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Cover Figure:

Colour relief illustration of an electrical resistivity imaging (ERI) of a section of the tailings facility at Brukunga mine site, Australia.

APPLIED HYDROGEOPHYSICS FOR CHARACTERISATION OF TAILINGS FACILITIES

RAUL MOLLEHUARA CANALES

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Applied hydrogeophysics for characterisation of tailings facilities

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Abstract

This thesis presents the investigation results of interpreting hydrogeological and elastic properties in tailings storage facilities within the framework of hydrogeophysics.

In this research, two geophysical methods were used for data acquisition: Seismic refraction (SR) and Electrical resistivity imaging (ERI). The application of seismic refraction (SR) and multichannel analysis of surface waves (MASW) was to obtain seismic velocity models (*i.e.*, V_p and V_s), whereas electrical resistivity imaging (ERI) was applied to obtain cross-section models with bulk electrical resistivity data. In this approach, the outputs of the SR method set the geometric constraint for the inversion of the apparent electrical resistivity data in the ERI model.

This research found that geophysical methods such as ERI and SR can retrieve high-resolution data from the subsurface of tailings facilities mapping the structure, the phreatic line, the dynamics of water, and detecting changes associated with the electrical resistivity response of the tailings media.

The thesis also describes the methods and workflow for establishing dependencies between the geophysical signature (*i.e.*, compressional and shear wave velocity models, electrical resistivity models) and the physical and water-related properties of the tailings media. The dependences in the form of empirical equations are key for filling the gap of theoretical deductions.

Furthermore, this thesis contributes to the research field through a unified workflow for integrating petrophysical and 'rock' physics principles in the interpretation of geophysical data in tailings facilities. The interpretation describes and estimates quantitatively the state condition of the tailings subsurface in terms of hydrogeological (*i.e.*, water saturation, water content, porosity) and elastic properties.

Keywords: geophysics, hydrogeophysics, electrical resistivity, seismic refraction, MASW, tailings.

Rikastushiekkojen karakterisointi hydrogeofysikaalisilla menetelmillä

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Tiivistelmä

Tämä väitöskirjatutkimus kuuluu hydrogeofysiikan piiriin, ja siinä tutkittiin rikastushiekan hydrogeologisia ja elastisia ominaisuuksia.

Rikastushiekka-altaiden (Brukungan kaivos Etelä-Australiassa ja Pyhäsalmen kaivos Suomessa) hydrogeofysikaalisia ominaisuuksia tutkittiin kahdella eri geofysikaalisella menetelmällä; seismisellä taittumisluotauksella (Seismic refraction, SR) ja sähköisellä maavastusmenetelmällä (Electrical Resistivity imaging, ERI). Seismisen taittumisluotauksen (SR) ja pinta-aaltojen MASW-analyysin avulla pyrittiin laatimaan tutkimuskohteina olleiden rikastushiekka-altaiden seismiset nopeusmallit (ts. Vp ja Vs), kun taas rikastushiekka-altaiden poikkileikkausmallien laatimiseen käytettiin maavastusmittausaineiston inversiota. Väitöskirjassa toteutetulla lähestymistavalla SR-menetelmän avulla saatiin geometriset reunaehdot näennäiselle inversiolle ERI-mallissa.

Tutkimuksessa havaittiin, että geofysikaalisilla menetelmillä, kuten ERI- ja SR-menetelmillä, voidaan saada resoluutioltaan tarkkaa numeerista tietoa rikastushiekka-altaiden tilasta, ja niiden avulla voidaan kartoittaa muun muassa rikastushiekka-altaiden rakennetta, freaattisen pinnan korkeutta, rikastushiekka-altaiden veden dynamiikkaa.

Empiiristen yhtälöiden muodossa olevien riippuvuussuhteiden selvittäminen on keskeistä, jotta teoreettista lähestymistapaa voidaan soveltaa rikastushiekka-altaiden kokonaisvaltaisessa hallinnassa. Väitöskirjassa kuvataan myös menetelmät ja työvuo, joilla määritetään petrofysikaalisten ominaisuuksien (ts. seismisten aaltojen nopeuden ja sähköjohtavuuden) ja rikastusallasmateriaalien geoteknisten ja veteen liittyvien ominaisuuksien riippuvuus. Näin saatu integroitu tieto kuvaa ja arvioi rikastushiekka-altaan hydrogeologista tilaa (vesipitoisuutta, huokosten kyllästyneisyysastetta ja vapaata huokoisuutta) ja kimmo-ominaisuuksia edistäen ja helpottaen rikastushiekkojen hydrogeofysikaalista karakterisointia..

Asiasanat: geofysiikka, hydrogeofysiikka, sähköinen maanvastusmenetelmä, seisminen taittuminen, MASW, rikastushiekka.

Science is spectral analysis.
Art is light synthesis.

- Albert Einstein

Acknowledgements

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Raul Mollehuara Canales

Abbreviations

ANCOLD	Australian National Commission of Large Dams
AMD	Acid and metalliferous drainage
DEM	Digital elevation model
e.g.	exempli gratia
EMI	Electromagnetic induction
ERI	Electrical resistivity imaging
etc.	et cetera
EU	European Union
GPR	Ground-penetrating radar
GTK	Geological Survey of Finland
HIS	Hyperspectral imaging
ICMM	International Council on Mining and Metals
ICOLD	International Commission of Large Dams
i.e.	id est
IP	Induced polarisation
LDM	Laser distance measuring
LiDAR	Light detection and ranging
MAC	Mining Association of Canada
MASW	Multichannel analysis of surface waves
OMS	Operations, maintenance, and surveillance
PRI	Principles for Responsible Investment
SCPT	Seismic cone penetration test
SI	International System of Units
SIP	Spectral induced polarisation
SP	Self-potential
SR	Seismic refraction
SRT	Seismic refraction tomography
SSR	Slope stability radar
TDR	Time domain reflectometry
TSF	Tailings storage facility
TSFs	Tailings Storage Facilities
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
VW	Vibrating wire
WRDs	Waste rock dumps
D, D_{bulk}	bulk mass density
$\emptyset_s$	solid phase
$\emptyset_{w,f}$	fluid or water phase (also volumetric water content)
$\emptyset_c$	clay phase
$\emptyset_g$	gas (air) phase
σ_b	bulk electrical conductivity
σ_w	electrical of conductivity of the fluid (water)
σ_s	electrical conductivity of the solid matrix (tailings)
σ_c	electrical conductivity of the clay phase
ρ_b	bulk electrical resistivity
ρ_w	electrical resistivity of the fluid / water
ρ_s	electrical resistivity of the solid matrix (tailings)
ρ_c	electrical resistivity of the clay phase
m_w	phase exponent for water

m_s	phase exponent for solid matrix
m_c	phase exponent for clay
m	Archie's law parameter for cementation
n	Archie's law parameter for water saturation
θ	gravimetric water content
φ	porosity
S	water saturation
V_p	P-wave velocity
V_s	S-wave velocity
K	Bulk modulus $[GPa]$,
E	Young's modulus $[GPa]$,
M	P-wave modulus $[GPa]$,
μ	Shear modulus $[GPa]$,
v	Poisson's ratio
γ	bulk unit weight $[N/m^3]$
g	gravitational acceleration $[m/s^2] = 9.80665$

Original publications

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

I   Mollehuara-Canales, R., Kozlovskaya, E., Lunkka, J. P., Moisio, K., & Pedretti, D. (2021). Non-invasive geophysical imaging and facies analysis in mining tailings. *Journal of Applied Geophysics*, *192*, 104402. https://doi.org/10.1016/j.jappgeo.2021.104402

II   Mollehuara-Canales, R., Kozlovskaya, E., Lunkka, J. P., Guan, H., Banks, E., & Moisio, K. (2020). Geoelectric interpretation of petrophysical and hydrogeological parameters in reclaimed mine tailings areas. Journal of Applied Geophysics, 181, 104139. https://doi.org/10.1016/j.jappgeo.2020.104139.

III   Mollehuara-Canales, R., Afonin, N., Kozlovskaya, E., Lunkka, J. P., Pedretti D. (2021). Leveraging active-source seismic data in mining tailings: Refraction and MASW analysis, elastic parameters and hydrogeological conditions, Bulletin of the Geological Society of Finland, In Press. https://www.geologinenseura.fi/fi/bulletin/articles-press

The articles included in this doctoral dissertation are result of a teamwork contribution. For all the articles, I have been the person responsible for the research planning, data acquisition, analysis, interpretation. The preparation of manuscripts was carried out by the author, with co-authors contributing to the analysis and providing feedback and commentaries during the revision process.

Contents

1 Introduction

1.1 Background and research environment

The research work focused on the most significant liability of the mining industry, that is Tailings Storage Facilities (TSFs), a critical mining infrastructure (Kyriakides, 2015) that can cause significant environmental and social impacts if it fails (Rico *et al.*, 2008; Caldwell & Oboni, 2014). In recent years, the industry, regulatory authorities, organisations, and research institutions have worked toward establishing a pathway for an adequate framework to properly design, operate and close TSFs (ICOLD, 2001a; ANCOLD, 2012; United Nations, 2014, 2020; ICMM, 2021). This is enabling the necessary changes for countries to adapt their policies for better management of TSFs and for science and industry to innovate and create technology that is resilient and capable to meet the requirements of tailings environments.

As most of the failure mechanisms in TSFs are caused by hydrological events or the interaction between water and the tailings matrix (Lyu *et al.*, 2019; Clarkson & Williams, 2021), this research leverages knowledge on near-surface geophysics for non-invasive and broad characterisation of the hydrogeological conditions. There is substantial literature supporting geophysical methods for the analysis of processes and subsurface properties relevant to hydrogeological investigations (Hubbard & Linde, 2010). As such, hydrogeophysics in geosciences emerges for characterisation of structures and hydrological processes in the subsurface, for instance, to investigate the geotechnical stability, fluid flow and contaminant transport (USGS, 2013), electrical conductivity, and unsaturated flow (Ma *et al.*, 2015; Mangel *et al.*, 2015), or hydrodynamic parameters in a controlled full-scale site (Chidichimo *et al.*, 2015). In TSFs, several geophysical techniques have been applied with most of these for mapping anomalies within the structure of the dam or dyke. A few applications aim to characterise the internal structure of the impoundment (Sherriff *et al.*, 2009; Cortada *et al.*, 2017; Martín-Crespo *et al.*, 2018) however the interpretation in terms of hydrogeological parameters is not straightforward and is yet to be developed.

The motivation for this research thesis captures the expectations and imperatives that are concerned with monitoring and surveillance systems of TSFs. As conventional surveying techniques are limited to sparsely distributed field data, geophysical methods are good candidates to cover larger areas and retrieve denser datasets. From the literature review, suitable non-invasive geophysical methods for near-surface geotechnical and geochemical investigations are electrical resistivity imaging (ERI), seismic refraction (SR), multichannel analysis of surface waves (MASW), ground electromagnetic induction (EMI), ground-penetrating radar (GPR). As tailings facilities are structures containing material to a depth ranging from tens up to a few hundreds of meters these geophysical methods turned up suitable for mapping the subsurface of these structures. At early stages of the research, the first trials revealed that ground EMI and GPR (airborne applications were not tested) could only map the shallow surface of the tailings (down to a few 3 to 5 meters) with quick dissipation of the signal strength as depth increased. Instead, ERI and SR methods showed more flexibility to target the investigation at greater depths, and

therefore, this research selected these methods to characterise the physical and hydrogeological conditions of the subsurface of TSFs.

The research thesis was conducted at Oulu Mining School, as part of the I4Future doctoral program looking at the application of geophysical imaging and characterisation methods to evaluate and implement innovations made in earth sciences (I4Future, 2016). The research is also in agreement with Finland's mineral strategy and the 2050 vision for mineral resources that promote solutions for global mineral chain challenges, mitigation of environmental impact, and implementation of life cycle thinking (Aaltonen *et al.*, 2017). Moreover, the research aligns well with the EU's guiding principles for managing mining wastes while transitioning from emerging technologies into best available techniques (BAT) (European Commission, 2009). The rationale and motivation of the research find coherence with sustainable mining seeking the integration of advanced technologies.

1.2   Objectives and scope

The main objective of this doctoral thesis is to investigate non-invasive geophysical methods for the characterisation of tailings storage facilities in terms of hydrogeological and elastic conditions. The research was classified into three sub-objectives:
- Investigate near-surface geophysical techniques for mapping the subsurface structure and conditions of the TSF.
- Investigate the relationship between the geophysical signature and hydrogeological and elastic characteristics of tailings subsurface.
- Interpret the geophysical dataset in terms of hydrogeological and elastic properties of the tailings.

2   Literature review

2.1   Tailing storage facilities (TSFs) and the imperatives for management, monitoring, and surveillance

Extractive mining generates approximately 15 to 20 billion tonnes of waste per year including waste rock and tailings (Lottermoser, 2007). In the management of wastes, operators and regulators play an active role in the outcome in terms of stability and long-time performance of disposal facilities. There is much information and codes of practice about how mine wastes should be managed, yet the performance of mine waste facilities continues to impact the environment with consequences that remain beyond the life of the mine. Mine wastes are key features in a legacy landscape that is 'transferred' to coexist with the natural and human environment after a mining operation ceases. Among these, waste rock dumps (WRDs) and tailings storage facilities (TSFs) are dominant. Impacted mining-influenced water is another non-solid category of mining waste.

TSFs are one of the large structures in the footprint of a mining environment. TSFs include the collective engineered structure, components, and equipment involved in the management of tailings solids, and any other mine waste (waste rock, residues) and water

associated with the tailings disposal activity which is not necessarily restricted to the TSF area (MAC, 1998). The main purpose of TSFs is to contain the tailings residue from the ore concentration process that involves particle size reduction to less than 1-2 mm and in the micrometre range. Tailings are transported and deposited in TSFs in several forms such as in slurry, thickened, filtered, or in a paste. The material is very loose, and of low cohesion at water saturation which makes it highly susceptible to liquefaction. The tailings often contain reactive minerals, heavy metals, and residues of chemicals and other toxic substances. When deposited hydraulically, the discharge of tailings forms "beaches" of fine-grained silty deposits that settle and consolidate by their own weight. Most of the compounds in the tailings are reactive in nature and their compounds could migrate and reach water bodies outside the domain of the TSF (*e.g.*, groundwater, seepage). Following mine completion, the TSF is decommissioned and the land where it sits is intended for reclamation. Whether a TSF is an active or closed system, it is an engineered structure of large extensions with properties and processes that are critical for its performance.

According to Davies & Martin (2000), there are approximately 3500 tailings facilities worldwide, a number that has been cited in many publications. A recent study (Franks *et al.*, 2021) reveals that the number of tailings facilities constructed per decade is increasing, and that stability issues in TSFs persist regardless of the construction method. The upstream method continues to be the construction method with higher stability issues; however, by engineering standards, all construction methods, even the in-pit/natural landform and dry stacking facilities are susceptible to stability risks (Fig. 1).
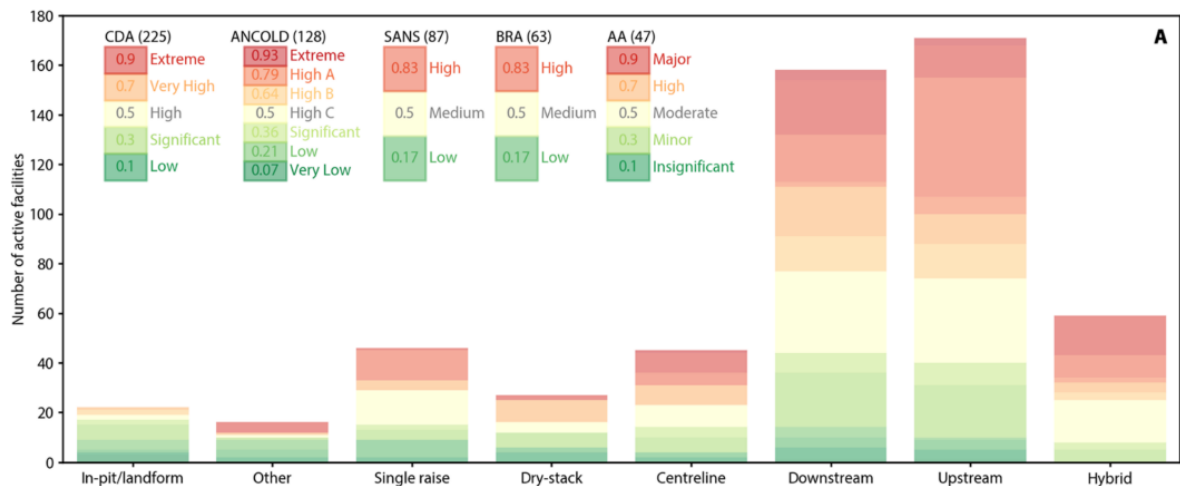
Fig. 1 Stability issues in tailings storage facilities by various construction methods (Source: Franks et al. 2021)

Along with various construction methods of tailings facilities, the characteristics of tailings and subsequent handling, treatment, and disposal depend on several factors (*e.g.*, methods of mining, mineral type, host-rock type, processing method, etc). Tailings storage facilities (TSFs) are tailored designed and constructed with the characteristics of the tailings in mind.

The major risk from tailings derives from its inherent physical-chemical complexity and the potential to be a source of pollution or to present stability issues. In an event of failure, water is the environmental value most likely to be impacted in the vicinity of

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mining wastes. Impacted water can become acidic containing heavy metals, or alkaline containing cyanide, or metals such as arsenic, copper, nickel, zinc, selenium. Other indicators of impacted mine water include sulphates, turbidity, salinity. In dry environments, aeolian erosion and blowing dust is a major environmental problem. The stability of a tailings facility is also affected by multiple factors in addition to the physical and chemical composition of the tailings, such as the disposal method, engineering conditions of the landscape, geochemical and hydrogeological interactions, and other parameters related to the elastic moduli of the tailings (*i.e.*, Young's modulus, shear modulus).

The following list of relevant imperatives highlights the significance and the need for robust management, monitoring, and surveillance systems for a timely and precise diagnosis of the performance and periodical appraisal on the condition of the TSF:

Imperatives for global strategies

–   Sustainably securing resources while protecting the natural and the human environment – The Brundtland Report, 1987 (World Commission on Environment and Development, 1987).
–   The precautionary principle, which means "where there are threats of serious or irreversible environmental damage; lack of full scientific certainty should not be used as a reason for postponing cost-effective measures to prevent environmental degradation" - The Rio Declaration on Environment and Development from 1992 (United Nations, 1992).
–   The reference document for the management of tailings and waste rock in mining activities (European Commission, 2009) that links to the definitions and criteria concerning Best Available Techniques.
–   The safety guidelines and good practices for tailings management facilities by the United Nations Economic Commission for Europe (UNECE) which emphasise the need for tailor-made approaches to ensure the safe, economically, and environmentally sound operation of tailings facilities. The report urges for measures to prevent accidents that can lead to pollution, and threats to humans and the environment (United Nations, 2014).
–   The first Global Industry Standard on Tailings Management (United Nations, 2020) that was commissioned by the United Nations Environment Programme (UNEP), the Principles for Responsible Investment (PRI) and the International Council on Mining and Metals (ICMM). The standard aims to improve safety in the mining industry and to establish 'much needed robust requirements for the safer management of both existing and new tailings facilities globally'.

Imperatives for industry codes of practice

–   Guidelines for automated dam monitoring systems by the International Commission of Large Dams (ICOLD), which sets the basis for the industry and technology developers

on surveillance systems and automated procedures for data processing and interpretation (ICOLD, 2000, 2018).

– The position statement by the ICMM, for preventing catastrophic failure of tailings storage facilities (ICMM, 2016a) and for defining the Tailings Governance Framework (ICMM, 2020) which sets out the governance principles to minimise the risk of catastrophic failure of tailings facilities. The position is the result of a rigorous review of the critical aspects that led to failure events in tailings facilities in recent years (ICMM, 2016b).

– The framework in the tailings management guide (MAC, 2017) by the Mining Association of Canada (MAC) and the subsequent releases of the surveillance manual for operation and maintenance (MAC, 2019a) and the tailings management protocol (MAC, 2019b). The protocol provides five specific and measurable performance indicators critical for tailings management that includes the operations, maintenance, and surveillance (OMS) manual. The OMS is specific to the acquisition of qualitative and quantitative data, analysis, and reporting of inspections, monitoring, and surveillance results.

Imperatives for regulatory compliance

– For regulatory purposes, TSFs are not of temporary nature, and are expected to contain the waste in "perpetuity". The guiding instruments and auditing strategies for waste management across the mine life cycle include environmental impact assessments, risk management systems, mine closure plans, and provisions for financial assurance (Jain *et al.*, 2016).

– The instruments are the official statements of mining companies on how waste management and land reclamation are designed and implemented. For instance, closure plans emphasise the objectives, the criteria, and the financial means for long-term management, monitoring, and surveillance (*i.e.*, in the span of decades and centuries) of mine waste areas including tailings facilities.

– The regulatory framework for tailings management varies across jurisdictions and typically is included in the waste management regulation. For instance, in Europe the directive from which all other connected actions branch out is the Extractive Waste Directive (Extractive Waste Directive, 2006) that aims to ensure that waste from extractive industries is properly managed to avoid damage to the environment.

Imperatives for industry credibility and social license to operate

– Perception of stakeholders about the industry is critical. Stakeholders are less receptive to the industry, where the activity adversely impacts the environment and communities.

– Poor environmental and social performance diminishes the credibility of the industry towards its "social license to operate" and constitute a liability for all parties involved (*i.e.*, the industry, communities, and governments).

–   Generally, the future use of the land and long-term stability requirements drive the design of closure criteria (Blight, 2009). The challenge is concerning the design life that can vary across jurisdictions worldwide. For instance, the closure design life of 100 or 200 years previously accepted based on current technology and engineering practice, is no longer seen as appropriate by most jurisdictions that are adopting long-term closure designs, *e.g.*, 1000 years (ANCOLD, 2012; Logsdon, 2013; Bennett *et al.*, 2016).

–   As most engineered materials and structures will not withstand the test of time, the design must incorporate considerations for maintaining and monitoring the structure stability of post-closure landscapes. These monitoring targets may include cover systems, erosion, seepage, phreatic line, stability of foundation and slope, porewater pressure, mechanical strength, bio-geochemical changes, porewater – groundwater interaction.

2.2   Failure mechanisms and controls in TSFs

Failure mechanisms in tailings dams were documented in early 2001 from failure events that occurred between 1917 and 2000 (ICOLD, 2001b). Other studies have confirmed these mechanisms (Lyu *et al.*, 2019; Clarkson & Williams, 2021), which include overtopping, slope instability, earthquake, static and seismic instability, foundation failure, anomalous seepage, internal erosion, and surface erosion.

The integrity of tailings dams concerning slope and foundation stability is analysed utilising principles of soil mechanics, *e.g.*, the finite element limit equilibrium method (Shivamanth *et al.*, 2015), the strength reduction method (Maji, 2017), or a combination of both (Lu & Chang, 2019; Vipul *et al.*, 2019). Under seismic load and water saturation, liquefaction is the dominant failure mechanism followed by slope instability (Villavicencio *et al.*, 2014) in particular in tailings dams with upstream construction method. Slope instability can result from slopes at or close to their natural angle of repose in cases of hydraulic deposition without mechanical compaction. Elevated water level, high saturation rates and low-strength tailings material in the dike can compromise the tailings dam structure.

The staged construction of the dam contributes to the vulnerability of tailings dams and any change on the physical and mechanical properties of tailings can cause anomalous seepage and erosion. An important consideration to manage the vulnerability of the dam is the design of the seepage field that controls the phreatic line. The seepage field is defined by the phreatic line known as the 'lifeline' of the tailings facility, which is complex to determine and numerical methods can only approximate it (Huang *et al.*, 2013; He *et al.*, 2014; S. Hu *et al.*, 2015). In practice, control points with measured data are connected into a curve in a cross-section representation. Seepage control and effective draining are critical to lower the phreatic surface, protect the tailings dam from seepage erosion, and improve dam stability. Several factors can affect the seepage field, rise the phreatic line, and induce seepage damage, among these elevated decant water level, rainfall recharge rates, floods,

and drainage issues. The seepage state is also influenced by the particle size distribution of the tailings (Yuan *et al.*, 2016), and is dependent on the equilibrium between the chemical action (*e.g.*, alkalinity, acidity, kinetic oxidation), and mineral solubility constraints causing dissolution and precipitation of phases and affecting the permeability coefficient of tailings (Govender *et al.*, 2009; Wang *et al.*, 2021).

Most of the failure mechanisms are directly related to the interaction between water and the tailings material which is also responsible for the increase of the pore water pressure. Tailings below the phreatic line have a slow consolidation rate. The effect of high pore-water pressures in fine-unconsolidated tailings decreases the shear strength and triggers liquefaction. Liquefaction in turn decreases the intergranular and basal contact areas and causes landslides and flow failures. The excessive rate of rising of the dyke also leads to instability in a hydraulic disposal method as the time taken for the pore pressure to reduce from its initial value to the hydrostatic value is shortened (Blight, 2009).

Another contributing factor to failure is related to the textural characteristics of the tailings used for raising the dyke or dam. Tailings with a high percentage of fine particles (<80 μm) can result from a poor classification of the material that is not adequate due to their low mechanical strength. Low-density silt-type tailings can form weak lenses in the dam structure that can lead to failure (Blight, 2009; Villavicencio *et al.*, 2014). In addition, poorly drained tailings form weak zones that may take many years to consolidate and gain strength.

The fluctuations of the phreatic line and of the water level close to the crest of the dam are contributing factors concerning water interaction. Water saturation increases pore water pressure, reduces the mechanical strength of the tailings matrix, and increases the dynamic forces. When the phreatic level is high, saturation increases and causes the shear strength to fall and consequently the factor of safety of the retaining dike is reduced. Therefore, monitoring the phreatic line and the fluctuations of the water level at the crest is crucial to water management in tailings facilities.

2.3   Monitoring and surveillance of tailings storage facilities

2.3.1   Monitoring criteria

The purpose of monitoring and risk assessments in TSFs is to inform about instability issues to implement corrective measures, maintain safe operating conditions, and thus prevent failure events.

According to Blight (2009), the conventional approach in the management and monitoring of mining waste considers: (1) the geotechnical aspect with regards to safety and shear stability of slopes and settlement of tailings. (2) the environmental performance concerning surface erosion, airborne dust transportation, surface and groundwater pollution, acid mine drainage, and other leachates. (3) the social concerns involving local communities such as potential threats to public health, quality of life, impacts to irrigation and agriculture, impact on property value. The relative weight of these factors is site-specific and can vary by geographic and socio-political conditions.

2.3.2 Monitoring practices

Geotechnical monitoring

Visual inspections are still the most common and easy monitoring practice that search for abnormal signs in the structure of the facility. Other cost-effective methods often used in the industry are presented in Fig. 2.

Prisms are used to quantify slope distance and rates of displacement. Wireline extensometers measure the most distal tension crack or zone of deformation in crests. Remote global positioning systems are used to locate specific positions in the facility and determine whether a change occurs. Slope inclinometers are used to monitor the stability of slopes and constructed embankments by measuring deformations and shear movements.

Time-domain reflectometry (TDR) in a coaxial grouted cable can detect movement at the point of deformation of the cable. Slope stability radar (SSR) uses ground-based interferometric radar principles and is commonly used for monitoring slopes in pits and slopes in waste dumps, stockpiles, and embankments. Laser scanning uses LiDAR technology and radar scanning is used for monitoring slopes especially in inactive areas. Tiltmeters use an accelerometer and a transducer to produce an output voltage proportional to the tilting caused by any rotational failures or differential settlement related to internal deformation. Tell-tales are simple devices used for observing and measuring the rate of extension across surface tension cracks that often develop in platforms of waste facilities in response to settlement and deformation. Laser distance measuring (LDM) systems use a laser source to measure changes in distance between the laser and a remote target, so linear movement rates are determined. Acoustic monitoring uses an array of geophones to measure acoustic emissions caused by the fracturing of waste rock blocks or movements along the failure plane. Most of these applications can be better suited for decommissioned sites that do not require frequent relocation of the instrumentation.

Applications that require field instrumentation may require frequent relocation in active sites, whereas scanning-based methods can be very well suited for both active and decommissioned sites.
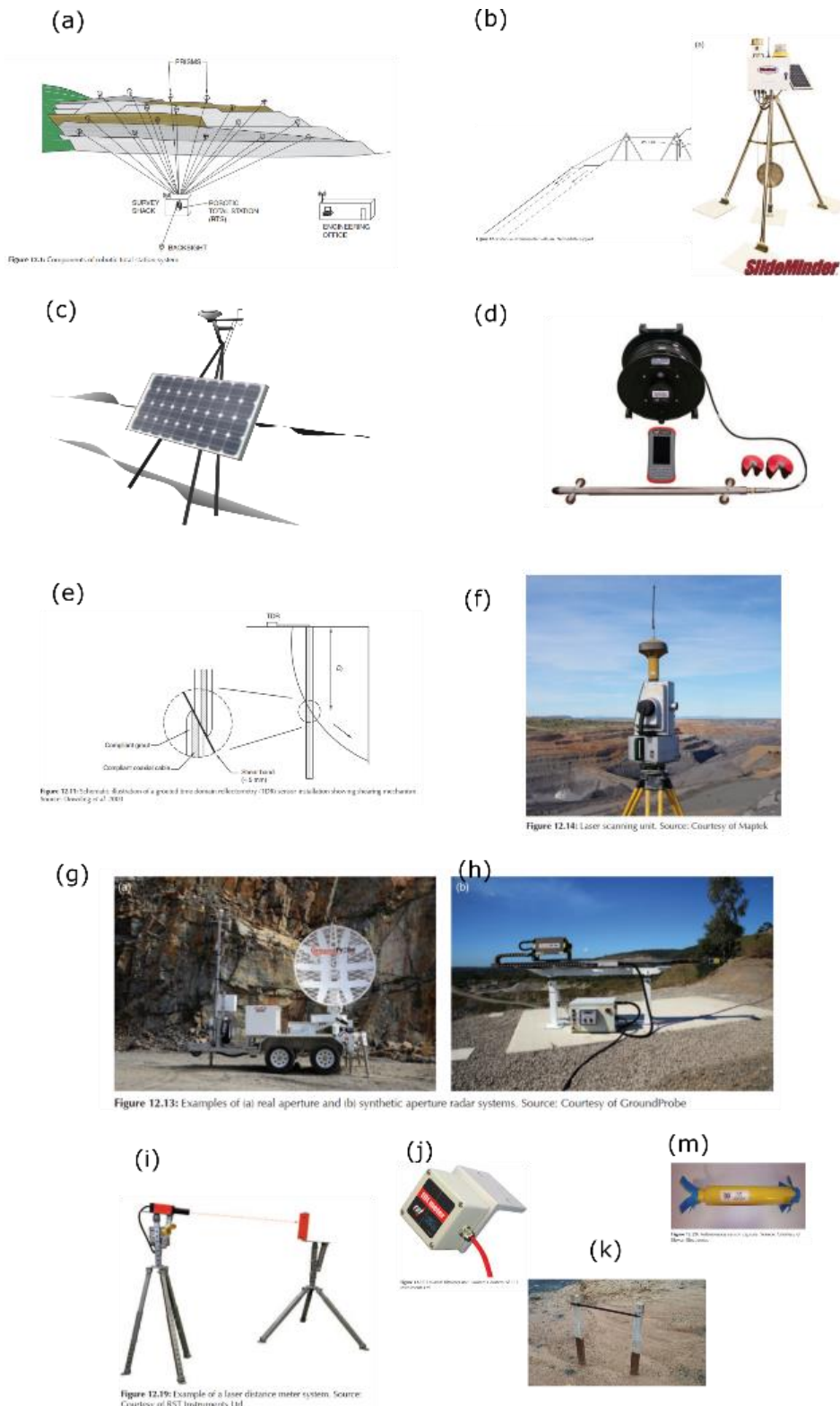
Fig. 2 Common geotechnical monitoring methods and devices used in TSFs (a) Prisms, (b) Extensometers, (c) remote global positioning system, (d) Slope inclinometers, (e) time domain reflectometry, (f) laser imaging / scanning, (g) real aperture radar, (h) synthetic aperture radar system, (i) tilt meter, (j) simple tell-tales, (k) autonomous wirelessly networked sensors, (m) laser distance meter system. (Source: Modified from Hawley & Cunning, 2017)

Hydrological monitoring

Monitoring surface and groundwater monitoring in areas of mining waste facilities include and target climatological monitoring (*e.g.*, adjacent weather station data), upgradient conditions (water level and chemistry), conditions within the facility (*e.g.* water content, pore water pressure and chemistry, geochemistry, acid-base accounting and static testing, runoff), conditions within the near-surface and/or cover (*e.g.* soil moisture, pore water chemistry, water content, freezing soil processes, vegetation), foundations (*e.g.* pore pressure, moisture content), downgradient conditions (*e.g.* groundwater levels and water quality, surface water flow and quality, sediment monitoring).

Pore pressure is one of the most critical factors affecting stability in fine-grained particles such as tailings and is monitored during construction, operation, and closure. Pore-water pressures are measured with piezometers that can be installed before, during, or after construction. Several types of piezometers are used: pneumatic, vibrating wire (VW), strain gauge, standpipe (slotted or porous media).

A pneumatic piezometer operates by balancing compressed gas pressure and water pressure across a diaphragm. These are inexpensive, easy to operate, and applicable to a wide variety of operational environments. It has limitations for continuous monitoring because it requires injection of compressed gas for each reading (*e.g.*, air, nitrogen). A vibrating wire piezometer measures pore pressure by measuring tension changes in a vibrating wire-diaphragm. The resonance frequency is proportional to the pressure acting in the diaphragm. They are very accurate, relatively stable over the long term. Strain gauge piezometer uses the principle of a conventional strain gauge that converts force, tension, pressure, weight into a change in electrical resistance which can be measured.

Standpipe piezometer (Casagrande) are simple devices and consists of a pipe installed into a borehole, perforated, or slotted over the area of interest (*e.g.*, bottom of the hole). Standpipes enable measurement of water levels, sampling of pore water, or testing of other parameters such as hydraulic conductivity (*i.e.*, falling or rising head tests).

2.3.3 *Monitoring challenges*

Monitoring programs and instrumentation are still designed to detect patterns and rates of deformation at the surface of the tailings facility. The conventional monitoring of the subsurface in tailings areas still resorts to intrusive methods (*e.g.*, drilling, SCPT).

Also, the expectation for the long-term performance of mining waste facilities, that is hundreds to thousands of years, is not concordant with the industry capabilities. Monitoring programs must align data acquisition and interpretation to those needs for long-term monitoring.

Most of the instrumentation can be integrated with telemetry systems and cover where possible real-time monitoring, but the challenge is the spatial continuity for data acquisition as most existing monitoring methods are still limited to a few discrete locations. In addition, spatial and temporal data continuity depends on site conditions and the availability of infrastructure for radio, telephone, cellular or satellite transmissions.

Other techniques such as geophysics, or remote sensing are in evaluation for potential applications in tailings facilities. These technologies have demonstrated capabilities for planning, classification, and change detection in mining areas but still lack the accuracy and spatial resolution of ground-based methods. Geophysical methods are closer to be adopted in the industry due to the advances in tomographic data acquisition, non-invasive application, and relative higher spatial resolution.

2.4 Applied hydrogeophysics in tailings

2.4.1 *Geophysical applications*

In the last decades, the application of geophysical techniques has focused mainly on mapping the structural geometry of the subsurface, and for detecting water movement and anomalous seepage conditions in tailings dams. From these applications, electrical resistivity imaging (ERI) is the most applied technique (Kuranchie *et al.*, 2015; Korneeva *et al.*, 2016; Martínez *et al.*, 2016; Olenchenko *et al.*, 2016; Benyassine *et al.*, 2017; Hen-Jones *et al.*, 2017; Martín-Crespo *et al.*, 2018; Dimech *et al.*, 2019). Other techniques used alone or with ERI include electromagnetic induction (EMI) (Ma *et al.*, 2015; Tycholiz *et al.*, 2016; Epov *et al.*, 2017; Yurkevich *et al.*, 2017), ground-penetrating radar (GPR) (Cortada *et al.*, 2017), induced polarisation (IP) (Placencia-Gómez *et al.*, 2015), self-potential (SP) (Mainali *et al.*, 2015), and seismic methods (Olivier *et al.*, 2017; Cracknell *et al.*, 2019). Such investigations have demonstrated that geophysical techniques could reveal structural variations in the subsurface of tailings facilities.

Electric resistivity imaging (ERI)

ERI for subsurface imaging is a geophysical technique that measures the distribution of electrical resistivity in the subsurface. ERI extended its applicability for imaging and monitoring land remediation during the 1990s (US Dept of Energy, 2000). ERI uses surface and/or subsurface electrode arrays to measure resistivity distribution in soil and rock between the electrode arrays. Electrode arrays are composed of electric dipoles arranged horizontally or vertically in a configuration such as some of these are acting as current-source electric dipoles and others acting as potential- measuring dipoles. The electrical resistivity data can be acquired and processed to produce continuous two- or three-dimensional subsurface images. ERI has been increasingly used as the primary geophysical technique for surveying tailings areas in applications that include mapping of the internal structure related to faults, seepage, and acid mine drainage plumes (Martínez-Pagán *et al.*, 2021). ERI's ability to map the internal structure of the tailings is based on the salinity of the pore water which acts as a tracer and by association it can infer water movement, saturation trends, and the geometry of the structure. Low resistivity values are associated with low resistivity pore water originated from the mine waste or areas with higher sulphide content and oxidation degree.

ERI combined with other techniques or alone has been applied to detect the thickness of soil cover and tailings, general geometry and geologic contact between tailings and

basement rocks (Grangeia *et al.*, 2011; Cortada *et al.*, 2017; Martín-Crespo *et al.*, 2018) which has also been used in volumetric estimations (Martin *et al.*, 2020). Several other applications based on electrical resistivity distribution include the detection of flow directions, anomalous seepage, mobility of heavy metals, preferential pathways into the underlying bedrock (Olenchenko *et al.*, 2016; Benyassine *et al.*, 2017; Yurkevich *et al.*, 2017; Duda *et al.*, 2020; Arcila *et al.*, 2021), and for reconstructing time-lapse 3D electrical resistivity variations to assess water infiltration and movement (Dimech *et al.*, 2019). ERI coupled with geochemical methods has also been used for tracing geoelectric zones in tailings and delineation of oxidised zones (Bortnikova *et al.*, 2013), for examining the evolution of sulphide weathering (Placencia-Gómez *et al.*, 2010), and for revealing the migration of acid mine drainage and the distribution of highly mineralised solutions (Korneeva *et al.*, 2016; Tycholiz *et al.*, 2016; Epov *et al.*, 2017).

Seismic refraction (SR)

Seismic waves comprise body- (P and S) and surface- (Rayleigh, Love) waves. Body waves propagate through the body of the earth, whereas surface waves move along the surface and have a dispersion property, so they have different propagation velocities at different wavelengths and thus have different penetration depths. From the seismic methods (*i.e.*, refraction and reflection), seismic refraction has been used the most for shallow surveys in engineering. Seismic refraction consists of measuring the travel time at known points along the survey line of compressional waves generated by an impulsive energy source (Redpath, 1973). The seismic energy is picked up by sensors and translated to travel times and distances which is then converted to information containing velocity variations with depth. Seismic refraction depends upon subsurface velocity contrasts and the distinct response of P-waves upon contrasts in density and reflection at the water table. For instance, seismic refraction can be used in unconsolidated soil-type where the compressional wave velocity varies from less than 500 ms^{-1} above the water table to nearly 1550 ms^{-1} at and below the water table (Dobecki, 1988).

   In tailings, SR alone and with other techniques has been used to investigate geological settings of tailings storage facilities as it can effectively detect the underlying ground or bedrock of higher compactness compared to tailings media (Lghoul *et al.*, 2012). Some of these applications include mapping depth to bedrock and bedrock fractures to calibrate gravity data (Vanhala *et al.*, 2004), mapping the internal structure of tailings deposits, and volumetric estimations for environmental and economic assessments (Cracknell *et al.*, 2019). SR in conjunction with electric and electromagnetic methods has been used to map alteration zones and contamination pathways (Lachhab *et al.*, 2020) and for investigations related to dam failure (Fookes & Dale, 1992).

Multichannel analysis of surface waves (MASW)

MASW analysis of surface waves (Rayleigh) for determining shear-wave velocity (V_s) was introduced by Miller *et al.* (1999) and since then the method has been adopted in the application of near-surface engineering to evaluate variations in the properties of the

subsurface, *e.g.*, ground stiffness. MASW with active sources is a non-invasive method that is relatively insensitive to cultural interference. MASW integration with the CMP approach for data acquisition enables the generation of 2D shear-wave velocity cross-sections that can be used to evaluate horizontal and /or vertical variations in the subsurface.

The integration of MASW with other geophysical techniques has been considered in site investigations such as for defining aquifer geometry (Paz *et al.*, 2020). In tailings, MASW has been mainly applied in geotechnical investigations of new tailings areas to determine shear wave velocity profiles and to assist to identify depth to bedrock.

2.4.2 *Hydrogeophysical framework for mining waste investigations*

Non-invasive imaging techniques have created new opportunities for the investigation of hydrogeological processes at the pore, field, and catchment scale. Among these, geophysical techniques have been increasingly investigated for applications related to flow, groundwater-surface water interaction, and transport processes in the subsurface at the field and catchment scale (Jarvis *et al.*, 2016; McLachlan *et al.*, 2017). There is abundant literature supporting geophysical methods for the analysis of processes and subsurface concerning hydrogeological investigations and the emphasis for an integrated approach of geophysics and hydrology has arisen in the past decade (Binley *et al.*, 2010; Hubbard & Linde, 2010; USGS, 2013). Hydrogeophysics emerged in the late 1990s to complement the demand for stochastic subsurface hydrology seeking better field-based techniques and it has grown since then along with developments in computing power and data inversion techniques (Binley *et al.*, 2015). The new field continued to evolve as the need for quantifiable interpretation of the heterogeneous subsurface and the associated fluid dynamics increased. As such, a hydrogeophysical framework proposes the use of geophysical methods to allow for large-scale aquifer characterisation and where hydrogeological techniques are limited.

In TSFs, several geophysical techniques have been applied to investigate the physical structure of the dam or dyke and only a few have focused in the hydrological processes of the TSF system (Sherriff *et al.*, 2009; Cortada *et al.*, 2017; Martín-Crespo *et al.*, 2018). In most cases the research objective is case-specific and the interpretation in terms of hydrogeological properties is not straightforward. The hydrogeophysical conceptualisation in Fig. 3 expands the hydrogeophysical approach of Binley *et al.* (2010) with application to mining environments. The concept applied to a mine waste domain integrates the constitutive relationships fundamental to most hydrogeophysical investigations and characterisation targets (*i.e.*, structure, properties, processes, and performance). The framework combines datasets from several sources including geophysics with site-specific information to characterise subsurface structures, and physical and hydrogeological properties that control the performance of the domain.

The approach leverages distributed datasets in TSFs (*e.g.*, climate data, geospatial information, hydrological and hydrochemical records) accumulated during the construction and operation of the facility although limited to discrete areas as ground-based observation has limited reach to wet zones, or to the subsurface. Documenting activities in TSFs is still a challenge but other options such as remote sensing with drones,

or satellite imagery are becoming available now. Therefore, surface characterisation can use geographic and spatial information generally accessible and available in most countries through global and national databases (*e.g.*, geological survey agencies, land survey, geospatial services). Light detection and ranging (Lidar), hyperspectral imaging (HSI), and satellite imagery are among the techniques with potential capabilities for data sourcing (Turner & Reinson, 2015).
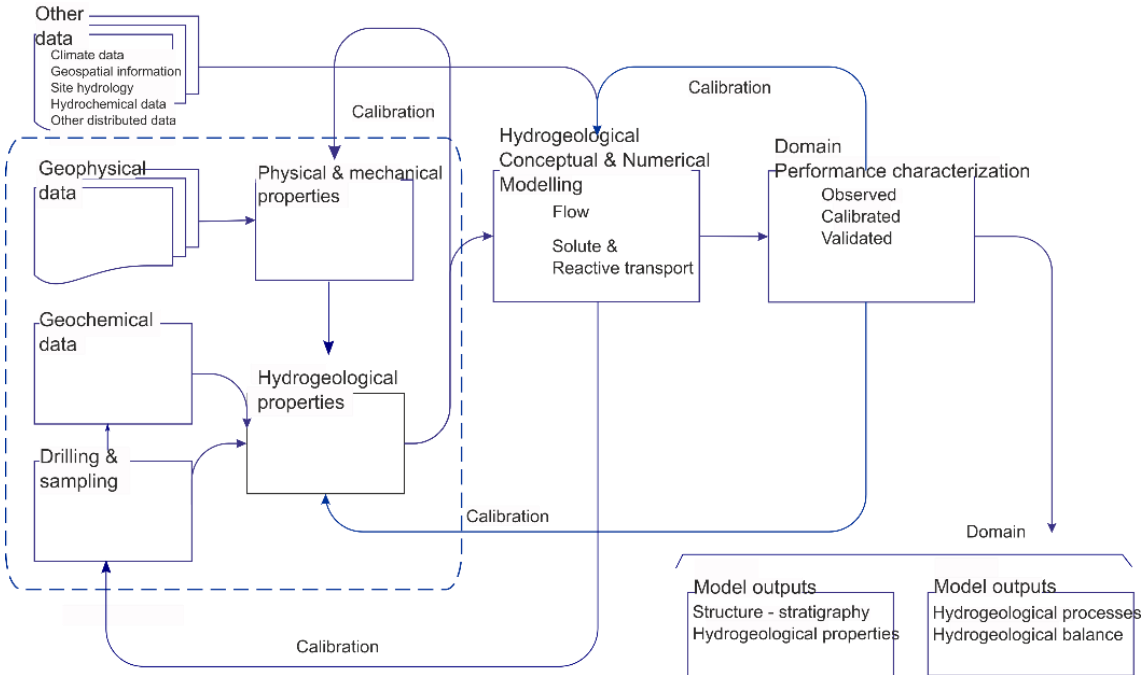

Fig. 3 Hydrogeophysical framework for mining wastes investigation, including tailings facilities. The dotted line focuses on the context of this research. Source: Adapted from Binley et al. (2010).

Generally, hydrogeological processes in the subsurface cannot be determined by direct observation and indirect measurements are often used to infer processes occurring at different scales, locations, or times (Vereecken *et al.*, 2015). As for dataset inputs to the hydrogeological model in the framework, geophysical data can complement sparse or unavailable data necessary for the parameterisation of numerical models. Geophysical tomographic techniques can image the subsurface in two- and three-dimensions with high spatial resolution and to a depth of few tens of meters which is adequate for most TSFs. For deriving hydrogeological properties from geophysical proxies, techniques that are adequate for this purpose include electrical resistivity imaging (ERI), seismic refraction tomography (SRT), ground-penetrating radar (GPR), spectral induced polarisation (SIP), and self-potential (SP). Quantitative information from the subsurface such as porosity, water content, and water saturation can be obtained by establishing a relationship between geologic and geophysical properties at a field scale.

For instance, seismic refraction data can be processed and interpreted with rock physics principles to evaluate the physical and mechanical properties of the tailings such as bulk density and elastic moduli. Whereas electric resistivity data can be interpreted with petrophysical relationships to evaluate hydrogeological properties such as water saturation, water content, and porosity. Another important determination is concerning the structure

and the stratigraphic facies which are associated with the chemical reactivity (*e.g.*, highly conductive zones) of the tailings and internal fluid dynamics.

The links in the framework propose the simulation of the hydrogeological processes in the TSF and calibration of the outputs to evaluate and tune the corresponding geophysical measurements. Finally, the outputs of the model are interpreted in terms of the spatial and temporal performance of the TSF.

3 Research methodology

3.1 Case studies

Two tailings storage facilities were selected as case studies. Fig.4 illustrates the location and layout of the survey areas for data acquisition. The first case is the TSF at Pyhäsalmi mine is in North Ostrobothnia, Finland, and contains tailings from a differential copper-lead-zinc sulphide flotation. The second case study is the TSF at Brukunga mine site in South Australia and contains tailings from an iron sulphide flotation.

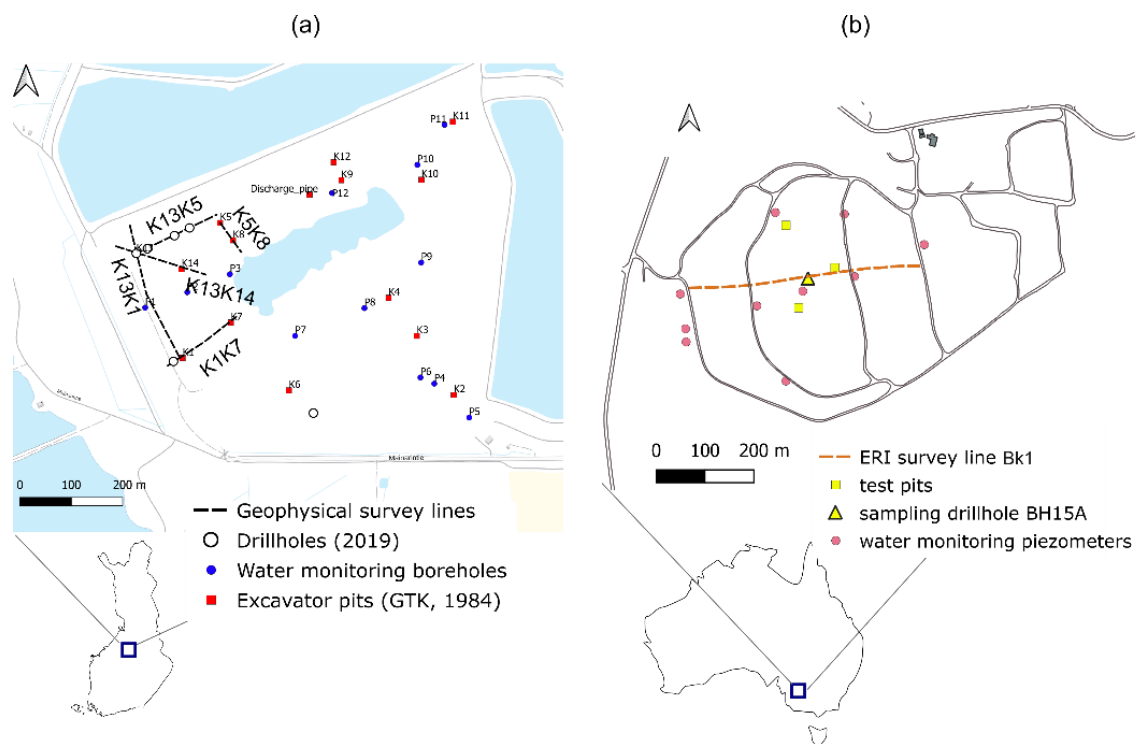**Fig. 4** Site locations for the two case studies. (a) Pyhäsalmi mine tailings pond A in Finland (ETRS89/TM35FIN 63.663oN, 26.013oE); and (b) Brukunga mine tailings facility (GDA94/MGA54 35.006oS, 138.945oE). (Base maps derived from QGIS/OSM).

3.2 Dataset

The research dataset is stored in the data management system of Mendeley. They all were disclosed for each research paper on corresponding publications.

3.3 Research methods

The various methods utilised in the research and interlinkages across them are presented in Fig.5, in which the interpretation of the results focuses on the main objectives of the research. The structural stratigraphy and facies analysis are addressed in **Paper I** (Mollehuara *et al.*, 2021a). The hydrogeological and elastic conditions are investigated in **Paper II** (Mollehuara Canales *et al.*, 2020) and **Paper III** (Mollehuara *et al.*, 2021b).
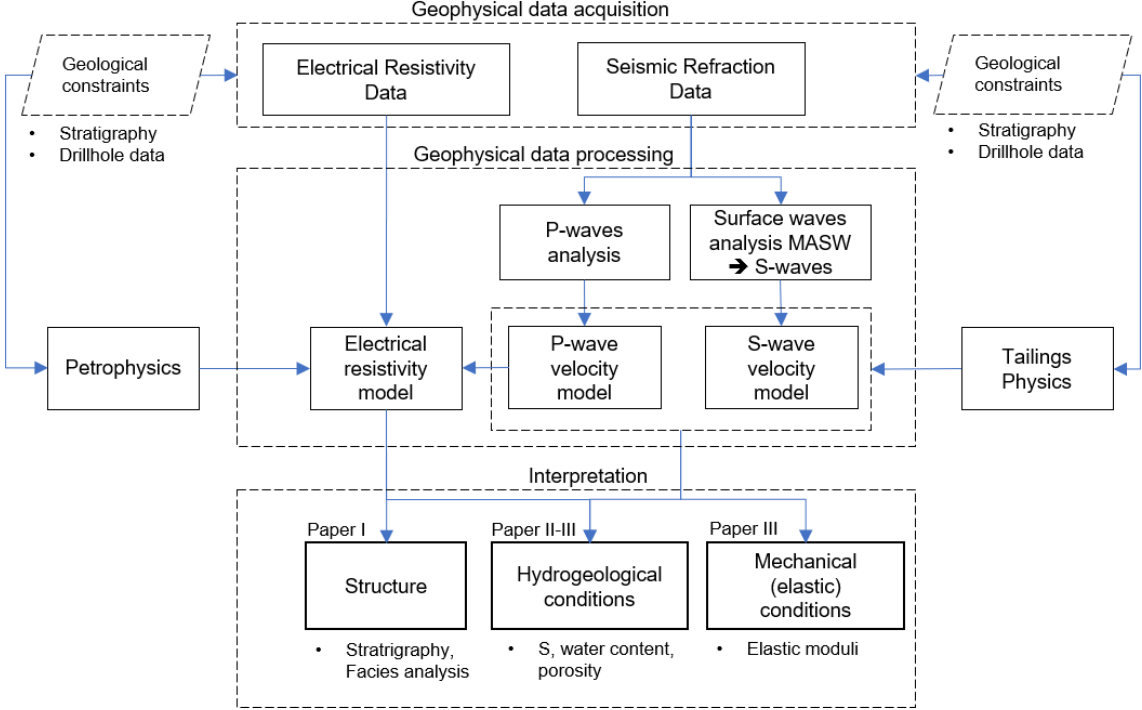
Fig. 5 Block diagram showing the research method and interlinkages across the research components.

3.3.1 Geological constraints

The first aspect of the research is the gathering of data and information of the tailings areas. Most mine sites have records of their TSFs relevant to the design, engineering, and construction. According to recent requirements, companies must have daily records on the operation and maintenance of the facility, but in the case of old decommissioned TSFs, these records are not always available. The relevant data concerning the geological constraints include the topography and digital elevation models of the basement and the surface. Other stratigraphic data from drill hole logs are also important but not always available for the region of interest. In our case, we conducted water sampling and a few drillholes along specific survey lines for the delineation of the current phreatic line. A sampling of tailings material was also necessary to determine the in-situ physical and hydrogeological conditions of the tailings (*e.g.*, bulk density, porosity, and water content).

3.3.2 *Geophysical data acquisition and processing*

Two geophysical methods were selected for non-invasive data acquisition, namely electric resistivity imaging (ERI) and conventional seismic refraction (SR). Other techniques such as ground-penetrating radar (GPR) and ground electromagnetic induction (EMI) were also used for data acquisition, but these techniques were less suitable for the present study due to their shallow penetration depth. The approximate height of the dam in both cases was about 20 m.

Electric resistivity imaging

The electrical resistivity imaging used a system Syscal Pro Switch resistivity meter (IRIS Instruments) with 72 electrodes at Pyhäsalmi site (Paper I) and 96 electrodes at Brukunga site (Paper II). The line spreads at Pyhäsalmi TSF had the electrodes spaced every 2.5 m except in line K13K1 where it was 4 m (Paper I). For the Brukunga TSF, the electrode spacing was every 5 m (Paper II). The measured apparent electrical resistivity data were pre-processed using the PROSYS II software from IRIS Instruments. The total number of measurements for the inversion on each line was 1318 for Pyhäsalmi tailings (Paper I) and 2370 measurements at Brukunga TSF (Paper II). The processing of the data was carried out using Geotomo's Res2DInv resistivity modelling software (Loke, 2018) that used forward modelling based on the robust finite element and non-linear smoothness-constrained least-squares optimisation based on Occam's method (Degroot-Hedlin & Constable, 1990) which was found to produce a model that emphasised the vertical resistivity contrast. The robust constraint refers to the L1 norm which applies a constraint factor to data and model and is less sensitive to noise.

The electrode array selected for all subsequent analysis in this thesis was the Wenner-Schlumberger configuration array because it provided a better signal-to-noise ratio and better vertical resolution compared to the dipole-dipole array which also depicted some horizontal detail (Fig. 6). However, concerning the zone occupied by the tailings media, both arrays captured well the phreatic line that separates the unsaturated from the saturated tailings. It is also noted that ERI delineates the phreatic line with a superior resolution to the projected piezometric measurements. However, it is not apparent the contact interface between the tailings media and the underlying ground in the ERI survey, but this is addressed ahead (section 3.2.3) by complementing the analysis with the SR method and facies analysis filters.
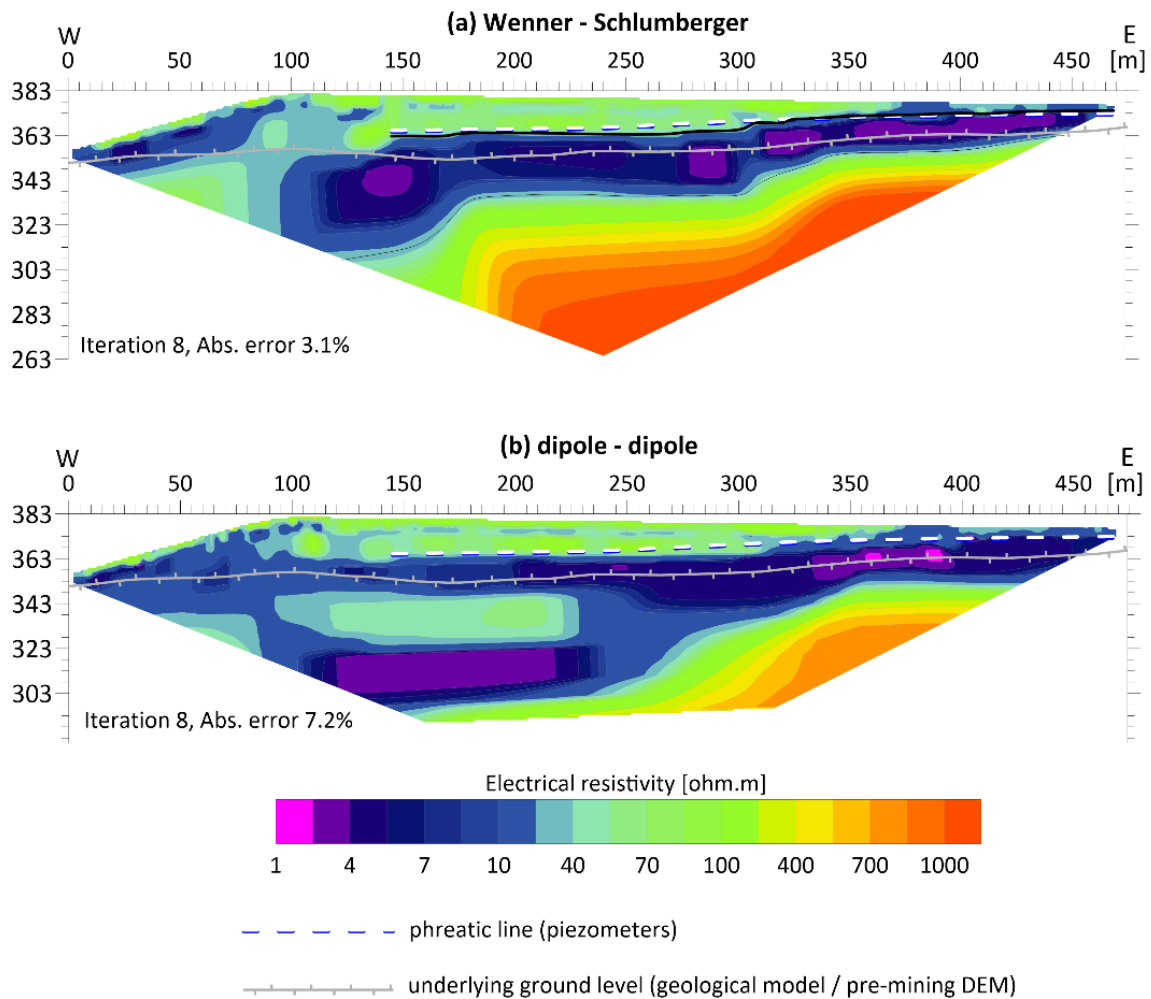
Fig. 6 Electrical resistivity imaging of the TSF at Brukunga mine – Survey line Bk1. (a) Wenner-Schlumberger configuration. (b) dipole-dipole configuration.

Seismic Refraction – P-wave velocity

For the seismic refraction survey (**Paper II-III**) we used a Geometrics Inc. Geode seismograph with a set of 24 geophones (4.5 Hz) and arranged every 5 m for a total length of 115 m. The geophones were planted vertically for the best coupling of the seismic signal. The energy source was produced with hammer shots over a striker plate fixed onto the ground. Seven-shot points were applied along with the spreads, two offsets at both ends, and three distributed within the spread at approximately every 30 m. The acquisition parameters included a sample period of 1 ms and a total recording length of 0.3 s, a low-cut filter of 15 Hz, and a notch filter of 50 Hz.

For processing SR data, we used SeisImager software modules Pickwin and Plotrefa from Geometrics Inc. Pickwin module was used to pick the first wave breaks in all shot records and for each trace. Then, the traveltime curves from the first breaks method (Fig. 7a) were computed to produce a layered representation of the P-wave velocity (V_p) model in Plotrefa module (Fig.7b). The process consisted of constraining the inversion with the geological data (*i.e.*, depth to the ground surface and to bedrock) and setting the starting velocity model with the minimum and maximum velocities from the traveltime curves.

The inversion algorithm in Plotrefa (White, 1989; Hayashi & Takahashi, 2001) creates a velocity model for each travel time by iteratively tracing rays through the model and comparing the calculated and measured traveltimes until the difference is minimised. The theoretical travel times are calculated using the raytracing method based on Huygens' principle (Yilmaz & Taner, 1997).
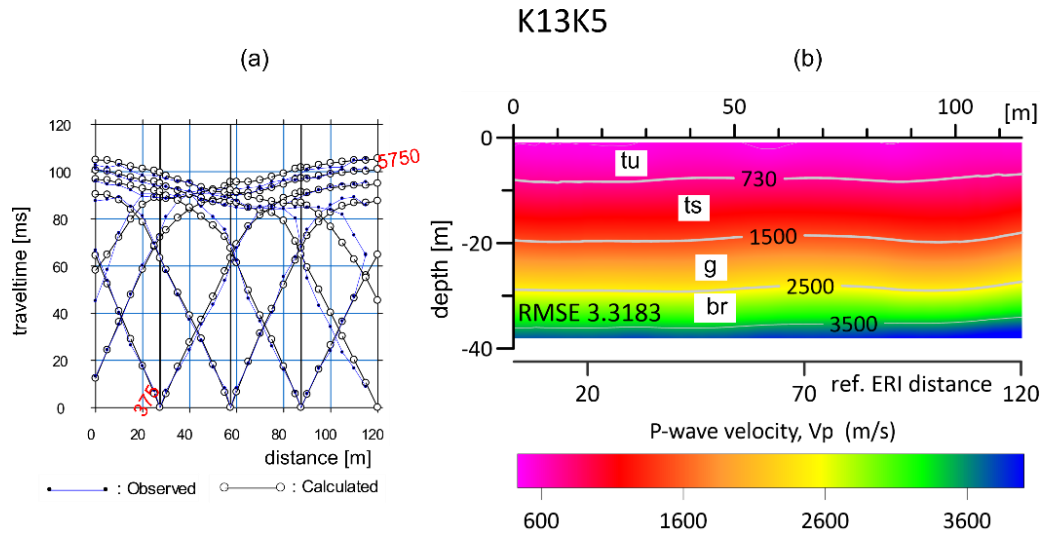
Fig. 7 Determination of P-wave velocity (V_p) model by conventional inversion of seismic refraction data. Figures correspond to line K13K5 at Pyhäsalmi TSF. (a) Observed and calculated traveltime curves, and (b) Layered P-wave velocity (V_p) model. tu – unsaturated tailings, ts – saturated tailings, gr – underlying ground, br – bedrock (Source: Modified from Mollehuara-Canales et al. 2021b).

MASW – S-wave velocity

The seismic refraction dataset was analysed by the MASW method to determine S-wave velocities (V_s). The procedure consisted of dispersive ground-roll data (Rayleigh-wave energy) acquisition, construction of the dispersion curves, and inversion of dispersion curves into an S-wave velocity (V_s) model. The dispersion curves (Fig. 8a and Fig. 8b) for the source positions at the beginning of the profiles were obtained using the Geopsy software (Geopsy, 2021). Then, to obtain the S-wave velocity models (Fig. 8c), and for the inversion of dispersion curves, we used the Geopsy/Dinver module. In the inversion process, a random Montecarlo algorithm generated 500 starting models, and the neighbourhood optimisation algorithm (Sambridge, 1999a, 1999b) generated 10000 models to obtain a 1D model with a minimal misfit less than 0.007 (*i.e.*, 0.7%).

Fig. 8 MASW analysis for line K13K5 at Pyhäsalmi TSF. (a) Spectral analysis of Rayleigh waves. (b) Theoretical and experimental dispersion curve in terms of phase velocity and frequency. (c) 1D S-wave velocity model (Source: Modified from Mollehuara-Canales et al. 2021b).
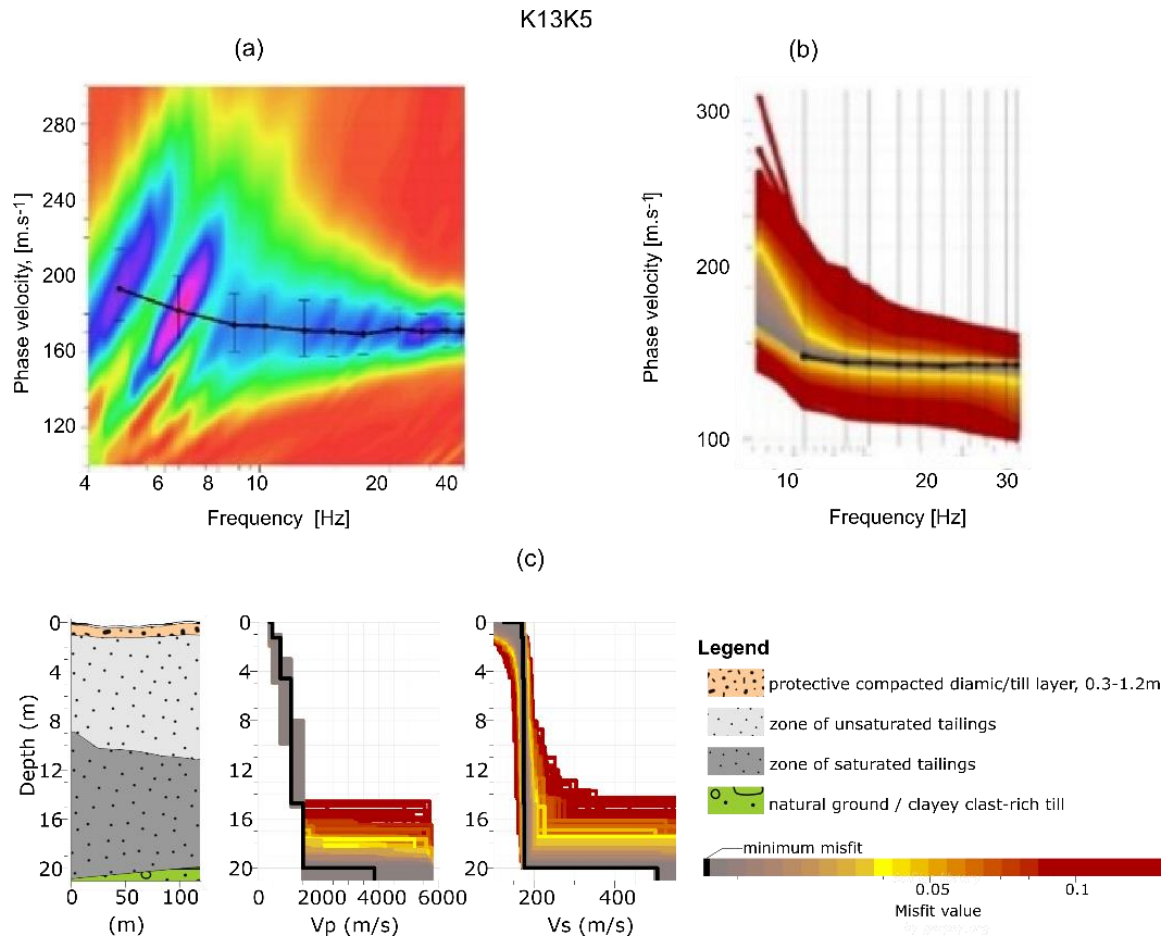
The parameterisation for the starting model and the corresponding inversion is also constrained by the geological model (*i.e.*, range of values for layer thickness and bulk density) and the results of the SR results in the layered P-wave velocity model (*i.e.*, V_p values) (Table 1).

Table 1 Parameterisation for the starting model and inversion of dispersion curves (Source: Mollehuara-Canales et al. 2021b).

layer	Stratum *	depth *	V_p **	V_p	ρ ***	thickness	Poisson's ratio	V_s range
1	cover	1	[300-500]	400	1450	[0-2]m	0.2-0.3	[100-1200]
2	tu	5	[300-500]	480	1960	[1-5]m	0.2-0.3	[100-1200]
3	tu	10	[400-900]	750	2000	[3-10]m	0.2-0.3	[100-1200]
4	ts	15	[750-1500]	1100	2100	[8-15]m	0.2-0.3	[100-1200]
5	ts	20	[750-1500]	1500	2100	[13-20]m	0.2-0.3	[100-1200]
6	gr	30	[1000-5750]	[1500-5750]	[2250-2635]	[>20]m	0.2-0.3	[500-3500]

* Geologic model / site data (tu – unsaturated tailings, ts – saturated tailings, gr – underlying ground)
** seismic refraction model
*** drillhole data

3.3.3 Data interpretation

Structure and facies analysis

The first part of the data analysis covers the structural mapping and facies analysis. The workflow in Fig.9 shows the steps of the analysis. The structural mapping is based on a conventional interpretation of the geophysical images where distinctive features are associated with geological zones. However, the problem arises when the stratification is not evident in the geophysical images, such as within the tailings material in the SR images and where highly conductive porewater has percolated across two different media in the ERI images. To enhance features not distinguishable in such images, directional derivatives were applied to the ERI image. For this, a first-order derivative (gradient approach) and a second-order derivative combined with a Gaussian filter (Laplacian approach) were applied to highlight facies and transition zones. By capturing the local extrema and the minimum threshold crossings, the delineation of local features like geoelectric zones and layered contacts can be enhanced. Then, the geoelectric zones can be interpreted in terms of other parameters in the tailings (e.g., water saturation, salinity).
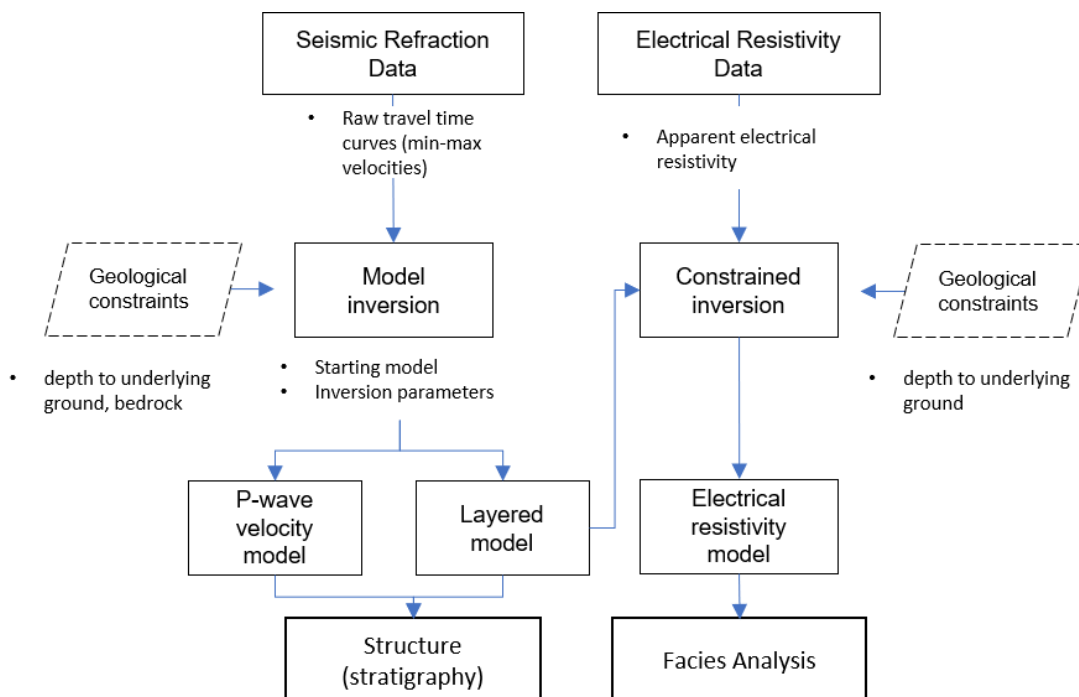

Fig. 9 Workflow for structure and facies analysis using geophysical data (Source: Modified from Mollehuara-Canales et al. 2021a).

Petrophysical approach – hydrogeological conditions

In the petrophysical approach, we conceptualise the tailings as an unconsolidated media with three major components expressed in volumetric fractions: tailings matrix ($\emptyset_s$), liquid

phase ($\emptyset_w$), and clay phase ($\emptyset_c$). The gas phase ($\emptyset_g$) is mainly air and considered an insulator with a negligible electrical conductivity (Fig. 10).
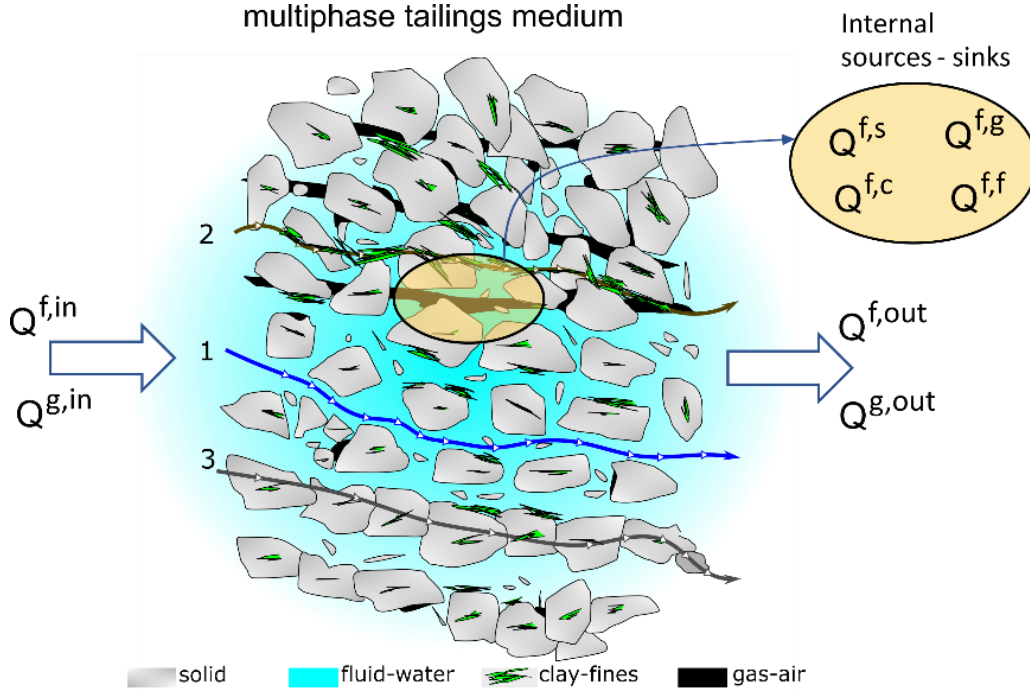

Fig. 10 Multiphase pathway model for electrical conductivity in tailings: 1 brine water, 2 clay & surface, 3 solid contact (Source: Modified from Mollehuara-Canales et al. 2020).

The medium is represented by *n* phases, each with a conductivity σ_i, a phase volume fraction $\emptyset_i$, and a phase exponent m_i (m_w for water, m_s for tailing matrix and m_c for clay). In this approach, the conventional Archie's law is generalised by Glover (2010), in which the bulk electrical conductivity (σ_b) of a solid matrix is the contribution of n phases.

$$\sigma_b = \sum_i \sigma_i \emptyset_i^{m_i} \; ; \text{and} \;\; \sum_i \emptyset_i = 1 \tag{1}$$

From this generalised approach, and considering the air in the pore space of negligible contribution, the model equation for the tailings system is expressed as:

$$\sigma_b = \sigma_w \emptyset_w^{m_w} + \sigma_s \emptyset_s^{m_s} + \sigma_c \emptyset_c^{m_c} \tag{2}$$

Expanding the volumetric water fraction in terms of saturation (S) and porosity (φ), Eq. (2) is rearranged as:

$$\sigma_b = \sigma_w (\varphi S)^{m_w} + \sigma_s \emptyset_s^{m_s} + \sigma_c \emptyset_c^{m_c} \tag{3}$$

in terms of electrical resistivity

$$\frac{1}{\rho_b} = \frac{1}{\rho_w} (\varphi S)^{m_w} + \frac{1}{\rho_s} \emptyset_s^{m_s} + \frac{1}{\rho_c} \emptyset_c^{m_c} \tag{4}$$

Eqs. (3) and (4) represent the three-phase model. Notations $\rho_b, \rho_w, \rho_s, \rho_c$ correspond to the bulk electrical resistivity of the medium, the brine resistivity, the tailings matrix, and the clay phase, respectively.

Tailings physics approach - Elastic and hydrogeological conditions

The workflow for evaluating elastic and hydrogeological conditions in tailings is presented in Fig. 11 (Paper III).

First, seismic velocities for P-wave (V_p) and S-wave (V_s) were determined as in section 3.2.2. Then, empirical relationships between V_p and V_s, and V_p and bulk mass density were established. Then, principles analogous to 'rock physics' named hereafter 'tailings physics' are used to evaluate the seismic response of the TSF subsurface in terms of elastic and hydrogeological (*e.g.*, water content, water saturation) conditions.
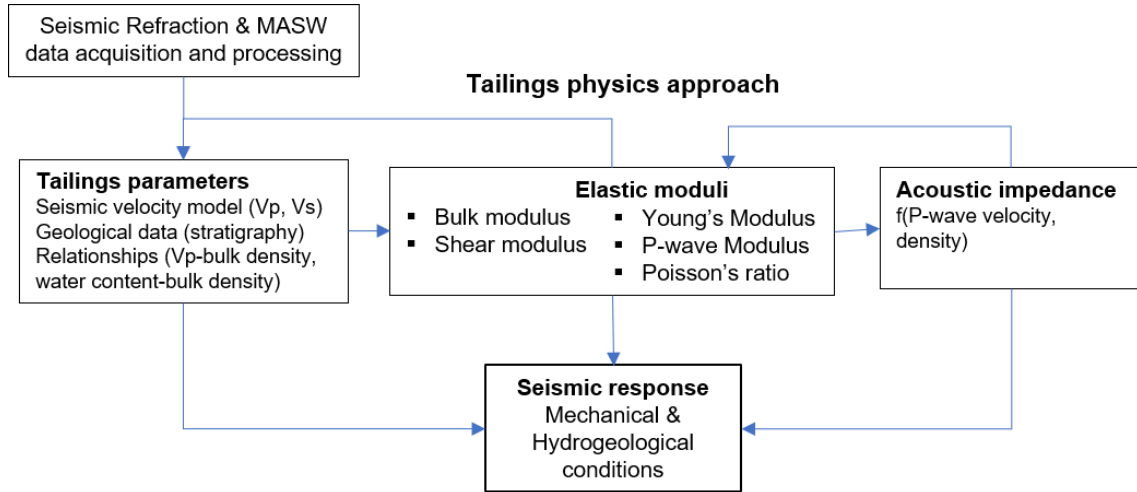

Fig. 11 Workflow of the tailings physics approach interpreting elastic and hydrogeological conditions from seismic refraction models (Source: Modified from Mollehuara-Canales et al. 2021b).

The tailings physics approach assumes that the tailings are subject to small changes of stress and hence linearity for the elastic parameters. The elastic moduli are described elsewhere (Schön, 2015; Mavko *et al.*, 2020) with the following equations:

$$2\mu(1 + v) = E = 3K(1 - 2v) \tag{5}$$

$$V_p = \sqrt{\frac{M}{D}} = \sqrt{\frac{E}{D} \cdot \frac{1-v}{(1+v)\cdot(1-2v)}} = \sqrt{\frac{\lambda + 2\mu}{D}} = \sqrt{\frac{k + \left(\frac{4}{3}\right) \cdot \mu}{D}} \tag{6}$$

$$V_s = \sqrt{\frac{\mu}{D}} = \sqrt{\frac{E}{D} \cdot \frac{1}{2 \cdot (1+v)}} \tag{7}$$

$$v = \frac{0.5(V_p^2 - 2V_s^2)}{V_p^2 - V_s^2} \tag{8}$$

Where the bulk mass density is given by $D = \gamma/g$ so that dimensionally the SI unit for all elastic moduli is expressed in GPa. Poisson ratio, v is unitless:

Bulk modulus (K) describes the resistance of the tailings to compression and it is defined as the ratio of the hydrostatic stress, σ, to the volumetric strain. Shear modulus (μ) or modulus 'rigidity' describes the response to shear, and it is a measure of elastic shear stiffness. Young's modulus (E) describes the response to linear stress and it is defined as the ratio of the stress to the strain in a uniaxial stress state. P-wave Modulus

(M) is defined as the ratio of stress to strain in a uniaxial strain state. Poisson's ratio (v) describes the response in the direction orthogonal to uniaxial stress and it is defined as the (negative) ratio of lateral strain to axial strain in a uniaxial stress state.

4   Results

4.1   Structure and facies analysis

The structure (stratigraphy) and geoelectric facies in the TSF of Pyhäsalmi mine are interpreted using data from seismic refraction (SR) and electrical resistivity imaging (ERI) (**Paper I**). Previously in section 3.2.2, ERI could detect the phreatic line, however, the contact zone between the tailings media and the underlying ground was not apparent (Fig. 6). Whereas SR detected the surface of the underlying ground and the bedrock but not distinctively the phreatic line (Fig. 7b). Two approaches were evaluated for detecting the contact zone underlying the tailings media, and for delineating zones in the electrical domain. Firstly, by applying SR and ERI combined (Fig. 12); and secondly, by filtering the ERI model with directional derivatives (*i.e.*, gradient and Laplacian) (Fig. 13).

Therefore, in the first approach, SR and ERI techniques when combined were able to detect all the stratigraphic units in the subsurface of the TSF including the phreatic line and the contact zone underlying the tailings media (Fig. 12).
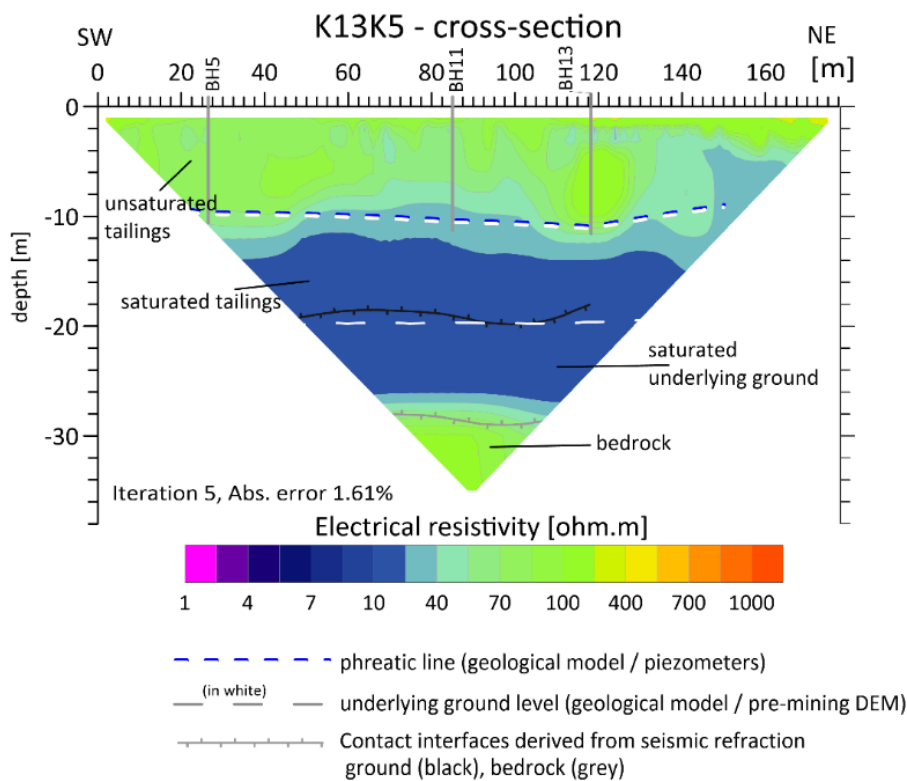

Fig. 12 Electrical resistivity imaging for line K13K5 at Pyhäsalmi TSF. The cross-section indicates the features from the geological and seismic refraction constraints, e.g., boundary layers. (Source: Modified from Mollehuara-Canales et al. 2021a).

In the second approach, the ERI model was analysed with the gradient and the Laplacian filter bands. In this case, the narrowband corresponding to +/- 0.01 was used for edge detection, whereas wider bands were used to evaluate and associate the rate of change with geoelectric facies (Fig. 13). As such, the edges can be associated with transition boundaries across stratigraphic units, and the facies in the electrical resistivity domain can be interpreted with petrophysical relationships (*e.g.*, the generalised Archie's law) to explain hydrogeological conditions such as saturation, or water content.
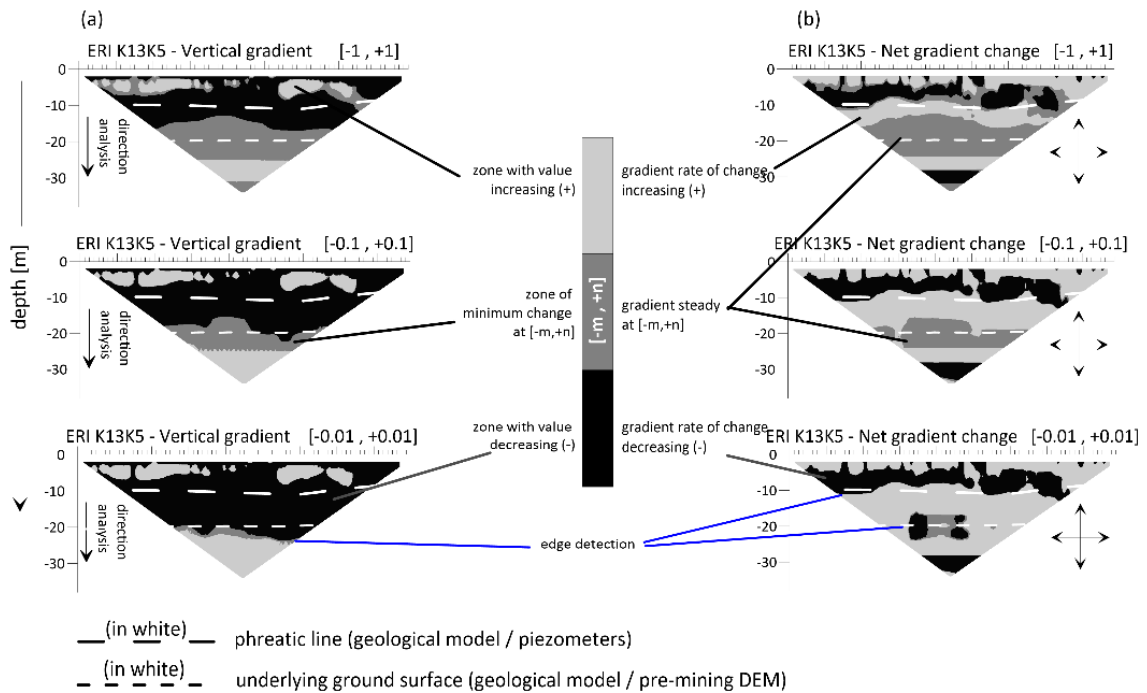

Fig. 13 ERI cross-section of line K13K5 at Pyhäsalmi TSF segmented in facies by filters based on differential operators. (a) gradient filter and (b) Laplacian filter. Segmentation to facies is based on the variability of the electrical resistivity in tailings.

With a threshold band in the vicinity of [-0.01, +0.01] the dividing line sharpens and depicts a transition zone (gradient analysis) and possibly an edge between two distinct facies (Laplacian analysis). For instance, in Fig. 13, the gradient and the Laplacian filters at the narrow band of [-0.01 - +0.01] highlighted the contact zone between the tailings and the underlying ground that was not apparent in the unfiltered ERI section.

As for facies analysis, the band threshold is widened to highlight local geoelectrical zones of low electrical resistivity variation in the gradient analysis and a zone with a constant net gradient change in the Laplacian analysis. In this way, by targeting specific variability of electrical resistivity change, classification and segmentation of local facies can be achieved. For instance, in Fig. 13, the threshold range [-m, +n] delineates a zone where the gradient change of electrical resistivity is minimum or almost invariable. The zone of increasing net gradient change is associated with an accelerated change of electrical resistivity or a low conductive media while the zone of decreasing net gradient change is associated with a slowdown of the electrical resistivity or a highly conductive media. Also, the gradient and the Laplacian filters highlighted a layered pattern of the

electrical resistivity variation consistent with a depositional media that is influenced by settling and lateral water movement.

4.2 Electrical resistivity imaging and petrophysical interpretation

The electrical resistivity data from the ERI survey is interpreted with the generalised Archie's law for a multiphase media (**Paper II**). The results revealed in this case that while the physical characteristics of the tailings material such as porous structure and grain size distribution do not change significantly, the bulk electrical resistivity is highly variable. The results showed that the major factor influencing variability of bulk electrical resistivity is water saturation that increases with depth. In Fig. 14a, the bulk electrical resistivity and the porewater electrical resistivity are plotted in the depth domain and it shows that low electrical resistivity is associated with water saturation. The electrical resistivity of the porewater is inherently in the low range (dotted lines) whereas the bulk electrical resistivity decreases as it approaches the phreatic line and below the water level.

The dependence of the bulk electrical resistivity to phase components in the tailings was evaluated. The conceptualisation of a multiphase tailings media allowed us to quantify and explain the relative contribution of phase components in the overall electrical response of the tailings media. Thus, for the case of the Brukunga tailings media, the research showed that the tailings matrix is responsible from 5% up to 52% of the tailings electrical response. However, it also showed that water in the pore space controls the response from about 30% at unsaturated conditions to above 90% at saturation. As for the contribution of the clay fraction, this was not significant and only accounted for less than 2% at saturation conditions and almost 10% at unsaturated conditions, which means that surface electrical conduction is not significant.

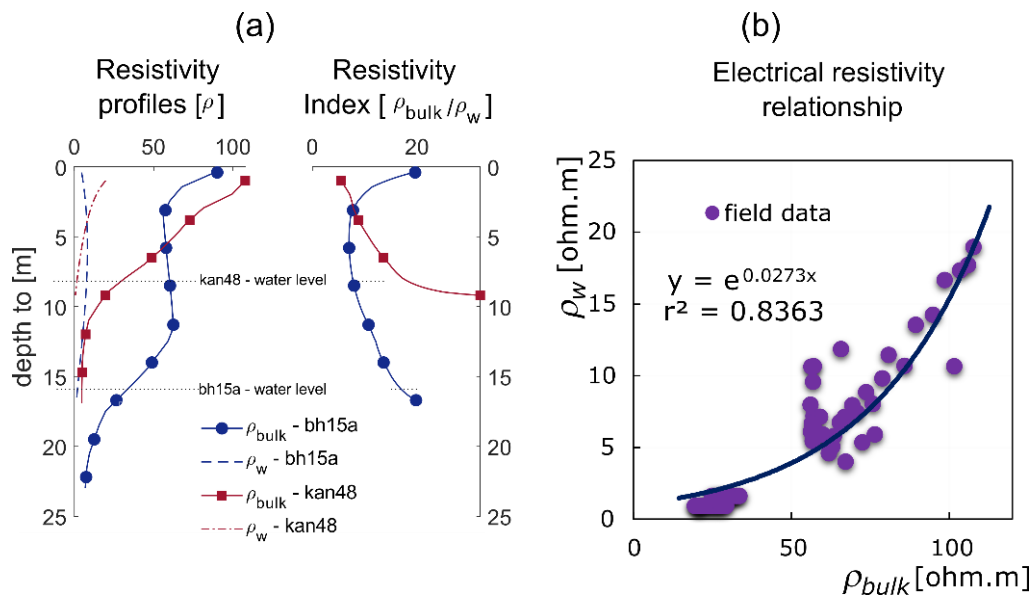**Fig- 14** Electrical resistivity signature of the tailings at Brukunga mine. (a) electrical resistivity (ρ) profiles and electrical resistivity index (ρ_{bulk}/ρ_w) in the depth domain (Source: Modified from Mollehuara et al. 2020). (b) Empirical relationship between porewater electrical resistivity (ρ_w) and bulk electrical resistivity (ρ_{bulk}) based on data from boreholes bh15a and kan48.

The interpretation in terms of hydrogeological conditions links to Archie's law where the bulk electrical resistivity is directly proportional to the relative contribution of each phase in the tailings media, in which the fluid in the pore space is the major contributor to the electrical response. The generalised mixing model considers the resistivity index that is found to absorb the spatial variability of both bulk and pore-water electrical resistivity. From this analysis, an empirical relationship that relates to the resistivity index is determined (Fig. 14b) and used to evaluate the porewater electrical resistivity in the unsaturated zone of the tailings.

To interpret the ERI cross-section in terms of water saturation and water content, equation (4) is applied. The results are presented in Fig. 15.
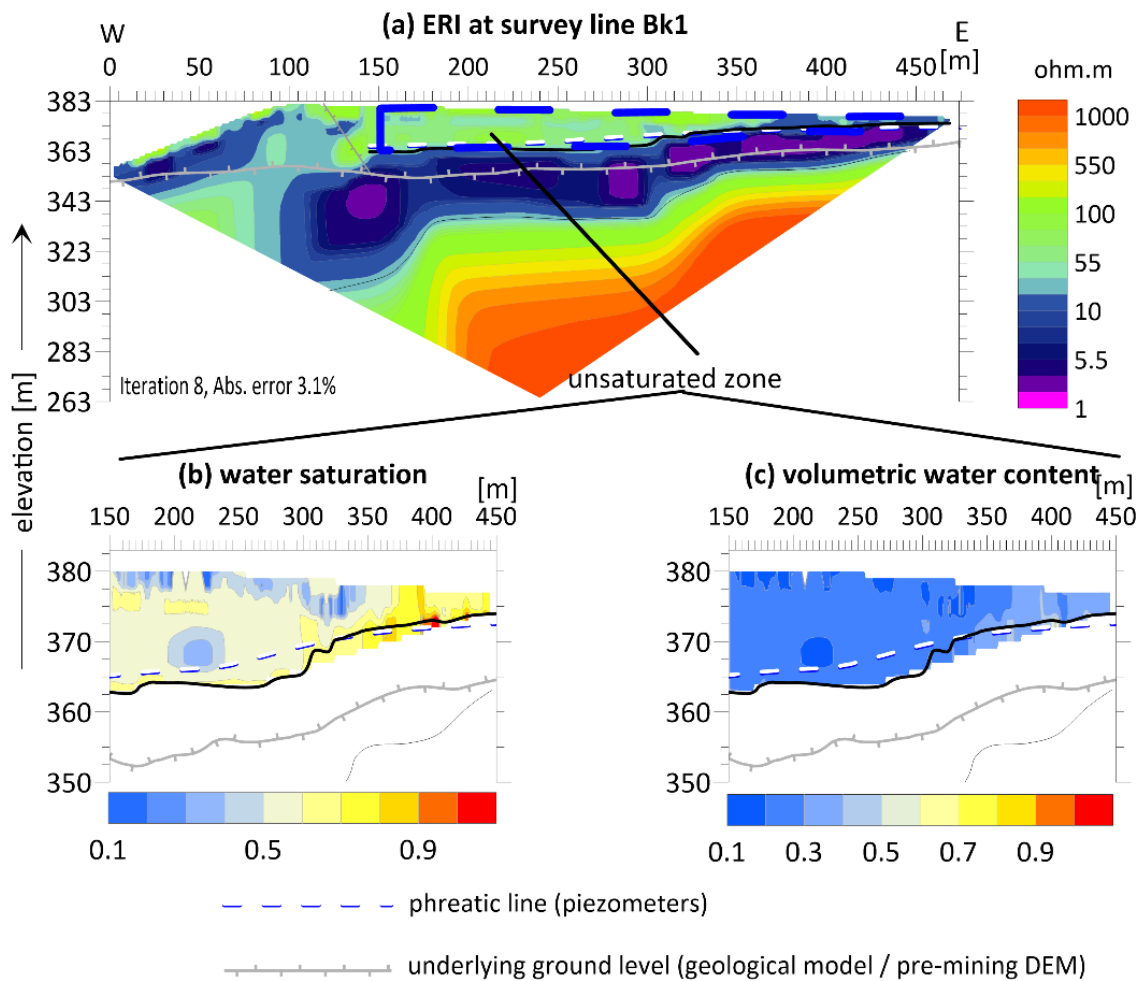
Fig. 15 Hydrogeological interpretation of ERI data derived from geoelectrical and petrophysical relationships: (a) Electrical resistivity model across survey line Bk1 at Brukunga TSF showing the unsaturated zone within the dotted blue line. (b) water saturation in the unsaturated tailings zone. (c) volumetric water content (v/v) in the unsaturated tailings zone.

Although the ERI model distinguishes graphically the unsaturated tailings from the saturated tailings, the generalised Archie's law enables a quantitative determination of the hydrogeological conditions. The model explains the sensitivity of electrical resistivity to water content in the unsaturated zone of the TSF and provides a reliable approximation of

the distribution of water content and saturation. It is assumed that below the phreatic line the media is saturated.

The model applied to the unsaturated tailings using additional borehole data determined the exponential parameters (m_w=2.61, m_s=0.731, m_c=0.731), Archie's law parameters (m=2.614, n=2.311), and the electrical resistivity values for the tailings matrix and clay (ρ_s=73.13 ohm.m, ρ_c=28.51 ohm.m). These values are within range of those found in **Paper II**.

4.3   Seismic refraction and tailings physics interpretation

This part shows the results of interpreting velocity models derived from seismic refraction data with principles of tailings physics (Paper III). The analysis is on the survey dataset corresponding to the Pyhäsalmi tailings facility.

The P- and S-wave velocity models were correlated to obtain empirical relationships for each survey line and is shown in Fig. 16a. Also, the relationship between the bulk mass density and the P-wave velocity in the depth domain is presented in Fig. 16b. These were the key empirical relationships linking the tailings seismic response with their physical characteristics. The results show a linear relationship between P- and S- wave velocities which are similar for various tailings profiles but different for the survey line close to the embankment (line K13K1).
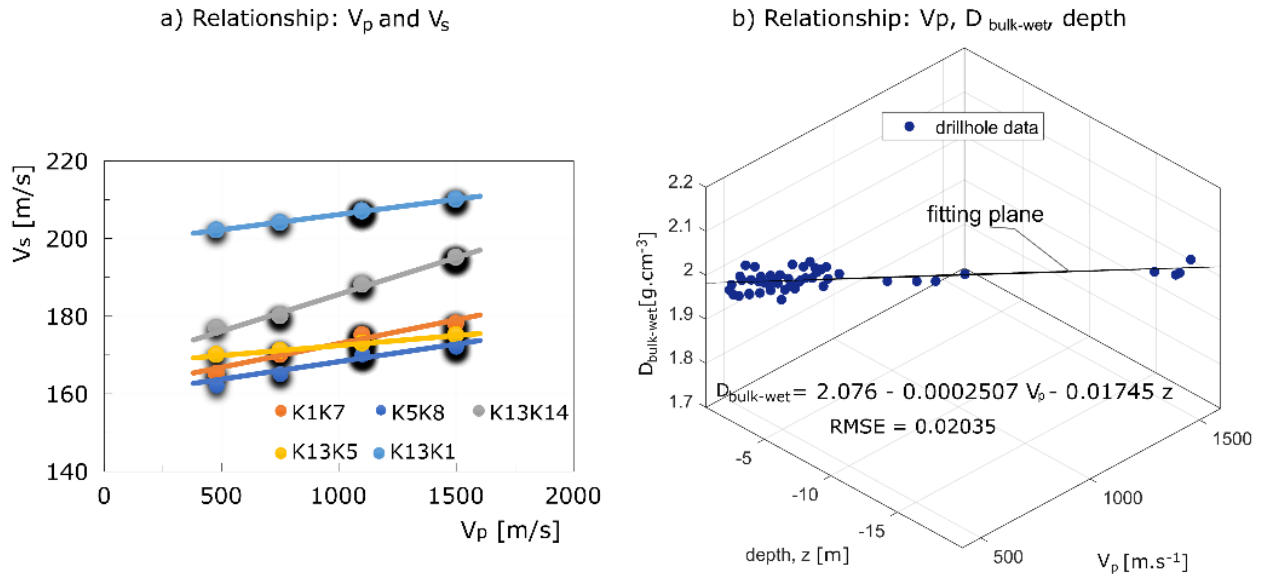
Fig. 16 Empirical relationships corresponding to survey lines in the tailings area of Pyhäsalmi mine. (a) V_s / V_p relationship; (b) V_p / bulk mass density / depth (Source: Modified from Mollehuara-Canales et al. 2021b)

Fig. 16a depicts the relationship of elastic seismic velocities that is specific to the unconsolidated tailings media at Pyhäsalmi mine and these are expressed in the following equations:

$$V_{s(K1K7)} = 0.0123 * V_{p(K1K7)} + 160.65 \qquad (9)$$

$$V_{s(K5K8)} = 0.009 * V_{p(K5K8)} + 159.28 \tag{10}$$

$$V_{s(K13K14)} = 0.0189 * V_{p(K13K14)} + 166.75 \tag{11}$$

$$V_{s(K13K5)} = 0.0051 * V_{p(K13K5)} + 167.34 \tag{12}$$

$$V_{s(K13K1)} = 0.0079 * V_{p(K13K1)} + 198.26 \tag{13}$$

Another relevant relationship is concerning the gravimetric water content (θ) as a function of bulk mass density (D_{bulk}) derived from Fig. 16b:

$$\theta = 1.5097 \cdot D_{bulk} - 2.825 \tag{14}$$

Velocity models and empirical relationships are combined to interpret the elastic moduli of the tailings. The results determined that variability of hydrogeological conditions (*e.g.*, water saturation) influences the seismic response (V_p and V_s) and the elastic parameters (Fig. 17). For instance, the Bulk modulus K that relates the change in hydrostatic stress to the volumetric strain was predominant between 1.0-2.0 GPa. The Young's modulus E in the tailings media was in the low range of 0.15-0.23 GPa. Poisson's ratio values in all sections were in the upper limit, meaning that the tailings media is highly susceptible to transverse deformation under axial compression.

The shear-wave velocity is directly proportional to the shear modulus (μ) which is a direct indicator of the stiffness or rigidity of the tailings material; however, it is greatly influenced by the void ratio and compactness. Across the survey lines corresponding to tailings material μ is between 0.06 and 0.07 GPa, whereas along the western embankment (*i.e.*, line K13K1) μ can reach up to 0.09 GPa. Compared with other unconsolidated materials such as silt or sand, the maximum shear modulus value (μ_{max}) is in the low range for the whole depth. For instance, for conditions of optimum water content, loose silts (void ratio, *e*=0.9) have the μ_{max} at about 0.18, for compacted sand (*e*=0.73) μ_{max} is 0.2 GPa, and for dense silts (*e*=0.7) μ_{max} reaches up to 0.3 GPa (Shuttle & Jefferies, 2016). For comparison purposes, other in-situ determinations in tailings have found the value of μ_{max} in the range of 0.04 to 0.20 GPa (L. Hu *et al.*, 2017).

In Paper III, the in-situ void ratio of the tailings was estimated in 0.62, and the water content was near saturation. This could explain the low in-situ μ_{max} value determined in this study, that despite the better compactness of the tailings, the extent of water saturation can greatly influence the shear modulus.
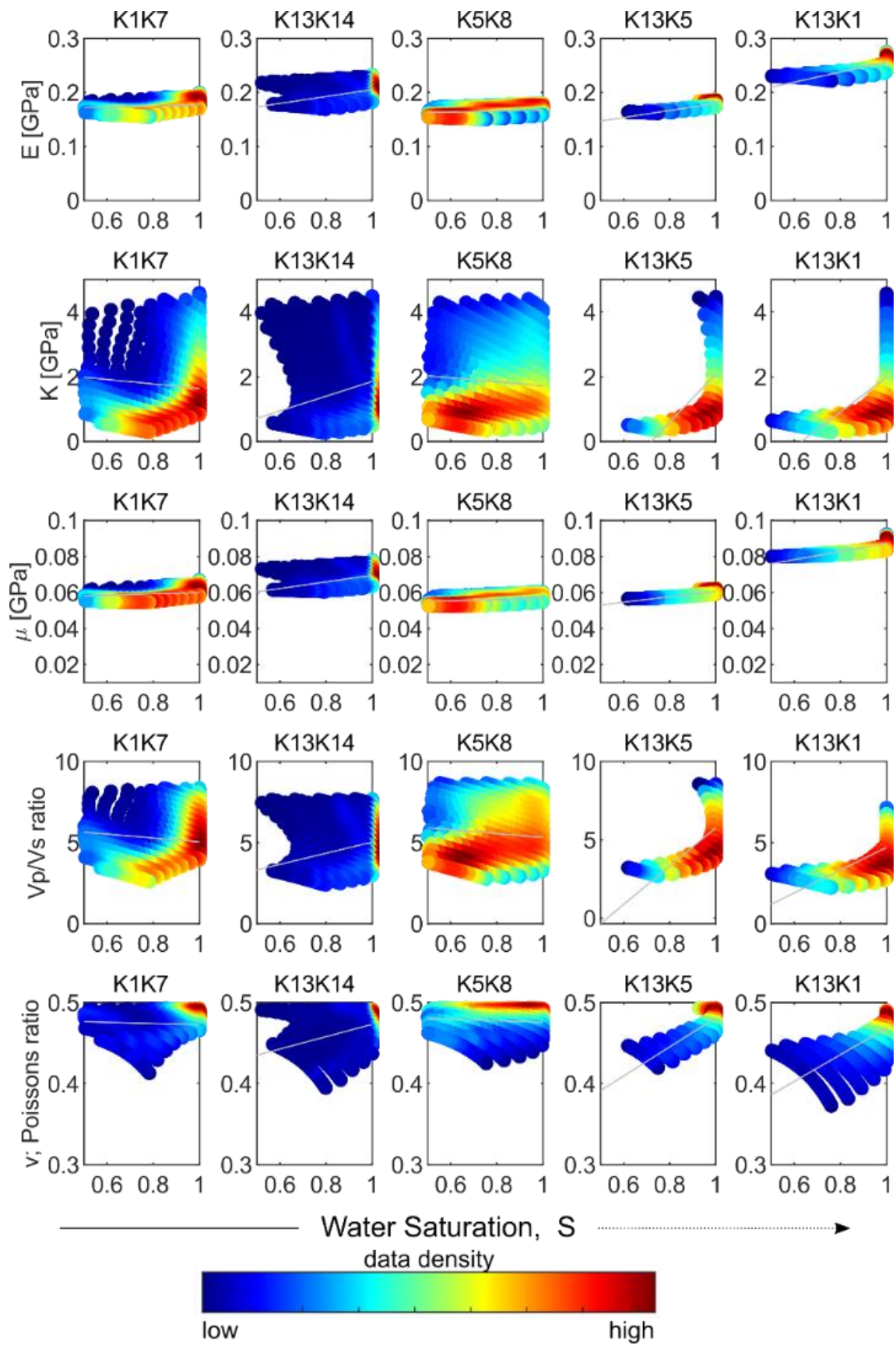
Fig. 17 Density scatter plots for Elastic moduli versus water saturation for survey lines at Pyhäsalmi TSF (Source: Modified from Mollehuara-Canales et al. 2021b).

Figure 18 illustrates the spatial distribution of the elastic parameters near and below the phreatic line as 2D cross-sections for line K13K5. The figures show a quantitative and agreeable interpretation that water saturation causes strength reduction in the tailings media and reduces stiffness, both effects related to Young's modulus. Poisson's ratio is higher in saturated tailings than in unsaturated tailings which means that the tailings in saturated conditions can exhibit large elastic deformation even under the action of small amounts of strain or applied forces. Shear modulus of the tailings is also observed to increase below the phreatic line in proportion to the marginal increase of V_s and the densification of tailings with depth and because S-wave is not affected by water. Shear modulus as initial modulus is essential to the dynamic analysis of tailings dams (Zhang and Lin, 1982). The increase of Bulk modulus with depth is directly proportional to the confining pressure, that is a function of the effective stress given by the total load and the excess pore pressure.
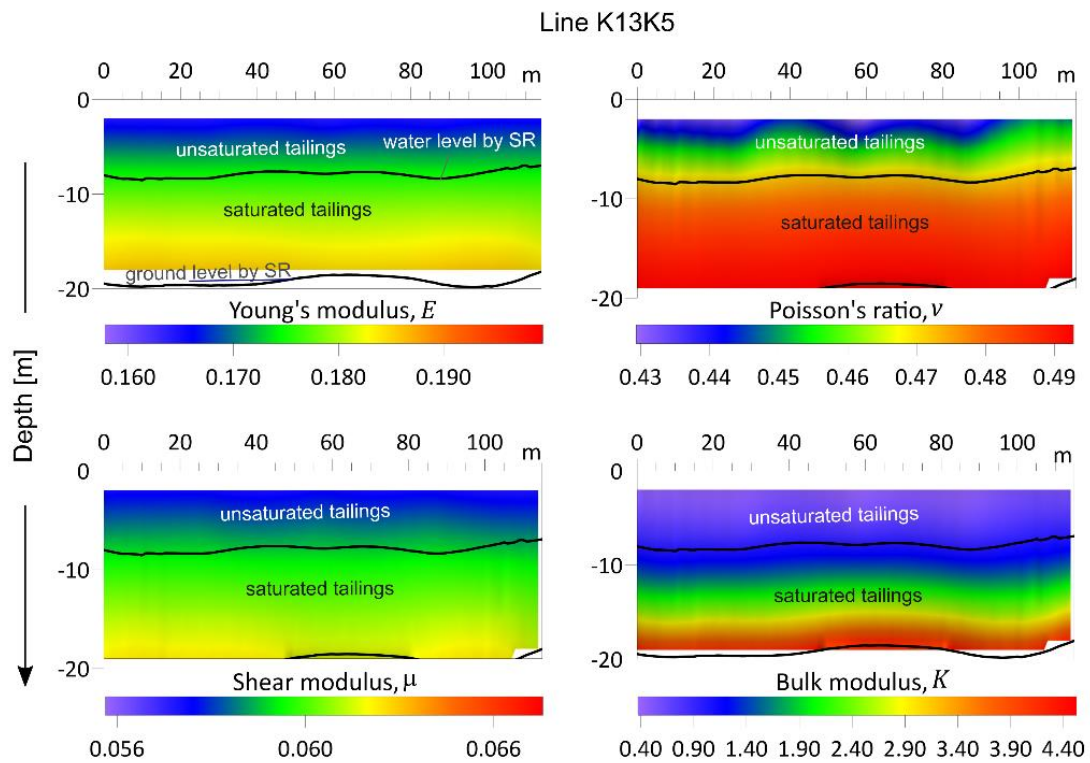
Fig. 18 Cross-section examples of principal elastic parameters determined by SR and MASW analysis for line K13K5. Black lines are SR inferred boundaries for water level (upper) and underlying ground level (lower).

From the established empirical relationships, water saturation, water content, and porosity are calculated and presented as cross-section for survey line K13K5 (Fig. 19). The plots show the subsurface hydrogeological state that is consistent with observed field conditions above the phreatic line with saturation in the range of 0.8 and water content between 15 and 20 percent. The plots depict a clear boundary that is consistent with the phreatic line determined from the piezometric measurements. The representation also suggests variability in porosity values that is marginal for tailings and in the range of 0.40 for the upper layer and 0.38 for deeper zones. It is also observed that water saturation is

slightly above the line of the phreatic line delineated from the piezometric measurements and this may be because of capillary rise.

Fig. 19. 2D representation of calculated water saturation, gravimetric water content and porosity for line K13K5 in Pyhäsalmi TSF. White dashed line corresponds to delineated phreatic level.

5   Conclusion and suggestion for future work

This study investigated non-invasive geophysical methods to characterise subsurface conditions in tailings facilities. The geophysical dataset used in this research thesis were
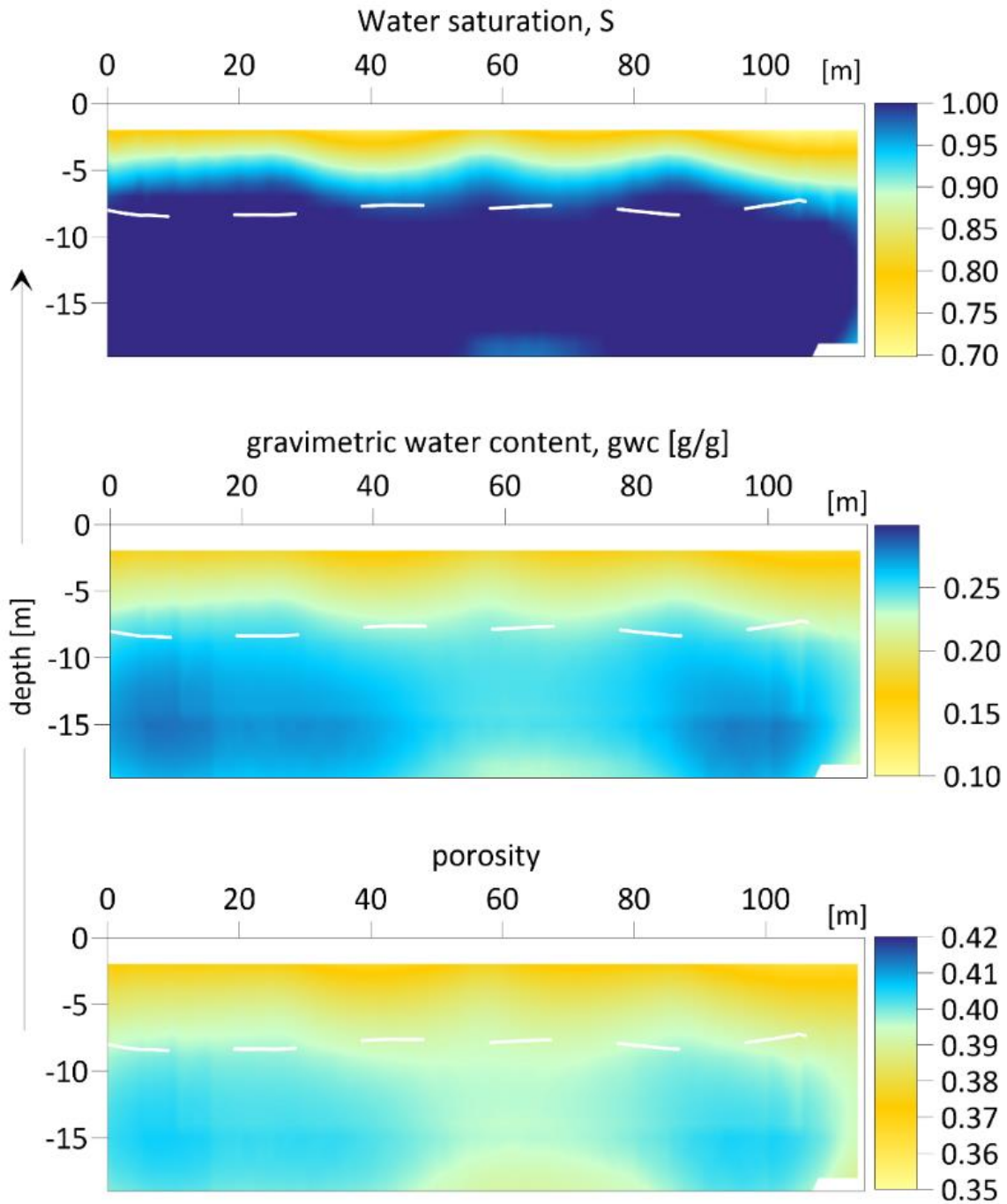
acquired by seismic refraction (SR) and electrical resistivity imaging (ERI) surveys. The contribution of this thesis to the research field concerning the characterisation of tailings facilities, is the quantitative interpretation of geophysical dataset in terms of hydrogeological and elastic conditions; and for which, principles of petrophysics and tailings physics were integrated.

In **Paper I,** the stratigraphic structure and local change detection are interpreted from SR and ERI datasets. The ERI method can use seismic refraction output for a constrained inversion or be analysed using filters such as the directional derivatives (*i.e.*, gradient and Laplacian). In the first case, the joint interpretation was effective to reveal the stratigraphic profile of the tailings subsurface. SR provided reliable depth approximations to the underlying ground and bedrock, whereas the ERI method captured well the phreatic line and the bedrock depth. In the second case, a second workflow alternative was also demonstrated by applying the directional derivatives to the ERI model. The filters highlighted the transition zone of two different stratigraphic units within the saturated zone in the tailings (*e.g.*, saturated tailings from the underlying ground) that otherwise was concealed by the permeated porewater. As for facies analysis, both the gradient and Laplacian filters complemented each other for edge detection and segmentation of the subsurface into distinctive zones. The filters enabled geoelectric zoning and for delineating facies associated with salinity dispersion.

In **Paper II**, the multiphase petrophysical approach was evaluated via the generalised Archie's equation that takes into account the volumetric phases in the tailings media (*e.g.,* tailings matrix, fluid phase, and clay phase). The results revealed that electrical response in tailings is governed by the physics of power-law applied to the volumetric phases in the tailings media. The research also showed that the electrical response of the tailings media is controlled by the porewater electrical resistivity and that the major parameter influencing variability of bulk electrical resistivity is water saturation that increases with depth. As clay content can influence the electrical response of the medium, the tailings material was characterised for clay. The overall electrical response was influenced by the relative contribution (RC) of the tailings matrix (up to 52% at unsaturated conditions), whereas the clay fraction only accounted for up to 10% RC in unsaturated conditions, and the fluid phase in the pore space up to 90% at saturation. The thesis expanded on the findings of Paper II and estimated the water saturation and water content in the ERI cross-section which depicted the wet zones that are inversely proportional to the electric resistivity values.

Paper III is related to the seismic refraction and MASW analysis to derive velocity models for the tailings facility at Pyhäsalmi mine. For the interpretation of the elastic parameters and the associated hydrogeological conditions, tailings physics principles were applied. The results show that elastic parameters (*e.g.*, Bulk modulus, Young's modulus, Shear modulus, V_p/V_s ratio, Poisson's ratio) are influenced by the hydrogeological conditions (*e.g.*, mainly water saturation, and void ratio). Hence the importance to monitor water saturation in tailings areas.

For instance, states of variable water saturation increasing from 0.4 to 0.8 were revealed above the phreatic line in the tailings facility. For this condition, the bulk modulus K was between 1.0-2.0 GPa which expresses the resistance of the tailings to changes in

hydrostatic stress. The Young's modulus E in the tailings media was in the low range of 0.15-0.23 GPa and the Poisson's ratio was in the upper limit values, meaning that the tailings media is highly susceptible to transverse deformation under axial compression. The shear modulus (μ) of the tailings was in the low range at 0.06-0.07 GPa, but mainly influenced by the water content in the tailings to near saturation.

Paper III also highlighted the importance of empirical relationships, velocity models, and water-related conditions for which the relation between P-wave velocity and the bulk mass density of the media was key. From there other properties were derived such as porosity, void ratio, water saturation, and water content. For the case of the Pyhäsalmi tailings facility at the survey conditions, the porosity of the tailings media was around 0.38, the void ratio was 0.62, and the water saturation above the phreatic line was above 0.90.

5.1 Research implications

This research demonstrates that geophysical imaging are not mere visual representations and rather they are datasets carrying information of geophysical signatures that can be related to the physical, mechanical, and hydrogeological properties. The application on tailings media which is less heterogeneous than the subsurface in natural environments opens a pathway opportunity for a novel characterisation at domain-scale of other similar structures in mining environments.

Geophysics can reduce the level of uncertainty about the subsurface conditions in tailings facilities. Integration with petrophysics and tailings physics can enable an analytic interpretation. Also, the delineation and segmentation of facies in the subsurface have relevance for the conceptualisation and parameterisation in hydrogeological models.

The workflow described in the research methodology integrates several data sources (geological and geophysical data) to interpret the corresponding model results by principles of petrophysics and rock physics well-known in the gas and petroleum industry. The selected geophysical methods such as ERI and SR have the flexibility to map the subsurface across a range of scales by arranging the sensor's layout (electrodes and geophones) to suit the needs of surveying a particular tailings facility. As geophysical inversion deals with ill-posed problems where multiple models can satisfy the data, geological information available for tailings facilities is critical to constrain the modelling process (both in ERI and SR) and reduce the uncertainties. Furthermore, ERI and SR joint interpretation improves the identification and delineation of stratigraphic boundaries and localised facies. However, SR in a tomographic approach can reduce the uncertainties only to an extent because of the non-uniqueness of the solution, and it requires additional fieldwork and time to survey with closer spacing and multiple shot-points. The workflow combines petrophysics and rock physics principles and enables a multi-physics interpretation that accounts for the combined effect of the tailings media and the fluid properties. In this way, the cross-correlations between properties can be associated with other geophysical datasets in the tailings facility. But as tailings facilities are open structures with fluctuating water balance, water saturation also varies and affects the geophysical response. Therefore, a time-lapse monitoring approach would be required to map the dynamics of a changing subsurface both spatially and temporarily.

5.2   Practical implications

This research has contributed with further knowledge about the capabilities of geophysical methods (ERI, SR, MASW) which is to map the subsurface of tailings storage facilities in terms of elastic and hydrogeological properties.

In mining waste domains, where access to the subsurface is challenging and costly, non-invasive geophysical methods emerge as the alternative to complement conventional technologies. Geophysical methods can render information from the subsurface at higher spatial resolution whilst covering areas at the domain scale.

The connectivity of geophysical equipment in the field with centralised monitoring systems in mine sites could make possible continuous time-lapse monitoring of the subsurface of TSFs. Recent developments in telemetry and wireless communication can overcome connectivity issues in remote locations.

Site-specific petrophysical relationships and velocity models can be integrated with the geophysical data from the monitoring platform of mine sites and provide continuous time-lapse monitoring of the subsurface conditions.

Further knowledge and validation of hydrogeophysics can positively influence the mining industry enabling the adoption of geophysical methods to streamline data acquisition in TSFs and overcome the limitations of conventional techniques. Industry and practitioners can improve workflow, quality, and confidence in the decision-making process and management practice of TSFs. This is a new application with the potential to be adopted in other areas of the mining cycle facing the same challenges (*i.e.*, mine waste management, environmental rehabilitation, closure, and post-closure monitoring of rehabilitated mine sites).

The interpretation of geophysical data in terms of stratigraphy and facies is important for the integration of geophysical data with other models investigating mining waste domains. Facies can potentially be used as geological constraints for model conceptualisation and parameterisation in hydrogeological investigations.

5.3   Recommendations for future work

For mine waste management and monitoring, there is an increasing need to focus on a larger scale characterisation of the controlling mechanisms concerning hydrological, geochemical, and ecological processes. This research has applied the hydrogeophysical concept in TSFs for a discrete location of the tailings domain. Other studies in TSFs have also concentrated the application of geophysics to small areas. Further research on TSFs should characterise the facility at the domain scale.

Conduct geophysical data acquisition with a tomographic approach, that is finer grids, smaller spacing between electrodes or geophones, and shots at every geophone in the case of seismic refraction. The depth of investigation and the resolution should be balanced and taken into consideration when designing the grid that suits each case.

In situ measurements of unconsolidated and saturated fine grain material are challenging in all conditions. Validating the in-situ measurement is inherently difficult even for benchmark technologies. In the case of tailings facilities, and concerning the

mechanical properties of tailings, it is recommended to investigate performance and reproducibility with other methods such as seismic cone penetration tests (SCPT). The industry has widely accepted parameters measured by SCPT to infer the mechanical strength of tailings, and the seismic interpretation of elastic moduli needs to be related to these terms.

We acknowledge the support of Pyhäsalmi mine and the Brukunga mine site management for permitting us to research their sites. Most of the time, it is difficult to get access to tailings facilities. Reference sites (*e.g.*, decommissioned tailings facilities open to research and testing of technology) are good alternatives for conducting this type of research and it is recommended to map the location of these facilities. It allows to have a historical dataset, revisit surveys at various conditions, shared knowledge among the research community.

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Ser. A, Contributions.

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