ASSESSING SEEPAGE FLOW CONDITIONS THROUGH A DAM QUICKLY AND ACCURATELY WITHOUT DRILLING OR DRAWING DOWN THE RESERVOIR

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This paper examines the application of a proven geophysical technology that is highly effective in assessing seepage flow conditions through, beneath and around earthen embankments. The technology works rapidly with minimal disruptions to dam operations—it requires no drilling or draining of the reservoir. It has become a competitive solution to many of the complex challenges faced with dam safety diagnostics and monitoring and the technology has consistently and repeatedly providing intelligence to dam operators in identifying problems with their dams and pointing to appropriate cost-effective methods for resolving them. At the 2009 SAGEEP conference in Austin, TX, a seepage related case study of the Method was presented. It showed that the Method found a two-meter sinkhole at the bottom of a reservoir, which was later independently verified. Now, three years later, the method has improved and results are significantly more detailed, accurate and descriptive in defining seepage problems. For instance, data reduction now involves predicting the magnetic field generated from electric current flow in a homogenous space and comparing that to the measured magnetic field. This comparison enhances detection of subtle flow paths in a more electrically homogeneous environment. In addition, a sophisticated inversion algorithm has been developed to quantify the distribution of electric current flow beneath the study area. With these upgrades, the Method is proving to be even more accurate at finding the zones of highest transport porosity related to seepage flow through dams. Although electrical and hydraulic conduction are governed by very different principles, the distribution of electric current flow can qualitatively infer a general distribution of hydraulic conductance, thus helping to appraise the integrity of a dam's embankment, abutments and foundation. To illustrate how the Method in its current form works, an actual case study and physical modeling experiments will be presented that demonstrate the Method's application and accuracy with regard to characterizing preferential seepage flow through earthen embankments.

Introduction

Groundwater systems have been notoriously difficult to map with high degrees of accuracy. Traditional methods often prove costly in terms of time, money and environmental trauma. This paper considers a high-speed, minimally invasive mapping technology called the Willowstick methodology (hereafter, "the Method" or "the Methodology") which evolved from Magnetometric Resistivity (MMR). The Method has been specifically designed for mapping preferential groundwater flow paths or areas of highest transport porosity within the subsurface. In addition to many other applications, the Method has most notably been used in the risk analysis of earthen dams facing critical seepage problems. In such circumstances, this Method has proven efficient and accurate in tracking preferential seepage flow paths.

This paper reviews the Methodology briefly and then details improvements that have been made in recent years and how these improvements impact the resolution and accuracy of the interpretations. In 2009, interpretations were made directly from magnetic field contour maps that were subject to a series of corrections, and then modeling was performed by a trial-and-error forward modeling process. Now, interpretation is based on the “Ratio Response” map or a comparison of the field data to the predicted data, which indicates where electric current is more or less concentrated than the homogenous condition. The modeling now utilizes a sophisticated inversion algorithm that calculates the subsurface Electric Current Distribution (ECD) based on the magnetic field data. These computational improvements to the data analysis procedures have boosted the reliability of finding the position and depth of subsurface preferential seepage flow paths.

In addition to highlighting the Method’s recent improvements, answers to questions concerning how the Methodology discerns groundwater flow paths are demonstrated through experiments. A physical modeling experiment will be presented to show how the Methodology highlights anomalous zones of both high and low conductivity and how electrical current reacts to these zones. All of these improvements in knowledge and data processing make the Method a sophisticated tool for mapping subsurface preferential seepage flow paths. A brief example from a recent project where the ECD model clearly resolves the depth and location of seepage is presented to show that one of the Method’s niche applications is seepage characterization of earthen embankments.

Summary of Methodology

The Methodology utilizes a low voltage, low amperage audio frequency electrical current to energize the seepage flow paths of interest. Electrodes are placed in strategic locations to facilitate contact with seepage from the dam. Attracted to the most conductive zones, electrical current tends to track preferential groundwater paths and high porosity zones within the saturated subsurface. As electrical current takes various paths through the dam, it generates a magnetic field (Biot-Savart law) characteristic of the injected electrical current. This unique magnetic field is identified and surveyed at the surface of the dam and reservoir using highly sensitive equipment. The locations of field measurement stations are identified by sub-meter GPS and recorded in a datalogger with the magnetic field readings. The measured magnetic field undergoes data reduction and then is contoured and interpreted in conjunction with other hydrogeologic data, resulting in enhanced definition of seepage flow paths.

Figure 1 shows an example of the physical concepts utilized by this Method to map subsurface electric current flow. An electrical current flows in a wire covered by a paper with iron filings. The iron filings align with the predominate magnetic field generated by electric current flow and reveal the “footprint” of the wire. The same concept applies to surveying where subsurface electric current gathers. Highly sensitive measurements become the “iron filings” to obtain a footprint of the subsurface electric current distribution. Resolution of these current flow paths is based in part on the spacing of measurement stations and the depth of flow.

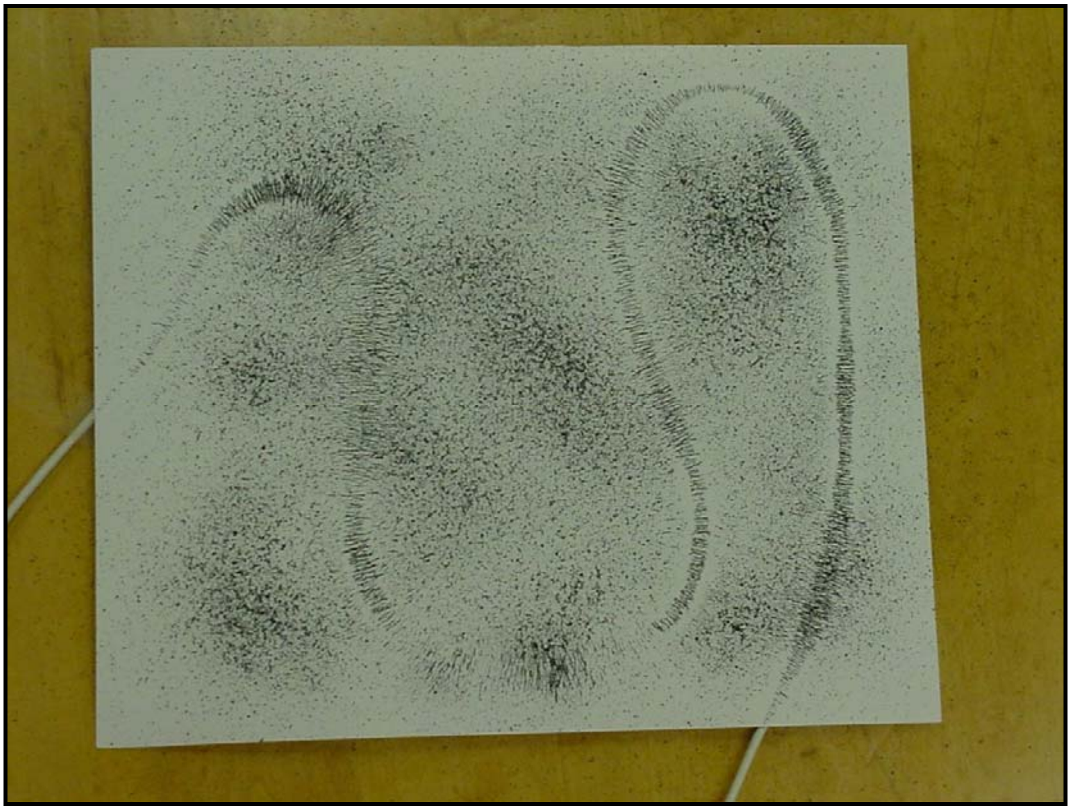

Figure 1: Iron filings align with the magnetic field generated from electric current flowing in the wire hidden beneath the paper.

The Methodology evolved from MMR (Edwards and Nabighian, 1991) and is specifically designed to map preferential groundwater pathways and zones of highest transport porosity. But even though the Methodology evolved from MMR, there are key differences between the Willowstick method and MMR. First, electrodes are placed in direct contact with the water of interest instead of just being placed at the earth's surface. In the case of a dam, an electrode is placed in the reservoir water and other electrodes are placed in the downstream seeps, piezometers, or any wells in contact with suspected seepage. Second, MMR data is interpreted in such a way as to ascertain the subsurface resistivity distribution; whereas the new Methodology, tailored for mapping groundwater, uses a unique and robust inversion algorithm to track preferential flow by calculating the distribution of electrical current density.

Advantages and Limitations of the Method

For characterization of groundwater locations and paths, the Method has strategic advantages over various other geophysical methods. First, the Method capitalizes on the conductivity-enhancing effect of water on subsurface materials which is discussed in the next section, Electrical / Hydraulic Conductivity Correlation. Secondly, the Method's low-frequency signature magnetic field is not attenuated by conductive overburden because it propagates independently from—or without being coupled to—an electric field (i.e. it is not limited by the "skin depth" effect). The Method, therefore, can characterize groundwater flow paths at significant depths (up to 1000's of feet). The distribution of electric current flow (derived from the magnetic field measurements) can be used to infer a qualitative distribution of hydraulic conductance in the subsurface. This a bold statement, but experience with the

Method—as well as published material relating to the electrical-hydraulic conductivity correlation—indicate that there is a very real link between groundwater flow paths and electrical current flow paths.

As with all geophysical methods, there are limitations. First, the electrodes must be in contact with the groundwater of interest to produce conclusive results; the Methodology cannot be applied on sites where there is no access to the water of interest. Second, circuit continuity, the ability to generate a recognizable subsurface electric current, must be established between electrodes. Problems here can arise when the groundwater is pure and void of ions which are necessary for the creation of an electrical circuit. (This case is very, very rare and can sometimes be remedied through the introduction of saline solutions around the electrodes). Third, the water of interest must create a sufficient conductivity contrast to cause diversion of electric current flow from the uniform or homogeneous case. Conductive culture (power lines, pipelines, guardrails, and other long continuous metal features) can also conduct the signature electrical current and interfere with or overshadow the subsurface signal. Fourth, a shallow flow path may mask a deep one; however, this situation is also rare. Finally, the Method does not provide an indication of groundwater flow rates.

Electrical / Hydraulic Conductivity Correlation

Hydraulic conductivity is the ability of a material to conduct water when pressure is applied. It is a function of interconnected pore volume (effective porosity—also referred to as transport porosity). The larger and better connected the pore spaces, the greater the hydraulic conductivity and the easier and faster water will flow through the earthen material given a potentiometric gradient.

Electrical conductivity is largely a function of the availability of free ions and the presence of a transporting medium (water) to allow ion movement. Most earthen materials are fundamentally electrical insulators with electrical conductivities ranging between 10^{-12} and 10^{-17} mho/m. Yet, in-situ measurements of electrical conductivities range from 10^{-1} to 10^{-8} mho/m—many orders of magnitude higher (Purvance D. and Andricevic R., 2000). This discrepancy is due to conduction of electrical current by way of ions dissolved in the groundwater. Recognizing that water is generally the primary facilitator of electric conduction in the typical geologic environment, the Method efficiently tracks groundwater paths by detecting differences in the magnetic field intensity arising with changes in electrical conductivity.

The Method naturally works best in environments where the degree of water saturation varies (i.e., between dry and highly saturated areas). However, it also works well within a completely saturated environment. When electrical conduction occurs primarily in open pore space of a saturated matrix, a positive slope correlation exists between electrical and hydraulic conductivities – meaning that hydraulic conductivity can be tracked along the higher electrical conductivity zones (Wong et al., 1984). When electrical conduction occurs primarily along pore surfaces, such as in wet clay, the positive correlation may disappear and can in fact become a negative correlation (Purvance D. and Andricevic R., 2000). In each environment, the Method provides valuable information by highlighting edges of zones with a marked change in effective porosity, thus revealing where groundwater preferentially flows and where it does not flow.

To better illustrate the point, consider water flowing around a large boulder in a river (Figure 2 Left side). Even if the boulder itself could not be observed directly, its shape and location is still revealed by the pattern and direction of water flow around it. Electric current flows in much the same way. If we consider the opposite case, where a large conductive body attracts the electric current flow to itself, the analogy would be more like that of water rushing by a submerged drain, which attracts the water toward it (Figure 2 Right side). Here the anomalous gradient in the water surface would reveal the drain's location, just like an electric current density increase within a conductive body would reveal its location.

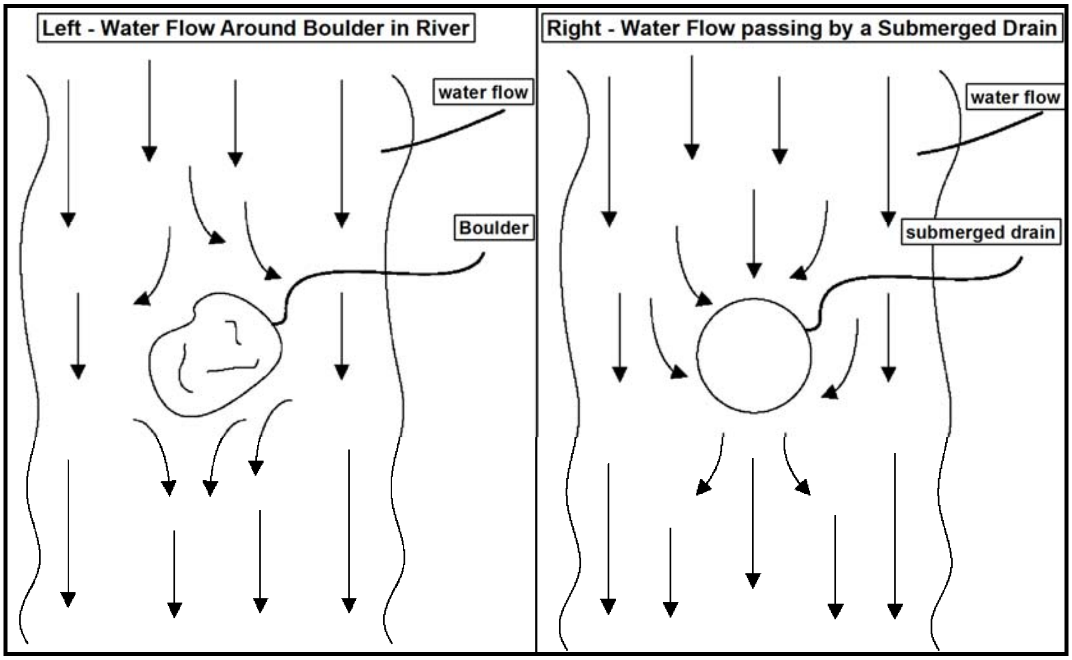

Figure 2: (Left) Water flows around a boulder in a river. (Right) Water passing by a submerged drain.

A simple lab experiment demonstrates how the distribution of electric current flow identifies the edges of resistive and conductive bodies. Two electrodes were placed in a 120 x 240 cm tub of sand and saline water. Two bodies were placed in the tub with the sand: a rectangular piece of steel and a triangular piece of plastic (see Figure 3). An AC electrical current was passed through the sand tub and a magnetic field was measured over the surface of the tub with a three axis AC magnetometer. Measurements (small red "+" markers) were made on a coarse grid over the whole tub at 6.4 x 6.4 cm, and fine grid (1.6 x 1.6 cm) was used to detail the anomalous zones around the two objects. Figure 3 shows a picture of the setup before sand and water were added.

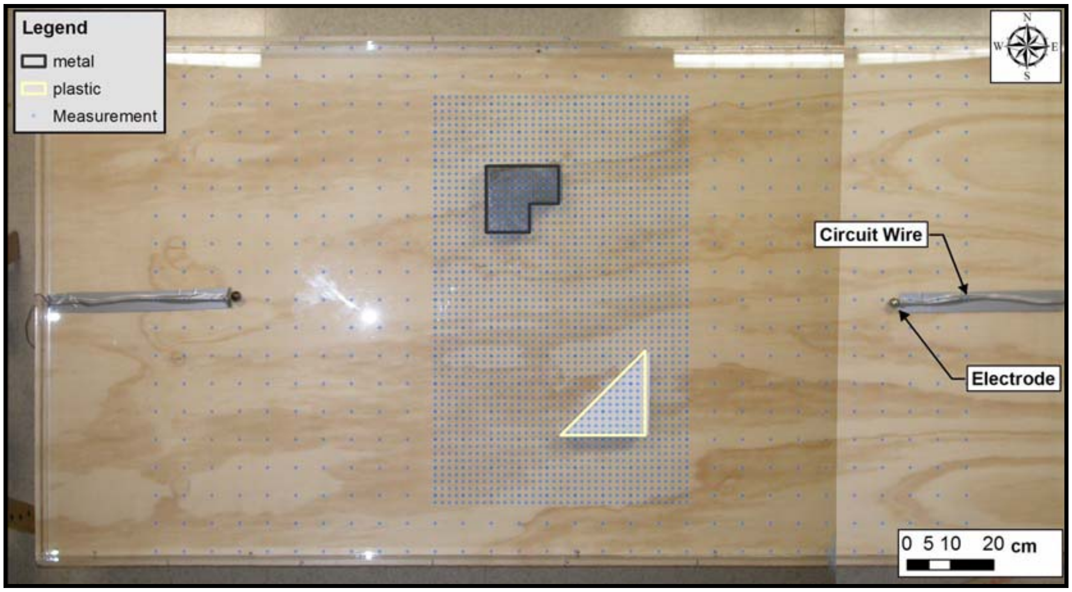

Figure 3: Plan view of experiment with conducting and insulating bodies

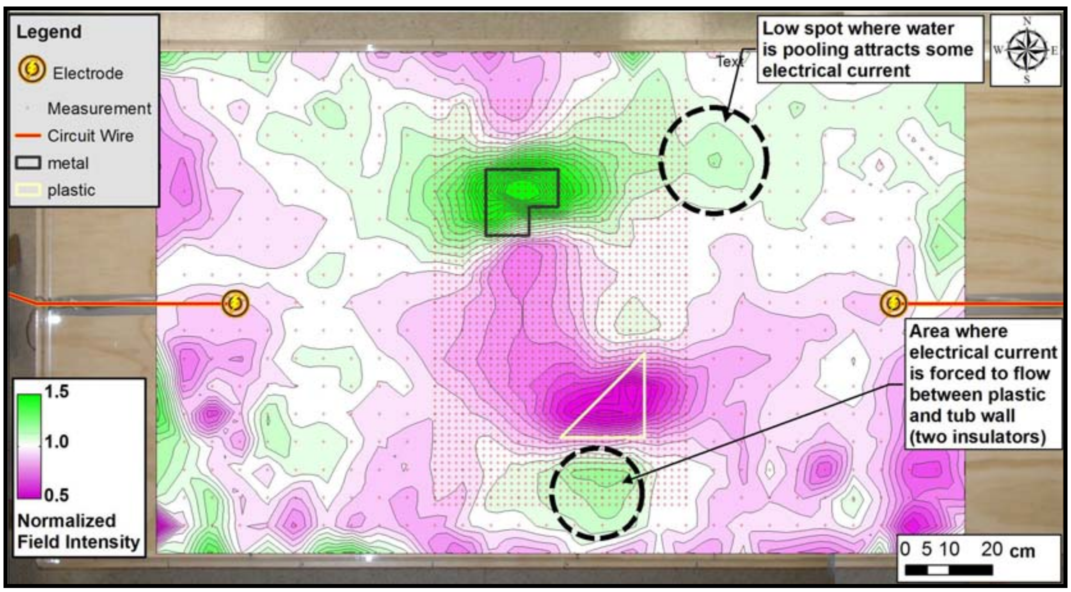

Figure 4: Ratio Response map showing anomalous electric current flow in the tub

Figure 4 shows the ratio response map for this experiment with each object's position indicated on the map. The white or light-colored areas indicate where electric current intensity is approximately equivalent to that predicted by the homogenous model. The purple indicates where electric current flow is less than predicted and green shows where electric current flow is greater than predicted. The map shows that electric current is attracted to the steel object (high magnetic field anomaly—dark green shading) and avoids the insulating plastic (low magnetic field anomaly—dark pink shading). Next an inversion of the magnetic field data was performed to estimate the electric current distribution in the tub. Figure 5 is a horizontal slice from this model. The green shading identifies where electric current is more concentrated, while the purple shading identifies where electric current is less concentrated. As can be seen, the inversion identifies the shape of the steel conductor, but because the plastic triangle forces most of the electric current around itself, the triangle's western side is fairly well defined while it's eastern edge is somewhat obscured.

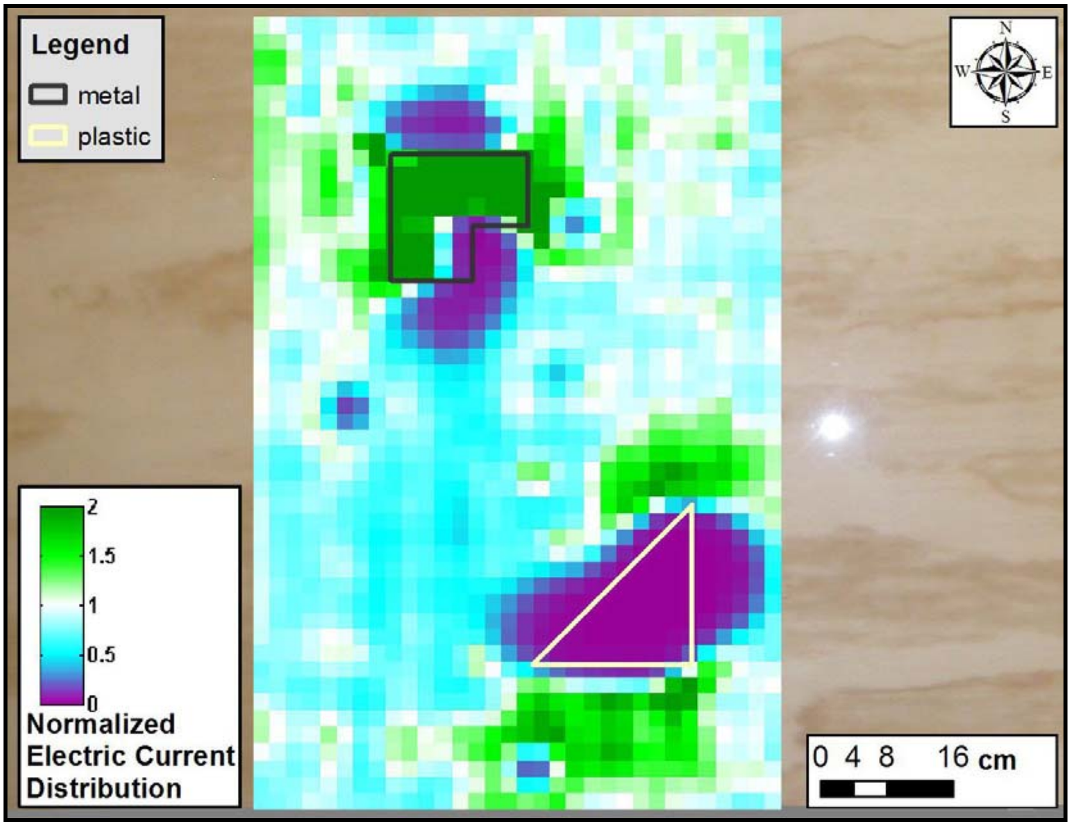

Figure 5: ECD model slice showing conductive and insulating areas within the tub.

Figure 6 shows how the electric current bends to flow around the plastic triangle. This simple experiment clearly demonstrates how the electric current distribution in a conductive or semi-conductive matrix can effectively reveal the locations of both conductive and resistive bodies.

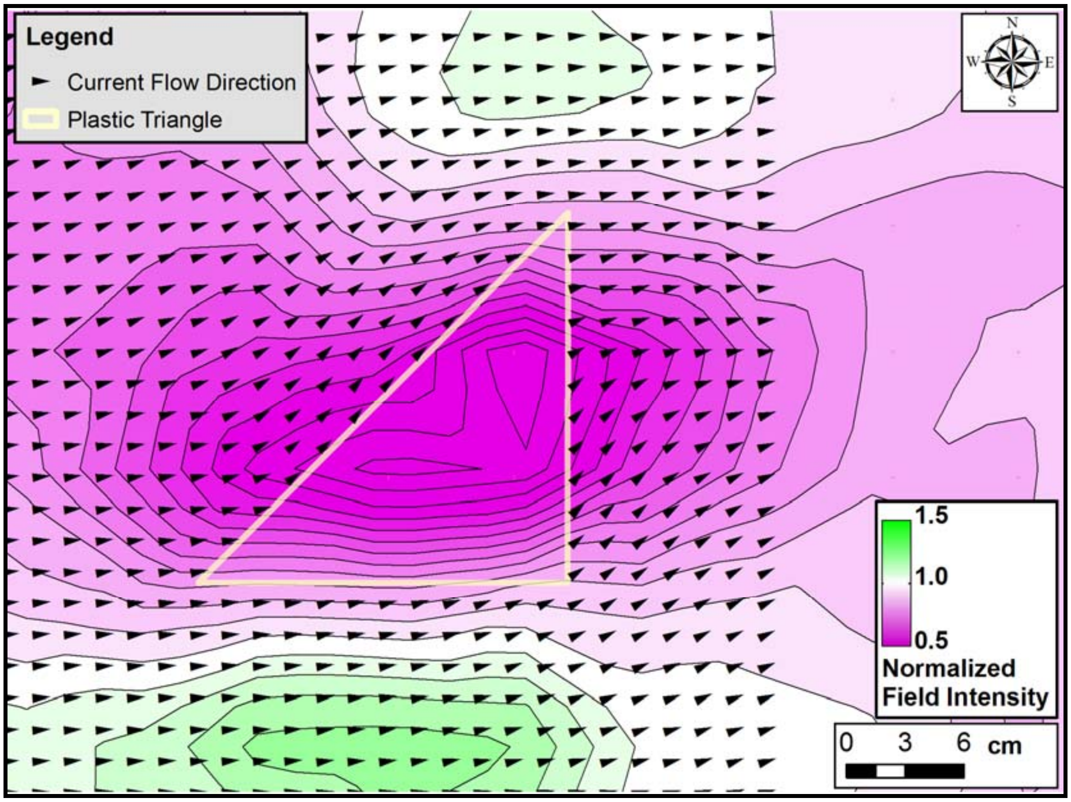

Figure 6: Electric Current Flow vector field map

Compared to this experiment, geologic conditions in real-world scenarios present much weaker conductivity contrasts, but the Method's magnetic field equipment is also far more sensitive than that used for this experiment. Conductivities in saturated unconsolidated sediments generally do not vary dramatically. In many instances saturated clays have a slightly higher conductivity than saturated sand or water-filled void space because of the clay surface conduction pathways. Therefore, there is still a question as to whether this Method would illuminate a seepage flow path in a saturated clay environment. Experience with the Method shows that, even in a saturated clay environment, seepage flow paths can be identified by detecting edges where the conductivity changes. If the water pathway is less conductive compared to the clay, electric current will bunch up around the edge because it prefers to flow in the more conductive medium. Besides this gathering effect around the edges, the change in electric current flow direction also reveals a feature's edges, as demonstrated in Figure 6. More often than not, seepage flow is bounded on all sides; therefore, electric current will concentrate around the seep if not within it and flow horizontally along the seepage pathway. As a result, the zone of highest transport porosity or highest hydraulic conductivity is identified.

Data Analysis Improvements

Improvements made over the past few years to the Method's data analysis and modeling. In 2009, interpretations were based primarily on the magnetic field contour map (such as that shown in Figure 7). Basic corrections were applied to account for magnetic field drift and differences between instruments (Kofoed et al., 2011). Also, circuit wire and electrode effects were removed from the data. However, many surveys were performed in environments where subsurface electric current flow was more homogenous than heterogeneous. As a result, it was determined that the degree of heterogeneity would be a better metric to resolve preferential electric current flow.

As an example to show and explain the improvements made to the Method, figures from a seepage case study will be presented and explained in the context of improving the accuracy of the Methodology. The case study is a large dam built on karst topography. Springs and wet areas have been observed downstream and grouting operations have been used to cut off the flow of water. This particular seep was passing under the earthen embankment part of the dam. It was surveyed, analyzed and modeled with the old procedures, and just recently remodeled and reinterpreted with the new procedures.

The magnetic field contour map presented in Figure 7 was used as a basis to model and interpret seepage flow before 2009. In this example, two seep paths were located and their depth estimated near the bedrock interface. The new modeling and interpretation methods confirmed that the old interpretation was indeed fairly accurate, but it also provided a more clear and confident picture of the problem in less time. The success of the old interpretation was attributed to the fairly high degree of heterogeneity (in the electrical sense). When surveys are more homogeneous, the new procedures become a much more critical element in producing an accurate and detailed interpretation.

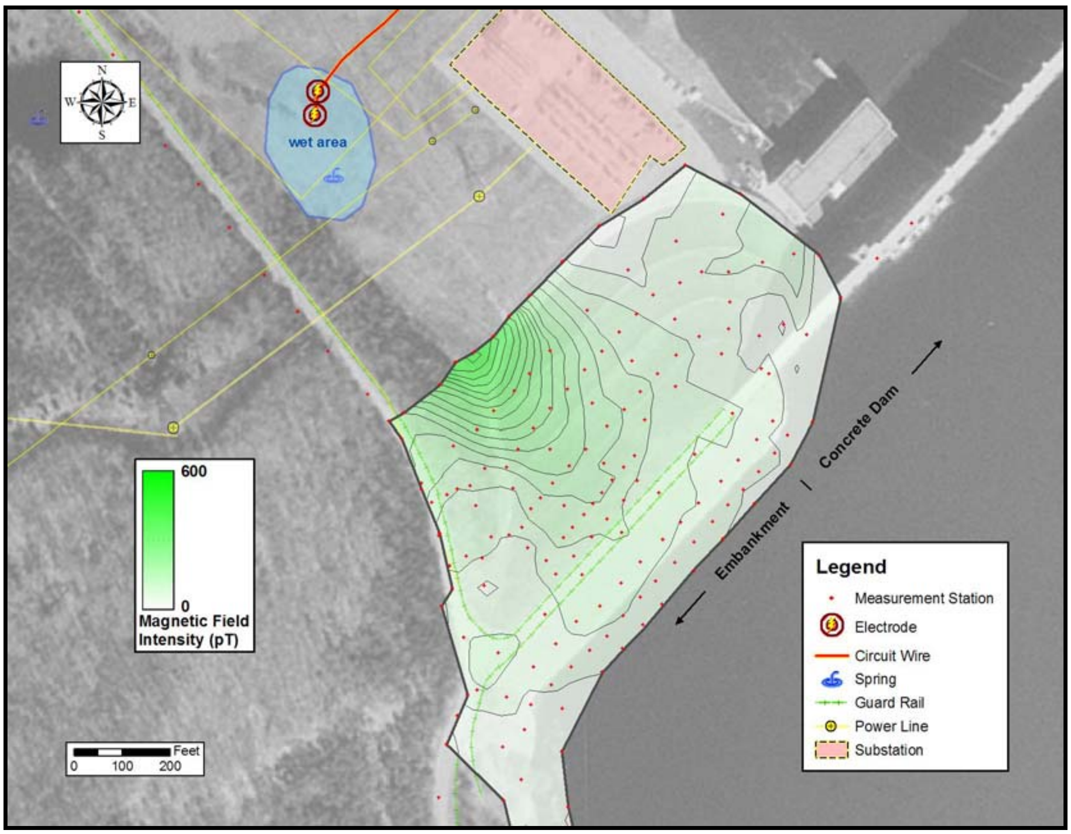

Figure 7: Example Magnetic Field Map for a Seepage Investigation (Old Way)

Predicted Field Model and Topographic Correction

To more accurately identify areas of greater or lesser conductivity, a model was created which predicts the magnetic field response expected at each measurement station given the position of the circuit wire, electrodes, and topographic changes. The model usually assumes an electrically homogeneous or uniform subsurface environment. The magnetic field generated from a uniform subsurface environment is calculated based on the Biot-Savart Law (Edwards and Nabighian, 1991).

The predicted magnetic field (Figure 8) is smooth and has fewer contour lines when compared to the magnetic field map in Figure 7. In this example the dam is quite tall and the measurement stations are high above most of the subsurface electric current flow. This is the reason for the broad contours and low amplitude observed in the predicted field.

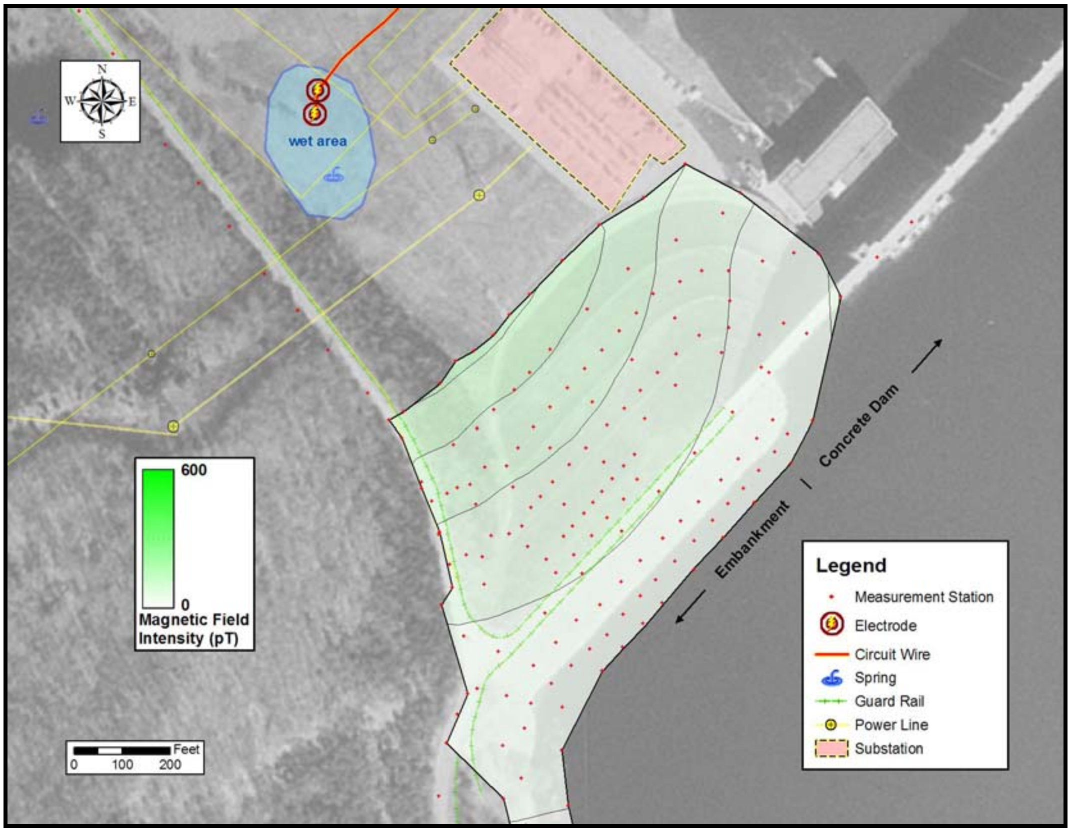

Figure 8: Example Predicted Magnetic Field Map

The predicted magnetic field model is an important tool that helps to emphasize subsurface heterogeneity by removing the "background" or effect of the homogeneous electric current flow between the electrodes and along the circuit wire. A comparison of the original survey data with the predicted magnetic field model is then performed and the results are presented in a Ratio Response Map.

Ratio Response Map

To better distinguish areas of greater or lesser conductivity through the subsurface study area, the observed magnetic field map (Figure 7) is compared to the predicted magnetic field model (Figure 8), to create the Ratio Response Map (Figure 9). The Ratio Response Map removes the effect of electric current bias and the resulting magnetic field due to the circuit wire and electrode positions, thereby highlighting areas of greater or lesser magnetic field intensity due to the subsurface electric current flow distribution.

Interpretation of the ratio response map involves noting patterns in the contours, regions of high and low magnetic field intensity and drawing connections between anomalies.

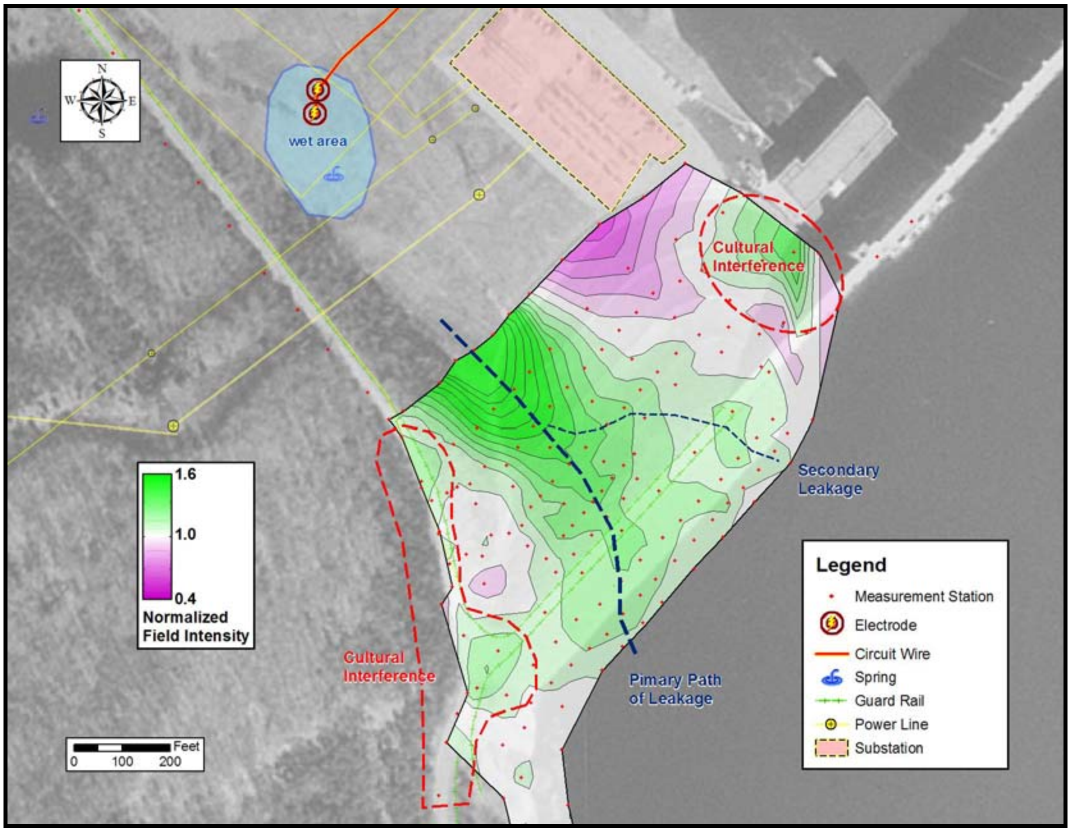

Figure 9: Example Ratio Response Map and 2D interpretation of seepage flow paths (New Way)

In Figure 9, there are two noticeable ridges that extend away from the electrodes (indicated by dashed lines and labeled leakage paths). These highly anomalous regions are preferential electric current flow paths most likely related to seepage below the dam. If the horizontal location of seepage flow is all that is required, then this cursory 2D interpretation may be sufficient to provide an accurate location of seepage flow. To obtain the depth and a more advanced delineation of the position of preferential flow paths, an inversion model is used to calculate the subsurface electric current distribution.

Electric Current Distribution Modeling by Inversion

The magnetic field map, predicted magnetic field map, and Ratio Response Map are provided to identify preferential electric current flow from a "map view" perspective. To better characterize the preferential pathways in three dimensions (3D), two modeling methodologies based on the Biot-Savart relationship have been developed. The new and primary modeling methodology utilizes a robust and powerful inversion method to produce a subsurface Electric Current Distribution (ECD) model. The second method is called Electric Current Flow or ECF modeling because it uses discreet channels or ribbons of electric current to simulate the observed magnetic field at the earth's surface. These channels represent paths where electric current concentrates strongly in the subsurface (Kofoed et al., 2011). It was the ECF model that was used exclusively before 2009 and to previously model the example case study. The ECF model uses the same path as the 2D interpretation (Figure 9) but provides an estimate of depth. The primary leakage path is estimated to pass under the crest of the dam near the bedrock interface about 50 m deep.

In 2011, an ECD inversion model was used to refine the interpretation of seepage through this earthen embankment. This model partitions the subsurface into very small cubes and calculates electric current density for each cube by the iterative conjugate gradient method of inversion with re-weighted optimizations for weighted parameters. Also the parameters are transformed into a logarithmic space during inversion as a technique to naturally enforce certain boundary conditions. Figures 10 and 11 portray horizontal and vertical slices, respectively, through the ECD inversion model.

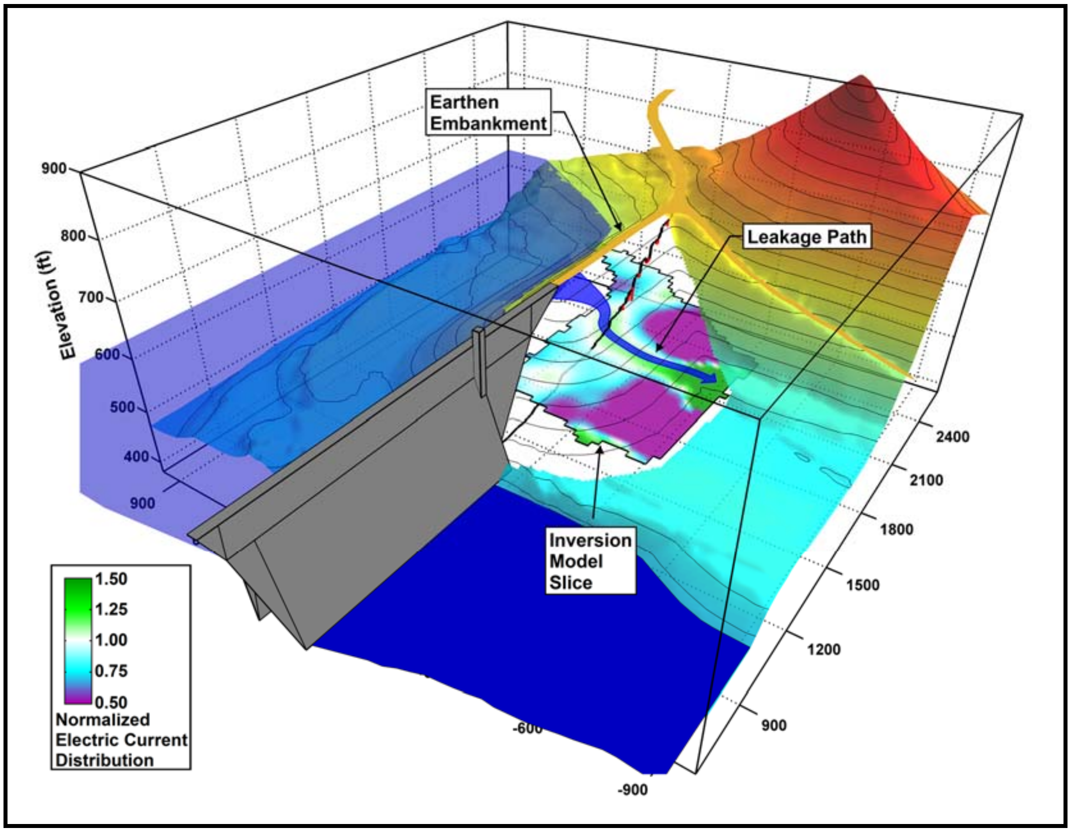

Figure 10: Example of Horizontal Slice through an ECD Inversion Model

It is important to note here that because all the data is collected on the surface, the ECD inversion model always casts a downward “shadow” below an area where higher electric current flow (green shading) is detected. The effect is like shining a flashlight from above on a dark subsurface. Therefore, a preferential flow path can be discovered by the sharp transition from purple to green, or in this case where that transition is elevated above the bedrock. This important location is highlighted by the blue circle marked in Figure 11 the “Zone of leakage.” The strong green anomaly on the upper right side, and the one along the left side, can both be dismissed as they are caused by near-surface conductive culture.

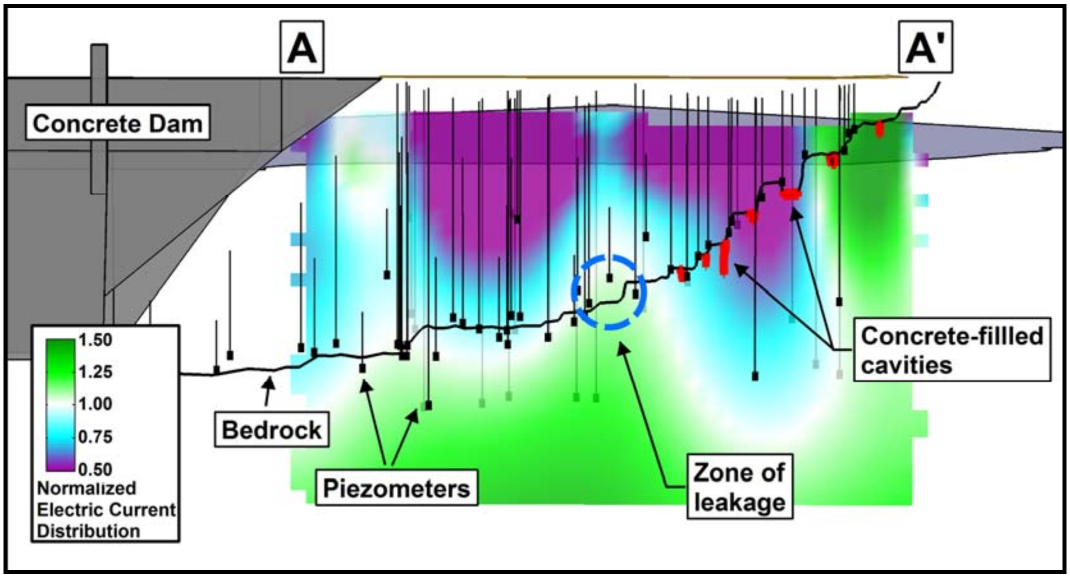

Figure 11: Example ECD Model Vertical Slice along the Crest of the Embankment

While the ECF and ECD models led to very similar conclusions in this study, the ECD model is an improved and robust modeling process. Like the ECF model, it indicated the primary flow path depth to be near the bedrock contact, but the ECD inversion is based on statistical guidance and not trial-and-error to find a best-fit solution to the data. In comparison to the ECF model, the ECD model is a more unique solution because of the added constraints the inversion algorithm imposes to calculate the electric current distribution. Also the ECD model reduces the modeling time and effort significantly.

Conclusions

The “Zone of leakage” is significant in this example because the bedrock dips suddenly in this area. Some cavities were filled with concrete at the time the dam was constructed (see red lines in Figure 11), but it is possible that a cavity was missed where the bedrock dips sharply in the “Zone of leakage”. Most of the monitoring piezometers shown in Figure 11 are located near the dam’s core, but of all these, it is important to note that they missed the “Zone of Leakage”. The one piezometer that appears to be in the right place is actually located on the embankment’s downstream side—some distance away from the core. This piezometer might still have intercepted the leak if it had been placed deeper into bedrock. With the results of this survey, piezometers can now be placed directly in the seep path and remediation operations can be targeted at the “Zone of Leakage.” This now limits the scope of work considerably, provides clear intelligence on the location of the problem, and saves the owner both time and significant money. Many other examples can be cited where superior intelligence, provided by the Methodology, has shown where to monitor and remediate seepage, such as the case studies presented in Kofoed et al. (2011).

Modeling the subsurface electric current flow distribution is a powerful tool for characterizing groundwater flow paths in most geologic settings and is based upon widely known and accepted scientific theory and principles. Proper data interpretation requires an understanding of site geology, groundwater physical principles, electromagnetic theory and experience working with and developing the Methodology. A great deal of effort has been put forth to improve the data collection, data reduction/normalization, modeling and interpretive process.

The Willowstick methodology is a quick, cost effective and accurate way to gain an understanding of the characterization of groundwater conditions. The Method is viewed as a means to guide and direct traditional exploratory work such as drilling campaigns to improve seepage characterization efficiencies (cost and time) and to arrive at conclusive answers about specific seepage issues.

Acknowledgments

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