

Article

Mapping Leachate Pathways in Aging Mining Tailings Pond Using Electrical Resistivity Tomography

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Abstract: Mining activities often leave behind a legacy of environmental challenges, with aging tailings ponds representing a significant concern due to their potential for leachate formation and subsequent contaminant release. Thus, this study employs Electrical Resistivity Tomography (ERT) to investigate the intricate pathways of leachate within an aging mining tailings pond, addressing the pressing environmental and human health concerns associated with potential contaminant release. Ten 2D ERT profiles were acquired at the El Mochito mine waste site, covering an area of approximately half a square kilometer. These profiles, ranging in length from 104 to 363 m, provided insights into subsurface conditions down to a maximum depth of 60 m. The subsurface mapping of the ERT data showed three different geoelectric layers. The uppermost layer, with a thickness of approximately 2.5 m and resistivity values ranging from 60 to 100 Ohm.m, was identified as a dry tailing/soil zone. Beneath it, the second layer exhibited moderately resistive values (30–60 Ohm.m) with varying thicknesses of 10–20 m, signifying a percolation/leaching zone (semi-saturated zone). The third layer, characterized by substantially low resistivity (1–30 Ohm.m), indicated saturation and the presence of conductive materials, strongly suggesting active leaching. Based on these findings, this study recommends further investigation through geochemical analysis of subsurface samples and more advanced geophysical imaging techniques to validate the distribution of anomalous zones and delineate remediation pathways. This study lays the foundation for future comprehensive research that will integrate geophysical surveys with geochemical analysis and establish 4D modeling techniques to monitor pollutant penetration over time, with a particular focus on mine waste tailings mapping. Plus, this study contributes valuable insights into the characterization of leachate pathways within mining tailings ponds, offering a foundation for informed environmental management and remediation strategies.

Keywords: mining; tailings; electrical resistivity



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1. Introduction

Mining activities have long been a cornerstone of industrial development, but they come with a significant environmental footprint. As mining operations expand and continue over time, they often leave behind a legacy of environmental challenges that demand our attention. One of the pressing issues in the mining industry is the management of aging tailings ponds. These reservoirs, which store the waste materials from ore processing, pose substantial environmental risks as they age and deteriorate. The environmental challenges

linked to mining encompass a wide range of issues, including soil and water contamination, habitat disruption, and air pollution. Among these, aging tailings ponds stand out as a key concern due to their potential to release hazardous materials into the environment [1,2]. Mining tailings can contain high concentrations of toxic metals such as arsenic (As), copper (Cu), nickel (Ni), zinc (Zn), lead (Pb), and chromium (Cr), which can have detrimental effects on biota and groundwater quality [3–6]. Tailings ponds typically harbor a composite composition of finely pulverized rock, chemicals, and aqueous solution. As time elapses, this amalgam can undergo a variety of chemical and physical changes, engendering the creation of leachates—fluids that comprise dissolved and suspended pollutants. These leachates possess the potential to traverse subsurface geologic features, thereby potentially accessing groundwater reservoirs and surface water bodies [7–9]. Consequently, the aforementioned pollutants, which bear significant danger to the environment and public health, may be transported by the leachates. Thus, prioritizing the study of leachate formation, migration, and containment within mining tailings ponds is of the utmost importance. Moreover, the failure to effectively manage these tailings can have dire consequences, ranging from severe to catastrophic environmental damage [10,11]. It is, therefore, paramount to continually monitor and map the extent of tailings leachates, both for immediate treatment measures and for the informed planning of future mining activities. The search for an effective tool to achieve this mapping and monitoring task is of utmost importance, as it underpins the continuous control of the environmental impact stemming from mining tailings.

Geophysical techniques are extensively employed for the monitoring of groundwater contamination, which can arise from diverse sources, including hydrocarbon contamination [12,13], landfills [14,15], and saline water intrusions [16,17]. Non-invasive geophysical techniques, particularly electrical resistivity tomography (ERT), have emerged as invaluable tools for hydrogeological studies and the mapping of mine waste tailings [18–22]. ERT surveys have found widespread application in studies related to groundwater mapping [23–26] and the mapping of groundwater contaminants [27–30]. Within the realm of hydrogeological investigations, electrical methods have consistently proven to be the most employed geophysical technique [31,32]. Changes in water saturation, temperature, and ion content are fundamental drivers of ERT variations [33,34]. Over the decades, ERT has become a staple method for solute transport and groundwater mapping [35,36]. ERT is celebrated for its rapidity [37], cost-effectiveness [38], and non-invasiveness [39], making it an ideal choice for delineating and mapping groundwater aquifers, particularly in areas where boreholes are limited. ERT has been used in various studies to detect leachate pathways and assess contamination in different types of waste disposal sites. Lu et al. have provided evidence that ERT is a highly effective means of detecting leakage within the impervious layer of a domestic waste landfill. Their research has thus established a novel technical foundation for detecting such leaks within landfills [40]. Martorana employed 3D ERT and induced polarization for the identification of regions with elevated leachate concentration in a waste landfill. Their findings indicate that the application of non-conventional arrays, including concentric squares, when coupled with the Full Range Gradient (FRG) Array, delivers a satisfactorily uniform resolution for research purposes [41]. Guireli Netto et al. conducted a geophysical investigation in a cemetery using the DC resistivity method with different electrode arrays, confirming the presence of low resistivity anomalies related to the presence of ionic compounds [42]. Also, ERT has proven successful in detecting leachate pathways in mining tailings [43–46]. It plays a crucial role in characterizing and monitoring tailings ponds, offering valuable insights into the spatial and temporal variations of subsurface electrical resistivity values, which are influenced by the site's physical and chemical properties [20]. ERT surveys have even delved into the exploration of abandoned underground mining excavations, effectively identifying old mining slopes and galleries [47,48]. Furthermore, ERT serves as a valuable tool for determining the physico-chemical composition of mine tailings ponds, enabling cost-effective and efficient surveys. It aids in estimating properties such as electrical conductivity, particle sizes, and metal

concentrations within the infilling wastes of tailing ponds as well as ERT used to locate hydraulically conductive zones and select suitable locations for mining tailings disposal to prevent groundwater contamination [49]. Despite these significant advancements, the study of leachate pathways in mining tailings ponds remains a dynamic field that warrants further multidisciplinary research, drawing from geophysics, geochemistry, hydrogeology, and environmental science.

The El Mochito mine, situated in north-western Honduras, operates on sulfide ores, yielding Pb, Zn, and silver (Ag) as primary products. The mining operations generate various forms of tailings, encompassing both solid and liquid components [50]. The ore-dressing plants, integral to the mining process, produce substantial quantities of waste, reaching up to 300 tons per day (t/d). The liquid tailings are subsequently pumped to tailings storage facilities (TSF) after separating the liquid from solid waste materials through a pipeline spanning over 4.5 km from the treatment plant [51]. The wastes disposed of in TSF are relatively benign concerning their environmental impact, primarily consisting of small suspended solid particles. Notably, any cyanide used in the flotation process is effectively degraded within the tailings before disposal. Once the liquid tailings are deposited into the pond, any remaining solid materials settle to the pond's bottom, after which excess clean liquid is released into the environment [51].

However, the geographical context of the El Mochito mine introduces a set of unique challenges in tailings management. Located in a tropical region, the mine contends with frequent floods, monsoons, heavy rainfall, karstic terrains, detritus flows, and water seepages. The survey area experiences substantial rainfall throughout the year due to its proximity to the Caribbean coast. Consequently, the solid tailings dump is exposed to these climatic conditions, and as rainwater infiltrates the surface, the potential for tailings to leach into the underground environment becomes a pressing concern. Leaching of this nature has the potential to generate pollutant leachate plumes within the aquifers, posing a considerable environmental risk. Consequently, it is essential to adopt suitable management approaches to govern and, if required, alleviate the forthcoming ecological consequences of the tailings.

The study aims to use ERT to investigate leachate pathways within an aging mining tailings pond. Therefore, this work sets out to delineate the extent of the leachate plume originating from the El Mochito mine's waste tailings. By acquiring ten 2D ERT profiles spanning the El Mochito mine waste site, covering an area of approximately half a square kilometer, we aim to map the distribution and extent of these waste tailings leachates. Our goal is to provide essential information that can guide decision-makers in Honduras in long-term planning, tailings management, and the remediation of any environmental hazards that may have already occurred.

All these multifaceted challenges posed by mining tailings and the pressing need for their effective management underscore the significance of this study. Utilizing advanced geophysical techniques such as ERT, we seek to contribute to the understanding and control of tailings leachates, ultimately advancing environmental sustainability within the mining industry.

2. Materials and Methods

2.1. Site Location and Description

The El Mochito mine site is in northwest Honduras, near the town of Las Vegas, approximately 88 km southwest of San Pedro Sula and 220 km northwest of the capital city, Tegucigalpa, as shown in Figure 1. The survey area is in a range (Long/Lat) of $-88.0699, 14.8621$: $-88.0648, 14.8667$, and the coordinate reference system is EPSG:4267—NAD27. The El Mochito area occurs within a northeast-trending graben. The major stratigraphic units are dark grey, massive micritic to biomicritic limestone with shale intercalations and which overlie limy siltstone. The faults in the graben area are characterized by northwest- and east-trending faults [51].



Figure 1. Location of El Mochito mine site.

The property consists of an underground (Pb-Zn-Ag) mine and a concentrator producing separate zinc and lead concentrates. The ore from the El Mochito mine is processed in a traditional, differential sulfide flotation system, and typically processes about 2250 t/d. In the flotation plants, massive quantities of waste are generated, reaching 300 t/d. The liquid tailings are pumped to tailings storage facilities (TSF) after filtering the liquid from solid wastes in the over 4.5 km wastes pipeline from the treating plant. There are three TSFs at the mine (El Bosque, Soledad, and Pozo Azul) to keep continuous mining operations, as shown in Figure 2. The El Bosque dump (the site on which this study is being conducted) is the earliest and holds around 5 million tons (Mt) of old mining tailings. This dump's surface has been re-vegetated naturally after officially closing in 2018. There was an underground decant system and a settling pond at the toe of the dam in the TSF to filter the clean water from solid waste materials. Also, the Nyrstar mine administration constructed a 180 m long retaining wall down from the dam to prevent potential soil erosion because of weathering factors such as rainfalls and flooding of the river of Quebrada Raices [51]. In addition to all these precautions, from time to time, the company monitors the state of water seepage/tailings leachate through old tailing to ensure the safety of the environment. One of the methods of this monitoring is to detect and map tailings leachate using geophysical techniques to know the extent of penetration and spread of pollutants underground. Geophysical techniques such as ERT are well-established techniques for hydrogeological studies to monitor and map the extent of tailings leachates for both treatments and future planning considerations. Therefore, we used 2D ERT in this study for subsurface mapping of mine tailings' leachates in the El Bosque dump.

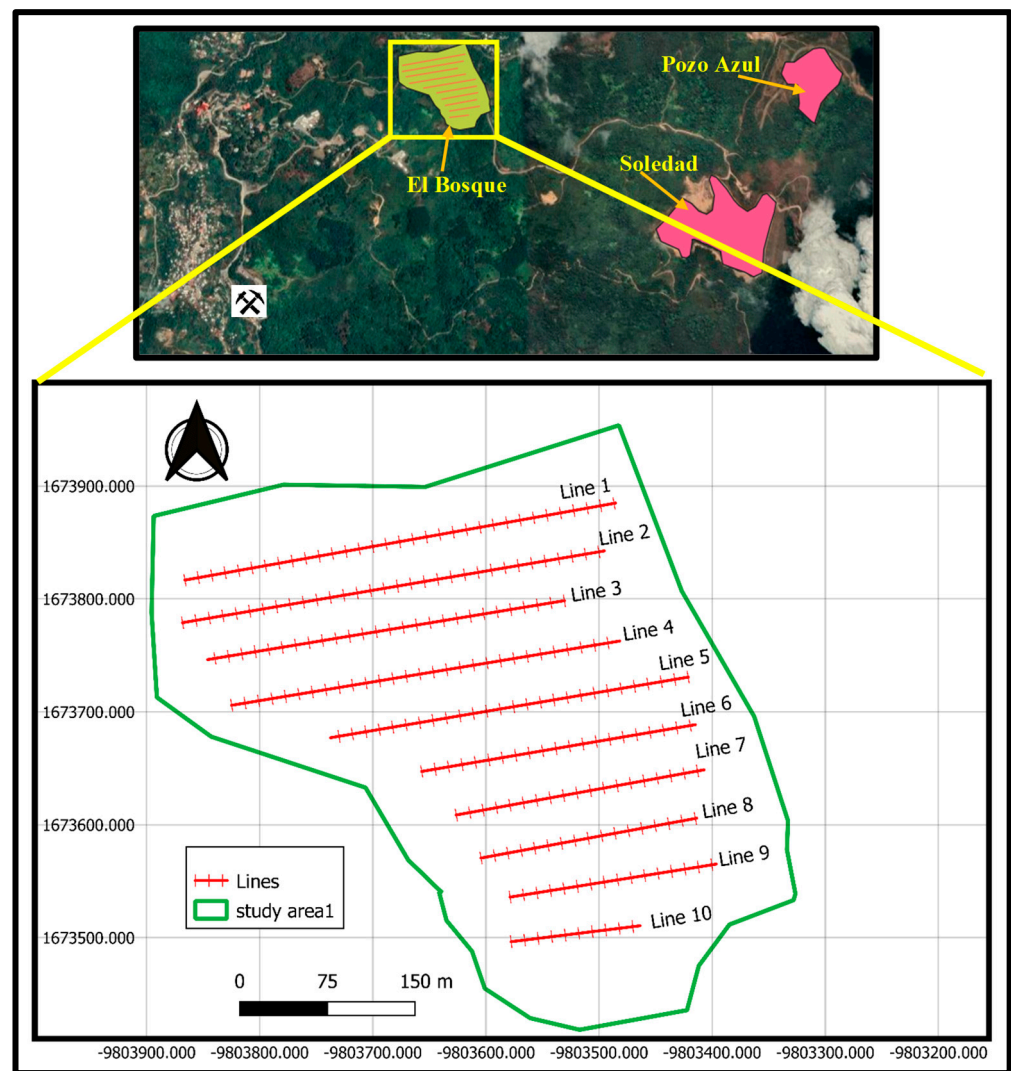


Figure 2. Electrode location map—El Mochito survey.

2.2. Electrical Resistivity Tomography (ERT) Technique

Electrical Resistivity Tomography (ERT), also known as Electrical Resistivity Imaging (ERI) or Electrical Resistivity Survey (ERS), is a non-invasive geophysical technique used for imaging and characterizing the subsurface properties of geological formations. ERT assesses the electrical resistivity or conductivity of subsurface materials through the introduction of electrical currents into the ground, subsequently measuring the resultant voltage distribution. Through the examination of the spatial arrangement of electrical resistivity values, ERT facilitates the generation of two-dimensional or three-dimensional depictions of the subsurface, thereby supplying pertinent data for a broad spectrum of purposes encompassing environmental analyses, geotechnical examinations, hydrogeological evaluations, and mineral prospecting [49,52,53].

ERT relies on the fundamental physical property of materials known as electrical resistivity (or its reciprocal, electrical conductivity). Electrical resistivity (ρ) is a measure of a material's ability to impede the flow of electrical current. It is typically expressed in Ohm.m ($\Omega \cdot m$). Insulating substances, including arid soil, stones, and solid rock, exhibit elevated resistivity measurements, typically varying from several hundred to several thousand Ohm.m. These materials restrict the flow of electrical current. Conductive materials, such as water, metals, and saline solutions, exhibit low resistivity values, often measured in fractions of Ohm.m [54]. These materials facilitate the flow of electrical current.

The collected data, consisting of current injection locations and corresponding voltage measurements, are processed and analyzed to create a resistivity model of the subsurface. This process involves mathematical inversion techniques, which aim to reconstruct a resistivity distribution that best fits the observed data [55–57]. Forward modeling is the first step to compute the expected voltage measurements for a given subsurface resistivity model. This phenomenon is achieved through the utilization of mathematical equations that elucidate the propagation of electrical currents across diverse substances.

The inverse modeling process entails modifying the resistivity distribution within the subsurface until the computed voltages align with the measured voltages to the greatest extent feasible. This process often employs iterative optimization algorithms to refine the resistivity model. The resulting resistivity model provides information about subsurface structures and properties. Some key points to consider during interpretation are included in [58,59]. Distinct ERT can identify and delineate different geological layers with varying electrical resistivity values. For example, it can distinguish between dry soil, saturated sediments, and bedrock. ERT can detect anomalies or features of interest, such as fractures, faults, cavities, groundwater bodies, and contaminant migration, based on their contrasting resistivity values.

2.3. Equipment and Data Acquisition

To obtain a clear picture of the tailings subsurface, an ERT survey was carried out using the EarthProbe high-resolution DCIP system, as shown in Figure 3. The system can be configured for the collection of high-resolution surface IP data, vertical profiles (VP), and/or multi-bore/surface-to-bore tomographic images. For this survey, data were collected using the high-resolution surface DC configuration. Only voltage and current were measured, thus obtaining the apparent resistivity. A summary of the survey system specifications is summarized in Table 1.

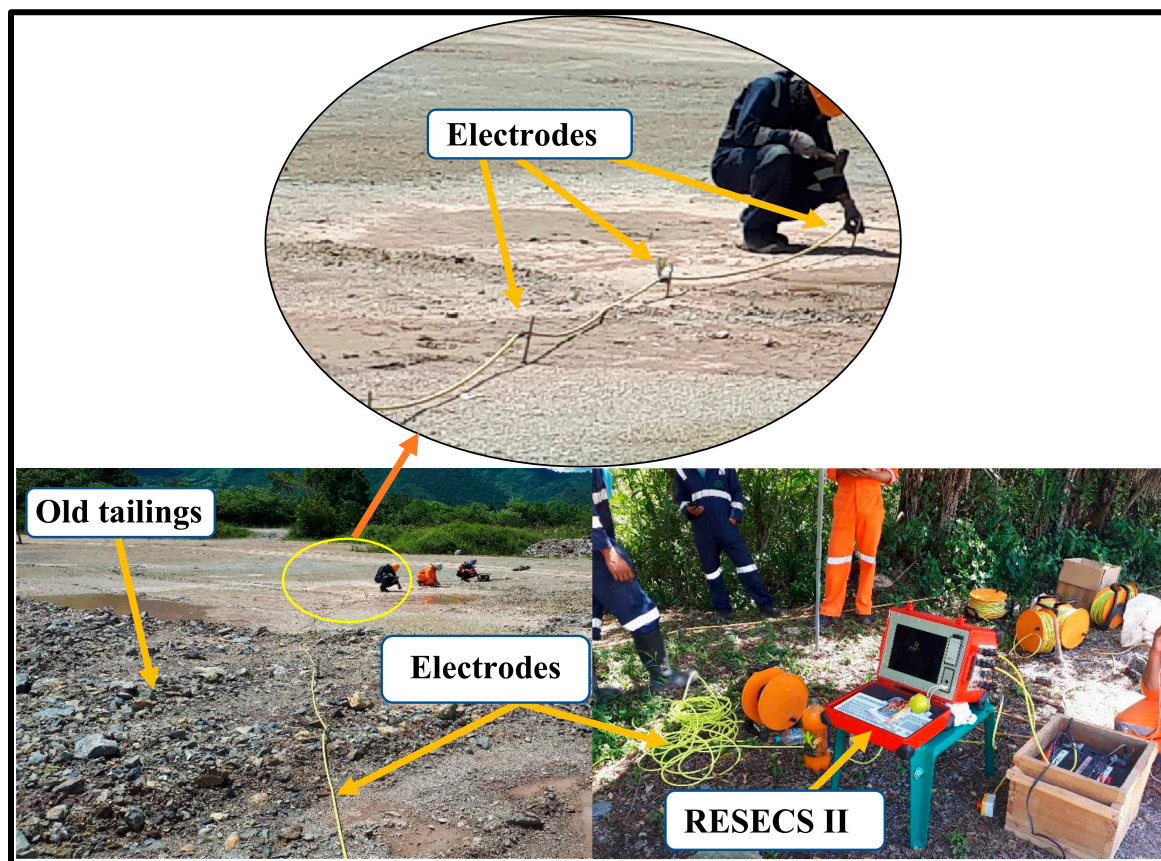


Figure 3. The EarthProbe system and its accessories.

Table 1. Specifications of the EarthProbe system.

Survey Item	Specifications
Survey Type	Direct current resistivity
Geophysical System	EarthProbe High-Resolution surface and borehole DCIP system
Data Type	Full-waveform, 256 ms on-time and 256 ms off-time, castle waveform
Survey Configuration	Surface DCIP: Wenner Alpha array
Voltage Input	The system uses 12V DC, it has a transformer inside to convert 12 V into 24 V to 800 V.
Electrode Spacing	2.3 m

Figure 2 shows the profile locations and electrode spacing across the tailing. DC apparent resistivity data were collected along 10 surface profiles spaced 40 m apart with electrode separation of 2.3 m. The rationale behind our choices for electrode spacing, profile length, and array type specifications in the ERT method is based on several key factors, including subsurface resolution, depth of investigation, and cost and time constraints. The electrode spacing was set at 2.3 m to achieve the desired subsurface resolution. While smaller electrode spacing can offer higher resolution, it may also demand more time and resources. The typical range for such applications is between 2 to 5 m, as referenced in [60]. Additionally, 2.3 m is the minimum electrode distance designed in the cable, as shown in Figure 3. The length of the ERT profile is determined by the dimensions of the area under investigation, aiming to cover the entire region of interest for a comprehensive view of subsurface conditions. Our selected profile length ensures that we capture all necessary information within the study area. The array type chosen is Wenner, selected to optimize both resolution/sensitivity and depth of investigation for detecting leaching in mining tailings. These decisions were made carefully to balance the need for detailed information with the practical considerations of time and resources. The ERT data were collected using the Wenner-alpha array. Stainless steel stakes were used for current electrodes (A-B) as well as for the potential electrodes (M-N). In this array, A M N B is equally spaced, and for each reading, the “a-spacing” between all electrodes is incremented by one. For this survey, the electric current waveform was generated using a 256 millisecond (ms) square wave change cycle (256 ms positive charge, 256 ms off, 256 ms negative charge, 256 ms off). A summary of the survey lines information can be found in Table 2.

Table 2. Survey lines information.

Line Label	No. of Spreads	No. of Electrodes/Spread	No. of Electrodes Are in Overlap	Total Data Points
Line 1	2	*S1 = 112 S2 = 112	64	4050
Line 2	2	S1 = 138 S2 = 57	36	3564
Line 3	1	134	---	2894
Line 4	2	S1 = 138 S2 = 91	80	4268
Line 5	1	136	---	2920
Line 6	1	105	---	1755
Line 7	1	96	---	1466
Line 8	1	80	---	1010
Line 9	1	80	---	1026
Line 10	1	48	---	359

*S1 is spread number 1.

2.4. Data Processing

Data processing is a critical step in ERT surveys, as it involves transforming raw field measurements into meaningful subsurface resistivity images. We used Res2DInv (V4.08, Geotomo Software, Penang, Malaysia) software for the resistivity data processing

and inversion. Res2DInv is a commonly used software package for ERT data processing, inversion, and interpretation [61–63]. This subsection provides a detailed guide on data processing using Res2DInv, focusing on the essential steps to generate reliable resistivity models from ERT field data.

- **Importing Raw Data:** Begin by launching the Res2DInv software and import the raw ERT data collected during the field survey.
- **Data Preprocessing:** Quality control checks are crucial to ensure data accuracy. Exterminate bad points, and check the ERT data set for any outliers, spikes, or abnormal values that may result from noise or measurement errors. The primary objective of this option is to eliminate data points that exhibit resistivity values that are incorrect. These erroneous data points may arise from malfunctioning relays in one of the electrodes, inadequate contact between the electrode and the ground due to arid soil, or electrical shorting between the cables caused by excessively wet ground conditions. These flawed data points typically display apparent resistivity values that are conspicuously larger or smaller than the surrounding ERT data points. The most effective way to deal with such ERT data points is to discard them so that they do not exert any influence on the resulting model [61–63]. Figure A1, in the Appendix A, illustrates a data set containing a few flawed data points in red color.
- **Forward Modeling:** Set up the forward modeling parameters. This includes defining the survey geometry, electrode configurations (e.g., Wenner in this case), electrode spacing, and pseudosection (Figure A2a). After that, perform a forward model simulation to calculate the expected apparent resistivity values based on an initial resistivity model. This procedure is instrumental in producing synthetic ERT data (Figure A2b) that will subsequently be examined alongside the acquired ERT data throughout the process of inversion (Figure A2c).
- **Inversion:** The process of inversion focuses on modifying the resistivity distribution under the surface to align it as closely as possible with the observed data (Figure A2). The inversion parameters, including the selection of the inversion algorithm (such as smoothness-constrained or Occam), damping factors (numerical parameters used to control the smoothness and stability of the inversion process), and convergence criteria (the predefined conditions or rules that determine when the inversion process should stop), need to be configured. These parameters impact the regularization and convergence of the inversion. Then, select an appropriate initial resistivity model, which can be based on prior geological information or initial assumptions about the subsurface. Initiate the inversion process, allowing Res2DInv to iteratively adjust the resistivity values in the model to minimize the misfit between observed and synthetic data (Figure A3). The aforementioned procedure persists until the attainment of convergence or the conclusion of a prearranged quantity of iterations.
- **Visualization (graphical representations for final resistivity model):** Generate comprehensive reports and visual representations of the final resistivity model. These reports should include geological interpretations, anomaly identification, and recommendations based on the findings. Utilize the visualization tools in Res2DInv or other software to create cross-sectional profiles, depth slices, and 2D/3D models of the subsurface resistivity distribution (Figure A2).
- **Model Interpretation:** Once the inversion process is complete, the software generates a resistivity model that represents the subsurface resistivity distribution. Interpret the resistivity model by identifying and characterizing geological features and anomalies, such as soil layers, bedrock, water bodies, or other subsurface structures. Use the visualization tools provided by Res2DInv to create contour plots, cross-sections (2D), and 3D representations of the resistivity model.

3. Results and Discussion

The ERT survey conducted in this study involved the acquisition of data along ten 2D parallel profiles oriented in an east-west direction. These profiles ranged from 104 to

363 m, with a maximum imaging depth of approximately 60 m. The inverted ERT data revealed consistent patterns of decreasing resistivity with depth across all profiles as shown in Figures 4–13.

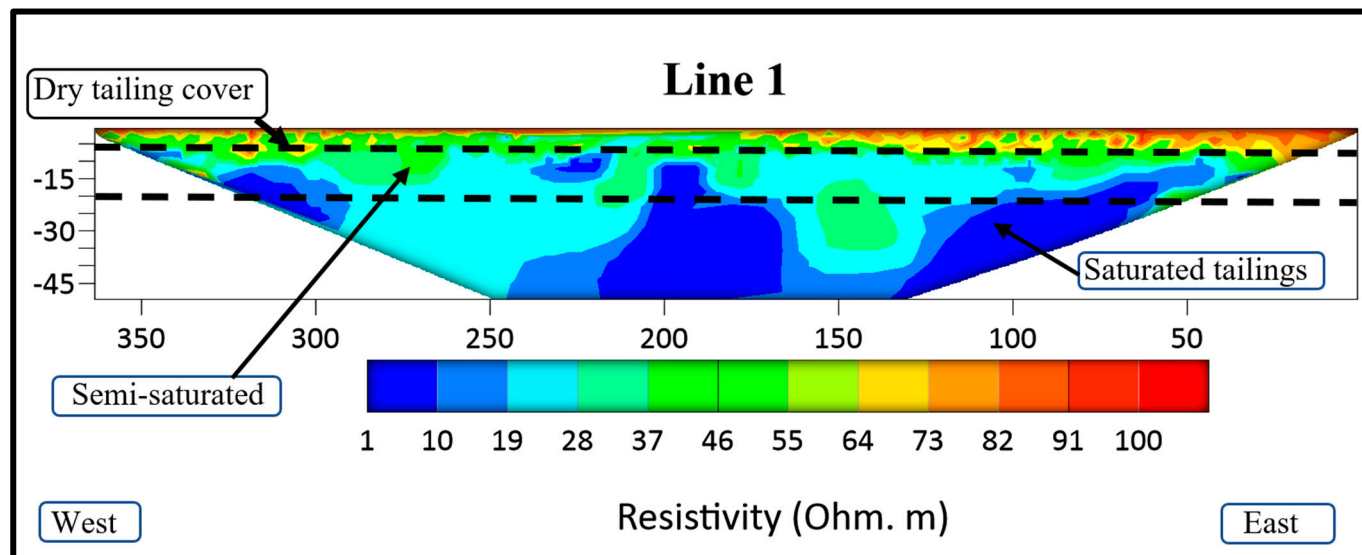


Figure 4. 2D inversion model of Line 1.

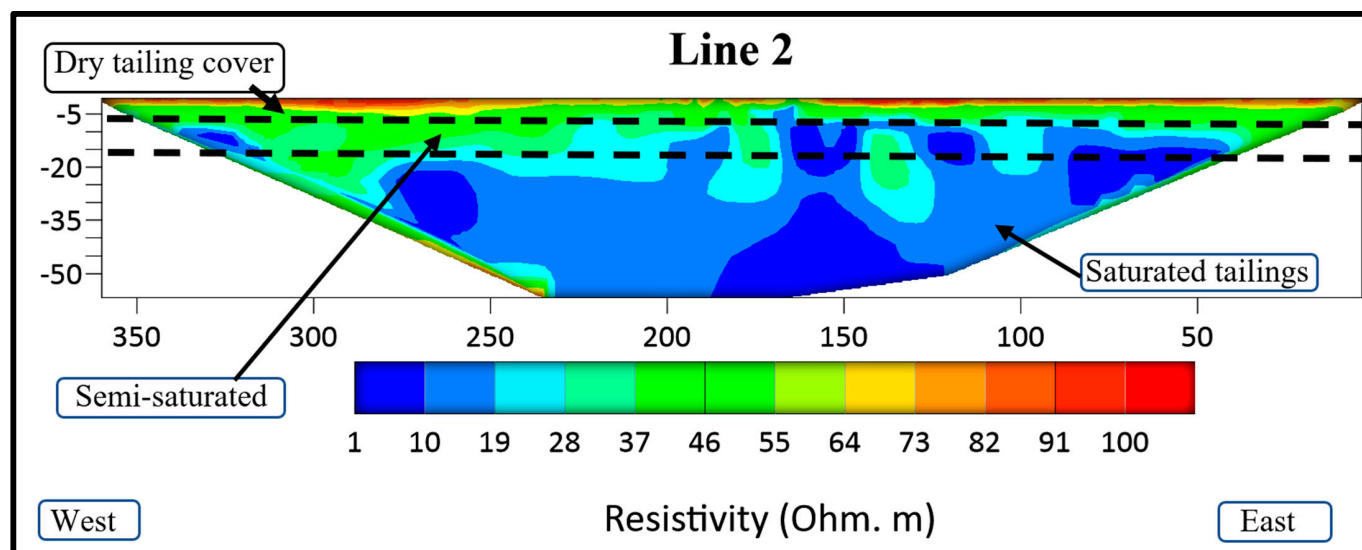


Figure 5. 2D inversion model of Line 2.

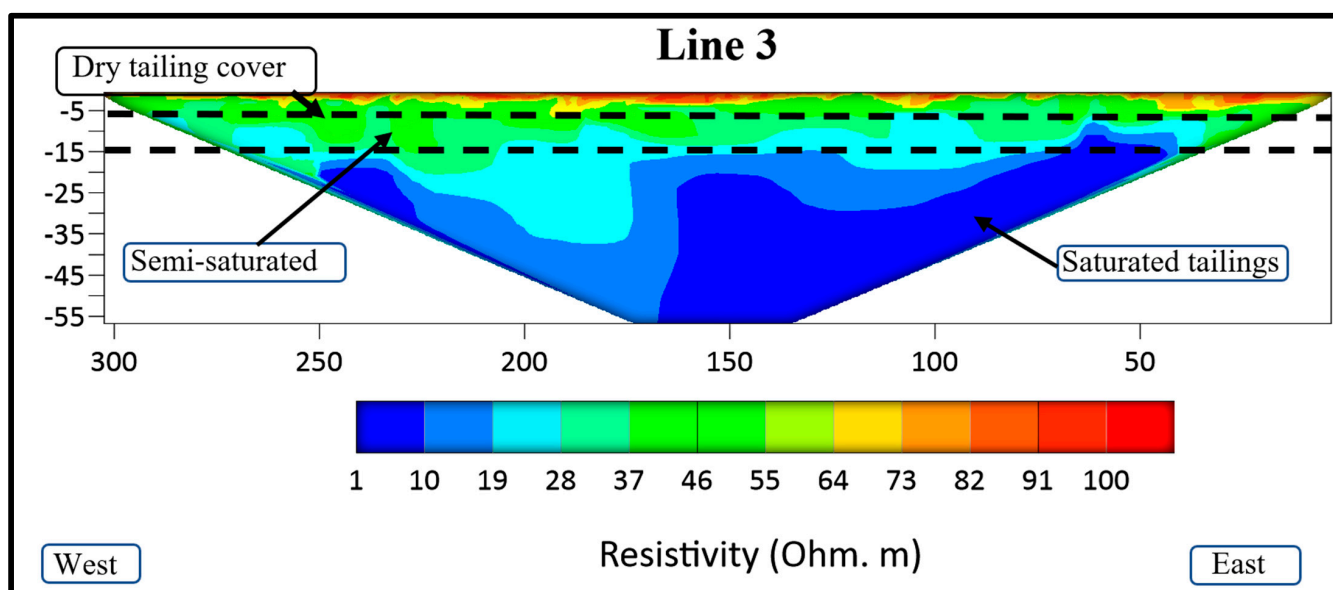


Figure 6. 2D inversion model of Line 3.

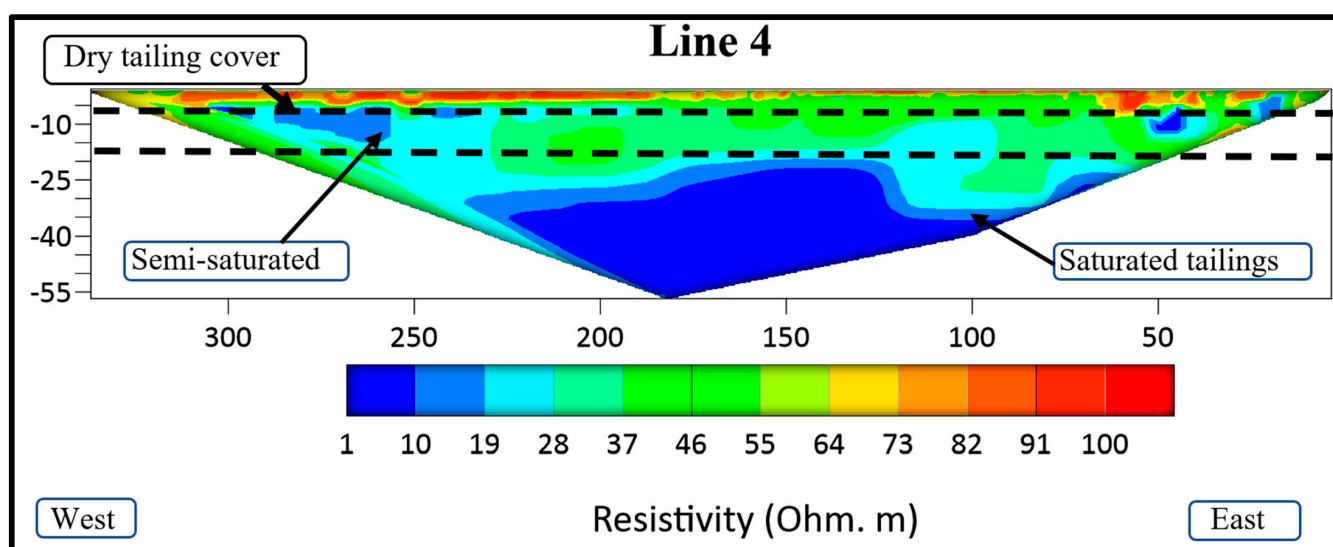


Figure 7. 2D inversion model of Line 4.

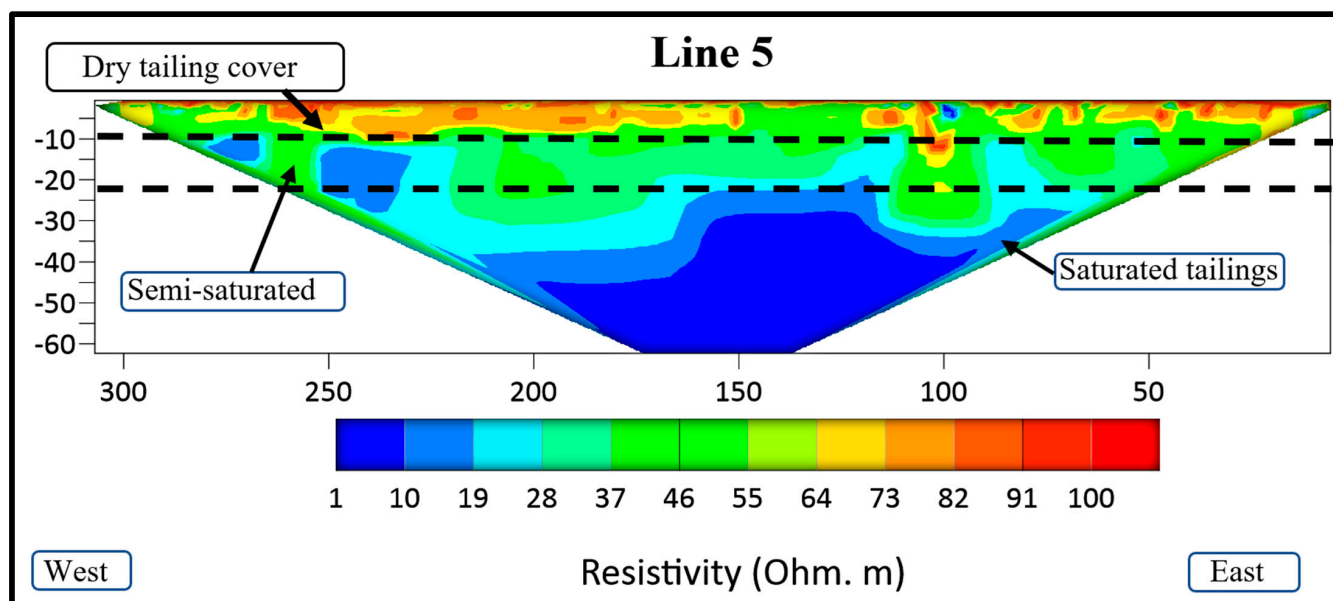


Figure 8. 2D inversion model of Line 5.

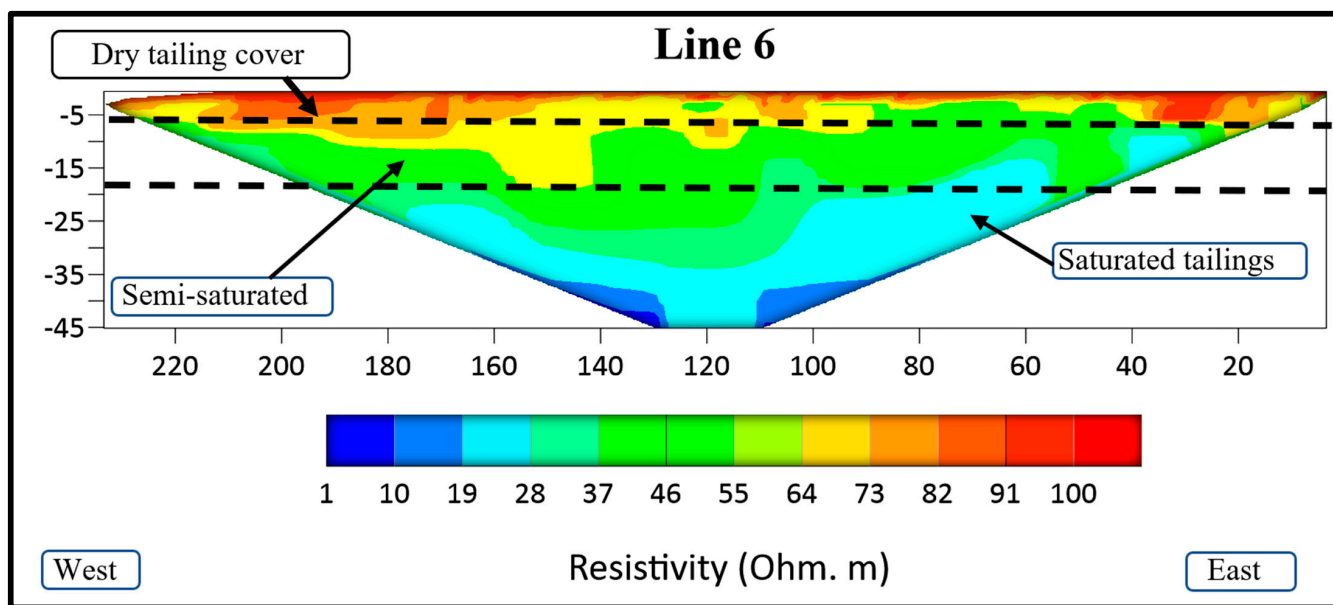


Figure 9. 2D inversion model of Line 6.

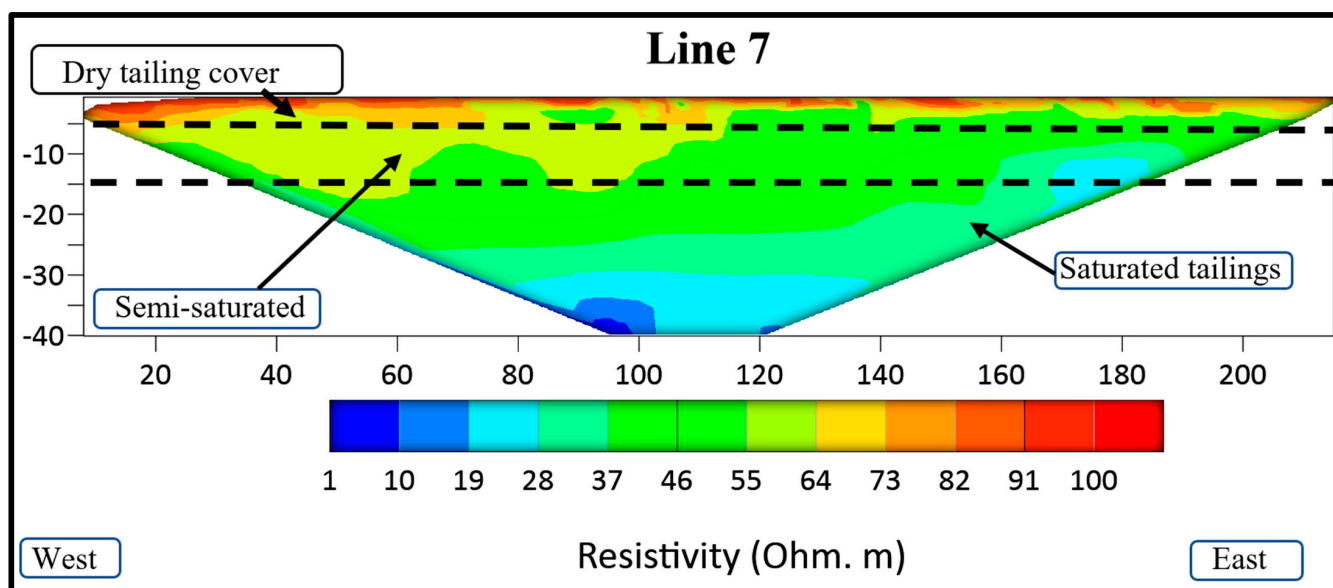


Figure 10. 2D inversion model of Line 7.

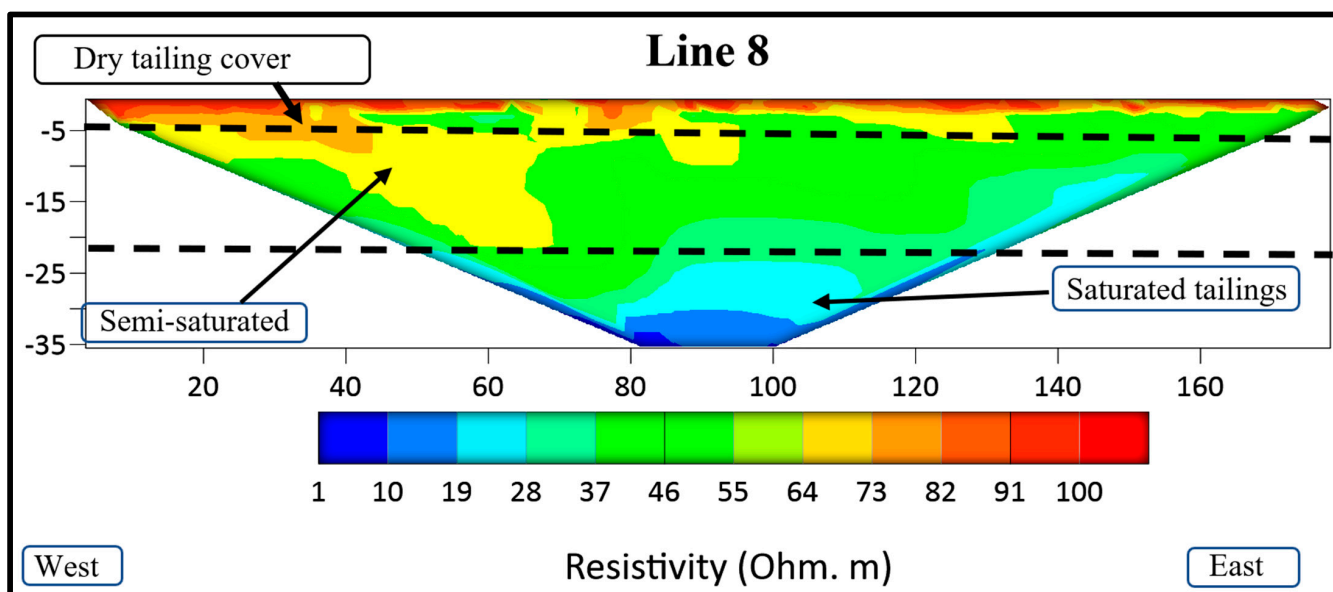


Figure 11. 2D inversion model of Line 8.

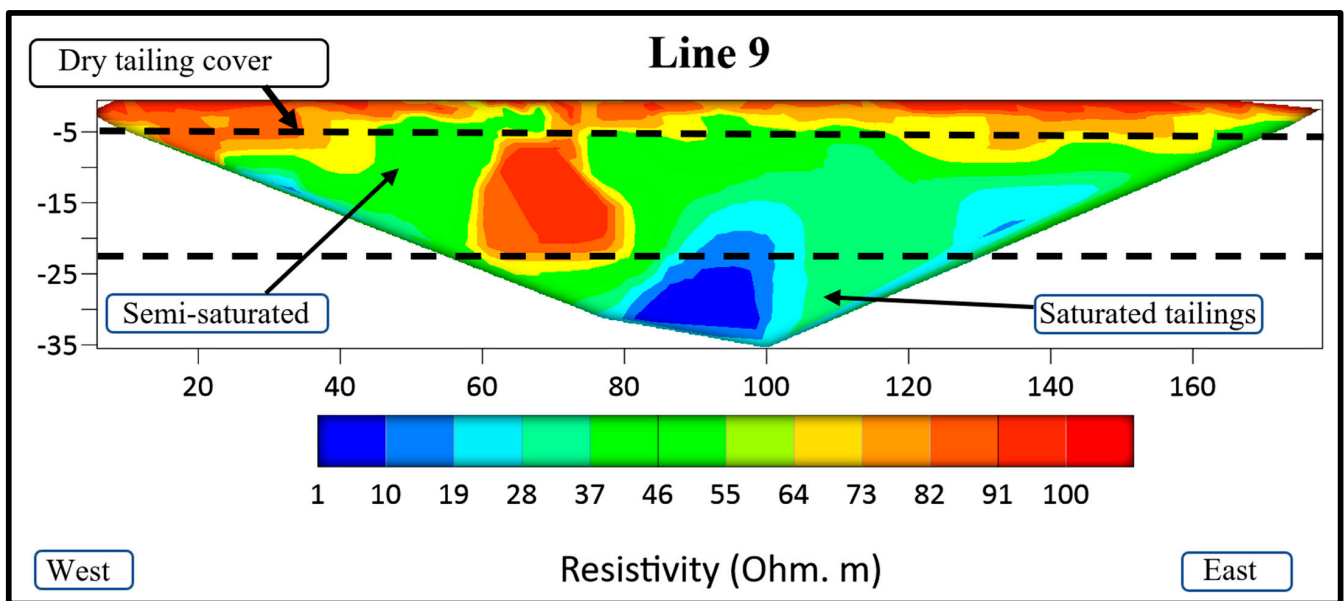


Figure 12. 2D inversion model of Line 9.

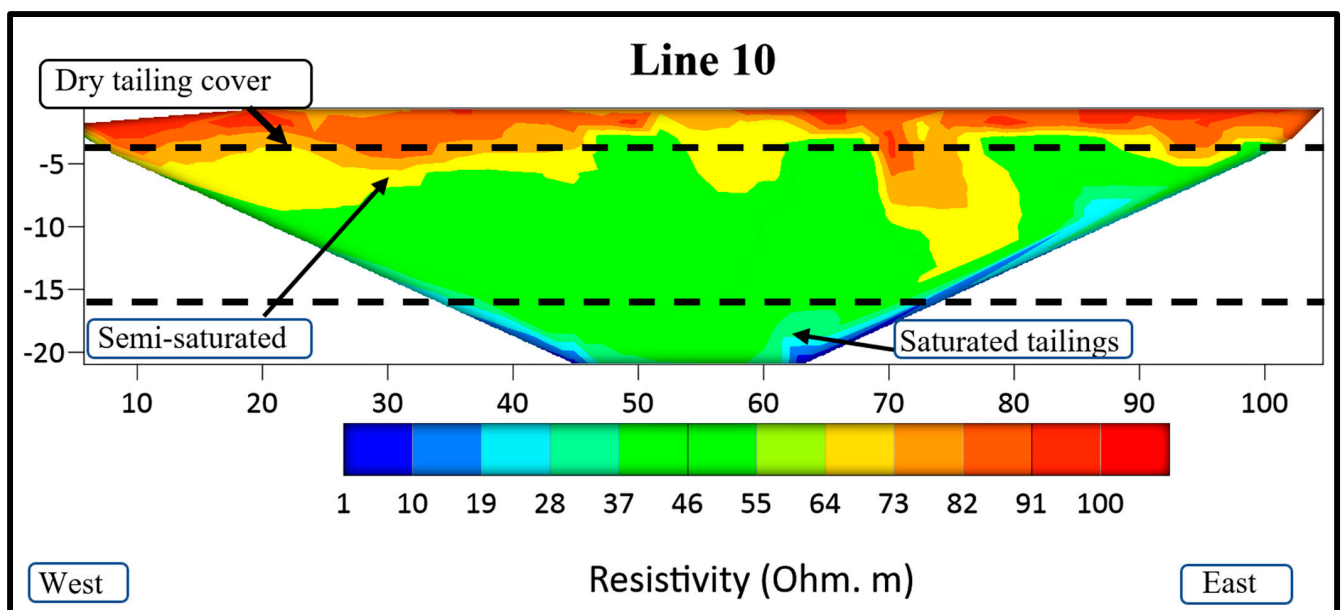


Figure 13. 2D inversion model of Line 10.

Upon analyzing the resistivity profiles in Figures 4–11, a consistent and distinct layering pattern became evident across all surveyed profiles. Three geoelectric layers with a varying thickness and depth can be distinguished across all profiles, as summarized in Table 3. The uppermost layer (A) exhibited relatively high resistivity values ranging from 60 to 100 Ohm.m, situated at a depth of approximately 2.5 m below the surface. Layer A is interpreted as a dry tailing cover, primarily composed of solid tailing/waste materials. Notably, the bottom boundary of this layer displayed uniformity along most profiles, except lines 9 and 10, where a spherical body was observed beneath it.

Table 3. Resistivity values and thicknesses summary for the identified geoelectric layers.

Geoelectric Layer	Resistivity (Ohm.m)	Thickness (m)
Top (A)	>60	~3–10
Middle (B)	>30:60	~10–20
Bottom (C)	<30	~10–40

The second layer (B) is positioned below the dry tailing cover layer, typically at depths ranging from 3 to 10 m below the surface. This layer exhibited relatively moderate resistivity values, spanning the range of 30 to 60 Ohm.m and ranges in thickness between ~10 to 20 m. Layer B is interpreted as a semi-saturated tailings zone. The third layer (C) represents the bottom geoelectric layer across all resistivity profiles. Layer C exhibits very low resistivity values of less than 30 Ohm.m. The transition from layer B to layer C is noteworthy, as this transition displays an irregular boundary.

The study area can be divided into two regions by comparing the thickness of the two geoelectric layers B and C. The first region spans lines 1–5, while the second region spans lines 6–10. In the first region, layer B is observed to be very thin in comparison to the second region. On the other hand, layer C is much thicker in the first region than in the second region. This abrupt change in the thickness can be interpreted in terms of two scenarios. The first scenario suggests that the tailings abruptly transition from a more conductive mineral region in the north to a less conductive mineral region in the south between lines 5 and 6, which can be simply explained in terms of tailings composition changes. While this scenario can explain the changes in the conductivity, it does not account for the irregular boundaries between geoelectric layers.

On the other hand, the second scenario suggests a structurally controlled uplift parallel to the resistivity lines between lines 5 and 6. This interpretation is supported by the fact that the area is deformed by grabens with east-trending faults. These grabens may have led to a collapse of one block that resulted in lithological lateral changes between impervious materials such as limestone versus limy silt. These lateral lithologic changes can lead to different leaching rates and, thus, changes in resistivity. This scenario can help in explaining the presence of irregular boundaries as we transition from one geoelectric layer to another across all lines. The leaching to limestone can result in dissolution and karstification, which can be an explanation for the presence of these rounded to semi-rounded bodies, as in Figure 12.

The identified geoelectric layers provide valuable insights into the subsurface composition and potential leachate pathways within the El Mochito mine tailings site. The semi-saturated tailings zone beneath the dry covering layer may indicate the presence of leaching from the mine tailings. The irregular boundary between the dry layer and the underlying low-resistivity layer suggests complex hydrogeological conditions. This information is important for understanding the movement and potential environmental impact of the leachate within the study area. To validate the existence, distribution, and fate of leachate pathways and conductive zones, it is advised to carry out geochemical sampling and analysis across these zones. This geochemical analysis will provide insights on the leachate pathways and potential environmental implications within the study area.

The active leaching within mine tailings area, especially the north region, can have significant environmental and human health implications. These implications include water and soil contamination. The leaching can lead to the contamination of surface water and groundwater with heavy metals including lead. This can harm aquatic ecosystems and make water sources unsafe for drinking, irrigation, and other purposes. Moreover, the leachate from tailings can seep into the surrounding soil, affecting its fertility and making it unsuitable for agriculture or other land uses. This contamination can persist for many years, impacting local ecosystems and agriculture.

4. Conclusions

An Electrical Resistivity Tomography (ERT) survey was conducted to delineate the subsurface conditions and fate of the leachate pathways at the old El Mochito mine tailings pond. The survey has provided valuable insights into the subsurface conditions within the study area and has led to several key conclusions.

The study revealed a layered subsurface structure across the survey area. The uppermost layer, characterized by high resistivity values (60–100 Ohm.m) and a thickness of approximately 3 to 10 m, was interpreted as a dry tailing cover layer. Below this layer, a second stratum with moderate resistivity values (30–60 Ohm.m) and varying thicknesses of 10 to 20 m was identified, suggesting a semi-saturated tailings zone. The transition between these two layers displayed irregular boundaries, indicating either a structurally controlled collapse due to graben and faulting or a lateral change in the tailings' composition. This led to a different leaching rate or a lateral change in conductive minerals. An irregular boundary was observed between geoelectric layer boundaries which suggests karstification of resistive dumps of tailing materials. A detailed geochemical work is needed on both regions of the area to understand the fate and distribution of contaminants within this zone. The variability in the dry tailing cover layer, particularly the presence of a spherical body beneath it in certain profiles, suggests localized variations in surface cover materials which may need a site-specific tailings management and monitoring approach to address potential environmental risks associated with variations in surface conditions.

In summary, the results of the ERT survey provided valuable initial insights into the subsurface conditions and suggested some potential leachate pathways at the old El Mochito mine tailings pond. The results underscore the significance of utilizing geophysical techniques in general and ERT in particular as reconnaissance approaches to tackle the intricate issues linked to the management of mining tailing/waste at mining legacy locations. Further research and analysis are essential to refine these initial observations and guide effective remediation strategies. We recommend: (1) a detailed geochemical sampling and analysis of subsurface samples to confirm the presence and distribution of leachate and conductive minerals, (2) a robust monitoring program to continuously assess changes in subsurface conditions and leachate pathways, and (3) tailored remediation strategies, informed by the results of the geochemical analysis and a thorough understanding of subsurface dynamics, to mitigate potential environmental hazards associated with the mining tailings.

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Appendix A

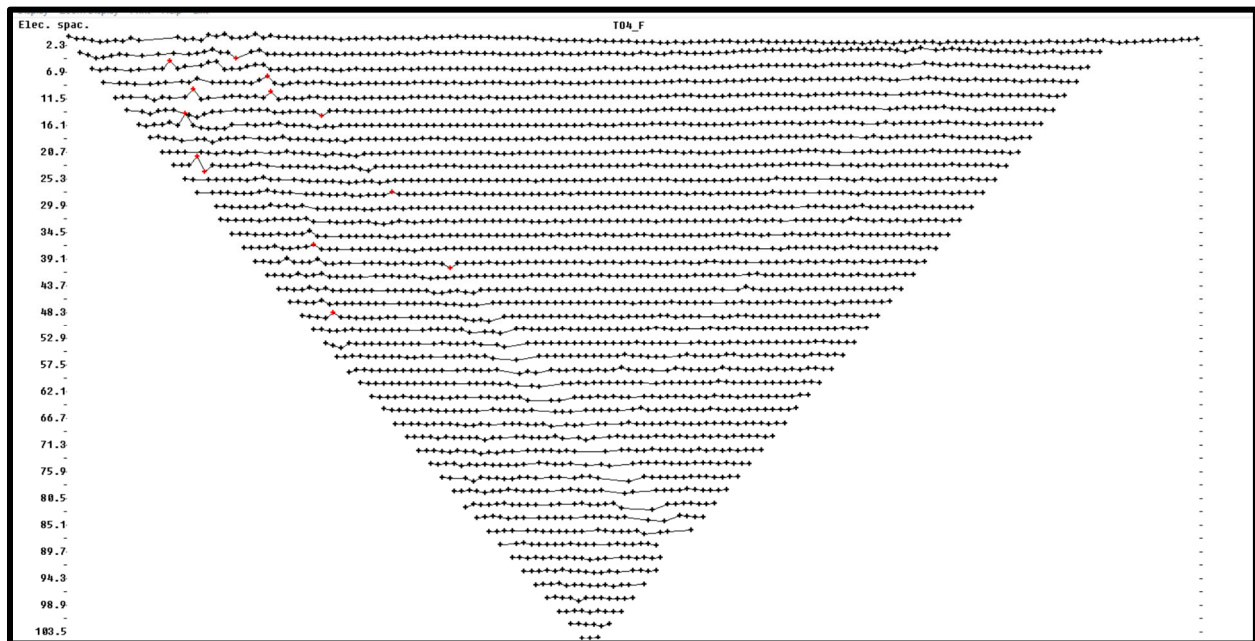


Figure A1. Illustrates a data set containing a few flawed data points in red color.

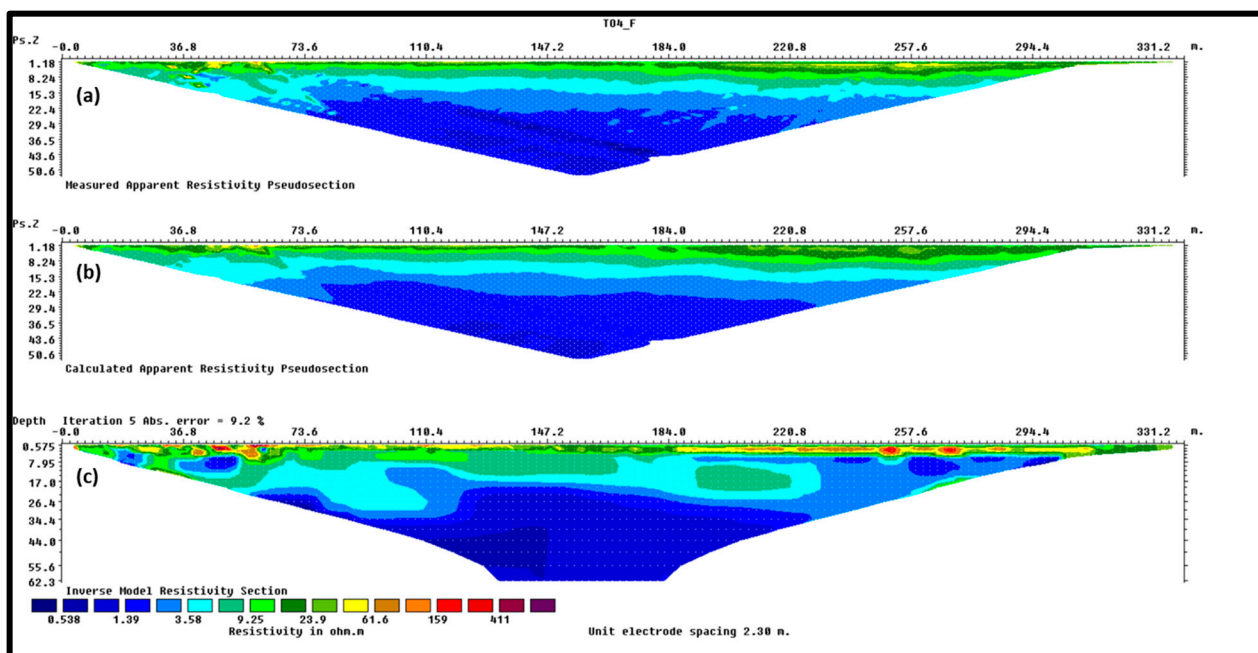


Figure A2. Illustrates the 2D resistivity model sections. (a) A pseudosection of ERT-measured data, (b) a section of synthetic ERT data, and (c) an inversion section of ERT data.

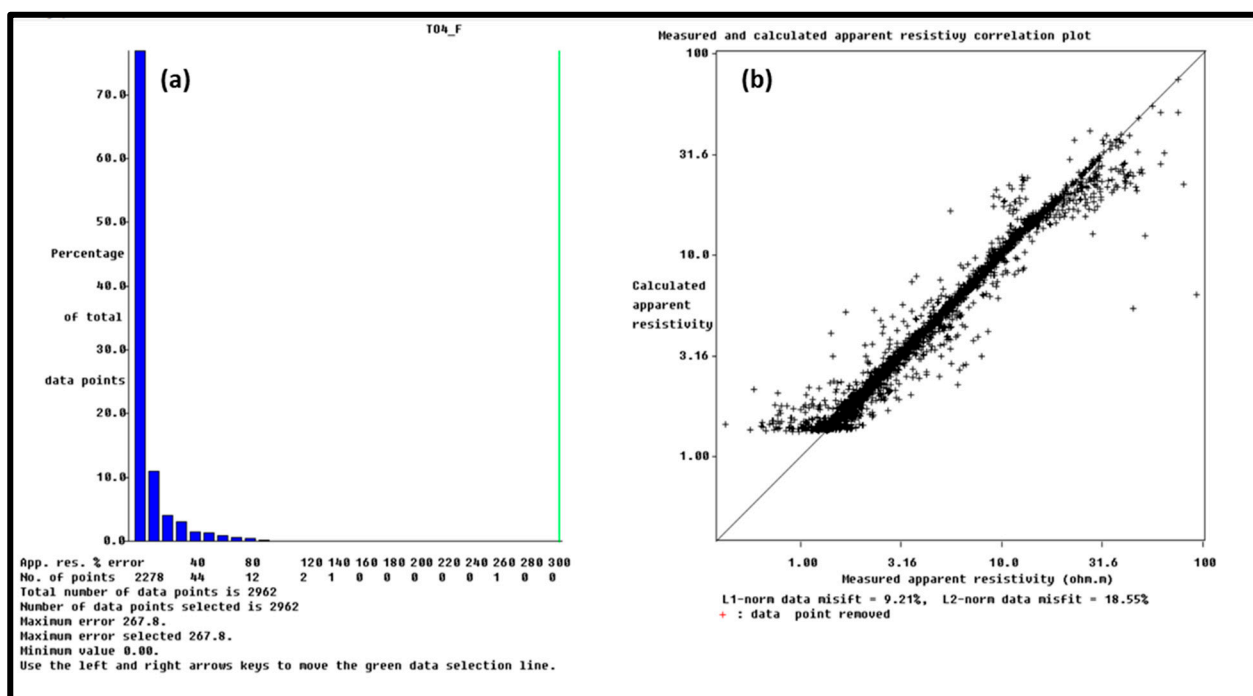


Figure A3. Illustrates the absolute and RMS errors without the exclusion of point outliers. (a) A histogram showing the misfit between the calculated and measured apparent resistivity values, and (b) a scatter plot showing the misfit between the calculated and measured apparent resistivity values.

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