GEOPHYSICAL INVESTIGATION OF SEEPAGE FROM AN EARTH FILL DAM, WASHINGTON COUNTY, MO.

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Abstract

Internal erosion and the development of sinkholes and other piping features is one of the major reasons for embankment dam failures. Geophysical methods have the potential of detecting internal erosion and anomalous seepage at an early stage before the safety and integrity of the dam is at stake. Two non-invasive and cost effective geophysical methods (electrical resistivity and self-potential) were used to investigate the internal seepage at Crystal Lake Dam, Washington County, MO. Previous engineering drilling and grouting programs had been applied to the dam to minimize and control seepage through the body of the dam. However, due to lack of information about the problematic areas (seepage flow paths) through the body of the dam, grouting procedures were not as effective as hoped. In an effort to delineate seepage pathways prior to a second phase of grouting, geophysical data were acquired.

Nine 2-D electrical resistivity profiles were acquired across the east and west side of the dam embankment. On the basis of the interpretation of these data, three zones of relatively uniform resistivity were identified and mapped. The first (uppermost) zone is characterized by moderate resistivity values (50-150 ohm-m). It represents unsaturated topsoil with thicknesses varying from 1 to 2.5 m. The second (intermediate depth) resistivity zone, with resistivity values ranging from 5 to 50 ohm-m and thickness varying from 3.5 to 10 m, represents a silty clay layer with high moisture content. The third resistivity zone represents bedrock (Dolomite) and is characterized by relatively high resistivity values ranging from 300 to 4500 ohm-m. Zones of relatively low resistivity within the bedrock are interpreted to represent fractured and preferential flow pathways. Locations of these zones were determined from the 3D view of the depth to the bedrock from the inverted resistivity data acquired on the west side of the dam embankment.

On the basis of the interpretation of the resistivity data, a grid of self-potential (SP) data was acquired. The SP data are characterized by anomalously high “spot” readings (17-27 mV) coincident with the bedrock anomalous features obtained from the resistivity profiles.

Introduction

The study area of the Crystal Lake Dam is located at Washington County, MO (Fig. 1). The dam is an earthfill embankment designed without a core. The embankment is composed of silty clay materials with an average thickness of 10 m above the dolomite bedrock. The normal water level of the reservoir at the eastern side of the dam was about 3.5 m from the crest of the dam but has been dropped to about 7 m due to water leakage through the body of the dam. The water leakage was observed at the most southern toe of the western side of the dam where bedrock is close to the ground surface. Previous engineering remedial processes (e.g., grouting) were unsuccessful in stopping the leakage due to lack of information about the problematic areas (seepage flow paths) through the body of the dam. Previous geophysical studies have demonstrated the utility of using electrical methods (e.g., electrical resistivity and self-potential) to detect and characterize the seepage conditions occurring at dams (e.g., Sirles, 1997; Butler, et al., 1989). Electric resistivity is one of the most sensitive geophysical methods for the changes in soil moisture and it is a very effective tool to determine depth to water saturated zone and groundwater flow pattern. The resistivity of soils is dependent on saturation, porosity, permeability, ionic content of the pore fluids, and clay content. In the case of water seepage through a dam, it can be detected as resistivity low using electrical resistivity methods.

The self-potential (SP) method involves the measurement of the natural-earth electrical potential between points on the surface of the ground. Several phenomena can produce measurable natural-earth potentials (e.g., streaming potential, electrochemical). The flow of water through the subsurface soil or rock generates natural measurable electrical voltages called streaming potentials (e.g., Schiavone and Quarto, 1984; Fournier, 1989; Fagerlund and Heinson, 2003). Therefore, the self-potential (SP) method has been used to detect areas of seepage through embankment dams by measuring streaming

potentials. The objective of this study is to detect the seepage paths and conditions at the dam and determine whether the seepage are associated with the embankment of the dam (due to internal erosion and piping) or resulting from the fracturing and dissolution of the dolomite bedrock underneath.

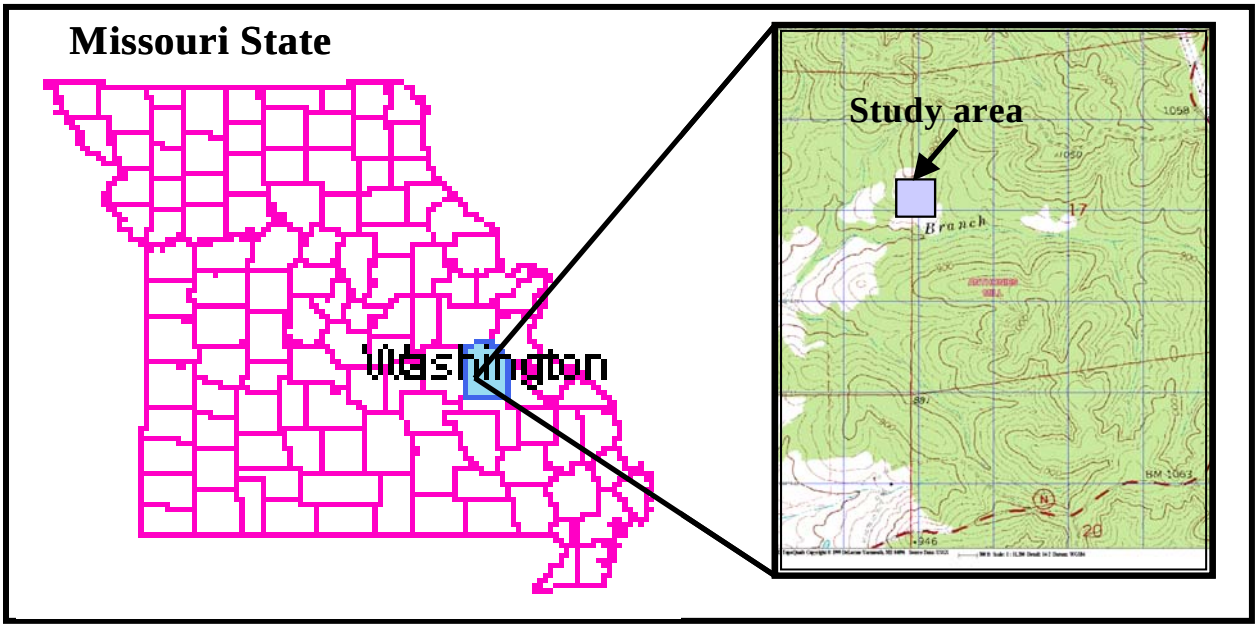

Figure 1: Location map of the study area (Crystal Lake Dam), Washington County, MO.

Data acquisition

Electrical resistivity and self-potential data were acquired to delineate seepage pathways prior to a second phase of grouting. Electrical resistivity methods involve the measurements of the apparent resistivity of soils and rocks as function of depth or position. During resistivity surveys, current is injected into the earth through a pair of current electrodes, and the potential difference is measured between a pair of potential electrodes (Telford, et al., 1990). SP field surveys are conducted by measuring an electric potential difference (voltage) between a pair of non-polarizable electrodes (e.g., copper-copper sulfate) that contact points on the surface of the earth. Figure 2 represents a schematic drawing of the location of the measured 2D dc resistivity lines and the SP survey area. Two resistivity profiles were measured at the east side of the dam (1E and 2E) and seven resistivity profiles were collected at the backside (1W, 2W, 3W, 4W, 5W, 6W, and 7W). The length of each resistivity line was 95 m and the resistivity measurements were collected from south to north using the AGI R-8 Supersting multichannel and mutlielectrode resistivity unit. The acquisition parameters of the 2D resistivity survey were selected to obtain a high resolution for imaging the shallow subsurface. The resistivity data were then inverted using a RES2DINV software package (Loke and Barker, 1995) and inverse model resistivity pseudosections were obtained. The zero elevation on the depth scale of resistivity sections represents water level in the lake at the eastern side of the dam.

A grid area for the SP survey is selected (12-36m West and 10-70m North) based on the preliminary interpretation results of the resistivity measurements (Fig. 2). Non-polarizable (copper-copper sulfate) electrodes were used and a high-input impedance voltmeter (~ 2 * 10^6 ohm.) was used to measure the potentials. Electrodes are placed in 5 cm holes to reduce the source of noise from the topsoil. One electrode is left as a reference at a fixed point and the second (rolling electrode) is moved at 3 m station interval and 3 m line spacing. SP readings in millivolts are taken with respect to a base station through the selected grid area. The obtained SP data are plotted in an excel spreadsheet and contoured

using a software package of Geosoft Oasis Montaj._Nine 2D dc electrical resistivity profiles were collected, using the dipole- dipole electrode array, 3m electrode spacing, and n increasing to 6 as shown in figure 3.

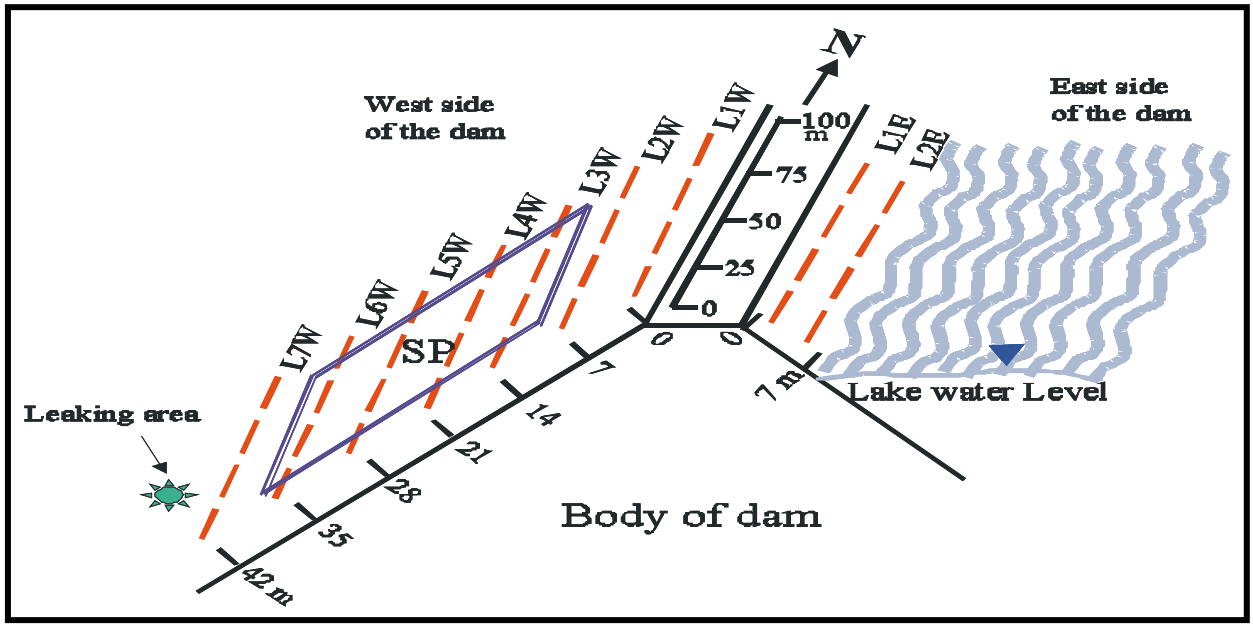

Figure 2: Schematic representation of the dam showing the location of the acquired dc resistivity lines, and SP surveyed area.

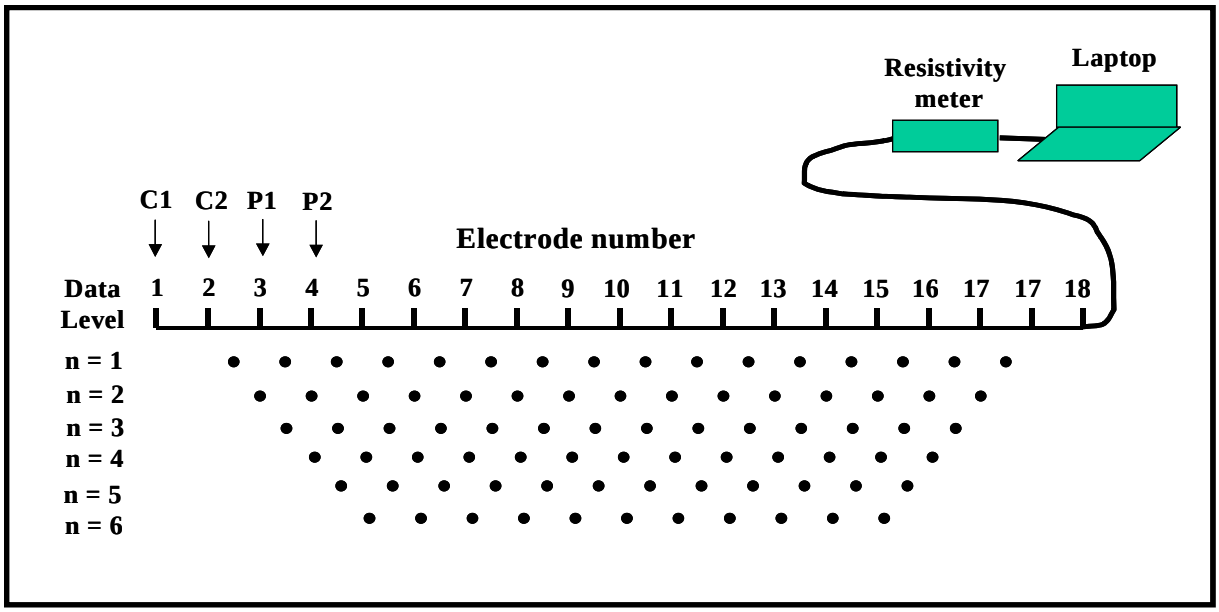

Figure 3: Schematic drawing of the Dipole-Dipole electrode array used in the resistivity survey.

Results and discussion

2D resistivity

Figure 4a and b show the eastern side pseudosections of the 2D resistivity profiles 1E, 2E, respectively. Both resistivity profiles show a top layer with resistivity values range from 50 to 150 ohm.m and a thickness varies from 1 m to 2.5 m. This layer is interpreted as a silty clay soil with very low moisture content. This moderate resistivity layer is followed by a homogenous low resistivity layer (5-50 ohm.m) observed with a thickness ranges from about 4 m at the southern part of the profile to about 10 m to the northern part. This layer is interpreted as clay rich layer and the low resistivity values may be due to high moisture content resulting from the leaking of water leaking through this layer under the effect of change in the hydraulic gradient on both sides of the dam. A high resistive layer with resistivity range from 300 to 4500 ohm is observed at a depth ranges from 10 to 13 m from the crest of the dam and represents the dolomite bedrock.

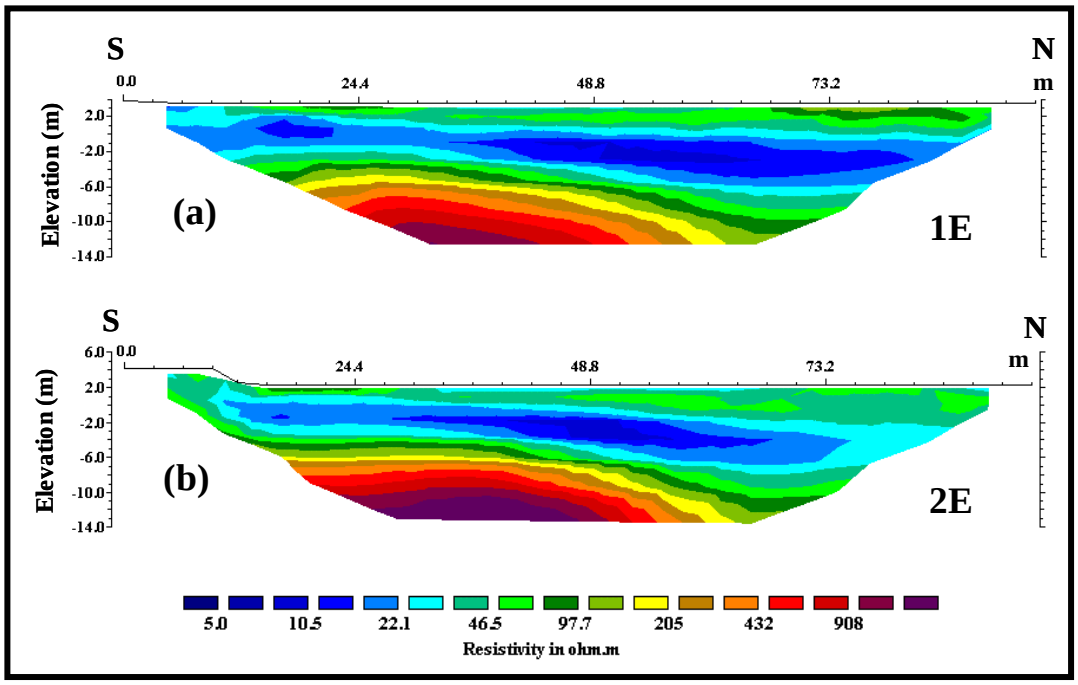

Figure 4: Results of resistivity pseudosections (a) 1E and (b) 2E, acquired at the eastern side of the dam embankment.

Result of the 2D resistivity profiles (1W, 2W, 3W, 4W, 5W, 6W and 7W) acquired at the western side of the dam embankment is shown in figure 5. Resistivity pseudo-section 1W and 2W (Fig. 5a and b) show identical and similar results (e.g., resistivity and thickness) obtained from resistivity pseudosection 1E and 2E at the eastern side of the dam. The resistivity ranges characterizing the bedrock (300-4500 ohm-m) is not observed in the resistivity profiles 3W and 4W. Instead, a moderate resistive layer (50-200 ohm-m) is observed. This layer may represent highly weathered bedrock or solutioned bedrock. Moreover, the resistivity pesudosection 5W shows a change in the bedrock pattern and an anomalous low resistivity zone (5-20 ohm-m) located within moderate resistivity zone of the weathered or fractured bedrock described above (figure 5e). This anomalous low resistivity zone may represent a conduit or flow channel for the water. It is clear that the depth to bedrock is decreased from resistivity profile 6W to 7W with the presence of the anomalous low resistivity zone as described above (Fig. 5f and g).

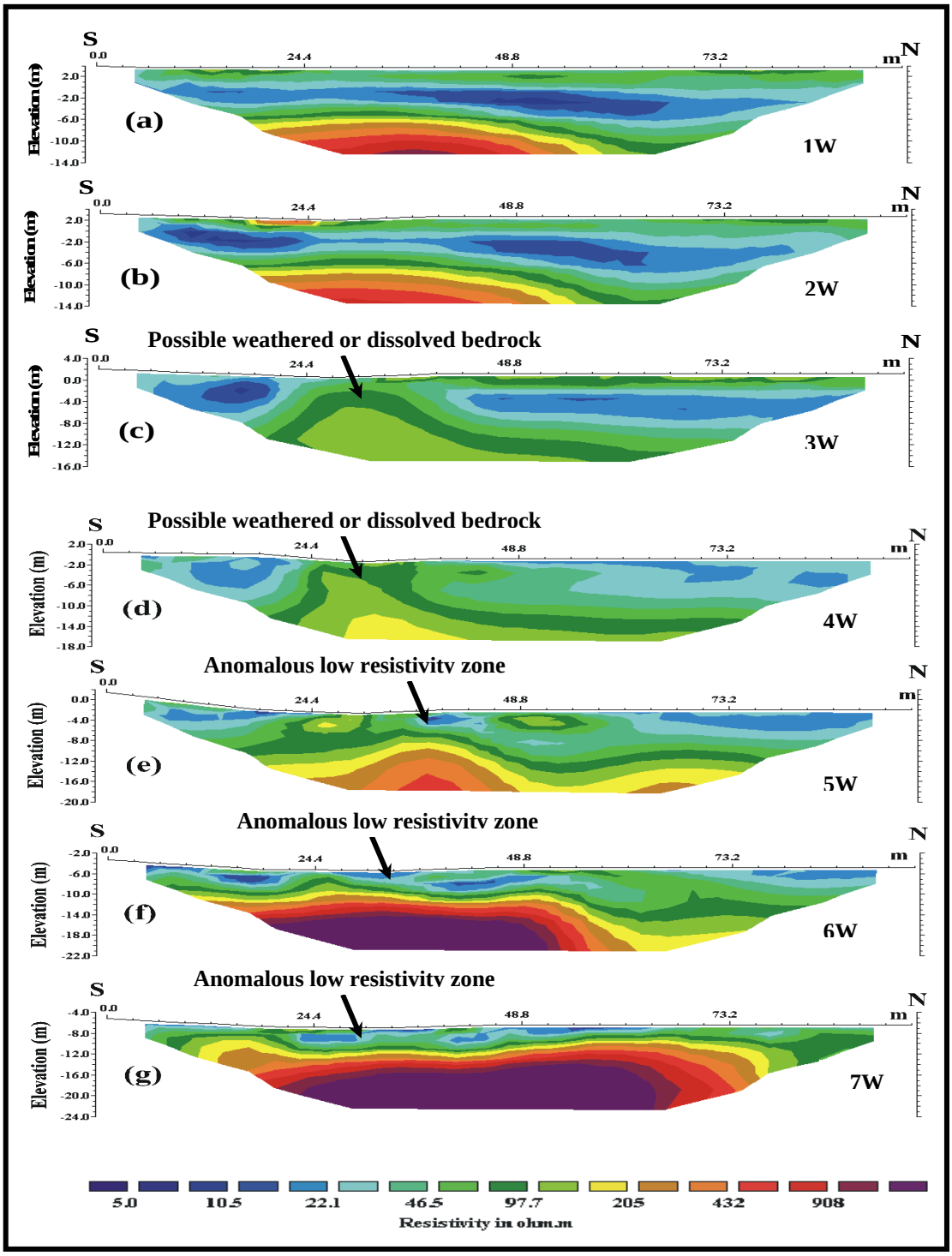

Figure 5: Results of resistivity pseudosections (a) 1W, (b) 2W, (c) 3W, (d) 4W, (e) 5W, (f) 6W, and (g) 7W, acquired at the western side of the dam embankment.

The shallowing of the bedrock observed at resistivity profiles 6W and 7W will allow the conduit (anomalous low resistivity zone) formed by the bedrock weathering or dissolution to intersect with ground surface further forming the observed seepage.

Figure 6, shows the 3D view of depth to the bedrock obtained from the resistivity pesudosections at the western side of the dam. The depth values to bedrock were referenced to the water level of lake at the eastern side of the dam. This figure shows the variations in the depth to the bedrock and areas of possible high weathering and dissolution representing by anomalously low depth values (Fig. 6).

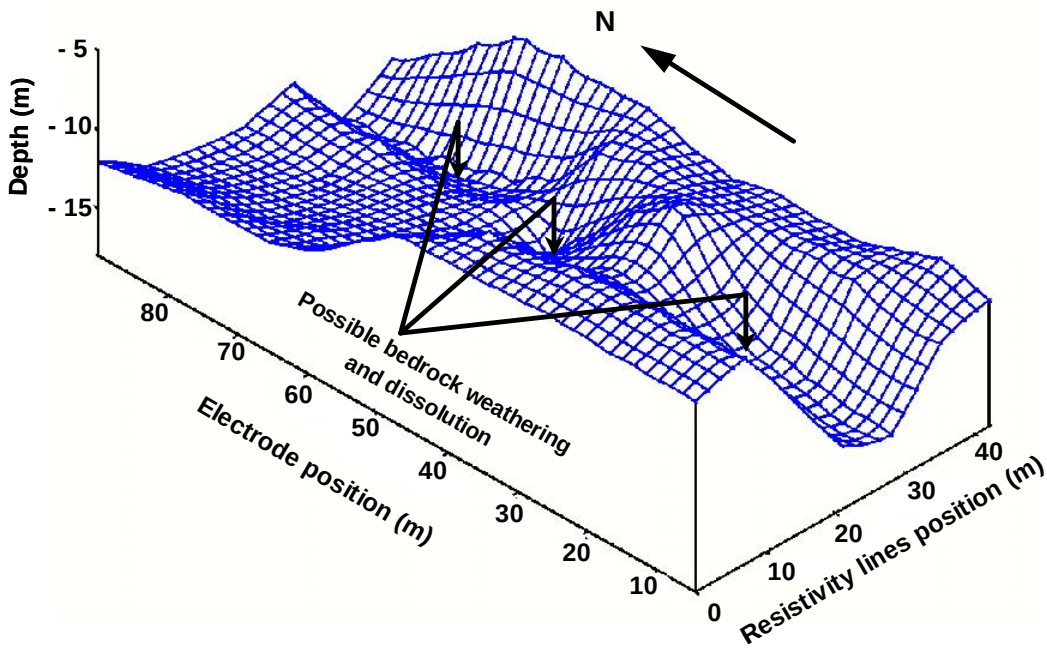

Figure 6: 3D view of the depth to the bedrock at the western side of the dam.

Self-Potential

Figure 7shows the contour map of the measured self-potential readings through the surveyed grid area. The SP background of the surveyed area ranges from 13 to 17 mV. The variation in SP readings reflects the variations in soil moisture content and to some extent topographic variations. High SP anomalous readings (17-27 mV) are observed and delineated by the rectangular area A, B, and C. These anomalously high SP readings suggest high streaming potentials resulting from water flow through the bedrock-fractured or weathered zone. The results obtained from SP survey is compared well with those obtained from resistivity profiles.

Conclusion

Three resistivity zones were observed along the resistivity profiles with distinct resistivity values and variable thickness. The first resistivity zone represents the topsoil with thickness varies from 1 to 2.5 m and has a moderate resistivity values (50-150 ohm-m) suggesting low moisture content. The second resistivity zone with a resistivity values range from 5 to 50 ohm-m and thickness varies from 3.5 to 10 m representing a silty clay rich layer with high moisture content.

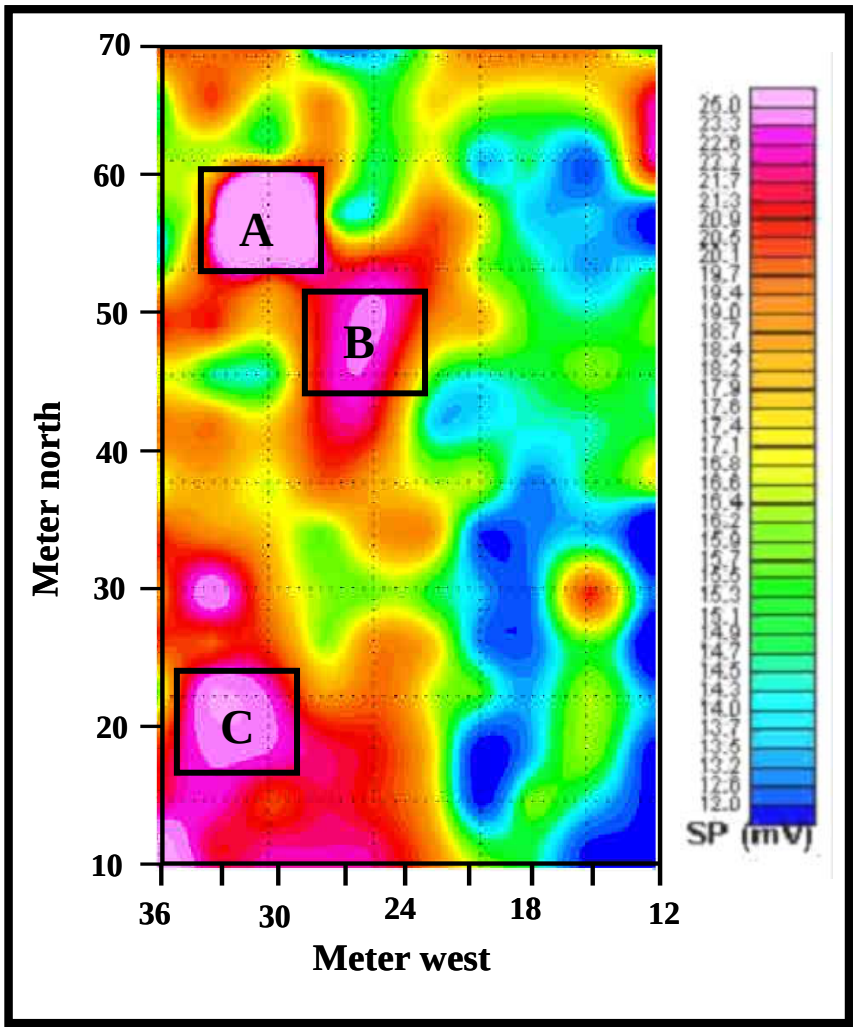

Figure 7: Self-potential contour map. A, B, and C, represents anomalous areas of high SP values.

The third resistivity zone represents the bedrock and shows a high resistivity values range from 300 to 4500 ohm-m. In some areas the high resistive layer representing the bedrock has been highly weathered resulting in a layer of moderate resistivity values starting at resistivity line 3W to 4W suggesting high probability of weathering or fracturing and dissolution at this area. Moreover, anomalous zones of low resistivity values were observed within the prementioned highly weathered zone and extends from resistivity line 5W to 7W suggesting a possible conduit for water flow. SP results show anomalous features with high SP readings coincident with bedrock anomalous features obtained from the resistivity profiles.

Based on the above discussion and conclusion, we recommend soil boring or drilling with grouting at the pre-mentioned anomalous features obtained from both the resistivity and SP results. Moreover, geophysical characterization of the entire body of the dam using electrical methods (e.g., dc resistivity and self-potential) is highly recommended to investigate the weakness areas and to find out if there is any more fracturing or possible dissolution that could act as flow channel or conduits for future water leakage.

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