \frac{L'}{\partial t} - \frac{1}{\partial x}\left(k\frac{\partial T}{\partial x}\right) = 0, \tag{3}$$

where C is the volumetric heat capacity for the soil mixture [J/(m^3 °C)], T is temperature (°C), t is time (s), L' is volumetric latent heat (J/m^3), x is the depth from the tailings surface (m) and k is the thermal conductivity of the tailings mixture [J/(s m °C)]. The simplified model assumes that no other energy flow occurs (Equation 3). The tailings' thermal properties (Table 3) were estimated based on the work of Andersland and Ladanyi (2004).

Table 3. Tailings properties and their calculated thermal properties (Adapted under CC BY 2.5 license from Paper III © 2021 Authors).

Input	Thermal conductivity, k W/(m °C)		Vol. heat capacity, C_{vol} J/(m^3 °C)		Vol. latent heat, L' J/m^3
	Unfrozen	Frozen	Unfrozen	Frozen	
S_r = 95% ρ_d = 1.77 t/m^3 w = 19.4% ρ_s = 2.77 t/m^3 q = 57.5%	2.03	3.25	$2.79 \cdot 10^6$	$2.06 \cdot 10^6$	$1.14 \cdot 10^8$

The effect of snow was considered using a thermal resistivity approach. The approach simplified the effects of the interaction between fresh tailings and snow. The model interpreted snow as causing resistance to heat flow on the surface of tailings. Melting was considered to indirectly decrease the measured snow cover. The simulation model and methodology used are described in detail by Knutsson (2018) and Paper III.

2.6 UAV analyses (Paper IV)

The data from four UAV campaigns was further analysed (data collection, see Section 2.2.3) using a UAV-SfM method. The collected image sets were processed using an Agisoft Photoscan program (Fig. 14) to create dense point clouds and digital elevation maps (DEM) using a SfM photogrammetry technique. Measured GCPs were utilized to improve orthorectification in ArcGIS 10.5. In CloudCompare the data sets were further processed to get a better quality of DEMs for the analysis. Around the monitored Laiva mine tailings storage facility, there were a number of stable landmarks, such as a service embankment road and the dams. The embankment road was used in the registration process to improve vertical co-registration. After co-registration finalising, 1 m/pix resolution accuracy DEMs were selected for the data visualization and displacement analysis in ArcGIS 10.5. The displacement analysis was calculated, comparing pixel to pixel with the different time elevation models

$$\Delta Z_{ij} = Z_{ij,1} - Z_{ij,2}, \tag{4}$$

where $Z_{ij,1}$ is the elevation of pixel ij during time t_1, $Z_{ij,2}$ is the elevation of pixel ij during time t_2, and $t_2 > t_1$. The accuracy of the results and the limitations of the method in the sub-Arctic locations were considered.

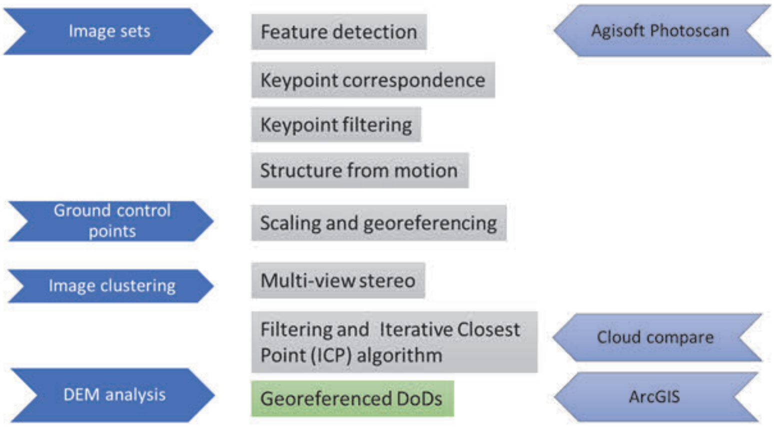


Fig. 14. The main processes for generating DEMs for monitoring the time related displacement analysis of the tailings storage facility.

3 Results and discussion

In this chapter, the main results of the thesis are described and discussed mainly in the order of the original publications (Papers I, II, III & IV). The full descriptions can be found in the original Papers.

3.1 Impermeable bottom structures of tailings ponds (Paper I)

The review (Paper I) summarized scientific knowledge about the use of geomembranes as a part of impermeable foundation structures in tailings storage facilities. Worldwide, geomembranes have been used to improve bottom structures for different purposes, mostly when heap leaching was an issue (Rowe et al., 2013). In Europe, the largest geomembrane-lined tailings pond can be found at the Lisheen Mine in Ireland (Dillon et al., 2004). There is a small number of documents giving information about the geomembrane-lined TSFs (e.g., Akcil, 2002; Cole & Walls, 2014; European commission, 2009; Hillgrove Copper Pty, 2016). Nevertheless, our focus was to find examples of the liners and good practices used in similar operation circumstances to those used in Nordic countries. No examples could be found for Canada, Norway, or Sweden, but they did provide information on applications like dam structures.

In tailings ponds, the main reason for using geomembrane-lined structures was to decrease the permeability of foundations and avoid contaminates and leaching waters entering the surrounding environment. One of the main challenges was found to be the lack of design guidelines, together with inadequate design knowledge. The operation of the selected structure must be done in a way that, if one of the layers fails, either the geomembrane or low permeable mineral layer continues to function. This is why the recommended structure consists of both the geosynthetic layers (geomembrane) and a low permeable mineral layer (Fig. 15). A single-composite liner system was known to be the most typically used structure for tailings ponds and a double-composite liner system was also commonly used for heap leaching, which was used to extract precious metal from ore in some mines.

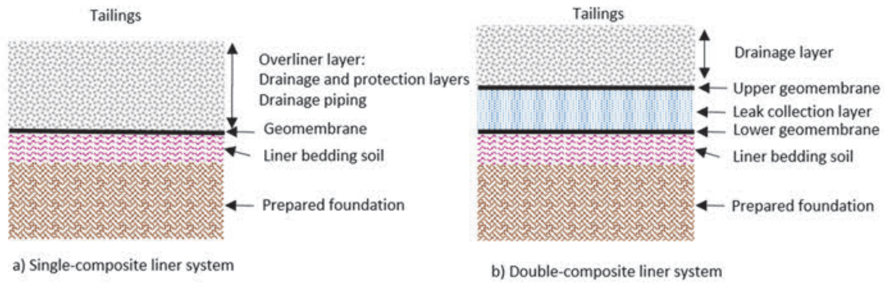


Fig. 15. a) A typical single-composite liner system used in tailings storage facilities (TSF) (Modified from Lupo, 2008), and b) an advanced solution rarely used in TSF, but more common in heap leaching (Modified from Lupo & Morrison, 2007) (Under CC BY 4.0 license from Paper I © 2021 Authors).

Design principles and criteria

In the design phase, several critical aspects, like modelling of seepage water routes, stability issues at the dam (if a dam exists) foundation and heaps, the foundation and drainage structures, and the tension and pressure caused by the load and consolidation of the foundation, must be taken into consideration, as well as the stress caused by the chemistry of the seepage water (Lupo, 2010). Therefore, the drainage layer plays a critical role in the structure in lowering hydraulic pressure while improving the strength and stability of the tailings above.

The drainage layer can be a part of the protective layer. Regularly, the drainage layer consists of natural material, such as sand or gravel (Lupo & Morrison, 2007). The hydraulic conductivity of the drainage layer must be high, and to ensure constant hydraulic conductivity, the layer has to be sufficiently strong to take the load placed on it without disintegration (Fourie et al., 2010). The drainage layer can also contain pipes, and these pipes have to withstand the conditions in the pond. Problems have occurred as pipes have collapsed or become blocked (Lupo, 2008). Lupo (2010) has discussed the factors affecting the selection of the underliner and overliner materials. The entire liner system has to be considered when choosing the materials for the foundation. If design indicates that the structure will not function properly with the selected materials, other materials need to be considered.

A suitable geomembrane must be selected carefully; attention must be paid to the upper and lower layers of the geomembrane. Currently, the following geomembrane materials are favoured: linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polypropylene (PP), ethylene propylene diene monomer (EPDM), and ethylene interpolymer alloy (EIA) (Table 4). Nevertheless, product development may be able to generate better materials in the future.

Table 4. Advantages and disadvantages of typically used geomembranes according to Scheirs (2009) and Fourie et al. (2010), complemented with data on the properties of bituminous geomembranes (BGM) (Cunning et al., 2008; Scheirs, 2009) (Adapted under CC BY 4.0 license from Paper I © 2021 Authors).

Material	Advantages	Disadvantages
HDPE [1]	Broad chemical resistance Good weld strength Good low temperature properties	Potential for stress cracking High degree of thermal expansion Potentially poor puncture resistance Potentially poor multiaxial strain resistance
LLDPE [2]	Better flexibility than HDPE Better layflat than HDPE Good multiaxial strain properties	Inferior UV resistance compared with HDPE Inferior chemical resistance compared with HDPE
PP [3]	Can be fabricated and folded at the factory, so fewer field-fabrication seams Excellent multiaxial properties Good conformability Broad seaming temperature window	Limited resistance to hydrocarbons and chlorinated water
PVC [4]	Good workability and layflat behavior Easy to seam Can be folded, so fewer field-fabrication seams	Potentially poor resistance to UV and ozone Potentially poor resistance to weathering Potentially poor performance at high and low temperatures
BGM	Can be used in challenging climates Not too sensitive to the quality of the upper material Being heavy, it can also be installed in windy conditions The only tools needed for installation are a welding torch and roller	Heavier and thicker (although these can also be advantages) Thickness is a critical factor for good properties The chemical resistance of bitumen
EPDM [5]	Good resistance to UV and ozone High strength characteristics Excellent layflat behavior Good low temperature performance	Potentially low resistance to hydrocarbons and solvents Potentially poor seam quality

[1] High-density polyethylene, [2] linear low-density polyethylene, [3] polypropylene, [4] polyvinyl chloride, [5] ethylene propylene diene monomer.

The relevant properties to be considered were the chemical and temperature resistance of the geomembrane, tensile strength, installation properties, costs, and earlier use experiences (Rowe et al., 2013; Thiel & Smith, 2004). When building the high-quality geomembrane lined structure, the main working stage to focus on was construction quality assurance (CQA). Earlier studies (Darilek & Laine, 2001; La Touche & Garrick, 2012; Lupo & Morrison, 2007; Rowe, 2012; U.S. Environmental Protection Agency, 2001) have shown that using high level CQA created better functioning, less damaged structures. The most critical construction stage was known to be the installation of the protective layer on top of the geomembrane liner. Globally, this is the most common geomembrane integrity method used, according to the American Society for Testing and Materials [ASTM] standard D6747 (Hruby & Barrier, 2017). One way to improve CQA was to install a leak detection system (ELL) to spot potential leakage routes (holes) (e.g., ASTM, 2016, 2020; Gilson-Beck, 2019; Guan et al., 2014). According to Lupo and Morrison (2007) the most important points to be taken into consideration in quality assurance were documentation, and the monitoring of geomembrane installation and the installation of drainage layers, and stress caused by climate.

The main thing missing was judged to be integrated legislation and instruction. Landfill requirements did not perfectly match the needs of tailings ponds. Even with many similarities in design, a few principles differed (Garrick et al., 2014). The unique operational circumstances of mining favors a risk-based approach over exact structural values (Butt et al., 2008; Butt et al., 2014; Høyer et al., 2019). The Authorities could demand the mining industry to lower certain protection levels (e.g., the amount (mg/l) of harmful contaminants that could be released at one time), then designers could create plans using the best available practices (BAT techniques) and show how the requirements would be met. To develop and promote excellent proven solutions, any innovation should be shared and published openly. Nevertheless, sharing poor practice is just as important as it enables similar problems to be avoided in the future.

Generally, several aspects were pointed to as important when constructing geomembrane-lined ponds like tailings storage or heap leaching. In heap leaching, the main purpose was to circulate leachate to collect vulnerable metal-rich solutions. From an economic point of view, it was significant to gather up all the liquid from heap leaching and the geomembrane was needed to maximize circularity. In the case of tailings ponds, the geomembrane-lined basal structure did not enhance the process in terms of economic output. On the contrary, the use of impermeable layers generated extra costs for companies and was one reason to refrain from their use.

The selected basal structure of the pond may affect the designing and costs of closure, as well as the available closure methods. If the aim is to build a compact surface over the pond, it must be possible to reduce the hydraulic pressure in the pond and to remove all free water. This can be challenging if drainage solutions have not been considered during the designing of the geomembrane sealed pond. The function of a compact surface is, above all, to prevent long-term environmental impacts and the formation of acidic seepage water. Overall, the used basal structure should be designed and constructed carefully. Previous research (Joshi & McLeod, 2018) has proven the geomembrane-lined structure lowers the risk of leakages, though the geomembrane still has a high risk of being punctured during operation. Therefore, the composite structure was recommended for use. If the design is created for a certain purpose, the primary purpose should not be changed later without a complete reanalysis/redesign.

3.1.1 Framework for geomembrane-lined tailings ponds

To improve TSFs construction quality and project management, more sophisticated project management logics were developed. In traditional design and construction, the steps were followed one by one. However, early involvement and integration provided the ability to influence the plans and project success (Aapaoja et.al., 2013, Bralla, 1996; Lehto et al., 2011; Olander, 2007). When the project was thought to be more complex, one of the issues was identifying the key stakeholders. The main advantage of early stakeholder involvement was that decisions made early enough reduced unnecessary changes during later development stages, this even lowered costs for the project overall (e.g., Aapaoja & Haapasalo, 2014; Lehto et al., 2011). Dowlatshi (1998) and Valkenburg et al. (2008) have listed several benefits of using early stakeholder involvement, like avoiding poor design, improving construction efficiency and increasing satisfaction with the final product.

When identifying geomembrane-lined tailings ponds as a stakeholder, the importance of the ponds was clear. The main idea of the framework was focused on the ability to influence the successful project and to prevent conflicts arising later in the process. In every project, the main supporting perspectives must be identified. Fig. 16 shows the key perspectives, such as the mining business, governments requirements, nature and society, which arose in the literature review (Paper I). National government requirements played a huge role when harmonious standards and guidelines were missing (Government requirements). Normally, the mining business followed instructions from authorities, e.g., maintaining construction quality at the required level (Mining business). Nevertheless, in a successful project, the meeting of these requirements should be the minimum and there should be a focus on exceeding these requirements. These projects should be made to be environmentally sustainable, with no negative impacts on society (Society).

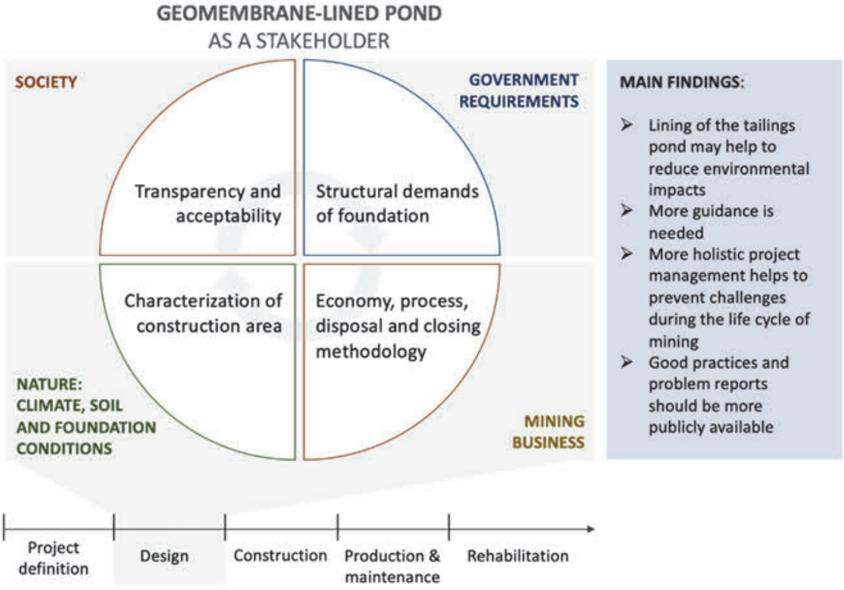


Fig. 16. A framework for identified geomembrane-lined tailings ponds as a stakeholder in early involvement and integration. The key supporting perspectives are identified as i) the mining business, ii) government requirements, iii) nature, and iv) society, which all include several details to be recognised at every phase of mining (Under CC BY 4.0 license from Paper I © 2021 Authors).

By using more sophisticated project management methods, like early involvement and integration, it may be possible to improve construction quality. The exact degree of improvement is difficult to calculate as all mines are unique. In every case, local conditions, material availability, national requirements and know-how differ (Nature). This means that the variety in operational environments makes every project specific, with the actual stakeholders needing to be identified case by case. The mine projects were known to be complex, but by admitting the importance of building tailings ponds, many environmental challenges could be avoided later. The most important part was to understand the meaning of the whole process. Why is it necessary to use the advanced project management methods presented? The main advantage is simply to perceive the critical factors involved in the construction of tailings ponds allowing for the avoidance of harmful consequences later. According to Schoenberger (2016), TSFs can be technically challenging but TSF failures are more political than technical.

3.2 Freezing behaviour of tailings (Papers II and III)

3.2.1 Freezing properties of tailings (Paper II)

The studied tailings samples from four different mines were heterogeneous. Based on the grain size distribution, they were classified according to ISO EN standard (SFS-EN ISO 14688-2) as sandy clayey silt (saclSi), silty sand (siSa) or sand (Sa). The grain size distributions were drawn together with limit curves proposed by ISSMFE-TC 8 (Fig. 17). The results indicated that the samples K1, K2, K3 (Kevitsa mine) and AK 1 (Aitik mine) were non-susceptible and L1, L2, L3 (Laiva mine) and SS1 (Sotkamo Silver mine) were frost susceptible.

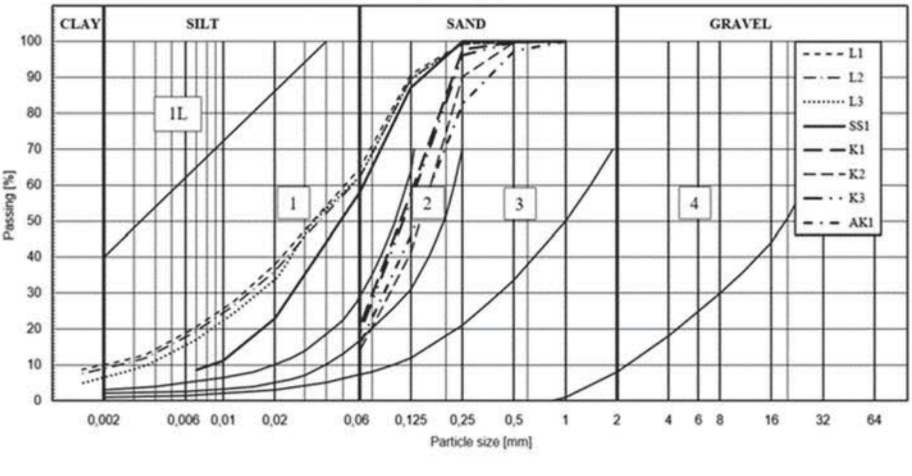


Fig. 17. Determination of the frost susceptibility of mine tailings on the basis of grain size curves according to ISSMFE-TC 8 (1989). Samples in regions 1L and 1 are classified as having low and high frost susceptibility, respectively. Samples in regions 2, 3, and 4 are classified as non-frost susceptible (Under CC BY 2.5 license from Paper III © 2021 Authors).

The observed capillary rise amount varied between 0.66 and 2.05 m. Comparing the results with the guidelines on grain size and capillary rise (Beskow, 1951; ISSMFE-TC 8, 1989), the samples L1–L3 were classified as frost susceptible, SS1 was classified as frost or low frost susceptible and the samples K1–K3 and AK1 as low or non-susceptible (Table 5).

Table 5. Frost susceptibility of tailings samples based on different categorisation systems (Under CC BY 4.0 license from Paper II © 2021 Authors).

ID	Texture classification (EN ISO)	Measured capillary rise [m]	Dry density [kg/m^3]	Overburden pressure [kPa]	Frost heave (96 h) [mm]	Segregation potential (SP) [mm^2/Kh]	Frost susceptibility based on SP (Konrad & Morgenstern, 1981)	Frost susceptibility based on grain size (ISSMFE-TC8, 1989)	Frost susceptibility based on capillary rise (Beskow, 1951)
L1	saclSi	2.05	2145.4	3	23.1	9.7	Strong	Frost susceptible	Strong
L2	saclSi	2.05	2130.1	3	19.9	6.2	Strong	Frost susceptible	Strong
L3	saclSi	2.02	2138.4	3	16.7	3.5	Strong	Frost susceptible	Strong
SS1	siSa	1.35	1666.8	15	1.7	1.1	Low	Frost susceptible	Low
K1	siSa	1.09	1823.3	3	0.2	0	Negligible	Non-susceptible	Low
K2	Sa	1.07	1813.6	3	0.2	0	Negligible	Non-susceptible	Low
K3	siSa	1.35	1921.0	3	0.6	0.1	Negligible	Non-susceptible	Low
AK1	siSa	0.66	1653.6	3	0.4	0.1	Negligible	Non-susceptible	Negligible

In the next step, the more specific frost heave tests were executed for the samples. The measured frost heaves after 96 running hours were between 0.1 and 23.1 mm. Fig. 18 shows the graphs for detected a) frost depth, b) temperature at 55 mm depth in the samples and c) cumulative frost heave during the frost heave tests. The samples' SP values were calculated to vary from 0 to 9.7 mm^2/Kh. According to Konrad & Morgenstern (1981), based on SP values, the samples L1–L3 were classified as strongly frost-susceptible, SS1 had low frost-susceptibility and samples AK1 and K1–K3 were negligibly frost-susceptible (Table 5).

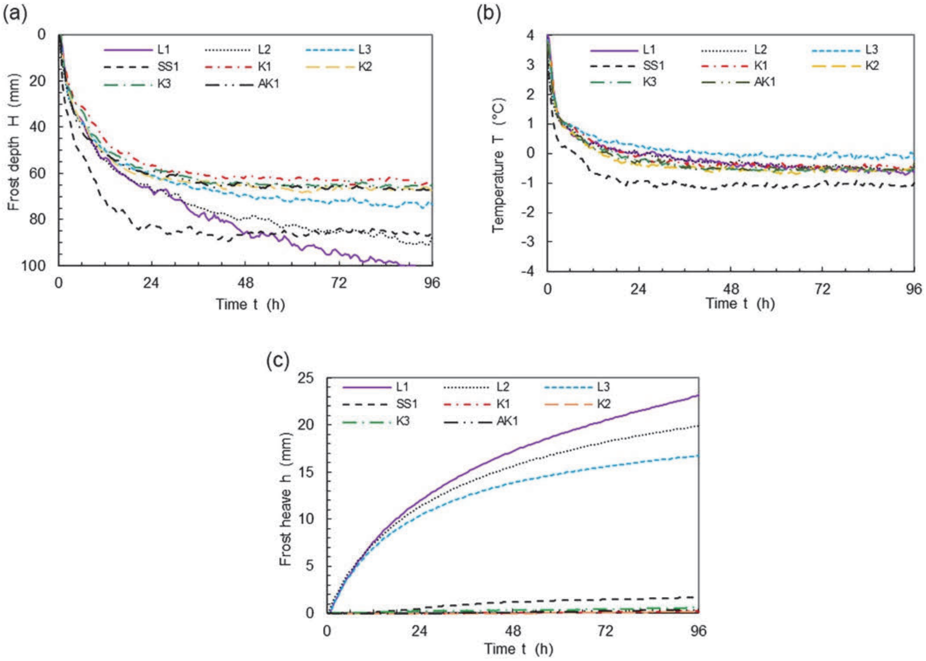


Fig. 18. Progress of a) frost depth, b) temperature at 55 mm depth in the samples and c) cumulative frost heave during the frost heave tests (Under CC BY 4.0 license from Paper II © 2021 Authors).

When comparing the results, it was found that the classifications were mostly in line, though there was some need for explanations (Table 5). It should be noted that unique disturbed samples were used in the different tests, so the grain size distribution may vary slightly due to the heterogeneous nature of material. In addition, other preparations could have affected the results, such as compaction, which can cause minor grinding or deformation (Borgne et al., 2019; Nurmikolu,

2005) this may occur in real constructions site too when the amount of frost heave increases.

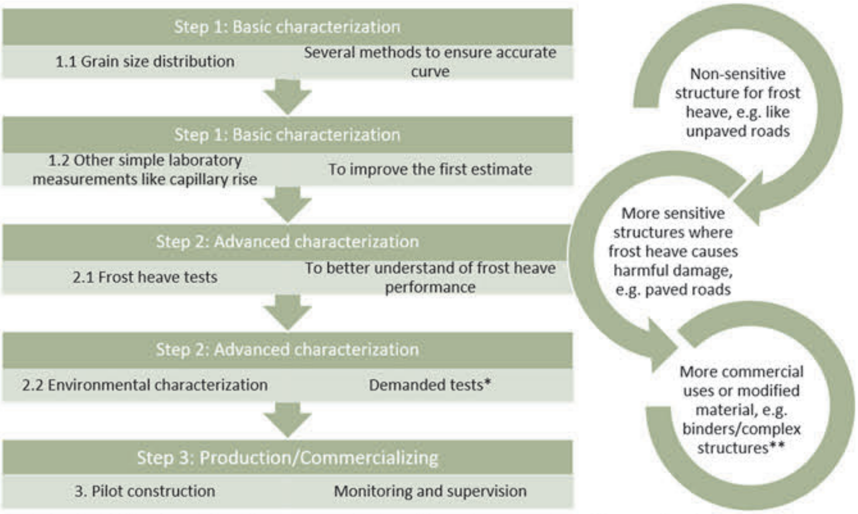
The characteristics of tailings can affect the results. Kerry et al. (2009) and Hu et al. (2017) have reported the difficulties of determining tailings grain size distribution and several methods have been recommended for use. Chemical residues were detected in the tailings. The use of the hydrometer test can be problematic when the process uses chemicals which speed up the settling rate of grains. The hydrometer test uses Stokes' law and used reagents can cause systematic errors in the finer part of tailings grain size distribution. If tailings frost susceptible estimation is done on the basis of too coarse grain size distribution, it may underestimate the potential for frost heave generation.

However, different layers of tailings were observed when slurry techniques were used. Robinsky (1978), Fourie (2009) and Bhanbhro (2014) have discussed the segregation of tailings materials around the pond. Typically, the coarsest material settles near the disposal place and the flow carries the finest material further. This means that frost susceptibility properties can vary across the pond. In addition, the chemicals were noted to have a potential effect on the freezing temperature. If the enrichment process or disposal technique are modified, it may influence tailings frost susceptibility too. After this kind of adjustments in the process, the tailings samples should be retested.

Operational circumstances vary from site to site and temperatures can have cycles in which freezing and melting periods vary randomly. Therefore, the thawing cycle should be studied more closely in future and the frost heave test methodology should be standardized to ensure comparable results from different sources.

3.2.2 Estimation process of frost susceptibility of mine tailings

This section describes how the results of the specific studies (Paper II) can be applied in a general classification of frost susceptibility. Freezing property characterization is started by determining the particle size distribution. Step 1 can be expanded with other basic geotechnical tests, like measuring the capillary rise of the sample (Fig. 19). Characterization is carried out step by step depending on the final aim. For example, in cases where the new material usage is planned to be commercial and wide, all the steps from 1 to 3 should be executed normally. The procedure starts with the basic characterization (step 1), followed by advanced characterization (step 2), finishing with step 3, where the pilot sites are monitored and supervised. In step 2, it is important to ensure that environmental characterization is done as this helps to foresee the effects of using different materials for different purposes. When using material in sensitive sites, like in potential groundwater discharge areas, it is vital to recognise the most critically harmful elements. The applied framework helps stakeholders like producers, designers, or authorities, to clarify the needed experiment levels for the frost susceptibility classification of the material. Currently, circular economy drives researchers to develop new technologies to decrease the amounts of wasted material (Ahmari & Zhang, 2012; Luukkonen et al., 2018; Rao & Liu, 2015). The mixing and use of reactive materials may harden the structure of the product, challenging laboratories to develop new methods to estimate material characterization.



*Check national limit values for harmful substances and other quality requirements for the earth construction sites

**The laboratory testing of e.g., hardened materials may be challenging to perform according to the standards, therefore pilots are needed

Fig. 19. Proposed framework for estimating the frost susceptibility of mine tailings before use in earthworks and other structures (Under CC BY 4.0 license from Paper II © 2021 Authors).

3.2.3 Modelling the depth of the freezing layer (Paper III)

The measured temperatures were compared with simulated ones at examination depths of 0.1, 1 and 2 m. The solid line represented the measurement temperatures from the Laiva mine and the dashed lines simulated values with the minimum snow density of 400 kg/m^3 (Fig. 20). During the summer period the agreement between values was strong (Fig. 20 a). The most challenging period to simulate was at the beginning of winter when the weather and temperatures were variable (Fig. 20 b). At the start of November, the deviation between in-situ measured temperatures to simulated ones was around 1.5 °C, with the temperature at depths of 1 and 2 m being lower in the simulation. Later, the differences between them gradually levelled out (Fig. 20 b–c).

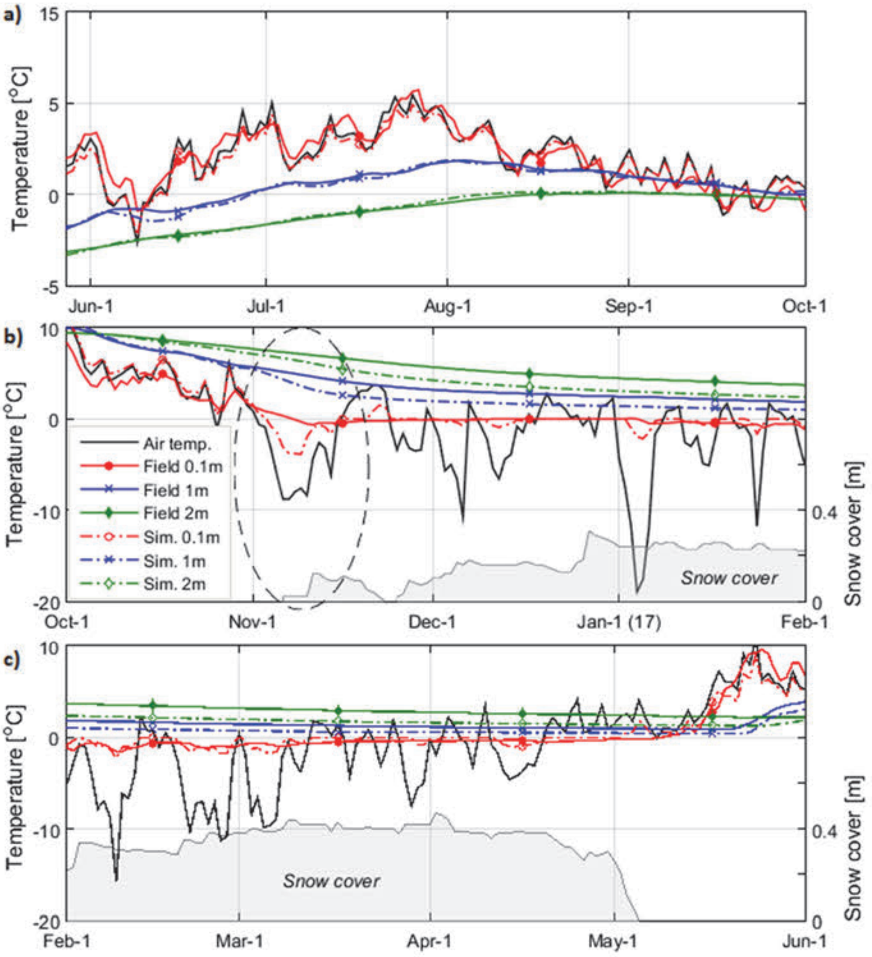


Fig. 20. Field and simulated temperatures from May 28, 2016, to June 1, 2017. The dashed line indicates the largest deviation between field and simulated data (Under CC BY 2.5 license from Paper III © 2021 Authors).

The sensitivity of the analysis results for snow density was studied (Fig. 21). The simulation with a lower density of 200 kg/m^3 developed less frost depths than a density of 600 kg/m^3. The deepest frost depths were achieved with no snow cover. This shows how snow can act as a resistor.

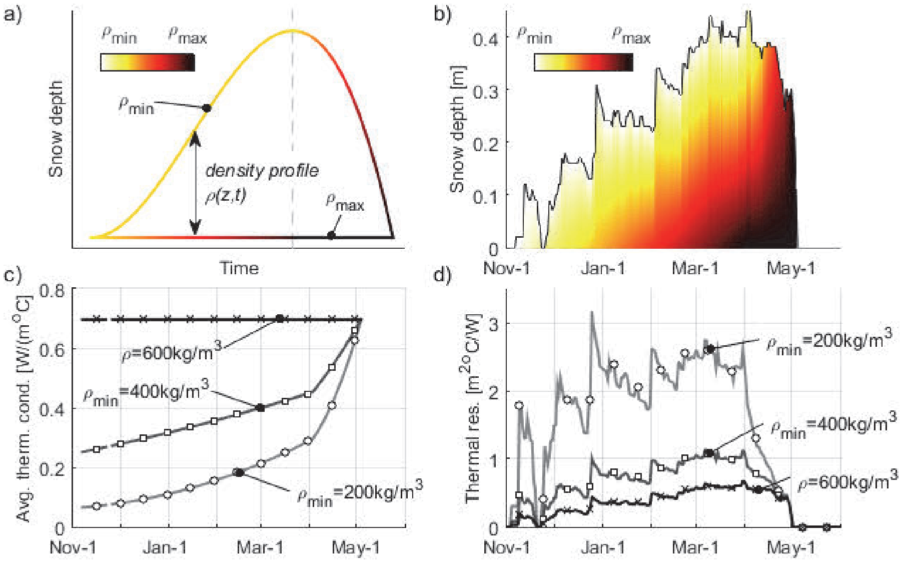


Fig. 21. a) Estimation of snow density (schematic). b) Calculated density variation in measured snow depth. c) Calculated average thermal conductivity in snowpack. d) Calculated thermal resistance of snow for three simulation scenarios (Under CC BY 2.5 license from Paper III © 2021 Authors).

The main simulated error was noticed in early November, when the temperature fluctuated around 0 °C. The simulation showed rapid frost penetration, but this could not be proven using field measurements. Snow cover variation between the observatory station and simulated mine area was deemed to be a possible explanation for this error. In addition, chemical activity was not simulated (salinity, moisture, flocculants, and coagulants) in the disposal of tailings, another reason for it resisting rapid freezing. The difference is reasonable, but done not play a significant role as, for the emergence of permafrost, the rate of frost penetration in early weeks has little effect. Generating layers of permafrost for tailings storage needs a longer freezing period. The other time periods had strong agreement between the simulation results and in situ measurements. The density profile of snow has been estimated (Fig. 21 a) and strongly affects the simulated values. To improving the model functionality, snow depth and density data should be collected from the mining area. The snow density is known to vary during the winter period and the measurement of it is known to be challenging (Bormann et al., 2013, Kinar & Pomeroy, 2015). When temperatures are below 0 °C, snow density stays quite stable, growing as temperatures get higher (> 0 °C) (Bormann et al., 2013). According to Bormann et al. (2013) the density of the snow is usually between 200 and 400 kg/m^3, therefore the simulation with the minimum value of 400 kg/m^3 is reasonable. Although the presented methodology was simplified, according to the results, the developer simulation model seemed to be a promising tool for predicting the thermal regime in tailings deposition. Since the input data needed is limited, the model is practicable in a real mine environment.

3.3 Monitoring tailings ponds with the help of drones (Paper IV)

First, high resolution digital elevation maps (Fig. 22) and dense point clouds were generated. The orthophotos, dense point clouds and raster DEMs were improved over the study years of 2015–2017. The improvements were the results of better camera quality and reduced flight height.

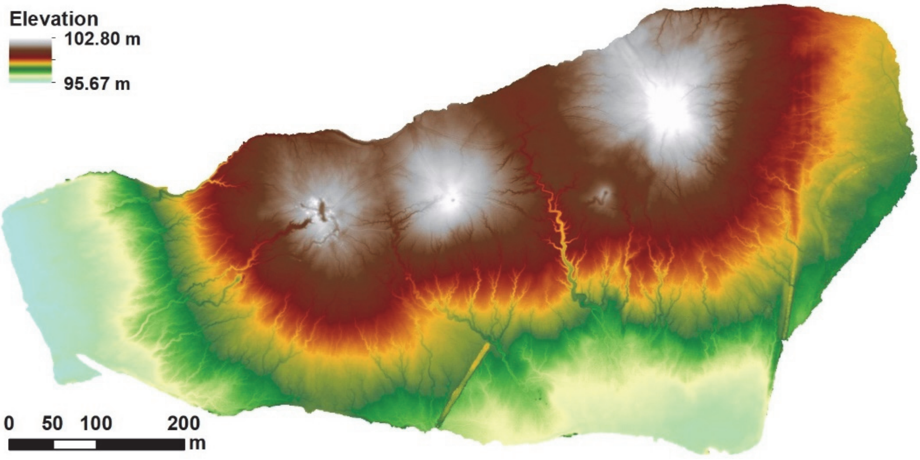


Fig. 22. Digital elevation model of the tailings surface produced from the images gathered during the June 2017 survey (Under CC BY 4.0 license from Paper IV © 2021 Authors).

To monitor the subsidence of tailings storage facilities, DEMs of Difference (DoDs) were created using Equation 4 (Fig. 23). The largest observed values, up to 80 cm of subsidence (see the red area on the map Fig. 23) was noticed to be quite near the disposal outlet pipes. Explanatory factors were judged to be mainly erosion-based patterns due to precipitation and snowmelt, small water ponds where water levels vary or dead treetops. However, in certain parts of the pond, it was found that the tailings surface had risen. This would be expected in the case of an active pond but was unexpected in the case of the tailings ponds where disposal was halted. The accuracy of these results was found to be 99% between −0.12 m and +0.13 m (Fig. 23 c). The erosion which had partly transported tailings material and raised surface levels are shown in green on the map and has another explanation (Fig. 23).

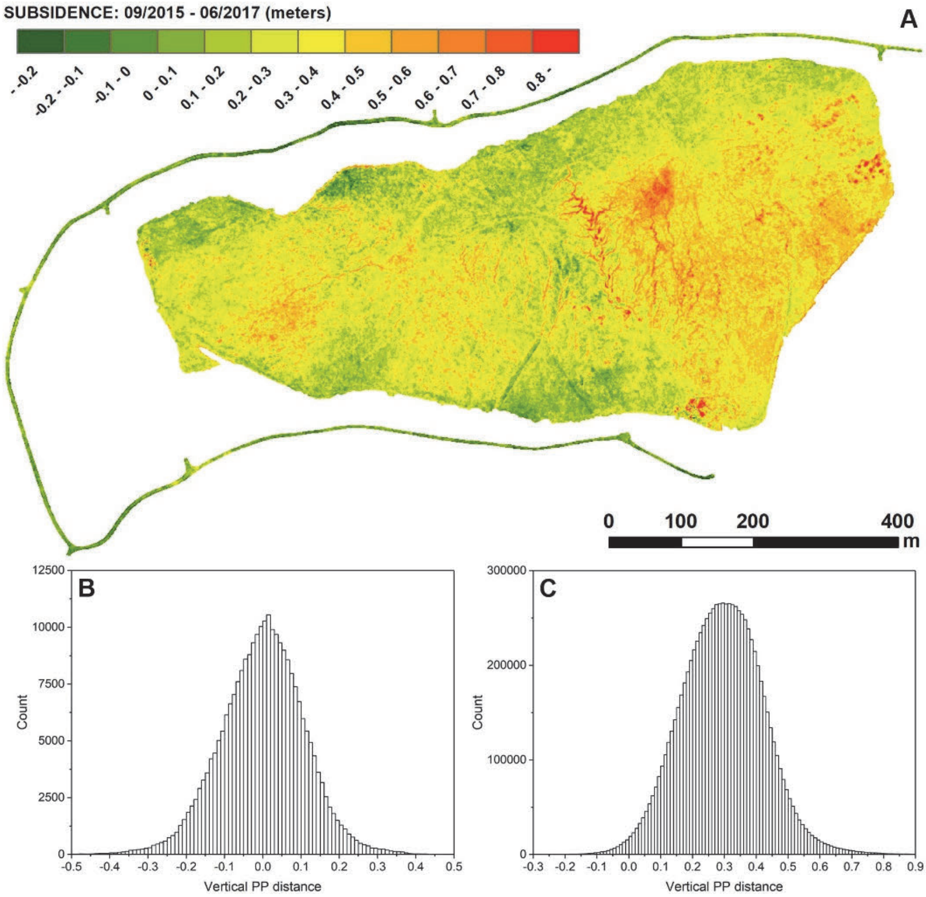


Fig. 23. a) Observed subsidence of the tailings surface between September 2015 and June 2017, b) distribution of point-to-point (PP) elevation differences in the service road, and c) distribution of point-to-point elevation differences on the tailings surface between the 2015 and 2017 point clouds (Under CC BY 4.0 license from Paper IV © 2021 Authors).

Altogether, the main conclusion was made under the assumption that the stable service road level stayed stable (±0 cm change), but the tailings surface distribution shifted +30 cm towards subsidence during the monitoring years 2015–2017. Although no measurement data was available, the main geotechnical process was assumed to be the consolidation and settlement of tailings as operations in the area were otherwise halted. It is noteworthy that depositions lay above the natural peat layer (at a thickness of at least 1 m) which may have compacted under the tailings load. Also, freezing and thawing was known to compact soil material and increase the rate of consolidation (Knutsson et al., 2016).

Nevertheless, the various factors affecting accuracy, such as camera parameters, acquisition parameters, environmental parameters, and processing settings, were taken into account. Some uncertainty in the analysis was caused by the differences between DEMs resolution, where the older dataset had a lower-resolution DEM (20 cm/pixel) compared with the newest generated DEMs (5 cm/pixel). While processing the datasets, it was noticed that the 2016 dataset had too small an overlap with the aerial images. Therefore, the elevation map generated was indistinct, and a comparison between the datasets of 2015 and 2017 was decided on. The other limitation under cold climates was snow cover preventing the visibility of monitoring, shortening the time window for measurements. The method is sensitive to other weather conditions too, e.g., heavy precipitation, storms, and snow-melt water cover. Due to the limitations of the method, we believe that, although it is an efficient method to enhance monitoring, it needs other monitoring systems to supplement it.

The study showed that, with preparation, the method can be affective at gaining excellent quality results. In the study, tailings storage facilities were used as a test area, with drones offering an efficient method for monitoring a vast area. Still, one of the main challenges was the accuracy of the method, meaning its use in the monitoring of dam safety is in question. There are multiple monitoring demands and some of them insist on exact measurements where centimetre accuracy is too vague. Nevertheless, in many cases, the drones offer a fast and cost-effective way of improving management in the facility. In the case of tailings storage facilities, the developed method can improve disposal techniques. The useful aspects were found to be a) mapping of the tailings' surface profile, b) calculating impoundment storage capacity, and c) predicting future needs more specifically, e.g., the need to raise surrounding dams or other maintenance work. In addition, the UAV-SfM method can be a useful tool for focusing on the best locations for tailings disposal across the facility, geotechnically, and for monitoring rising surfaces. It cannot, however, explain the reasons for the changes observed in the facility. The methods used can be expanded to be used outside of just the active operation phase. After the closure of the mine, long-term settlements and movements can be monitored in the planning phase of mapping potential locations for new mine facilities.

As mentioned above, drones can have wider uses with the addition of other instruments or cameras like near infrared (NIR) cameras, hyperspectral imaging sensors or geophysical instruments (Jakob et al., 2017; Negara et al., 2021; Parshin et al.,2021; van der Meer et al., 2012). For example, one way of using thermal infrared (TIR) imaging could be the creation of map of the large mining areas to identify colder spots of water which may otherwise go overlooked. The water temperature is known to correlate with the source of water (groundwater is colder than surface water during summers) (Isokangas et al., 2019). Examples of different UAV methods of exploitation can already be found in the literature and are commercially available (e.g., Banerjee et al., 2018; Colomina & Molina, 2014; Negara et al. 2021; Pajares, 2015; Pierzchała et al., 2014; Wan et al., 2019). Satellite based technologies, e.g., InSAR (interferometric synthetic radar) or DinSAR (Differential interferometry), can offer other fascinating options for improving deformation surveillance systems (Carlà et al., 2018; Colombo & MacDonald, 2015; Cumming & Wong, 2005; Perski et al., 2009). SAR-based technology has advantages like being less sensitive to weather conditions (clouds, dust, daylight or wind) and accuracy in the millimetre range (Colombo & MacDonald, 2015). The main challenges arise from data collection and related limitations. The SAR technique is based on the wavelength, and if two acquisition difference is higher than $\lambda/2$ (effective wavelength), relevant deformation information cannot be detected. Displacement can only be seen in the line-of-sight (LoS) direction related to the satellite orientation and long revisit time can cause further limitations on use (Grebby et al., 2021; Mura et al., 2018). In addition, the processing and handling of data needs efficient computers, storage capacity and specific skills (Grabby et al., 2021; Mura et al., 2018). Since these techniques are not reliable for real-time monitoring, they need ground-based application, at least at the operational phase. Grebby et al. (2021) has shown that satellite-based ground deformation analysis would have helped to identify undesired settlements around the long dam crests and, with the help of satellite-based analysis, could be used to avoid similar failures of tailings dam in the future. Therefore, satellite-based technologies have rapidly evolving potential and applications (Mura et al., 2018).

4 Conclusion and future recommendations

The main aim of the thesis was to enhance the knowledge of mine tailings performance under cold climate conditions and develop the monitoring and safety of tailings storage facilities. Novel methods and approaches were developed for frost susceptibility estimation and the improvement of management in tailings storage facilities. By using these methods, this thesis produced new information about frost penetration of tailings and its simulation, as well as new knowledge around using UAVs for monitoring.

The study confirmed that geomembrane-lined structures are used worldwide. With careful design, these structures reduced harmful loads being released into the environment. The most commonly used structure in tailings storage was the single composite liner system, combined with well-prepared foundation soil with a natural low permeability soil layer and a geomembrane with a drainage layer above. When the importance of building high-quality TSF was understood, the need for a design for this was recognized. With the framework shown in this study, future weak design could be avoided. Further attention must be paid to up-to-date legislation and demands which would help to improve the quality of the design. The mining industry needs guidelines and recommendations, and real-life examples of success or failures to learn from.

The Arctic conditions were known to be a challenge for mining. The studies provided new knowledge of metal mine tailings behaviour under zero temperatures and a framework for identifying material frost susceptibility. The conducted laboratory measurement results indicated how mine tailings behave similarly to natural soil in terms of frost properties. The characterization of grain size distribution of tailings was noticed to be one systematic error source, which can be avoided using several methods together. The lack of standardized freezing test methods was observed to be an issue; this led to the comparison of test results from other sources being impossible. To harmonize the test methods, standardization will play a key role. Tailings were seen to have a significant potential for lowering natural soil material use in construction and increase the circular economy of mines. There were still remarkable challenges created by this utilization, like environmentally harmful leaching substances, but new technologies could help to achieve harmless workable materials. Nevertheless, next generation materials and technologies demand new material testing procedures, which must be validated and implemented. There is one matter which should be taken into consideration when inspecting tailings behaviour further; how do natural circumstances affect the behaviour of materials? Should the testing examination procedure use mining water or rainwater instead of clean neutral water as it done in leaching tests?

A one-dimensional simplified geothermal model was developed to help the estimation of thermal regimes on the tailings surface from a geotechnical perspective to help management of the disposal of tailings. The in-situ measurements were compared to simulated ones. The model was kept as simple as possible to avoid input data problems. The simulated results showed strong agreements when compared with the field measurements. The most challenging simulation period was at the beginning of winter. The simulation error was thought to be due to the tailings including chemical components which were not modelled, in addition to the snow cover differences between the real site and observation area. To carry out further field measurements would be beneficial to develop the model's capacity to simulate freezing and thawing cycles. Also, enhanced properties to follow freezing and thawing cycles and the consequences of these should be added to the laboratory frost heave equipment. Still, if the model is kept simple enough, it can serve as a practical tool for the mine industry and help manage tailings storage by preventing permafrost layers from emerging.

Finally, UAVs were used to gather the data to produce digital elevation models (DEMs) to map movements in the tailings storage facilities between the summers of 2015–2017. The achieved accuracy was around a decimeter. Nevertheless, it was noticed that the model accuracy could be increased with camera quality, flight height and increasing the number of ground checkpoints. The generated subsidence map was useful for observing erosion patterns and could be exploited for volume calculations and tracking surface movements generally. The method was not sufficient or suitable for monitoring dam safety, where the accuracy needed is in the millimetre range. Still, the UAVs potential was clear. The mine areas are huge and often barely accessible. Therefore, the methodology can be utilized for other mine monitoring if the achieved accuracy is acceptable. Current camera techniques and sampling devices offer a huge variety and potential for monitoring other things too, like the quality of water or vegetation, or changes in vegetation, to list just a few.

In conclusion, resource-wise and sustainable mining requires more research. The new techniques should be examined and tested, at least at the pilot scale. Climate change demands that we act as fast as possible. The unnecessary disposal of side material like tailings should be reduced; this can be achieved through the further development and testing of new material treatment techniques. Cold climates cause their own demands for material use and examination of these demands should be normal standardized practice.

Proposals for future studies

Based on the results presented in the thesis and discussed in the literature, the following research topics would further advance the understanding of the sustainable use and disposal of tailings:

- Cold climates cause their own demands for mining and these should be considered. Material frost action tests should be further developed, and the frost susceptibility testing method standardized. The results are not comparable without standardization. Freezing and melting performance should be included in the test apparatuses and material performance must be further investigated.
- Tailings face harsh environments and, to get more relevant knowledge at the laboratory scale, an estimation of the effects of used test water quality would be beneficial. Often clean water must be used according to the standards in the testing, but in-situ, the tailings are circulated with totally different water quality, like rain waters, leaching waters or process waters. Therefore, it would be interesting to test the effect of the quality of water.
- Thermal modelling could be developed by getting more relevant in-situ data. Modern sensors and remote sensing techniques could provide more efficient ways to measure snow density or depth in the field. Inaccuracy in models could be reduced at a reasonable workload and cost.
- During the research, we faced challenges in finding scientifically published knowledge. More illustrative examples of TSF solutions are needed. The knowledge and experience of the longevity of geomembrane lining systems in mining circumstances is missing. The whole industry, not only cold climate areas, demands more information on both successes and failures. With the experience of challenges previously faced, further unsuccessful attempts could be minimized. Globally, this would provide the mining industry with clearer guidelines and examples of what to follow.
- New technologies produce new material structures. Many techniques change the materials’ structure and make materials harden. From a geotechnical perspective, testing these in a traditional way is impossible. To acquire geotechnical parameters, a testing procedure for the hardened mineral material should be developed and standardized worldwide.

- A circular economy for tailings should be the first priority for decreasing the amount of disposed tailings. Currently, tailings are wasted in an unsustainable manner. New innovations are needed to find methods of using left-over materials in an environmentally safe way, decreasing the need for natural soil material.

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