Non-invasive geophysical imaging and facies analysis in mining tailings

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ABSTRACT

Stratigraphy and facies analysis in a mining waste domain such as in tailings storage facilities (TSFs) is still a complex task due to sparsely distributed field data. Geophysical techniques and the interpretation of geophysical data in terms of stratigraphy and facies get relevance for integrating geophysics with other models investigating mining waste domains (e.g., hydrogeological-geochemical).

In this paper, we introduce a conventional application of differential operators for interpreting geophysical data in terms of stratigraphy and facies analysis in TSFs. The geophysical data is acquired in a tailings area in the Pyhäsalmi mine, Finland, using seismic refraction (SR) and electric resistivity imaging (ERI) techniques. The SR inversion model constrained by a geological model approximated the ground and bedrock layers by delineating P-wave velocities (Vp). The SR layered model served as a constraint for the electrical resistivity (ρ) model in the ERI method. ERI inversion model data was used for facies analysis and interpretation in terms of other subsurface variables (e.g., water saturation, salinity). 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. The approach embeds the data as scalar functions within a space domain defined by the model local structure. When applied to the ERI data, the gradient and the Laplacian functions captured the local extrema and the minimum threshold crossings respectively enhancing local geoelectric zones and layered contacts in line with field observations. This paper demonstrated that such image analysis can be proposed for interpretation of geophysical data in terms of segmentation and analysis of local facies, relevant in model conceptualization and parameterization of hydrogeological models.

1. Introduction

Reclaimed land in mine sites includes areas previously disturbed by mining activities or areas that hosted mining waste such as tailings or waste rocks. These environments are classified as landfill areas for hazardous waste, hence monitoring the changes and conditions in the subsurface is critical to make decisions such as ensuring their long-term stability and performance. Hydrogeological and geochemical models that aim to this purpose (Vriens et al., 2020; Wolkersdorfer et al., 2020) use stratigraphic information for defining geologic constraints and model parameterization. A major difficulty for these models is the parameterization because of the limited knowledge about the subsurface and heterogeneity of the mining waste. The use of discrete facies to deal with heterogeneity (Bianchi et al., 2015) and correlation of features (Middleton, 1973) is common in groundwater investigations and the application can expand to facies analysis in mining waste domains, such as tailings storage facilities (TSFs). Identifying facies is of importance because they define the constraints and narrow the range of parameters to assign (Pyrcz and Deutsch, 2014) enabling a better description of the depositional domains. Domain properties such as porosity, permeability, clay content, hydrochemistry can be adequately assigned having a clear definition of stratigraphy and facies that are agreeable to field conditions.

In TSFs, deposition and settlement processes lead to a layered consolidation of the tailings material commonly described as stratification. While the concept of stratigraphy is not novel in mining waste analysis (Lorca et al., 2016), the use of stratigraphy and facies analysis for model parameterization in reclaimed mining areas has not been extensively explored due to several reasons. First, the reach of conventional techniques for surveying and sampling is limited to sparse discrete locations. Second, retrieving direct core measurements from saturated media is a challenging task. Third, maintaining post-reclamation monitoring of the subsurface is cost prohibited. Also, monitoring of reclaimed mine waste areas is a specific type of monitoring where

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intrusive surveys are not recommended.

The significance of a non-invasive method for stratigraphic and facies analysis in TSFs is of interest in the mining industry. Typically, the general distribution of facies and corresponding domain properties are predicted from geological understanding, but it is not always the case if the spatial coverage and access are limited (Sausss and Sams, 2012). Here is where geophysical methods can overcome the limitations of sparse core data. Geophysical techniques have been applied increasingly in TSF areas, being seismic refraction (SR) and electrical resistivity imaging (ERI) methods the most popular applications. SR and ERI can map the distribution of compressional P-wave velocity ($V_p$) and electric resistivity ($\rho$) in the subsurface of tailings and the data can be used to interpret physical boundaries and associated parameters. Where the contrast in a geophysical image is not evident due to model parameterization used or regularization applied, the relationship between stratigraphy and tailings physical properties may not be evident. In addition, saline pore water moving across porous layer horizons can mask physical boundaries, and a quantitative approach to associate geophysical models with common facies is yet to be addressed.

The objective of this paper is to demonstrate the use of geophysical methods for data acquisition in tailings areas and to propose a method of interpretation of stratigraphic facies in TSFs by using differential operators (i.e., the first-order derivative and the Laplacian filters). The gradient and Laplacian approach which has not yet been applied in tailings are used in this paper for geoelectric zoning as facies and for interpreting the spatial physical variability of electrical resistivity in terms of associated hydrogeological parameters.

1.1. SR - ERI applications in tailings

1.1.1. Seismic refraction (SR)

Surface seismic methods (i.e., refraction and reflection) have been used widely for sallow surveys in engineering site investigations. 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 digitized in terms of 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 (Dobecki, 1986). SR has been used to complement other techniques in the investigation of geological settings of tailings storage facilities as it can effectively detect the underlying ground of higher compactness from the tailings media. Some of the applications include distinguishing basement morphology of tailings deposits (Lghoul et al., 2012), 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 and Dale, 1992).

1.1.2. Electrical 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 processes 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 on an emplacement string with some of these acting as current-source electric dipoles and others acting as potential-measuring dipoles. The electrical resistivity data can be acquired and processed by a processing control unit to produce continuous two- or three-dimensional subsurface images. ERI has been increasingly used in tailings areas (Martínez-Pagán et al., 2021) because of its ability to map the internal structure of the tailings based on the salinity of the pore water acting as a tracer to measure the distribution of electrical resistivity and therefore infer water movement. Low resistivity values are associated with low resistivity pore water originated from the mine waste or areas with higher sulfide content and oxidation degree. By association, it can infer water movement, saturation trends, and the geometry of the tailings. ERI combined with other techniques or alone has been applied mainly to depict the thickness of soil cover, the thickness of the tailings, identify general geometry and geologic contact between tailings and basement rocks (Martín-Crespo et al., 2018; Cortada et al., 2017; Grangeia et al., 2011) that can also be used in volumetric estimations (Martin et al., 2020). Other applications include detecting flow directions, anomalous seepage, mobility of heavy metals, and preferential pathways into the underlying bedrock (Arcila et al., 2021; Duda et al., 2020; Benyassine et al., 2017; Yurkevich et al., 2017; Olchenenko et al., 2016; Mainali et al., 2015; Acosta et al., 2014; Lghoul et al., 2012) or 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 oxidized zones (Bortnikova et al., 2013), for examining the evolution of sulfide weathering (Placencia-Gómez et al., 2010), and for revealing the migration of acid mine drainage and the distribution of highly mineralized solutions (Epov et al., 2017; Korneeva et al., 2016; Tycholiz et al., 2016).

2. Materials and methods

2.1. Site and geological model

The site is a TSF at Pyhäsalmi mine in North Ostrobothnia, Finland containing a reject product from the ore enrichment process. Fig. 1 illustrates the pre- and post-mining conditions of the area and includes a layout with the survey locations. The tailings area consists of four sections known at the site as ‘pools’, namely A, B, C, and D (Fig. 1d). Pools B, C, and D are active pool areas for storing pyrite-rich tailings, recycled water, and tailings after pyrite enrichment, respectively. ‘Pool A’ is a disposal area decommissioned between 1999 and 2002, and it is the area selected in this study. The reclamation works consisted of covering the dam structure and the surface of the tailings area. The cover system slopes down from the edges to the center, so a water pond forms in the middle of the ‘pool’ where a decantation well drains out the excess water. Pool A covers a footprint of 41 ha and contains about 10 Mt of tailings. (Pyhäsalmen Mine Oy, 2017). Karlsson et al., 2018 describe the mineralogy of the tailings at pool A consisting of sulfide phases (> 31% w/w) with pyrite being the major sulfide mineral (~30%w/w), and relatively smaller fractions of pyrrhotite, chalcopyrite, and sphalerite. The tailings materials also contain a small fraction of calcite and dolomite in addition to aluminosilicate mineral phases (tremolite, biotite, albite, serpentine, K-feldspar, chlorite, anthophyllite, and phlogopite).

A 3D geological model around pool A is presented in Fig. 2(a). The model is constructed using site information illustrated in Fig. 1. The water level in pool A was determined from observations and measurements at existing well pipes. Percussion drilling down to 6 m into the tailings was carried out to complement and observe the stratigraphy around the survey lines. The model containing contours and surface maps was reconstructed using a soft mapping interpolation known as kriging in Golden software Surfer 18. The geological model allows the creation of smooth stratigraphic cross-sections at any location in the entire tailings domain and Fig. 2(b) shows stratigraphic profiles across the survey lines. Cross-sections K17, K13K14, and K13K5 traverse towards the center of the tailings zone. Cross-section K13K1 runs parallel and close to the western embankment. Cross-sections contain information about topography, stratigraphy, and water level.

The survey revealed that the cover structure in the tailings area comprises a thin layer of topsoil 0.1 m thick overlaid by a protective soil
layer of fine till with a thickness ranging from 0.3 m around the center of the tailings area and increasing to about 1.2 m approaching to the edges. The water level at the time of the survey was estimated from water monitoring boreholes and drill holes around the study area shown in Fig. 1. The water line approximates the two distinctive unsaturated and saturated zones in the tailings. The bottom level of the pool at 141 m.a.s.l. and the final height level at 163 m.a.s.l. were derived from reports as elevation data for pre-mining conditions were not available.

The stratigraphic profile is consistent around the mine site. To the west and south of the tailings area drilling and test pits (Rantala, 2017) revealed surficial topsoil and peat overlaying the ground (0.5–0.9 m thick). A fine layer of silt (0.2–0.3 m thick) lies beneath the peat and overlies a 0.8–0.9 m thick layer of clay. A layer of sand-rich diamict containing lenses of gravel is underlying the clay zone (0.6–2.0 m thickness) and passes into a layer of fine-grained till containing boulders (2.8–3.3 m thick) at deeper zones. Bedrock is lies at 6–7 m below the ground surface. Immediate to the west and south side of TSF A, peat overlies the clayey silt layer. Clayey silty diamict is found at a depth of 1 m down to 2 m before transitioning to fine-grained diamict with smaller clast, clast-size increasing into boulders at deeper levels (Komulainen, 1996).

The soil in the vicinity of the TSF covers a flat terrain except for a few moraine hummocks. The dominant soil type is fine-grained till with a thickness ranging from 5 to 15 m that cover the bedrock. The soil types covering the till are peat, clay, silt, and sand. Peat deposits are generally on the order of less than a meter. The clay is usually 0.5–1 m thick and at some places is covered with sand or peat. The soil can also be fine-grained till in places right up to the surface (Huttunen, 1995). The bottom layer of the tailings area is compacted peat.

The ground underlying the tailings zone is assumed to continue to

Fig. 1. Survey site is “pool A”, a reclaimed tailings storage facility of Pyhäälä mine, Finland. (a) Constructed contour levels overlaying an aerial photography from 1960 prior any discharge of tailings in the area; (b) Satellite orthophoto corresponding to year 2020; (c) Site layout shows current and previous surveys; (d) LiDAR base elevation model corresponding to year 2018. Sources for images in (a), (c) and (d): National Land Survey of Finland (2020). Source for aerial image in (b) is from Google Earth.
the south of the tailings area. This was reported from excavation trenches as clayey-silty-diamict which transitions to cobble- and boulder-rich fine-grained till / diamict about 2.7–3.0 m below the ground (GTK, 1995). This horizon is also reported to contain dense small-rounded stones in the upper zones forming clast-rich layers infilled with fine-grained diamict/till that are unbreakable assembles down to the groundwater table.

The TSF was built in a bedrock depression covered by a compact water-retaining soil consisting of fine-grained till and peat. Bedrock ridges are present on the eastern side of the disposal area and the low till-covered rock ridges to the western part. To the west towards the Pyhääjärvi lake, there is a bedrock ridge at a depth of 2.1–4.7 m from the ground surface. To the south, the rock is at a depth of at least 10–16.7 m and to the north at a depth of 12.5 m. On the east side, the bedrock is

Fig. 2. (a) 3D geological model of the pool “A” in the TSF area. (b) Cross-sections show stratigraphic profiles along the geophysical survey transects (sliced from the geological model).

Fig. 3. Overview of workflow for geophysical data acquisition and interpretation that aims to facies analysis.
exposed over a large area (Nenonen, 1995). The bedrock around the Pyhäalsalmi tailings area consists mainly of mafic and felsic volcanic rock overlying porphyritic granite and granodiorite (Marttila, 1993).

2.2. Geophysical interpretation workflow

The workflow for data acquisition, processing, and interpretation is presented in Fig. 3. Prior information from the geological model serves as a constraint for geophysical modeling. This information is more likely known in most mine sites otherwise it is estimated from historical reports and survey observations. In the case of the Pyhäalsalmi tailings facility, the ground surface underlying the tailings was approximated at about 20 m depth from the surface and the bedrock was approximated between 10 and 15 m below the surface of the natural ground (i.e., 30–35 m from the tailings surface). Seismic refraction data acquisition scheme was designed with respect to site geological information. The initial velocity model and inversion parameters are constrained by the geological information containing approximated depths to natural ground and bedrock, and by the velocities derived from the travel time curves. The resulting inversion model serves to produce a layered model based on P-wave velocity isolines at the approximated depths of interest. Electrical resistivity data were computed using the boundaries information from the seismic refraction layered model. This information was incorporated into the inversion to produce the electrical resistivity model with sharp transitions in between boundaries. The last part of the workflow corresponds to the stratigraphic and facies analysis. For this, differential operators are used as filters to visualize the variability of electrical resistivity within the tailings. The first-order derivative was applied to interpret gradient and the Laplacian operator for interpreting the rate of change of the gradient function. Then electrical resistivity data were interpreted in terms of other parameters in the tailings (e.g., water saturation, salinity).

2.3. Geophysical data acquisition and processing

The survey area is the North-West corner of the tailings facility “A” (Fig. 1). The location was suggested of interest to evaluate among others the identification of connecting water pathways and seepage across the tailings ponds and to the east of the embankment. The geophysical data is serving other purposes such as connecting geophysical signature with hydrogeological parameters which are not discussed in this paper. The transect lines consist of two lines across the tailings in the saturated zone towards the water pond (K1K7, K13K14), and two lines along the western and northern embankments (K13K1, K13K5). Geophysical data processing used software provided by the manufacturers of geophysical equipment. Golden software’s Surfer 18 was also used as visualization software for all geological and geophysical models.

2.3.1. Seismic refraction (SR)

2.3.1.1. SR field data setup. A conventional seismic refraction survey used a Geometrics Inc. Geode seismograph and a set of 24 geophones spaced at 5 m intervals along the survey lines for a total length of 115 m. The geophones were planted into the ground as vertical as possible to achieve the best coupling of the seismic signal and connected to the battery-powered seismograph through a spread cable. The energy source for the trigger impulse used a sledgehammer with a switch fixed onto the shaft. A striker plate was placed firmly onto the ground for coupling the energy from the hammer blow into the ground and to achieve maximum signal. The lead from the trigger was connected to the seismograph which was further connected to a field PC via a digital cable. The energy strikes were applied at seven-shot points along with the spreads, two offsets at each far end, and three distributed within the spread with a 30 m spacing between shot points. The field parameters and the sequences for data acquisition were set up in the Seismodule controller software from Geometrics Inc. In the software interface, digital checks were carried out to ensure the validity of the setup, geophone positions, trigger points, and the signal tests for the corresponding seismic data. A typical set of acquisition parameters for a refraction spread was selected with the sample interval of 1 ms and a recording length of 0.5 s. A low-cut filter of 15 Hz was used for filtering noise data of low-frequency wind and traffic and a notch filter of 50 Hz was selected for filtering nearby power lines frequency.

2.3.1.2. SR data processing. SR data was processed in two stages with Seislager software modules Pickwin and Plotrefa from Geometrics Inc. First, Pickwin module was used to pick up the first P-wave arrivals in each of the 24-channel lines for each data set. The first arrivals were picked up at the first wave break across the travel time axis for all geophones and this travel time information transformed into a time distance graph in the Plotrefa module. The process generates smooth curves with distinctive bends known as the travel time curves.

In the second stage, the travel time curves representing a change in the seismic velocity are computed to produce a layered representation of the P-wave velocity model. The process consisted in setting up the initial velocity model with the field constraints (i.e., depth to the ground surface and bedrock) from the geological model and the minimum and maximum velocities derived from the travel time curves. Since the problem is semi-constrained, the solution uses an iterative, least-squares approach. The inversion in Plotrefa is based on an iterative inversion algorithm (Hayashi and Takahashi, 2001; White, 1989) that creates a velocity model for each travel time. The process iteratively traces rays through the model and compares the calculated and measured travel times, modifies the model, and repeats the process until the difference between calculated and measured travel times is minimized. The theoretical travel times are calculated using the raytracing method based on Huygens’ principle to assess the validity of the inversion results.

2.3.2. Electrical resistivity imaging (ERI)

2.3.2.1. ERI Field data setup. The resistivity imaging used a computer-controlled system Syscal Pro Switch resistivity meter (IRIS Instruments) with 72 electrodes. Survey line K1K1 had electrodes spaced every 4 m and a total length of 284 m. Lines K1K7, K13K14, and K13K5 had electrodes placed every 2.5 m and a total length of 177.5 m. The apparent electrical resistivities were measured in a Wenner-Schlumberger array because it provided a better signal-to-noise ratio and higher vertical resolution compared to a dipole-dipole array. Also, the mapping objective targeted a depth less than 40 m and a general view of the vertical and lateral variations. The maximum electrode spacing AB was 284 m for line K13K1 and 177.5 m for all the others.

2.3.2.2. ERI data processing. Measured apparent resistivity data were pre-processed and incongruent data caused for example by noise were filtered out using the PROSYS II software from IRIS Instruments. The total number of measurements considered for the inversion was 1318. Inversion modeling was carried out using Geotomo’s Res2Dinv resistivity modeling software (Loke, 2018). The inversion used a forward modeling program based on the robust finite element method and a non-linear smoothness-constrained least-squares optimization based on Occam’s method (Degroot-Hedlin and Constable, 1990) to produce a model that emphasizes the vertical resistivity features. Res2Dinv offers two choices for the inversion modeling. The standard L2 norm produces a model with a smooth variation in the resistivity values. The robust constraint refers to the L1 norm which applies a constraint factor to the data and the model and is less sensitive to noisy data points. The L1 norm inversion was used to target sharp boundaries such as the interface between the tailings and the underlying ground. The constraint factors were equal to 0.05 for the data and equal to 0.005 for the model inversion. The cut-off factors represent percentages to minimize the
effect of differences between the measured and calculated apparent resistivity values and to minimize the absolute changes in the model resistivity values. The model error from the L1 norm inversion method is presented as the absolute difference between the measured and calculated apparent resistivity.

2.4. Directional operator filters for facies analysis

The ERI method allows the transformation of the data into a discrete scalar function (inversion model) within a local spatial structure; thus, the directional derivatives can be used for analysis since electrical resistivity is represented in a spatial domain (distance and depth). The facies detection will depend on the choice of the inversion methods; therefore, the differential operators are rather interpretation tools of the inversion model. Fig. 4(a) shows a conceptual one-dimensional (1D) geophysical scalar function \( f(x) \) (e.g., electric resistivity) with a smooth transition of intensity values decreasing and increasing at certain depths. Detection of transition zones using the derivatives approach would be to locate \( z_1 \) and \( z_2 \), where the first derivative of the function \( f' \) (gradient approach), or where the second derivative \( f'' \) (Laplacian approach) locates the zero-crossing at \( z_1 \) and \( z_2 \).

The gradient or the Laplacian approaches can be extended to 2D or 3D dimensions to assist in resolving transition zones and facies analysis. The vector differential operator \( \nabla \) applied to three-dimensional scalar functions (differentiable scalar fields, \( r = xi + yj + zk \)) results in a vector field called a gradient (or conservative) vector field (Eq. (1)). The vector differential operator applied to the gradient field results in a vector field called the divergence of the gradient (Eq. (2)).

\[
\nabla f(x, y, z) = \frac{\partial f}{\partial x} i + \frac{\partial f}{\partial y} j + \frac{\partial f}{\partial z} k
\]

\[
\nabla^2 f(x, y, z) = \frac{\partial^2 f}{\partial x^2} i + \frac{\partial^2 f}{\partial y^2} j + \frac{\partial^2 f}{\partial z^2} k
\]

The maximal directional derivative of the scalar field \( f(x, y, z) \) is in the direction of the gradient vector \( \nabla f \), i.e., the magnitude of the maximal rate of change. Thus, to detect local extrema, the magnitude of \( \nabla f \) is calculated as (Bovik, 2009; Horan and Lavelle, 2004):

\[
|\nabla f(x, y, z)| = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + \left(\frac{\partial f}{\partial z}\right)^2}
\]

The directional derivative is the component of \( \nabla f \) in any direction and it is the rate of change of \( f \) in that direction. The Laplacian convolution is an extension of the second derivative and for a two-dimensional analysis of the inversion model it can be generalized to:

\[
\nabla^2 f(x, y, z) = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} = 0
\]

In the Laplacian convolution, the most quickly changing areas on the image are highlighted. Fig. 4(a) shows that for \( f(x) \) with a constant intensity value or with a linear variation, the second derivative or the Laplacian is zero, therefore any local minimum or maximum happens on the boundaries. The five-point difference formula for Laplace’s equation is illustrated in Fig. 4(b) and it applies an iterative finite approximation to generate the grid for the Laplacian cross-sections. The Laplacian is combined with a Gaussian filter to reduce any small-scale features or noise that might cause spurious edges to be detected.

The ERI sections were processed with the Gradient and Laplacian approach. A threshold criterion \( |\nabla f(x,y)| = 0 \) and \( \nabla^2 f(x,y) = 0 \) are applied in all cases to detect boundaries, whereas the gradient and the Laplacian magnitudes are computed and compared within predefined threshold values [-m, +n] to delineate quickly changing areas, therefore facies.

3. Results and interpretation

Extraction of P-wave first arrival times in SR generated travel time curves with distinctive propagation velocities (Fig. 5). The minimum and maximum velocities on each travel time curve revealed the upper and bottom stratigraphic units corresponding to the tailings media and the ground-bedrock zone. In between, a transition zone is depicted by the curve bend on each travel time curve which is suggested to be the interface between the saturated tailings and the underlying ground. For the upper stratigraphic unit that corresponds to the tailings the P-wave velocities approximated from the travel time curves are between 375 and 435 m/s, while for the denser fast propagating media the velocities range between 5350 and 5750 m/s.

Travel time curves can also anticipate a shallower depth of tailings in...
line K1K7 as it approaches the center of the tailings domain (towards distance 120 m) where an early increase of $V_p$ values suggest a transition to a faster velocity propagating stratigraphy. A similar pattern is captured in K13K14 at the end of the line. Lines K13K5 runs parallel to the Northern embankment and K13K1 runs along the Western embankment where the distribution of velocities along the transects is more symmetric. The SR inversion models presented in Fig. 6(b) confirm these layering trends and provide a visual representation of the major stratigraphic units with tagged contour lines for $V_p$ depicting the transition zones. The approximated depths to contour levels in the layered model revealed that $V_p$ values increase with depth which is consistent with the compactness of the stratigraphic units. $V_p$ values in the tailings increase from 375 m/s in the unsaturated zone up to 1500 m/s for the saturated zone. The $V_p$ in the ground underlying the tailings is in the range of 1500–2500 m/s, whereas the bedrock $V_p$ range is 2500–5750 m/s.

The electrical resistivity model cross-sections for K1K7, K13K14, K13K5, and K13K1 are presented in Fig. 7(a) and to the right of each cross-section in Fig. 7(b) a set of images illustrating the facies detected by the differential operators. The ERI cross-sections in Fig. 7(a) depict the state condition of the TSF in terms of electrical resistivity at the time of the survey. Color code is in logarithmic scale from 1 to 1500 Ω.m to display more details in the low resistivity range of tailings up to 200 Ω.m and less in the higher range where is either dry soil cover or ground/bedrock. Crossing points between survey lines are also indicated to show the coherence of the ERI method to map electrical resistivity distribution in the tailings domain. References to the geological and the seismic refraction model in terms of water level, ground surface and bedrock are also indicated in each cross-section. The bedrock line from SR coincides with the contrasting contour levels in the ERI as it served as a constraint for the inversion model. The ground level from the SR model was not used as a constraint because the interface between the tailings and the underlying ground is not considered a sharp boundary in terms of electrical resistivity values.

In all ERI cross-sections, an accentuated contrast is noticeable at the transition zone between the unsaturated and saturated tailings, and where the bedrock boundary was revealed by seismic refraction. However, this contrast in the electrical resistivity image is not evident at the interface between the tailings and the underlying ground. As depth increases the ground matrix phase contributes to the electrical response and increases the electrical resistivity until reaching a high resistivity bedrock zone. The high electrical resistivity zone at the surface corresponds to the protective layer in the cover system which is evident in cross-section K13K14 and to a lesser degree in cross-section K1K7 because of its proximity to the water pond. K13K5 and K13K1 are lined further away from the water pond with the latter running along the western embankment and showing a high variability compared to the other cross-sections. This is attributed to the saturation and heterogeneity of the soil material as the Western embankment has been compacted during construction and used as an access road. Also, the terrain at the time of the survey was saturated at the surface. The variability of electrical resistivity in cross-sections K1K7, K13K14, and K13K5 is a result of the combined electrical response of the tailings matrix and the saline pore water which is explained later in the facies analysis.

The ERI models revealed changes in the electric response of the tailings subsurface which is associated with low resistivity water movement carrying salinity across the media. Water flow is revealed at the low electrical resistivity zone in cross-sections K1K7 (NE-SW direction), and K13K14 (SE-NW direction) and coincides with field observations where the high hydraulic head is near the water pond in the central part of the TSF and the low hydraulic head is towards the Western embankment. Cross-section K13K5 does not show the hydraulic head difference and suggests water flow that is perpendicular to the survey line and across the tailings “pond A” and the adjacent tailings.
pond to the North. Cross-section K13K1 shows local zones of low electrical resistivity revealing water flow that is perpendicular to the survey line and towards the Western embankment where seepage has been observed.

Fig. 7 (b) shows cross-sections segmented by facies detected by the differential operators in terms of horizontal and vertical gradient of electrical resistivity (first-order directional derivatives), and the net gradient change (Laplacian approach). The interpretation of the distinct facies in terms of the electrical resistivity is illustrated for line K1K7 in Fig. 8 and it can be extended for the interpretation of all the cross-sections in Fig. 7 (b).

Fig. 8 illustrates the interpretation of the delineated zones (facies) in the K1K7 cross-section. The differential operators are used as threshold filters to capture trending zones or for sharpening the contact zone. Where the threshold widens such as in the depicted zone within the [-1, +1] range, it suggests a facies with low electrical resistivity variation for the gradient analysis and a zone with a constant net gradient change for the Laplacian analysis. Where the threshold gap narrows in the vicinity of the zero value as in [-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).

The interpretation in terms of hydrogeological parameters associates the electrical response of tailings material with the electrical resistivity of the tailings matrix (including clay) and the pore water. A generalized Archie’s law (Glover, 2010) describes the contribution of n phases to the effective electrical conductivity of a solid matrix, and the law applied to a multiphase pathway model is adequate to describe the electrical response of mine tailings (Mollehuara et al., 2020). The expression for the bulk electrical resistivity \( \rho_b \) takes into account the volumetric phases in the tailings medium, e.g. tailings matrix \( \rho_s \), liquid phase \( \rho_w \) and clay phase \( \rho_c \), affected by their respective phase exponents \( m_i \). Therefore, the bulk electrical resistivity is directly proportional to the relative contribution of each phase in terms of electrical response but is controlled by their volumetric phase. For instance, the electrical resistivity can depend significantly on the response of the tailings matrix but is mainly controlled (partial at
Fig. 7. (a) Electrical resistivity imaging cross-sections incl. Approximated layers by geological model and Seismic refraction. (b) Electric resistivity distribution analysis for each cross-section, Horizontal (H) and vertical (V) gradient by directional derivatives and the net gradient change by the Laplacian operator.
unsaturated conditions and total at saturation) by the amount of water stored within the pore space. Since the liquid phase component or volumetric water content \((v)\) is a function of porosity \((\phi)\) and water saturation \((S)\), the expression \(v = S \phi\) connects electrical resistivity with hydrogeological parameters.

The rationale above is used to interpret the delineated facies in terms of water saturation and salinity \((i.e., \frac{1}{\rho})\) if the electrical response of the tailings matrix does not vary significantly across the tailings domain. For instance, Fig. 8(a) deals with the vertical electrical resistivity variation in cross-section K1K7 and shows a flat gradient zone within the threshold value \([-m, +n]\) coincidental with the saturated zone depicted in the correspondent resistivity inversion model in Fig. 7(a). At the minimum threshold range \([-0.01, +0.01]\) the zone sharpens to depict a transition between a high electrical resistivity zone \((i.e., \text{light greyed area covering the underlying ground, bedrock, and unsaturated tailings})\) and a low electrical resistivity zone \((i.e., \text{the blacked area corresponding to saturated tailings})\).

In Fig. 8(b), the threshold range \([-m, +n]\) delineates a zone where the gradient change of electrical resistivity is minimum or almost invariable. As the threshold range narrows to zero proximity the zone of constant net gradient sharpens and delineates distinct facies of increasing and decreasing net gradient change. 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.

From the set of images in Fig. 7(b), the vertical gradient \((\text{first-order vertical derivative})\) and the net gradient change \((\text{Laplacian})\) plots follow a layered pattern of the electrical resistivity variation which suggests a depositional media influenced by the settlement process and lateral water movement. The analysis of the horizontal gradient \((\text{first-order horizontal derivative})\) shows a more random variation of electrical resistivity influenced by local percolation zones. By controlling the threshold filter range of the differential operators electrical resistivity models can be segmented for facies analysis and interpreted in terms of volumetric water content, saturation, and electrical resistivity (or electrical conductivity).

4. Discussion

The combined use of seismic refraction and electric resistivity imaging in tailings is not new. While SR has been used in tailings complementing other techniques for mapping structure and geometry, ERI has focused on monitoring applications. Other few perspectives have explored ERI in data correlations such as with geochemical \((\text{Gabarrón et al., 2020})\) and geotechnical parameters \((\text{Sousa and Gomes, 2020; Hen-Jones et al., 2017})\), yet its potential integration as a data source to other models remains in development.

Compressional wave velocity \((V_p)\) and electrical resistivity \((\rho)\) are dependent on other tailings variables such as saturation and salinity causing them to vary proportionally and suggests that the variability is connected in a spatial and temporal domain. In our study, the compressional P-wave velocity model was used mainly to constrain the electrical resistivity model. For analyzing SR data from tailings areas, the gradient- and the Laplacian approach on their own do not provide a useful interpretation of facies. \(V_p\) in the tailings space domain is connected to settlement and compactness, whereas electrical resistivity is connected to the action of water content and salinity. As the bulk density in the tailings media is driven by slow settlement processes, \(V_p\) in SR models increases with depth but not to the extent to be captured by the gradient and Laplacian operators. Instead, electrical resistivity was selected as the variable of control for facies analysis. The gradient analysis of ERI data reveals two distinctive features in the tailings with a contrasting resistivity change in the vertical direction and only a marginal lateral variation. The resistivity decreased down to the saturated zone and towards the bottom of the tailings impoundment but shifts to increase passing downward the interface between the tailings and the underlying ground surface. This is not evident in the conventional ERI cross-section images despite the gradient shift suggesting two distinct strata, hence the use of the gradient and the Laplacian operators.
The ERI method captured water movement in the tailings domain and the extent of water flow expanding laterally along the survey lines in line with field observations. As the electrical response is controlled by the pore water electrical resistivity, delineating the unsaturated and saturated tailings zone was a relatively simple task. The difficulty emerged where the pore water had permeated across different zones masking the contact zone or physical boundaries such as between the saturated tailings and the underlying ground. The resistivity distribution from the ERI cross-sections did not capture this interface which suggests that saline water had permeated into the ground. The interface is not evident in the gradient analysis and it could only be visualized by rehearsing the vertical resolution of the contour levels. In this regard, the SR method proved to complement well the analysis because it was able to detect the media transitions to higher compactness such as the tailings-ground and ground-bedrock interfaces. SR not only complemented the mapping of the boundaries but also provided input to constrain the ERI inversion model, so the electrical resistivity distribution is more representative of the media transitions.

The gradient and Laplacian operators are simple yet useful filters for facies analysis and recognition of distinctive zones within the tailings domain. Facies, where a geophysical image has not much variability, can be allocated with parameters constrained to equilibrium conditions. Zones with high variability (either decreasing and increasing) can warrant detailed discretization and consideration about the parameterization. As the differential operators were applied to ERI data, the contact zones are not necessarily physical boundaries and only coincide with the stratigraphy where the contrast in electric resistivity is pronounced. The differential operators link electric resistivity variation with transition zones across different stratigraphic units. By applying directional derivatives to the scalar function of electrical resistivity, gradient and the net gradient change zones were delineated. The predefined threshold for the local extrema and the near the zero crossings in the Laplacian function was selected to [-0.1, +0.1] with the purpose to visualize the region near the boundaries but this could be modified depending on the variability required for visualization. It is also noted that the sensitivity of the differential operators depends on the resolution of the inversion model.

A generalization of the facies analysis in tailings using ERI data is that the vertical gradient results in segmented cross-sections depicting facies of distinctive layered pattern whereas the horizontal gradient facies are more irregular. This is congruent with the depositional process and the subsequent stratification of the tailings. The gradient operator captured the variability of the electrical response in the tailings subsurface and the Laplacian operator allowed to detect the net gradient change of salinity migration dominated by the horizontal flow. This phenomenon suggests a strong association with stratigraphy, water flow, and electric resistivity of pore water and the media. For instance, percolation of freshwater can displace pore water, modifying the solute concentration, and likely causing variations in saturation and temperature of pore water. The occurrence is consistent with variations of electrical resistivity in mine tailings associated with variable saturation and temperature. The occurrence is more representative of the media transitions.

In an engineered structure such as a TSF, the distribution of facies is controlled by the segregation and depositional processes in the domain. If the TSFs contain one type of waste, as in the TSF of the Pyhäsalmi mine, the interpretation of the facies is relatively facilitated compared to more complex and heterogeneous media. Still, multiple factors such as separation processes, deposition methods, different rock sources, as well as alteration processes after deposition (Constantinescu et al., 2019; Stumbea et al., 2019) can cause multiple facies in TSFs.

5. Conclusions

ERI and ERI together can reduce the level of uncertainty in mapping subsurface conditions in tailings facilities and the integration can have significant application to support data acquisition and analytic interpretation. This paper demonstrated a methodology to source and interpret geophysical data for segmentation and analysis of local facies in tailings storage facilities.

The research used two geophysical techniques for data acquisition in TSFs, Seismic refraction (SR) and Electrical resistivity imaging (ERI). SR determined the compressional P-wave velocity ($V_p$) and established the geometric constraint in the ERI model to determine the distribution of electrical resistivity ($\rho$) in the subsurface. A joint interpretation revealed the stratigraphic profile of the tailings domain with SR providing reliable depth approximations to underlying ground and bedrock in the tailings domain, whereas ERI complemented the stratigraphic information by delineating the water table, hence the unsaturated and saturated zones. Further interpretation of the electric resistivity model allowed segmentation of the tailings domain into interpretable zones or facies. For this, differential operators (gradient and Laplacian approach) were used to interpret the tailings' electrical response and enable the delineation of facies based on their increasing or decreasing variability. The interpretation is associated with other hydrogeological parameters to explain state conditions.

ERI complemented by SR has served for characterizing the inner structure and determining the geometry of the tailings subsurface. ERI method revealed higher moisture zones and determined saline water flow paths through the tailings media. ERI and differential operators served for geoelectric zoning and for delineating facies to interpret salinity dispersion. 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 conceptualization and parameterization in hydrogeological investigations.

Data availability

Dataset related to this article can be found at https://doi.org/10.17632/2tv7sm9cyj.2, an open-source online data repository hosted at Mendeley Data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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