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Integrated Geophysical Methods in Identifying Preferential Flow Paths in an Earth Dam

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ABSTRACT

The evaluation of safety conditions in dams is of utmost importance to ensure stability and often involves subsurface investigation methods. Geophysical methods have emerged as a modern and relevant alternative, often more practical than traditional direct methods. This study aims to integrate the application and interpretation of resistivity and self-potential methods to identify preferential flow paths in a small earth dam. The investigation was conducted at a dam located on the Viçosa Campus of the Federal University of Viçosa (UFV), with three main soil layers: embankment, silty clay, and alluvium. Analysis of the results revealed potential conductive zones and negative spontaneous potential anomalies, suggesting the occurrence of piping and the presence of buried structures in the spillway area. Moreover, the geophysical investigation methodology proved effective in evaluating geotechnical characteristics and flow conditions of the dam, contributing to the foundation for future safety and stability analyses of the structure.

Keywords: Self Potential, Electrical Resistivity, Earth-dam, Interpretation.

1. Introduction

Earth dams can pose significant risks when subjected to failure mechanisms such as piping, overtopping, and liquefaction. These processes can lead to catastrophic breach of the structure, resulting in severe consequences for downstream areas. Utilization of geophysical techniques enables early detection of these phenomena, facilitating implementation of preventive measures and ensuring safety of the surrounding communities.

1.1. Preferential flow paths

The phenomenon of piping consists of a form of internal erosion that results in the formation of a channel, through which water continuously percolates between the upstream and downstream portions of the dam mass or its foundation (Fell and Fry, 2007).

The occurrence of internal erosion can be divided into four categories, according to the mechanisms responsible for triggering this process (ROBBINS and GRIFFITHS, 2018):

- Concentrated flow: A process in which water flows freely along openings in the mass, such as fractures or excavations made by animals, eroding the soil along the edges of these openings.
- Regressive erosion: A process in which erosion channels, created when percolation forces are sufficiently high, progress upstream causing the transportation of solid particles. Generally associated with the foundation of the mass, when it is composed of sandy material.
- Internal instability: Occurs when the process of water percolation is capable of transporting finer particles present in a coarser soil matrix. It can be subdivided into suffusion (when there is no volume variation) and suffosion (when volume variation occurs).
- Contact erosion: Occurs when the percolation process along coarse material causes erosion of an adjacent material, in contact with the former, composed of finer particles.

1.2. Geophisical

1.2.1. Self-potential method

The Self Potential (SP) method utilizes natural potential measured between two surface electrodes without artificial electric field application (Corwin, 1990). In earth dams, spontaneous potential signals are primarily generated by electrokinetic flow potential resulting from water movement in porous mediums. This process involves anion absorption forming an electrical double layer in the soil's capillary network, while cations are carried by water flow, leading to increased positive ion concentration downstream (Gallas, 2005).

SP surveys in earth dams are commonly employed to detect infiltrations in the massif, indicative of internal erosion (Panthulu et al., 2001; Bolève et al., 2011; Netto et al., 2020). Negative SP anomalies downstream are typically associated with this phenomenon.

1.2.2. Electrical resistivity method

The Electrorresistivity (ER) method is an active technique involving the transmission of an electrical signal into the subsurface. It calculates the electrical resistivity of underground materials, indicating the medium's resistance to electrical current propagation. In sedimentary media, resistivity is affected by factors such as porosity, water saturation, and ion concentration in pore water (Lowrie, 2007; Dentith and Mudge, 2014), with water acting as an electrolyte.

ER surveys in earth dams are commonly used for various purposes, including delineating contact zones between materials with different electroresistivity, mapping the water table, and identifying preferential flow paths within the massif (Cardarelli et al., 2010; Grangeia et al., 2011; Bedrosian et al., 2012; Rocha et al., 2021; Bièvre et al., 2017; Camarero and Moreira, 2017; Raji and Adedoyin, 2019). These applications typically focus on areas displaying anomalous resistivity bands compared to their surroundings.

2. Location

The study area in Viçosa, Minas Gerais, Brazil exhibits a diverse terrain, characterized by undulating and mountainous landscapes, as well as flat-bottomed valleys hosting small streams (Corrêa, 1984). The geological composition includes gneiss formations, displaying varying textures and weathering alterations, along with other metamorphic rocks like amphibolites and migmatites (Daker, 1983; Andrade, 2010). Quaternary sediments with diverse textures are also found along the valleys (Marques, 2008).

Hydrogeologically, the area features a porous, unconfined aquifer formed by Quaternary alluvial deposits and residual gneiss soils (Rocha, 2015).

Geotechnical investigations by UFV (2018) and Dalmaschio et al. (2019) identified three main geological layers. The dam's backfill layer consists of sandy silt to red silty clay, while the foundation layer comprises alluvial materials with organic matter, mica, and gravel. Residual gneiss soil forms the base layer, with lenses of silty-sandy clay and medium sand exhibiting high permeability (Figure 1).

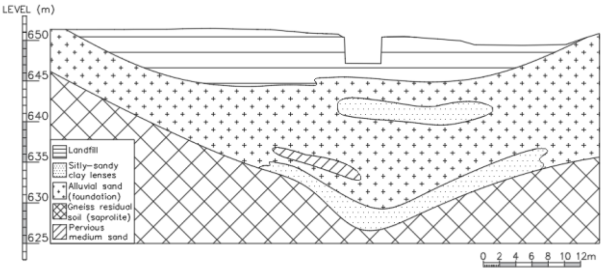

Figure 1. Longitudinal cross-section of the embankment (adapted from UFV, 2018).

Situated within the campus of the Federal University of Viçosa, the dam is a small earth embankment designed for water storage (Figure 2).

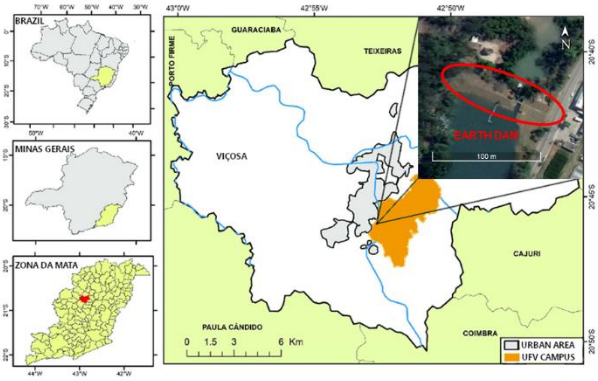

Figure 2. Location of the study area (adapted from Avila-Diaz et al., 2020).

It lacks an internal drainage system and features a concrete spillway on its crest, supplemented by an additional spillway excavated on the right bank to manage heavy rainfall (Figure 3).

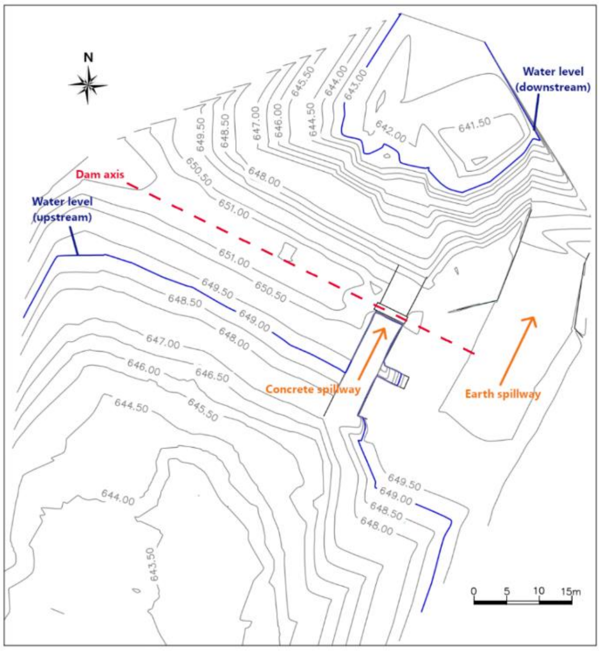

Figure 3. Detailed view of the contour lines and structures present on the dam (adapted from UFV, 2018).

Concerns about water loss through the dam's foundation layer and erosion near the concrete spillway led to emergency interventions to prevent structural collapse (Minette, 2015). These interventions have effectively maintained stability over several years, with no indications of new leaks or anomalies suggesting further piping processes.

3. Survey

3.1. Spontaneous potential

The SP data were collected using a fixed-base configuration, where potential values were measured between a stationary electrode and a mobile electrode moved along the survey lines. This setup was chosen for its simplicity and minimal cumulative errors (Corwin, 1990). The stationary electrode was placed on the dam crest near the L04 line, while the mobile electrode was affixed to the ground surface, maintaining a 3-meter spacing between measurement points.

To compensate for electrode polarization effects, potential measurements were taken near the fixed electrode at the beginning and end of each line during data collection. The equipment utilized was the SAS 1000 resistivimeter from ABEM, along with a pair of non-polarizable copper sulfate (CuSO4) electrodes attached to the surface.

Data processing involved correcting electrode polarization effects using Microsoft Excel software. Surfer software from Golden Software was employed to create a 2D model depicting potential value distribution across the study area. This software employs a kriging process for interpolation, with measured data influence decreasing as distance from calculated nodes increases.

3.2. Electrical resistivity

The ER survey was conducted using ERT measurements along lines L01 to L08. Equipment included the Super Sting R8 IP resistivimeter, a switch box, and metal electrodes. Dipole-Dipole and Gradient arrays were used with 1-meter electrode spacing and an approximate depth of 16 meters. The roll-along technique was used for lines longer than 63 meters. For lines passing through the dam spillway, electrodes were not coupled due to accessibility, resulting in no electrorresistivity readings for those points.

Data were processed using RES2DINV software for inversion, ensuring differences between measured and calculated data were acceptable. Voxler software created a 3D representation using the "Inverse distance to a power" method for grid modeling, with resistivity values interpolated between profiles.

4. Results

4.1. ER survey

The results of the ER survey (Figure 4) showed the presence of three low resistivity zones (LRZs). The first is shallow (LRZ-1), approximately 1 meter thick, whose location coincides with the earth spillway on the right bank of the reservoir. Low resistivity values are associated with the intense rains occurring before the geophysical survey, since excess water from the reservoir flows through this spillway, causing an infiltration along its length. Thus, we interpreted that the soil mass delimited by the LRZ-1 represents an infiltration zone due to the dam configuration.

The second (LRZ-2) is a large area whose upper limit is approximately at an elevation of 649 meters, extending between sections L03, L04 and L05. The position of LRZ-2 is consistent with the water level of the reservoir, implying that its upper limit corresponds to the water table inside the massif. The third LRZ is deeper, recorded in sections L01, L02 and L03 (LRZ-3), and is located below the concrete spillway. We interpreted that this zone delimits a preferential percolation path, since it is located below the water table and has low resistivity values in relation to its surroundings.

Two high resistivity zones (HRZs) were identified below the downstream slope. The first starts 2 meters below the surface at line L03 (HRZ-1), extending between the massif and foundation layers. This result indicates that HRZ-1 delimits an unsaturated region of the soil, presenting a high void ratio, probably due to a poorly executed compaction process during the construction of the embankment. Thus, high resistivity values can be explained by the high resistivity of the air filling the voids in the soil.

The second HRZ is shallow and of small extent (HRZ-2), located in a region affected by the action of biological agents, such as large anthills and tree roots, which were identified during visual inspection. These biological agents can damage the soil, increasing porosity (ANA, 2016), which as interpreted as the cause of the observed resistivity values.

It is also important to notice that the region corresponding to the cross-section of the concrete spillway is also shown in Figure 4. In general, high resistivity values were recorded, although resistivity data were not measured along the spillway section, due to difficulties in reaching the spillway sill to couple the electrodes, thus it wasn't possible to exclude the region corresponding to the spillway section, so resistivity data corresponding to its location were generated during data processing, without subsequent interpretation by the authors. Therefore, no geological property of the site should be inferred from their interpretation.

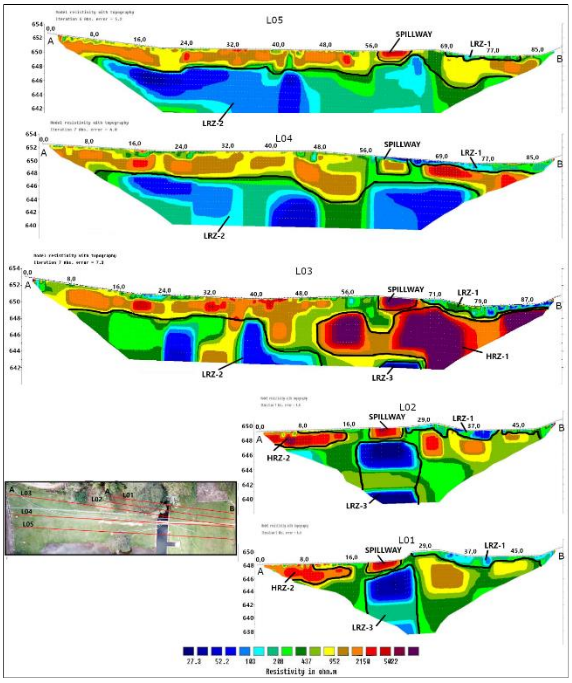

Figure 4. Results from the ER survey

4.2. Results of the SP survey

The results of the SP method (Figure 5) indicated two superficial flow zones (SFZs) along both the upstream and downstream slopes of the dam. The configuration of potential values in these regions is consistent with the electrokinetic mechanism, with the direction of the flow determined by the topography, and the potential values increasing downstream. We interpreted that these shallow flow zones were identified due to heavy rains in the study area prior to data acquisition, and were generated by the runoff through the surface of the embankment.

A negative potential anomaly (NPA) was identified on the downstream slope of the dam, recorded on L01, L02 and L03 profiles. This anomaly is located around the concrete spillway, and was associated with an intense cation displacement that may have been caused by the existence of a preferential flow path through the subsurface (Reynolds, 2011).

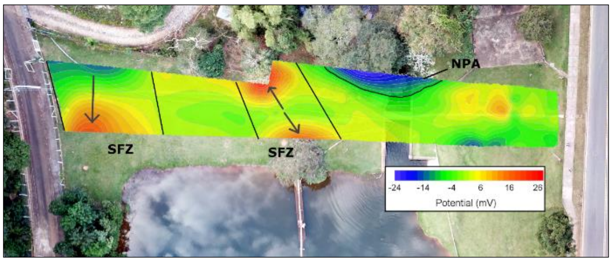

Figure 5. SP survey results.

4.3. Preferential flow paths and detection of an infiltration process

The integrated interpretation of the geophysical survey results allowed the authors to identify a preferential flow path through the massif. A 3D resistivity distribution model is shown in Figure 6. This model was created using the software Voxler, produced by Goldensoftware, using a gridding model, applying the Inverse distance to a power method. In this process, data are weighted during interpolation such that the influence of a point datum declines with distance from the lattice node, and then resistivity value was determined in the space between the profiles. It is possible to note two deep LRZs identified in the ER survey results. LRZ-2 delimits the subsurface region in which water percolation occurs with more intensity, due to low resistivity values in relation to its surroundings. Considering that the water table level is associated with the upper limit of LRZ-2, we interpreted percolation occurs preferentially under the structural embankment.

The SP survey results are also presented in Figure 6. Both NPA and LRZ-3 were recorded in similar positions in the embankment, thus it is possible to infer that this correlation of results indicates a process of water loss through the foundation layer of the dam, in the region below the concrete spillway. The occurrence of this infiltration process is consistent with the abrupt lowering of the water level in the L3 profile, as registered by the ER results, indicating the existence of a sink in the alluvial sand layer. High resistivity values recorded in HRZ-1 are also consistent with this abrupt lowering of the water table, as these values can only be explained if voids in the soil mass delimited by HRZ-1 are mostly filled with air.

The convergence of the results herein presented indicates the existence of a critical region, in which an infiltration process is responsible for the emergence of a preferential flow path delimited by LRZ-3, confirming the reports of previous reports of loss of water from the reservoir.

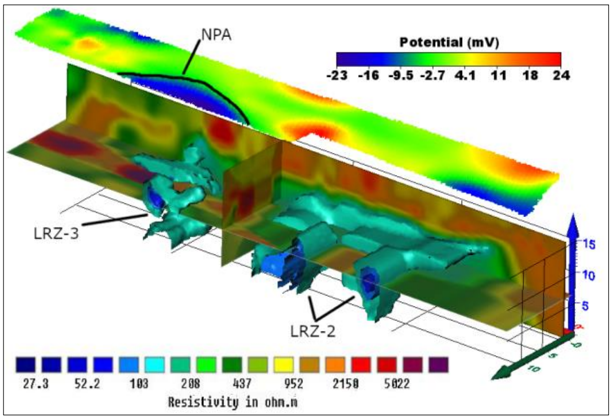

Figure 6. 3D view of the resistivity and self-potential data.

5. Conclusion

The integrated analysis of the results allowed to conclude that the geophysical survey conducted in the present study proved to be effective for the evaluation seepage conditions through the massif and foundation layers of the embankment, fulfilling the objectives of this study. It was possible to delimit surficial and deep flow paths through the study area, that were properly associated with the phenomena responsible for their occurrence.

The integrated interpretation of the available data proved to be an effective tool for better grounded and more precise interpretation of the phenomena presented, confirming the formulated hypotheses. In addition, data acquisition by two different methods on the same line profiles provided the necessary redundancy of information required to mitigate possible ambiguous interpretations.

Also, it is important to notice that in the geophysical section analysis, clay lenses were not delineated due to interpretational constraints, given the subjective nature of the study. The absence of clay lenses within the surveyed area does not definitively denote their non-existence but rather reflects the limitations inherent in the interpretive process.

Regarding the evaluation of the dam safety, the results show that although the original erosive process caused by piping has been treated, the phenomena responsible for the occurrence of this process have not been mitigated. In addition, the results show the importance of constant monitoring of geotechnical structures as a tool to avoid the development of hazardous processes.

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