Using Innovative Geophysical Techniques to Characterize Abandoned Mine Workings and Mine Water

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Abstract

Mine operators and consultants play a crucial role in the management of abandoned mine water and drainage systems, which can have significant impacts on waterbodies and the surrounding environment. These systems are often complex and difficult to characterize due to subsurface hydrogeologic complexity and a lack of historical data. Traditional approaches to water treatment, such as mine water treatment schemes, can be costly and may not address the root cause of contamination. As a result, there is a need for more accurate and comprehensive methods for assessing and understanding abandoned mine water and drainage systems. This paper describes two innovative geophysical techniques by case studies and how they enabled characterization of abandoned mine workings and mine water.

Keywords: Geophysics, seismic, groundwater, 3D modeling

Introduction

In recent years, innovative geophysical techniques have been developed to provide a more detailed understanding of mine water flow and identify potential sources of pollution. One such technique is Micro Seismic Resonance (MSR), which can identify locations of geologic, lithologic, and structural anomalies as well as stratigraphic units; assisting in the holistic understanding of an abandoned mining complex. MSR works by detecting structural weakness in rocks by measuring the resonance intensity and thus can also locate weak or fractured zones of high permeability. Another technique, Willowstick magneto-metric resistivity, is able to map and model groundwater flow paths and patterns through abandoned mine workings in three dimensions.

In our work, we have employed these innovative techniques in two case studies to assess groundwater conditions in abandoned adits and interconnected mine workings. The results of these studies have provided valuable insights into how and where water preferentially infiltrates the underground mine workings. By combining the results of the MSR and Willowstick techniques, Willowstick is able to help clients identify locations of potential contamination and develop a comprehensive model of groundwater flow through the mine workings. Holistic modeling and interpretation allow for the implementation of targeted remediation measures and the rehabilitation of the site, reducing the potential for ongoing water pollution.

The use of innovative geophysical techniques has significant implications for the management of abandoned mine water and drainage systems. By providing a more accurate and comprehensive understanding of these systems, mine operators and consultants can take targeted remediation efforts to reduce the long-term costs of traditional water treatment approaches and protect waterbodies and the surrounding environment from potential pollution pathways. Our work is an example of the potential of these techniques to improve the management of abandoned mine water and drainage systems and reduce their impact on the environment.

Non-Intrusive Investigative Geophysical Techniques

This paper describes two geophysical techniques. The MSR method is a passive seismic technique which detects structural weaknesses in soil and rock and is apt at locating zones of higher permeability. The constant cycle of tidal motion that affects the oceans, resulting in high and low tides twice a day, is common knowledge. It is a well-established fact that the moon and sun drive these ocean-tidal events. A lesser-known fact is that there are tidal movements in the earth's crust as a result of these same gravitation forces. Earth tides fluctuate between 15 cm (6 inches) and 45 cm (18 inches) a day depending on the location on the earth's surface and the position of the sun, moon and earth in relation to one another. As a result, it is now an established fact the ground below our feet is constantly in motion—rising and falling on a continuous 12-hour cycle. Although we cannot feel the earth's movement (other than during relatively large seismic events—i.e., earthquakes and tremors), it is only detectable with sophisticated and sensitive equipment. Movement of 15 to 45 cm (6 to 18 inches) a day may seem minor in comparison to the earth's diameter; nevertheless, when considering there are hundreds of meters (thousands of feet) of rock and soil beneath our feet in constant motion, we can start to appreciate the magnitude of this geologic fact.

Over time, stresses build in the earth's crust from the repeated rising and falling of the earth's crust until stress release points or zones are established along faults and fractures in rock formations and along zones of secondary permeability in soil formations. As the earth moves, frictional grinding takes place. This grinding creates a resonance signal. The movement and grinding of the earth's crust in conjunction with groundwater naturally collecting in these areas produce resonance signals that can be measured and modeled to identify zones of higher permeability in the rock and soil matrix. MSR measurements, which identify active resonance signals with high resonance frequencies within the resonance frequency domain, indicate that the stress relief point is near the surface. Lower resonance frequencies (within the resonance frequency domain) indicate a deeper anomalous zone. Thus, the zones of highest structural weaknesses within the alluvium and rock matrix can be identified beneath the earth/s surface.

This technique is compact and easily deployable, and 2D acoustic profiles showing strengths or weaknesses of the underlying stratigraphy can be produced rapidly in the field (see Figure 1). 3D modeling is also provided to show pertinent site features in relation to subsurface features and anomalous zones, 3D site models of the subsurface are created to serve as helpful tools in the interpretation and presentation of the results.

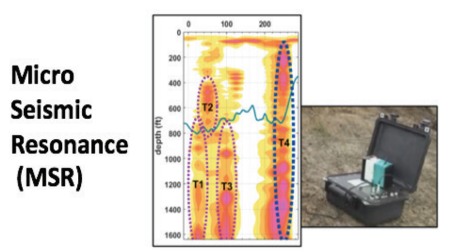


Figure 1 *MSR Equipment & Stratigraphy Profile*

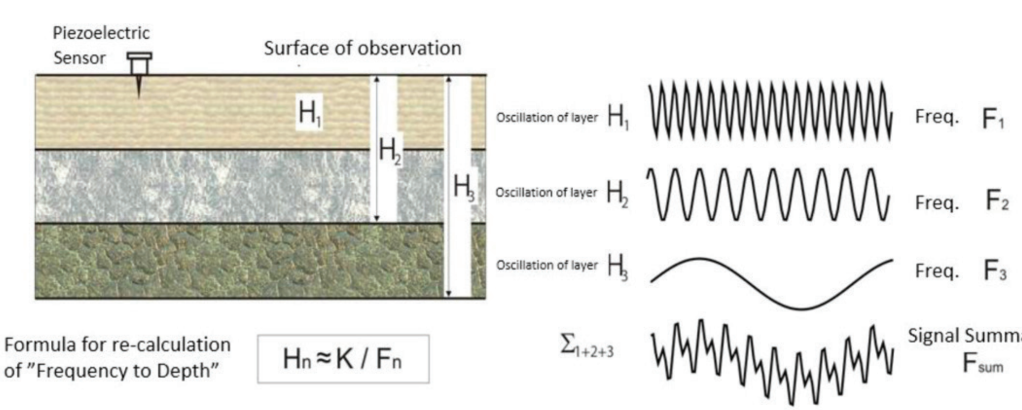
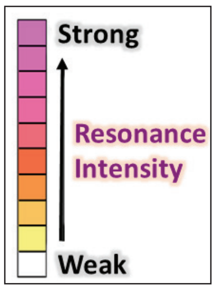


Figure 2 MSR Measurement and Data Collection Illustration

Full analysis and detailed 3D models can be produced within days of collecting the data.

The MSR measurements are conducted by utilizing two types of sensors: a spike geophone piezoelectric sensor for soils or a flat sensor for hard surface or rock. MSR surveys do not require bulk source excitation (sledgehammer) or vibration machines, explosives, etc. The method is easily deployed and non-destructive, falling under the sub-category of passive seismics with the exception of a tap on the ground next to the sensor to trigger the data collection (see Figure 2).



In the MSR profiles, we provide a Resonance Intensity Indicator. The white to yellow colors indicate a relatively competent soil or rock formation (i.e., void of any anomalous features that would indicate a weakness—stress relief point or permeable zone within the alluvium/rock matrix). The orange to pink colors, going up the scale, represent higher degrees of signal strength—strong pink zones representing the strongest signal or more permeable zones.

The Resonance Intensity Indicator does not provide any measurement of the geo-mechanical properties of the soil or rock matrix (i.e., strength, consolidation, shrinkage, swell, permeability, particle analysis, etc.). The Resonance Intensity Indicator simply reflects a relative comparison of where resonance signals are stronger or weaker. Based on our experience, resonance rich measurements (producing strong resonance signals) have proven to be helpful in identifying weak and permeable zones in the soil and rock matrix (i.e., faulting and fractures in rock formations and increased secondary permeability in alluvium formations).

The Willowstick magneto-metric resistivity technique uses a low voltage, low amperage, alternating electrical current to energize subsurface water by electrodes placed strategically upgradient and downgradient of the study area and an electrical circuit is established between the two electrodes (Figure 1).

The application of the technique to mine water is based on the principle that water increases the conductivity of earthen materials through which it flows. As the signature electric current travels between electrodes strategically placed upstream and downstream of the mine water, it concentrates in the more conductive zones, or highest transport porosity areas. Measuring the resultant magnetic field at the surface reveals the electric current flow and distribution. Data is processed and compared to a predicted magnetic field from a theoretical homogenous earth model to highlight deviations from the

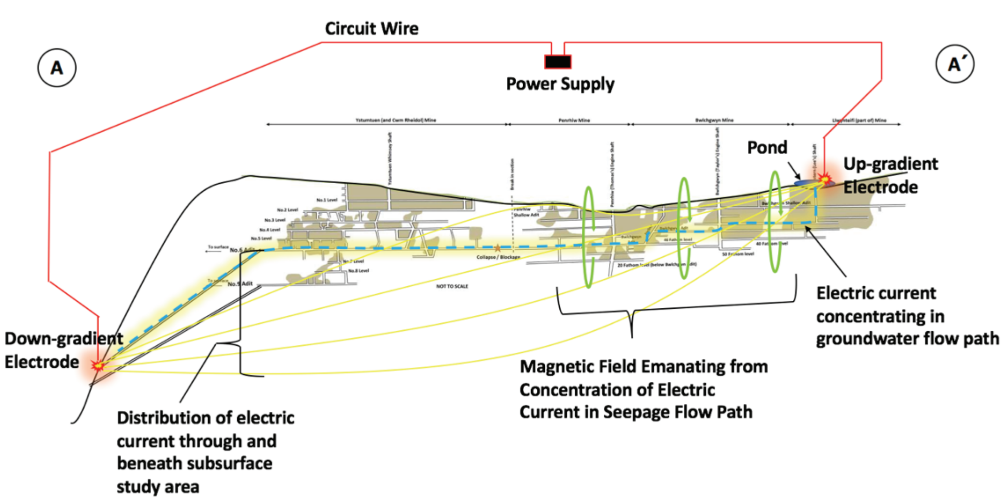


Figure 3 Cross-sectional Schematic of Willowstick Technique at Abandoned Mine

"uniform" model. 3D models are generated and combined with known sub-surface data to enhance preferential seepage path definitions. The technique maps and models preferential groundwater flow paths like an angiogram that lets doctors to "see" blood vessels in a human body.

This paper, through three tailings dam studies, illustrates the procedures, findings and benefits of this technology. Results range from confirmation of design decisions to identifying new seepage paths. In the latter case, the designs are now being updated based on the new information to provide a more safe and stable tailings dam and reduce the risk of failure.

Mine Water Case Study

A close-up aerial photograph of an earthen dam with a grout curtain is shown in Figure 5. The dam was currently under construction at the time of the investigation. The dam consisted of a bedrock grout curtain (see red vertical line), a cement-bentonite (CB) slurry wall with vibro-compacted gravel zones on both sides of the grout curtain on top of native gravels. It should be mentioned that the CB slurry wall failed to reach bedrock in some locations due to very dense gravelly material, leaving a gap between the red and green lines.

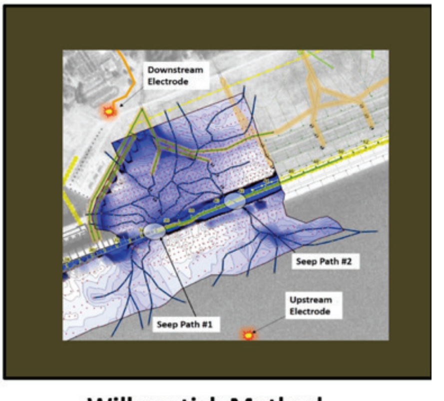
A longitudinal profile drawing of the dam's grout curtain is shown in Figure 6. The drawing represents the completion of the grout curtain prior to the investigation. The brown line identifies the top of bedrock. The blue line identifies the top of native gravels.

While constructing the grout curtain, unexpected grout takes occurred—more specifically in the center area of the grout curtain. Before completing grout work (which was nearing completion), the owner wanted to identify any potential weaknesses where seepage could possibly escape the impoundment through, beneath or around the grout curtain. Therefore, the purpose of the investigation was to identify, map and model preferential electric current flow paths and patterns that indicate high-probability pathways for seepage to follow as electric current was biased to flow through, beneath and around the grout curtain (i.e., the Willowstick Method). The investigation also included a MSR survey to detect structural weaknesses in the soil/rock matrix to identify any potential weaknesses or fractured zones of high permeability through the fill and foundation materials. Therefore, the overall intent of the investigation was to identify areas that warrant additional grouting while the grouting contractor was still on site.

The Willowstick Method identified two preferential electric current flow paths through the dam's existing grout curtain (see Figure 7).

In Figure 7, the green shading represents areas where the signature electric current density is more concentrated than expected. On the other end of the scale, the dark-purple shading identifies areas where electric current

Angiogram



Willowstick Method

__Figure 4__ Angiogram / Willowstick Comparison

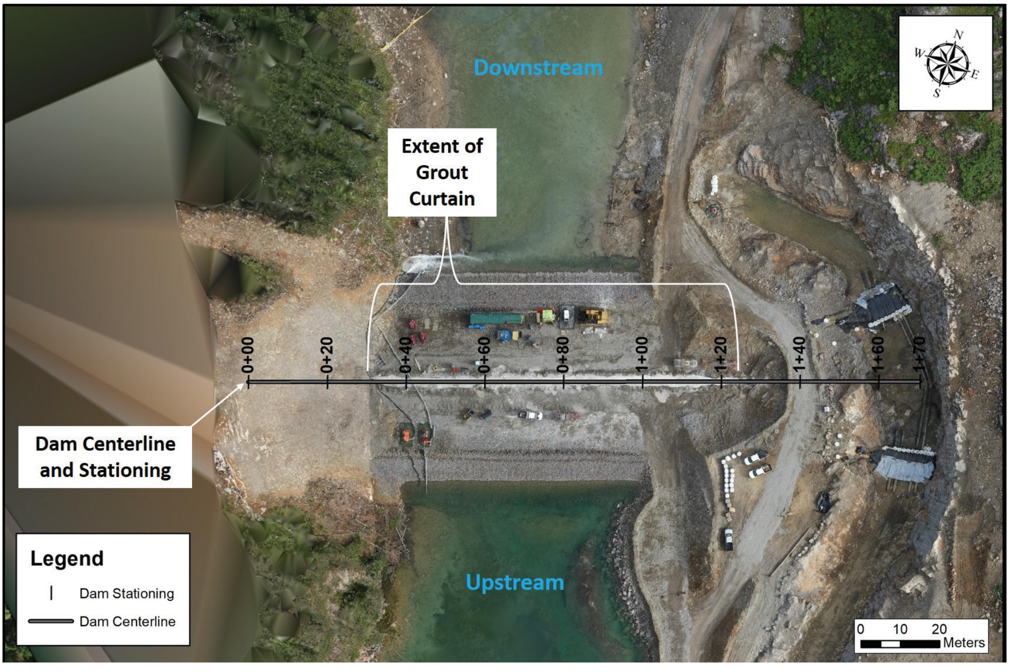


Figure 5 *Site Map of Dam w/ Mine Water*

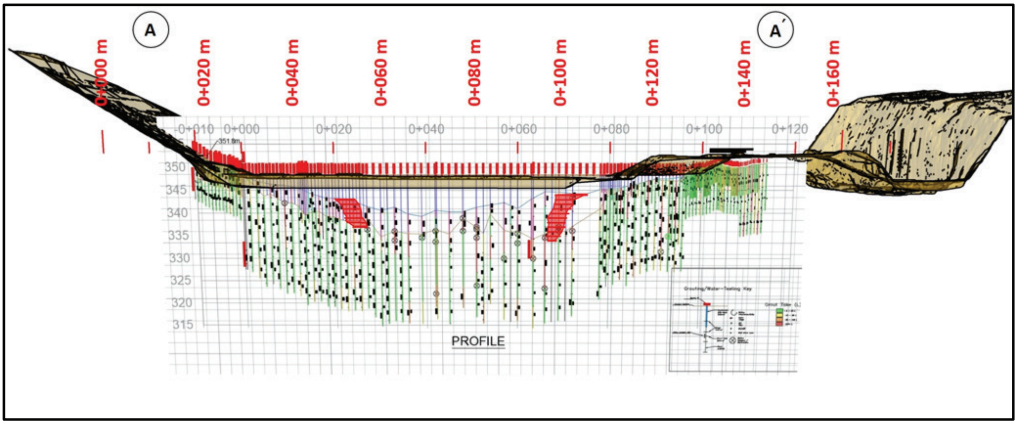


Figure 6 *Longitudinal Profile As-built Drawing of Grout Curtain*

is less concentrated. The yellow arrows highlight the more intense locations where the signature electric current preferentially concentrates as it escapes the impoundment – interpreted as following along preferential seepage flow paths.

To describe the depths of the seepage flow paths, Figure 8 (Section A–A´) presents a longitudinal profile slice of the electric current distribution model taken directly beneath the center axis of the dam—looking downstream through the embankment and grout curtain.

To further describe the location of the electrically conductive flow paths, Figure 6 presents Section A–A´ (i.e., the same view as shown in Figure 8, but with the ECD model slice turned "off"). The red hatched horizontal lines remain to show the position of the preferential flow of electric current in

Figure 7 *Willowstick Method Results (Plan View)*

relation to the grout curtain, bedrock surface, native gravels and earthen embankment fill interface. The brown line identifies the top of the bedrock. The blue line identifies the top of native gravels. The preferential flow of electric current (red hatched area) is located above the bedrock surface in native gravels and below the embankment fill.

The MSR results revealed several weak areas at or just below the bedrock surface with a few deeper anomalous features noted (i.e., representing possible fracture or faulted zones – see Figure 9). Please know that the MSR line shown in Figure 9 is taken upstream of Section A–A´ (center axis of dam roughly 4 m).

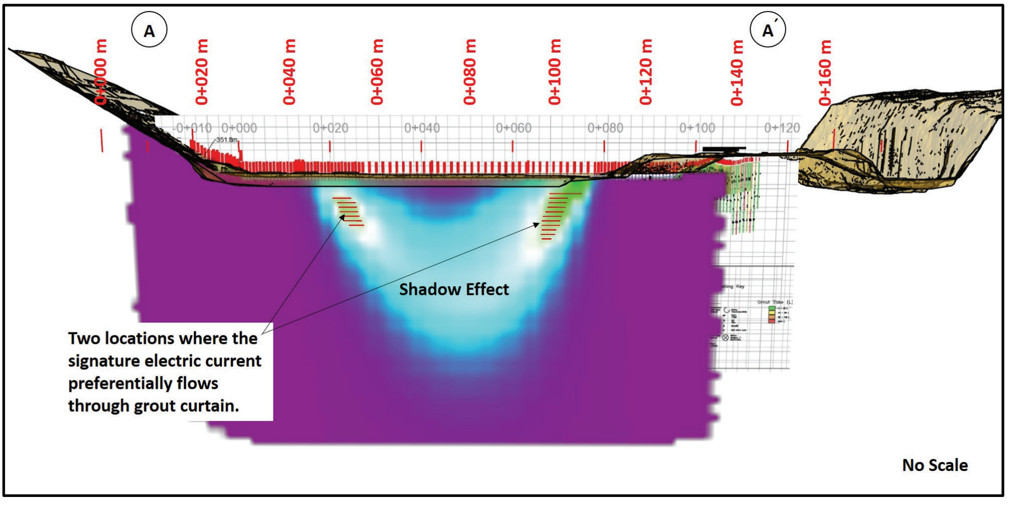


Figure 8 *ECD Model Slice Section A–A´*

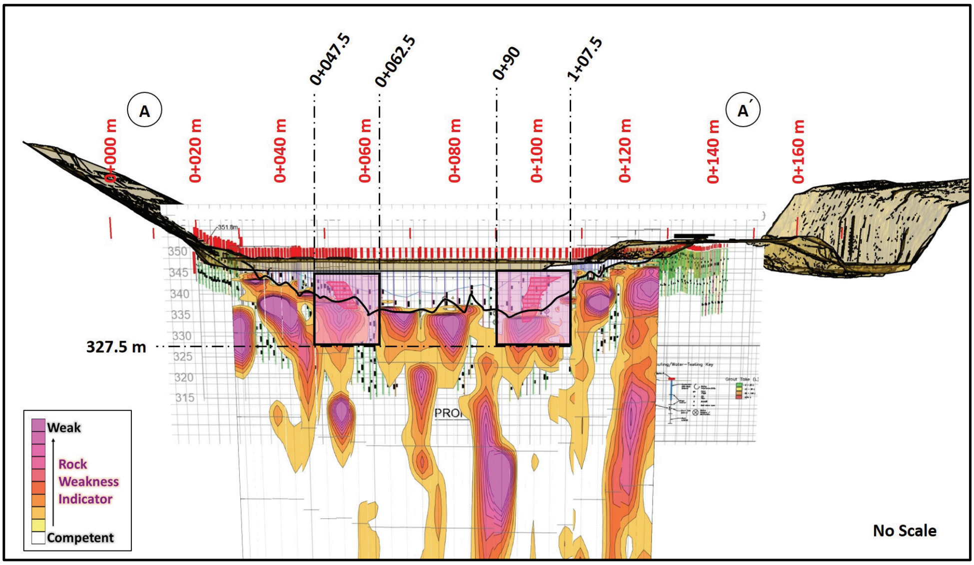


Figure 9 *Willowstick Method Results (Plan View)*

In Figure 9, the transparency (white shaded areas) on the MSR profile indicates competent soil and rock. The yellow to orange to pink shading, going up the scale, represents higher degrees of soil/rock weakness—strong pink shading representing the weakest, highly fractured or weathered and permeable zones. The anomalous vertical features identify what is interpreted as deeper fractures. The bedrock grout curtain appears to extend down through the weathered zone.

During a conference call with the owner and grout contractor, wherein the preliminary results of the investigation were presented, the grouting contractor revealed that unexpected grout takes occurred in the center of the grout curtain. Based on the results of the Willowstick and MSR techniques in conjunction with known grout takes, weaknesses were found in the native gravel layer on either side of the center area of the grout curtain. Target locations were recommended for additional grout work to reduce potential seepage out of the impoundment. These locations are represented by the pink rectangular windows shown in Figure 9.

The investigation confirmed that the grout has filled voids in the weathered bedrock and porous zones in the native gravel layer; however, on either side of this area, it appears more grout was needed to minimize seepage. The fact that both techniques identified common anomalous features and patterns (which use entirely different scientific principles) provides a great deal of confidence in the results of the investigation.

Conclusions

The case study shows how non-intrusive techniques can be used to supplement known geological, geotechnical, hydrological and groundwater information to enhance the knowledge of existing mine water and mine workings conditions. This knowledge can then be used to cost-effectively support the remediation efforts and to provide long-term safety and stability for abandoned mine water and drainage systems.

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