# CONDUCTING A SUCCESSFUL GEOPHYSICAL CAMPAIGN: BENEFITS, GUIDELINES AND PITFALLS

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## ABSTRACT

*Geophysical surveys play a key part in dam safety investigations and engineering design. Combined to modern monitoring tools, the use of geophysics can reduce construction and maintenance costs and help avoid unforeseen events. However, these tools are frequently overlooked or misused. Moreover, existing geophysical data is sometimes undervalued or wrongfully dismissed. The current paper identifies potential pitfalls that can lead to an unsuccessful geophysical program. We discuss how to plan a proper geophysical campaign according to different engineering, design and monitoring needs and challenges. We also present current technological advances in applied geophysics. Finally, we discuss a few case studies showing the potential of modern geophysics to dam safety investigations.*

## 1. INTRODUCTION

Conducting high resolution geophysical surveys for surficial or shallow investigations can provide a very useful tool for geological, geotechnical, environmental and hydrogeological studies in the course of large infrastructure projects. Historically, geophysical methods have always been an integral part of dam safety investigations and with the increase of risk assessment of aging infrastructure around the world, combined with the increasing costs of maintenance and remediation, it is foreseeable that geophysics will play a bigger role in dam monitoring in the future.

Conventional geophysical methods such as seismic refraction, Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) are widely used for geotechnical investigations, but in some cases, these tools are overlooked or misused, and proper geophysical assessment of dam structures is inexistent or incomplete. In order to optimize these methods, proper survey planning needs to be done and site-specific limitations, conditions and potential pitfalls must be identified. The following sections will present the benefits from using geophysical methods, frequent pitfalls observed in the use of geophysics for infrastructure projects, proper survey planning guidelines to avoid these pitfalls, recent advances in applied geophysics for dam investigations and some case studies of successful geophysical programs. The purpose of this paper is to present general guidelines for successful survey campaigns and will not focus on method specifics, but rather discuss a more global assessment on the use of geophysics.

## 2. BENEFITS FROM GEOPHYSICAL IVESTIGATIONS

There are number of reasons why geophysical methods can be used for dam safety investigations and monitoring. They bring complimentary data that cannot be provided by conventional geotechnical or geological investigations. More so, geophysical methods are non-invasive and, in most cases, highly efficient and cost effective. Also, geophysics will allow enhanced data coverage and supplement conventional monitoring methods. A well planned and well executed geophysical program will bring added value to a project and this value will by far exceed the expenses incurred by geophysics.

## 3. FREQUENT PITFALLS

### 3.1 Client expectations and knowledge of geophysics

More often than not, dam owners have limited knowledge of geophysics and its applications. In many cases, Client expectations will be greater than what geophysics can provide. When exposed to commercial presentations and product information leaflets, a person with limited knowledge in geophysics will remember the applications that are put forward (e.g. Ground Penetrating Radar detects voids) but will not necessarily be presented with the limitations of the methods. Therefore, it is important to provide the proper information on these limitations when proposing geophysical methods. On rare occasions, a dam owner can even be presented with misinformation about geophysics in order to advantage other solutions. Commonly, misconceptions are encountered in the areas of target identification, target resolution, and depth of investigation.

### 3.2 Poor communication between parties involved

In some cases, poor communication between the geophysical contractor, the geotechnical advisor, site operations and the site owner can lead to situations that will have negative outcomes to the project. In addition to unmet expectations, as stated in the previous section, lack of proper communication will have direct incidence on the success of field operations and avoid frustrating situations for all the parties involved.

### 3.3 Predefined investigation programs

Geophysical contractors are frequently presented with rigid investigation programs that are already set with specific geophysical methods, equipment makes and specifications, data quantities, sampling parameters, etc. In some cases, these work orders are based on old projects that were carried out with similar parameters and were not necessarily analyzed in regard to project specific objectives and challenges. They can include obsolete equipment, inadequate survey planning or even geophysical methods that are not optimal for the purpose of the project. It is recommended that dam site geophysical investigation programs focus on the objectives of the project rather that on specific geophysical methods. More so, Request for Proposal (RFP's) documents should allow latitude to the geophysical contractors to propose alternative methods or work programs if they believe that this could be beneficiary to the project objectives. In some cases, this could lead to better results and more cost-effective investigations.

### 3.4 Lack of account of method limitations

One of the principal reasons of unsuccessful geophysical programs is the lack of account of method limitations. This can lead to frustrating and costly experiences, considering that most dam sites are located in remote areas requiring special logistics to carry out the projects. "Go-to" methods such as seismic refraction and ERT are often used because the limitations are well known and somewhat easy to overcome. However, methods such as GPR and Self Potential (SP) are "high-risk" if their limitations are not taken into account in the survey planning and field operations. In order to reduce the risk attached to specific method limitations, it is frequently recommended that a geophysical investigation program includes more than one geophysical method, unless the objectives are very specific, so the results are somewhat guaranteed.

### 3.5 Site specific challenges

Site specific challenges must be considered for a successful geophysical campaign. These may have an impact in the field data collection operations and/or the collected data interpretation. These are numerous and will vary according to topography, geology, seasons/weather, vegetation, water current, temperature and atmospheric and ionospheric activity.

In addition to these natural considerations, one has to take into account the presence of man-made infrastructure which may affect the survey procedure and/or the data collected. Examples of these include the presence of power lines, buried infrastructure, buildings, stations, etc. When working near or on a dam, the geometry of the structure will have direct impact on wave propagation and may invalidate the theoretical assumptions of the geophysical methods in use.

Finally, work site constraints such as work teams scheduling, ongoing site operations and traffic, health and safety procedures, access and site supervision are all items that can delay the data acquisition or directly affect the data quality. These constraints can be minimized with good communication between actors and proper planning of the surveys.

Lack of account of unfavorable site conditions can result in an unsuccessful geophysical investigation program. The results of such program are expected to influence decision making and the lack of quality results can bring unexpected delays, force additional investigations and increased costs to achieve the desired project objectives.

### 3.6 The place of geophysics in a project's lifespan

In many cases, geophysics is used in a reactive manner, in order to asses a punctual problem that needs rapid attention (e.g. locate a void). Notwithstanding the usefulness of such approach in numerous occasions, geophysics brings a greater return on investment when it is part of a well-organized and structured assessment program. Therefore, the use of geophysics needs to be included upstream of an investigation program, such as in preliminary geotechnical investigations or as part of a yearly dam safety evaluation program. Table 1 shows the average reclamation depending on the type and quantity of field data gathered in the investigation process. This data clearly shows that the use of geophysics before the design phase greatly reduced the risk of the project. Moreover, geophysics can play an important role at any moment in a project's lifespan, including post-construction monitoring for maintenance programs.

### 3.7 Poor survey planning, management and follow-up

Poor survey planning will lead to poor results. During the planning phase of a geophysical program, many aspects, such as the proper geophysical method, line locations, reliable equipment, data sapling, need to be considered to conduct a successful project. Other logistical decisions during planning, such as the type and number of resources deployed, the time frame attributed for the data collection and the period needed for the interpretation of the data can induce problems as the project goes along.

**Table 1** : The number of officially reported plague cases in the world.

| Type of information provided to contractors | Average reclamation value / Contract value |
|---|---|
| Minimal investigation no samples or test results | 15-25% |
| Sparse information (1980's standard) borelogswith limited interpretative content | 10-12% |
| Comprehensive investigation/design information& test results, no geotechnical or geophysical model | 2-2.5% |
| Comprehensive investigation/design information,detailed geotechnical and geophysical models | <0.1% |

(Kinlan, IADC Brisbane, 2014)

Once the project in underway, depending on the size of the project, a proper project management team must be in place. Geophysical contractors tend to underestimate the logistics involved in large scale projects and in some cases, the field crews lack the management support needed to carry out an optimized field program. This results in production delays, equipment failures and increased survey costs. This can compromise the end client's confidence towards geophysics and in the end, produce results that will not meet the client's expectations or the project objectives.

Finally, proper survey follow-up is also very important. Geophysical data interpretation should be revise when new data (geotechnical, hydrogeological, etc.) is available. The conceptual model of the site can therefore be reworked and improved to reflect the actual conditions of the site. Moreover, once the final reports are produced, it is important for the geophysical contractor to make sure that they are well understood by the end user and follow-up meetings or presentations should be included in the initial work program.

### 3.8 "Black box" data interpretation

Resorting to automated software interpretation algorithms can have a great influence in the quality of the data interpretation. Commercially available software packages commonly have automated picking, inversion and interpretation modules that quickly produce results that can seem reliable to the untrained eye. More so, the interpretation of these results can lead to erroneous conclusions that will guide follow up actions. In the case of dam safety assessments, this can have very serious consequences if improper actions are taken or the opposite. A proper assessment of the experience of the geophysical contractor is very important to avoid such situations.

### 3.9 Undervalued and wrongfully dismissed data

Modern geophysical surveying produces very large amounts of data. This data is used for a specific application and then stored in hard drives. In some cases, valuable data can be included in these archives that could be used to make an in-depth analysis of the geophysical data available. This can be in the form of additional geophysical interpretation or other type of analysis such as geostatistical correlations.

Good quality archived data from former geophysical campaigns can also be used and valued to reduce the scope of a new geophysical campaign and optimize data acquisition to complete the data that is already available for the site. In order for this to be possible, data need to be well organized in the archives so that other users can access the data without any problems. Finally, the arrival of new interpretation methods or software can give value to data that was previously used for other applications or dismissed.

## 4. SURVEY PLANNING

### 4.1 Introduction

As pointed out in section 3.7, proper survey planning plays a crucial role in the success of a geophysical field program. There are several elements that have be considered when planning small- and large-scale projects. The current section presents some guidelines for proper survey planning.

### 4.2 Identify the objectives

It is important to identify the objectives of the investigation campaign. This will allow to choose the best suited method or methods to achieve these objectives and to draw up the best approach to carry out the surveys. At this stage, communication between the client and the geophysical contractor should be ongoing in order to make sure that the project is designed on solid bases.

### 4.3 Gather existing data

In most cases, the site owner possesses valuable site data that can be very helpful for the geophysical survey planning. Existing site maps, satellite imagery and online street photography (when available) allows the geophysicist to visualise the conditions in which the surveys will be conducted.

Reports of former studies carried out on a site (geotechnical, geophysical, environmental, NDT) provide guidelines on what type of response to expect from the soils, bedrock and structure and the type and quality of the results that will be obtained.

It can occur that existing geophysical data can also be reinterpreted and produce interesting results that may help reduce the scope of work and costs of the current project.

### 4.4 Analyse site specific challenges

Knowing what to expect from a specific site can prevent many mishaps during the field surveys. Initial assessment of site-specific challenges can be performed by studying site maps and aerial photographs. These can be related to work site access (air, water, land), health and safety particularities, ongoing site operations that could affect data acquisition or natural features that can cause operational challenges.

Communication with site operators is very helpful at this stage of the survey planning since they will be the most suited to identify such challenges. Once these are identified, proper actions have to be taken to make sure that the standard field procedures can be followed or if new methodologies have to be thought to perform the surveys.

### 4.5 Draw up a survey methodology

Once all the necessary preliminary information is gathered, the actual survey methodology has to be established. The geophysical contractor should be included in the survey design team which will decide the methods that will be used, the location of the geophysical surveys and the density of the data. It is the geophysical contractor's duty to evaluate the time it will take to gather this data and advise the site owner for scheduling and planning.

Once the general methodology is set, more specific decisions have to be made, such as the geophysical equipment that will be needed and all the auxiliary equipment that may be required to conduct the surveys (vehicles, positioning, tools, spares, perishables, etc.). In some cases, this may require the need of subcontractors to provide some of the work, such as line cutting and surveying.

Resource planning is also important, since key personnel might be needed to conduct a specific survey or heavy manpower might be useful for certain type of work. Lack of resources will result in lower productivity, lower data quality and increased risk of health and safety events.

At this stage, all the data acquisition parameters should be known and if needed, computed survey modelling may be performed to test these parameters with known site conditions.

Finally, a key aspect before conduction the actual survey is to allow enough time for preparation before mobilising to site. Last minute equipment tests and purchases are often required. Site owners also need time to have the site ready for the geophysical contractors. Occasionally, parties involved have the tendency to rush to begin acquiring data, but this mindset can have negative outcome on the actual length of the surveys and the quality of the data.

### 4.6 Think outside of the box

Ambitious objectives and/or particular site challenges might discourage engineers to rely on geophysics to achieve the desired results. Thinking outside the box in regard to geophysical methods, survey methodology, on-site operations and interpretation techniques may allow conducting successful surveys in challenging situations. Relying on experienced geophysicists is very important to be able to propose innovative solutions and their know how should be valued accordingly.

## 5. RECENT ADVANCES IN APPLIED GEOPHYSICS

### 5.1 Improvements in geophysical equipment

Even though new generation geophysical equipment tends to appear on the market at larger time intervals than consumer electronics, some interesting advances have been released in the recent years. The fast-changing technologies that are deployed in computing and electronics might accelerate the release of ground-breaking geophysical equipment in the near future. In the meantime, some advances are worth noting.

Most of the GPR manufacturers have released new generation digital antennas with improved sampling and stacking capabilities. These High Dynamic Range (HDR) or Hyper-Stacking models allow improved signal to noise ratios, resolution and depth of penetration compared to the older generation GPR systems. Moreover, these antennas do not need as much power to produce the pulse, thus a new generation of lower frequency antennas, which disappeared from the market due to radio broadcasting regulations, are starting to be developed. Manufacturers have also included wireless technology to new GPR antennas in order to eliminate the use of a cable between the antenna and acquisition system. High frequency antennas used for concrete investigations have also seen great improvement in the resolution and depth of penetration.

Wireless technology has also been recently implemented in the fields of seismic and electrical resistivity equipment. Autonomous reception nodes now allow greater flexibility in survey design and eliminate the inconvenience of long cables that need to be deployed with conventional acquisition systems. The integration of SIM cards or Bluetooth technology to the units allow instantaneous data transfer to the end user without the need to connect the instruments to a computer via a wired connection.

Improved electronics has also allowed the introduction of high-resolution borehole imaging probes that allow unprecedented imaging, as much as 1800 radial pixels, of the borehole wall. Improved sampling also allows faster logging velocities that allow greater productivity on the field. Other advances in borehole geophysics have been made in Nuclear Magnetic Resosnance (NMR), Spectral Induced Polarisation (SIP) and slimline borehole gravity tools for rock property analysis.

New generation seabed imagery equipment now allows very detailed investigations of dam reservoirs and structural inspections. Multibeam bathymetry is now the norm and point cloud imagery gives very detailed images of the reservoir bed and of possible structural defects on dam structures. High definition real-time 3D imaging sonars produce a complete tri-dimensional imagery of the underwater environment that shows moving objects in video-like data format in low-visibility water conditions. Combined to the use of ROV's, reservoir inspections can now be performed periodically with minimal safety risks.

The use of ROV's and drones is also being more and more incorporated in geophysical surveying with higher load bearing vessels available on the market. Light sensors like magnetometers, different types of cameras and even GPR antennas can now be used to survey large areas autonomously.

The reduced cost of electronic components has also allowed the arrival on the marked of low-cost entry level geophysical systems such as engineering seismographs and resistivity meters. The occasional or small geophysical contractor can now compete on the market with units purchased at about one third of the main manufacturer's prices. In many cases, this type of equipment is sufficient for standard geophysical investigations.

## 5.2 Evolution of data interpretation programs

In recent years, data interpretation programs have been widely improved and include automated modules to help the geophysicist and optimize the processing time. Although great care has to be had in the use of this type of software to avoid the "black-box" pitfall presented in section 3.8, these tools help provide better results.

Academic research is now focusing on Artificial Intelligence (AI) and machine learning to develop new interpretation algorithms that could one day reduce the role of the geophysicist in the data interpretation process. These tools will not only allow to automate data processing but could also help to classify anomalies and geophysical images and correlate them with structural defects in civil structures. Equipment manufacturers are now hopping on the AI bandwagon and commercially available software is starting to see light of day.

## 5.3 Innovative geophysical methods

In recent years, efforts have also been deployed to develop new innovative geophysical methods for dam site investigations and other geotechnical applications. These methods were designed to provide solutions to problems that were not resolved with conventional geophysical methods.

Frequency domain analysis of seismic data has allowed many advances in data analysis. The frequency analysis of the seismic resonance phenomenon of the ground layers has brought the Hydro-TISAR method, which allows detailed structural imaging of the overburden and bedrock, similar at what can be achieved with GPR, but to depths up to 100 meters. This method, which employs similar field procedures as the seismic refraction or MASW methods with low impact energy sources, has the ability to locate small fractures in the bedrock as well as thin sedimentary layers within the overburden. The method has also been successfully used for groundwater exploration, detection of underground mine galleries and gas pockets in sedimentary deposits. In the area of dam site investigations, the method can image the internal structure on an earth dam to locate possible anomalies in the dam core.

In the field of seepage and leak detection for earth dams, controlled source audio frequency domain magnetics, commercially known as the Willowsitck or AquaTrack methods, has been successfully documented to provide an alternative to the Self Potential method. The field procedure uses a pair of electrodes that are strategically placed upstream and downstream of a dam to generate an electromagnetic field that passes through the dam. A custom magnetic sensor is used to measure the field along the area of interest and a special inversion algorithm is used to produce a normalized electric current distribution map that allows to identify potential seepage flow paths in the dam.

# 6. CASE STUDIES

## 6.1 Structural imaging of an earth dam, Quebec, Canada

Hydro-TISAR and 2D MASW surveys were carried out on a small earth dam in order to provide data for stress-deformation and dynamic stability analysis. Geophysical data was needed as a complement to geotechnical data in order to assess compacity levels through the cut-off wall and core.

The surveys were carried out along an area of interest of 220 m along the crest of the dam. This covered about one third of the structure length.

The Hydro-TISAR survey allowed to obtain a detailed image of the dam structure showing several layered features. Figure 1 shows the Hydro-TISAR profile and the structural interpretation of this image. Results indicate two structurally distinct areas along the surveyed line. The first portion of the profile (ch. 400 to 500) shows the presence of intermediate reflectors, whereas the rest of the profile suggest a more homogeneous structure. Historical borehole data indicates alternating sandy and silty materials, thus the variations in shear wave velocity. A hard till layer is present at depths of around 25 metres, corresponding to the strong reflector identified with the Hydro-TISAR method.

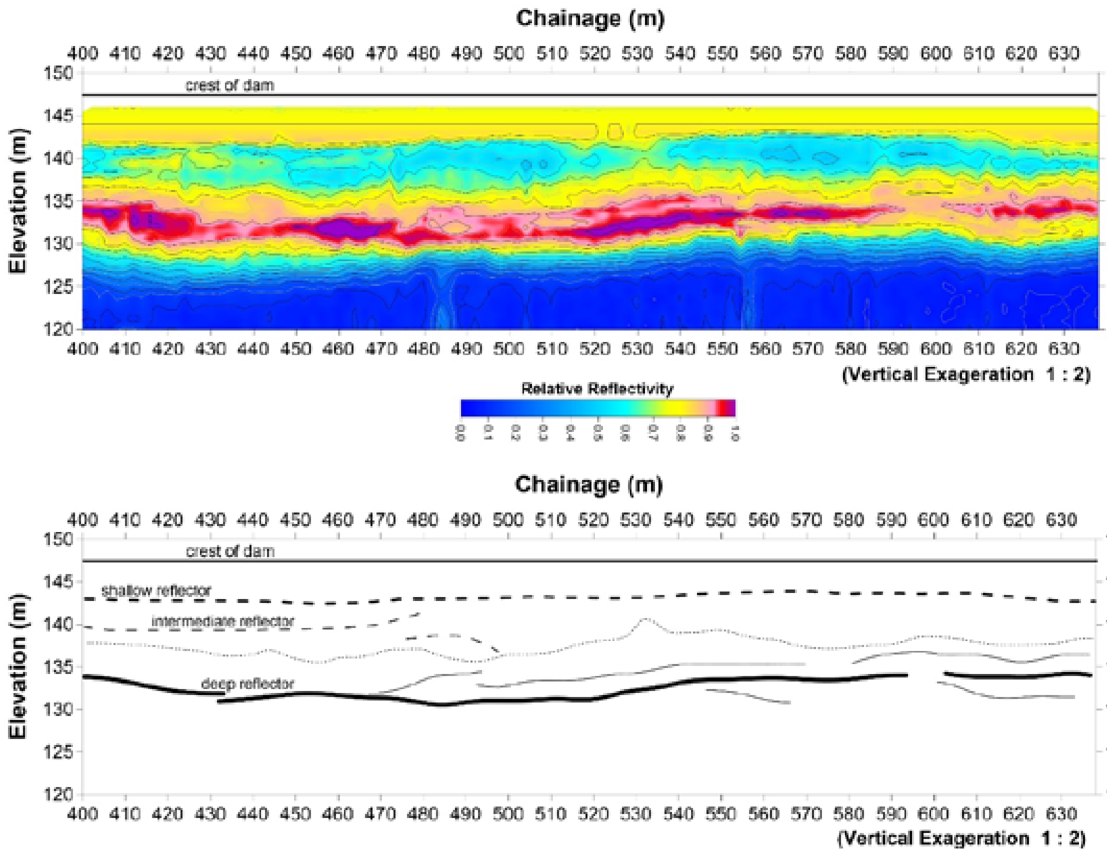


**Figure 1** : Hydro-TISAR profile and corresponding structural interpretation along the surveyed area.

Figure 2 shows the 2D-MASW profile along the same chainages. The MASW data was constrained with regard to the depth of the lithological changes shown by the Hydro-TISAR survey. This allows a more robust shear-wave velocity model since unconstrained inversions can lead to inexact shear-wave velocity calculations. If there is a discrepancy between the template and these instructions, the instructions take precedence.

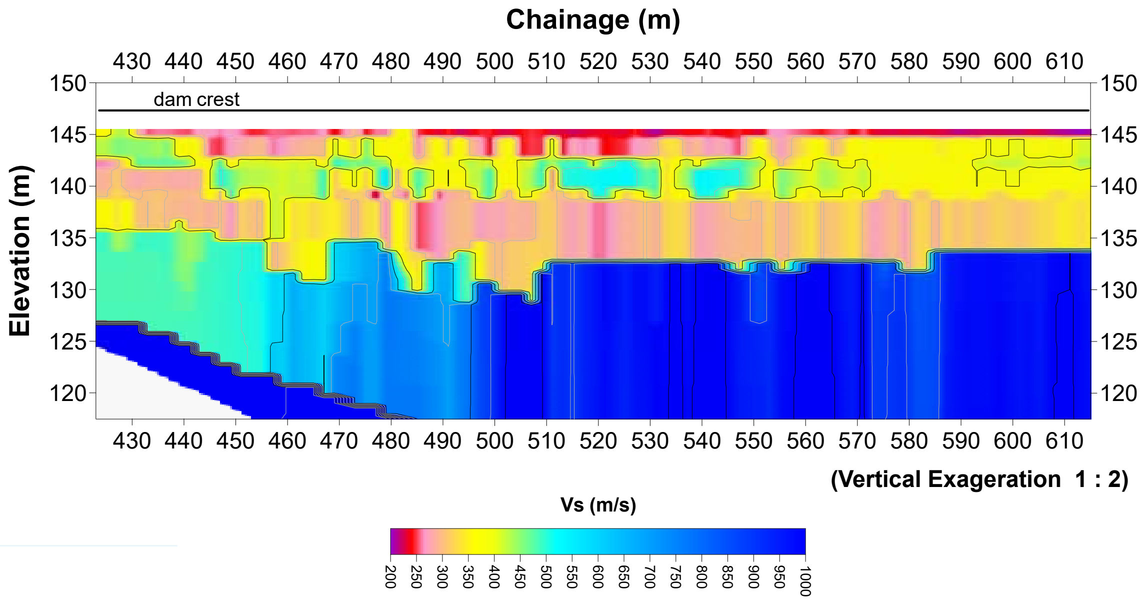


**Figure 2** : 2D-MASW section along the surveyed area.

## 6.2 Multi-method geophysical investigation of a dam reservoir, Québec, Canada

Multibeam Bathymetry (MBB), Side-Scan Sonar (SSS), Sub-Bottom Profiler (SBP) and marine GPR surveys were conducted in order to image and characterise the upstream reservoir of a dam site. These results were needed for maintenance work of the dan spillway.

The MBB and SSS methods were used to obtain a detailed image of the reservoir bed. The SBP and GPR methods were used to map the bedrock topography within the reservoir. Great care was taken in precise data positioning in order to have accurate images of the reservoir bed. In this case, elevation values had a precision of ±0,2 m.

Figure 3 shows detailed images obtained with the MBB and SSS methods. These allowed to identify possible bedrock outcrops as well as the presence of concrete debris on the reservoir bed.

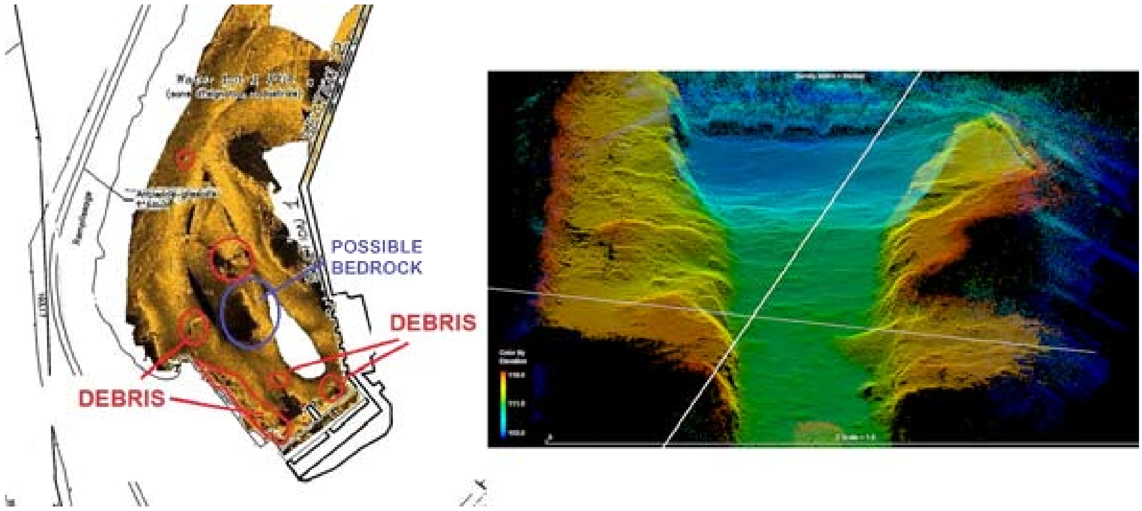


**Figure 3** : SSS (left) and MBB (right) survey results along reservoir.

By subtracting the interpreted bedrock topography from the SBP and GPR results to the MBB bathymetry, it was possible to calculate the probable deposit thickness along the main reservoir canal as shown on Figure 4.

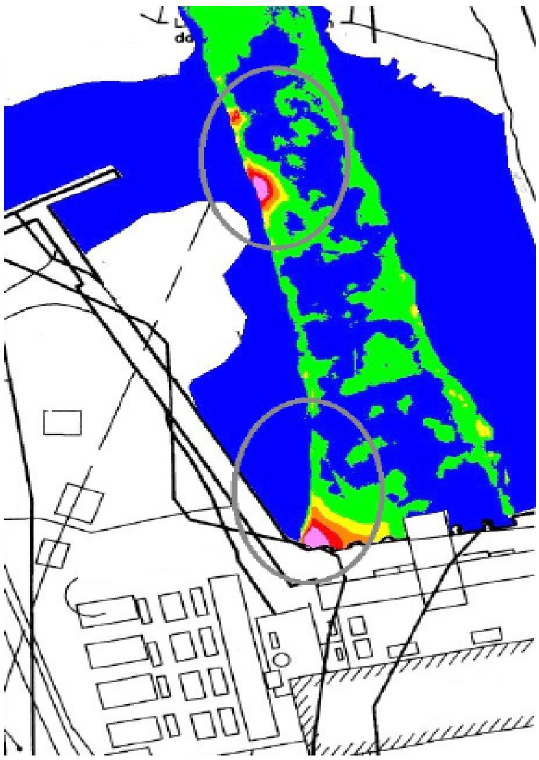

**Figure 4** : Contour map of sediment thickness along reservoir canal.

## 7. CONCLUSIONS

With the increasing commitment by dam owners to ensure the safety and sustainability of their assets, geophysics will continue to play an important role in dam site safety assessment investigations. By maintaining all parties involved well informed on the benefits, capabilities, limitations and technological advances of applied geophysical methods, confidence in this field will remain strong and positive experiences will strengthen its role in the toolbox of solutions for dam site investigations.

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