Hydro-TISAR and Hydro-SEEp – Innovative geophysical techniques for geotechnical and hydrogeological investigations

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ABSTRACT

Geophysical methods are part of the tool box for geotechnical and hydrogeological investigations. Geophysical tools can be used to improve our knowledge of the soils and structures that are investigated. However, few innovations have been made in this field in the last twenty years and conventional investigation methods are still the norm. Hydro-TISAR represents a new seismic acquisition and interpretation method based on the analysis of resonant frequencies of earth materials. The technique can detect thin fractures in bedrock, as well as lenses and thin beds of granular material in unconsolidated and building materials Hydro-SEEp is an innovative methodology integrating electrical, electromagnetic and seismic principles for the detection of leaks in earth dams. Multi-parameter analysis minimizes the limitations of conventional detection methods and allows the establishment of a detailed structural (2D or 3D) model to identify the structures that control the preferential flow of water.

RÉSUMÉ

Les méthodes géophysiques font partie des outils disponibles pour les investigations géotechniques et hydrogéologiques. Les outils géophysiques peuvent être portés à contribution pour améliorer les connaissances sur les structures investiguées. Cependant, peu d'innovations ont été faites dans ce domaine dans les vingt dernières années et les méthodes d'investigations conventionnelles sont toujours la norme. Hydro-TISAR propose une nouvelle méthode d'acquisition et d'interprétation sismique basée sur l'analyse des fréquences de résonance des matériaux. Cette dernière permet de détecter des fractures minces dans le roc, de même que des lentilles et lits minces de matériaux granulaires dans les dépôts meubles et les matériaux de construction. Hydro-SEEp est une méthodologie novatrice intégrant des principes électriques, électromagnétiques et sismiques pour la détection de fuites dans les barrages en terre. L'analyse multi-paramètres minimise les limitations des méthodes de détection classiques et permet d'établir un modèle structural (2D ou 3D) détaillé servant à identifier les structures qui contrôlent l'écoulement préférentiel de l'eau.

1 INTRODUCTION

Conducting high resolution geophysical profiles 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 play an important role in geotechnical studies; however, few innovations have been made in this field in the last twenty years and conventional investigation methods are still the norm.

The use of Ground Penetrating Radar (GPR) for this purpose is limited in depth by specific limitations of the method, which are the contrast of electromagnetic impedance and the electrical conductivity of the materials. Alternatively, classical seismic methods (refraction and P-wave reflection) are limited in terms of resolution or effectiveness, due to the lack of information (blind window) for reflections above depths of approximately 30 m. Electrical and electromagnetic methods also lack resolution and can be subject to cultural electrical and electromagnetic interference.

Recently, alternative seismic methods such as S-wave reflection, MASW or other interpretation techniques related to surface waves have gained in popularity. These methods, in general, operate with the frequency analysis of the seismic data. The Hydro-TISAR (Testing and Imagery from Seismic-Acoustic Resonance) method also uses the frequency content of seismic records but is related to the resonance of seismic signals instead of the propagation of the surface waves. Although the method was developed for surface investigations (1 m to 15 m deep), the field tests show that it can be applied to concrete investigations (0.1 m) as well as deep investigations, up to the order of 100 m. The Hydro-SEEp method takes Hydro-TISAR even further, combining it with other geophysical methods in order to establish a detailed structural (2D or 3D) model to identify the structures that control the preferential flow of water through and around civil works.

This paper presents the basic concepts behind Hydro-TISAR and the methodological principles of Hydro-SEEp. A series of case studies will present the application of the methods to various engineering challenges.

2 THEORETICAL CONCEPTS OF THE HYDRO-TISAR METHOD

Abraham et al. (1998), as well as Leonard (2000) presented the basic idea behind this method. The first practical applications of the method were demonstrated by Arsenault et al. (2001) & Arsenault et al. (2002).

The mechanisms of seismic resonance were inspired by the Impact-Echo NDT method (ASTM C1383). The transition of this method to geological applications required modifications, adjustments and important transgressions to the basic concepts of the Impact-Echo method. First, the distinct resonance signal from the geological materials led to a different approach for seismic data acquisition in the field and for data analysis. Secondly, the relative location of the resonance response in relation to the source-receiver distance (Tx-Rx) necessitated other considerations in the acquisition and also limitations in the processing of the data.

2.1 The Impact-Echo method

The Impact-Echo method considers an acoustic impact on the surface of a solid material, which generates a compression wave (P) that propagates in the medium and is reflected at the interface of a defect (or at an interface with another medium) to finally return to the surface. The wave travels this path in repetition (resonance phenomenon) until the complete dissipation of the energy. Considering a defect such as a fracture or delamination in a concrete slab, the multiple reflections of the wave are recorded with the same polarity due to the change of medium (and impedance). It is important to note that at the moment of impact, shear (S) and Raleigh waves are equally generated. At the beginning of the development of the Impact-Echo, the displacement of particles was simply considered in the time domain. Later, frequency domain processing allowed a better analysis of the data. The use of the Fast Fourier Transform (FFT) of the signals was preferred due to its capacity to consider the "repetitive reflection" signals in the time domain. The basic concepts of the Impact-Echo method are illustrated in Figure 1.

As shown in Figure 1, a receiver (accelerometer) located near the seismic source records the displacement of particles in the time domain. The period of the waves with multiple reflections can be identified by the corresponding resonance frequency following a spectral analysis of the signal.

The thickness of the material (H) can be calculated with the seismic velocity of the medium (V) and the two-way travel time of the seismic wave (T). Assuming a negligible distance between the source and the receiver, it can be considered that T = $t_{dwn} + t_{up}$ and that $t_{dwn} = t_{up}$. In such case:

$$T = \frac{2H}{V} \quad [1]$$

Which can be presented as follows:

$$H = \frac{VT}{2} \quad [2]$$

The "multiple reflection" time (T) is determined by its corresponding resonance frequency, f = 1 / T.

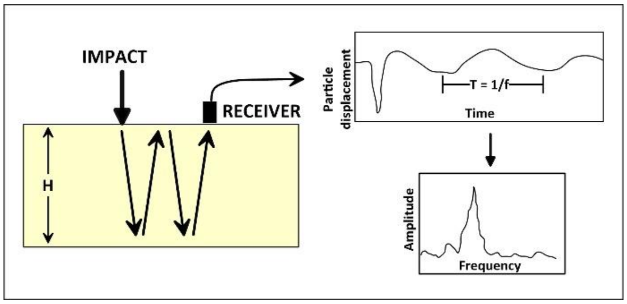

Figure 1. Representation of the principle of the Impact-Echo method.

2.2 The Hydro-TISAR method

Several authors have tried to extend the Impact-Echo technique to geological settings, such Abraham (1998) and Leonard (2000), producing mixed results. It is noted that these studies rigorously followed the Impact-Echo requirements as to the source-receiver distance. Following 1999, research carried out at Polytechnique Montreal has considered the resonance phenomenon of the geological layers to extend the principles of the Impact-Echo method.

The Hydro-TISAR method developed by Geophysics GPR distinguishes itself from Impact-Echo in regard to data acquisition and also to data processing operations. The method allows resolving multi-layered models, which show different acoustic impedance contrasts and different thicknesses between the geological layers.

In order to identify the capabilities and limitations of the Hydro-TISAR method, several synthetic seismograms for different geological models (thickness, geometry and impedance) were analysed. The seismograms were generated using a 2D finite difference software (FLAC from ITASCA). Figure 2 shows a synthetic seismogram for a simple model corresponding to 4 m of glacial till on a bedrock base, with each seismic trace normalized to its maximum amplitude. P-wave (direct and refracted), direct S-wave and Rayleigh waves, as well as guided waves (between the refracted P wave and the Rayleigh wave arrivals) can all easily be identified. The contribution of the resonance signal is important, even more so at a certain distance from the seismic source.

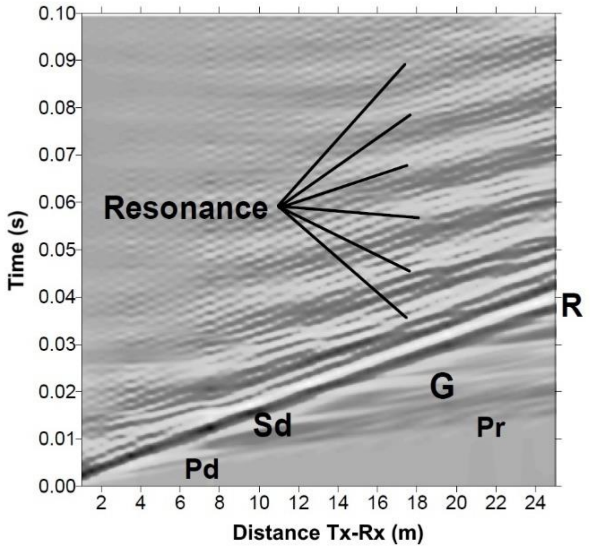

Figure 2. Synthetic seismogram with normalized amplitude for each receiver.

One of the challenges of using the resonance signal for data processing was to isolate this phenomenon from the other seismic signals. Abraham et al. (1998) and Leonard (2000) suggested time windowing to extract the resonance signal from the data. This method appeared to produce good results, but it is tedious to apply to actual field data and its application resulted to be very difficult in cases with complex geological geometries. Figure 3 presents a continuous wavelet transform of the receiver located at Tx-Rx = 18 m relative to Figure 2, where the resonance frequency can be identified in an optimal time window. Arsenault et al. (2002) proposed to isolate the resonance frequency using a spatial filtering process (Tx-Rx distance windowing).

The spectrogram shown in Figure 4 demonstrates that specific frequency signatures appearing in the vicinity of the shot point location (short distance noise) and long offset noise due to signal attenuation can easily be excluded from the data. A simple adequate (or “optimum”) Tx-Rx distance window can then be applied prior to further processing. The use of a spatial filter was therefore privileged for the Hydro-TISAR method for its calculation efficiency and its flexibility related to depth and geometry, even if it contravenes some of the assumptions for Impact-Echo.

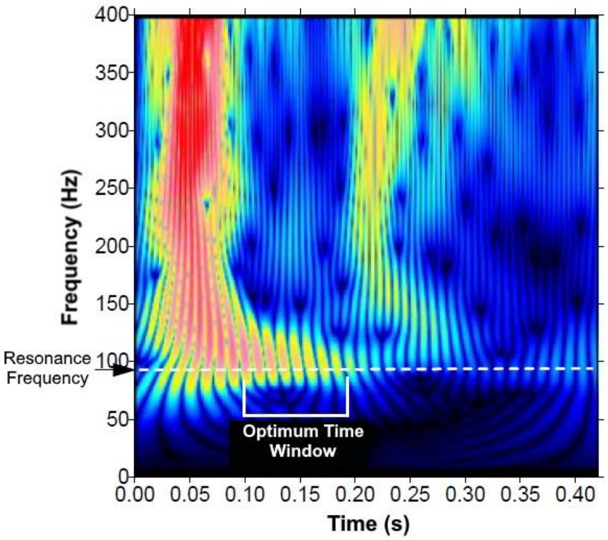

Figure 3. CWT scalogram transformed into an f-x spectrogram, showing the resonance frequency between the 90-190 ms time window.

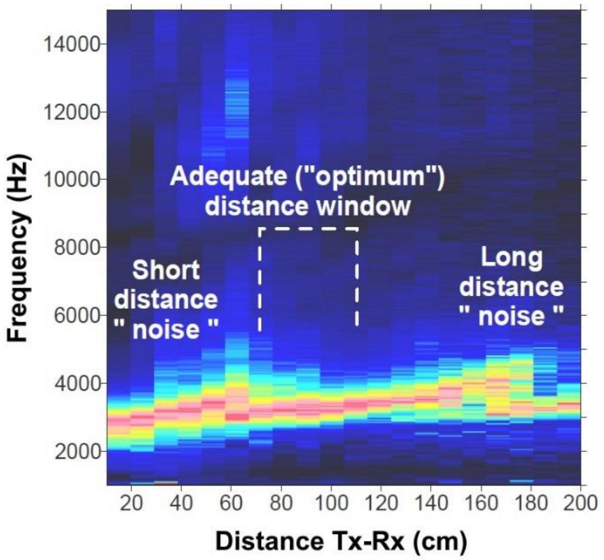

Figure 4. Experimental *f-x* spectrogram on a paved road; optimal distance window is far from the seismic source.

3 GEOPHYSICAL BACKGROUND OF THE HYDRO-SEEP METHODOLOGY

3.1 Overview of geophysical methods used for seepage and leak detection

Groundwater flow and seepage has been widely studied from a geophysical point of view and there are numerous papers discussing the advantages and limitations of many geophysical methods for this type of application such as Ikard et al. (2014) and Sirles, P. (1997). Whilst most of common geophysical methods will provide information on the structural and physical properties of the studied area or civil work, other methods allow to precisely map preferential fluid flow areas within earth materials.

When considering the investigation of an earth dam, seismic refraction and Multi-Channel Analysis of Surface Waves (MASW) will allow generating a model of the compressional (P) and shear (S) wave velocities of the construction materials. These velocities are directly related to the density (or compaction) of the materials and can allow locating areas of loose soils due to groundwater erosion. The Hydro-TISAR method can identify thin layers of permeable or impermeable materials such as clay and gravel lenses of centimetric thickness up to depths exceeding 30 m. However, the method does not allow to measure structure thickness albeit the fact that it will show up in the data. In general, the deeper a structure is located, the thicker the feature will show up in the profile, notwithstanding its actual thickness. Moreover, the method does not allow distinguishing between hard and soft materials even though it relies on seismic impedance contrasts calculated in the frequency domain..

Electrical Resistivity Tomography (ERT) can identify low permeability areas associated with higher electrical resistivities and can detect variations in water content using time-lapse ERT surveys. The self-potential (SP) method can specifically detect groundwater movement by measuring small currents produced by the flow of groundwater through porous materials (streaming potential).

Ground Penetrating Radar (GPR), although limited in depth of investigation, can gather high resolution images of the structure of a dam. When correlated to other geophysical data, this can provide useful information for leak detection. Controlled source audio frequency domain magnetics has been proven to accurately detect groundwater seepage in earth dams.

Obviously, all these methods have specific settings in which they are most useful and other considerations, such as cost effectiveness and time constraints, have to be taken into account when planning a geophysical investigation program.

3.2 The Hydro-SEEp methodology

Geophysical methods can be limited by site specific particularities that can render poor or bad results. For example, the presence of underground utilities or power lines can distort potential fields and create false anomalies for electrical and electromagnetic methods.

Recent developments in geophysical processing software and, more importantly, in geoscience data management software, introduced the possibility to integrate various types of geophysical data into one conceptual model for a specific site in order to minimize the risk of using a single geophysical method versus using several complimentary methods for applications such as seep detection.

The idea behind the Hydro-SEEp methodology was to be able to choose the most appropriate and cost effective methods for a particular case, to acquire the geophysical data using settings based on the cross-correlation of the chosen methods and to integrate the results, including geotechnical and hydrogeological data, in order to produce the most realistic conceptual model of the investigated area without having to rely on long and costly studies.

The methodology was centered around the Hydro-TISAR technique, due to its versatility and reliability for near surface investigations (0-100 m). Figure 5 shows the typical workflow for the Hydro-SEEp methodology.

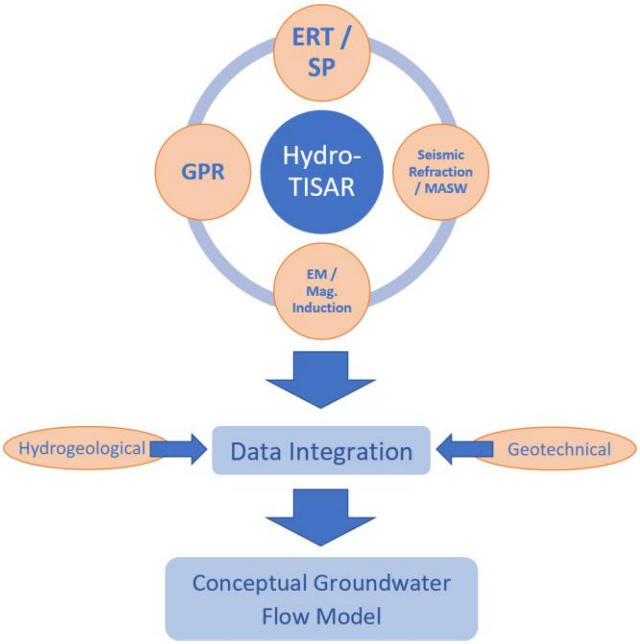

Figure 5. Typical workflow for the Hydro-SEEp methodology.

4 CASE STUDIES

4.1 Locating fracture networks in a bedrock mass, Napierville, Canada

Population growth in suburban areas leads to an increase in the demand for drinking water. In the case of the municipality of Napierville, QC, a new well with a capacity of 2000 l/min had to be developed. Local geology does not lend itself to wells in Quaternary deposits. Indeed, local Quaternary materials are composed of glacial sediments with low permeability, which can be characterized as aquitards. Regionally, most of the wells are found in the bedrock, at depths between 50 m and 100 m below the surface. In order to optimize hydrogeological exploration, a geophysical program was established to identify areas showing the greatest potential for exploratory wells in the bedrock.

The geophysical program consisted of the combination of seismic refraction and the Hydro-TISAR method. The combination of these two methods is essential, because seismic refraction allows the construction of the basic geological model used for the processing of seismic data with Hydro-TISAR. Two sites were investigated along several seismic profiles. The geological model was established with the results of the seismic refraction surveys and corresponds to a thin layer of loose sediments on a horizon of denser glacial sediments. The bedrock shows high seismic (Vp) velocities (5900 m/s) corresponding to a dolomite with a low fracture level. Figure 6 shows the geological model obtained by seismic refraction. Considering these results, it remains impossible to determine a precise site for an exploration well. However, when considering the Hydro-TISAR profile of the same line, several structures in the bedrock can be identified. Figure 7 presents the Hydro-TISAR section and the corresponding geological interpretation, which shows a dipping fracture zone that communicates with another area of sub-vertical fractures. In light of these results, a drilling target was proposed to maximize the hydraulic gradient at the well site. An exploratory well was drilled in the fracture zone at a depth of 100 m. Lithological information, as well as fracture occurrences, along this well are shown on Figure 7. As shown by the Hydro-TISAR profile, several water bearing fractures were intercepted within the bedrock up to 105 m deep. The final capacity of the Napierville well was estimated to be between 2600 and 3800 l/min.

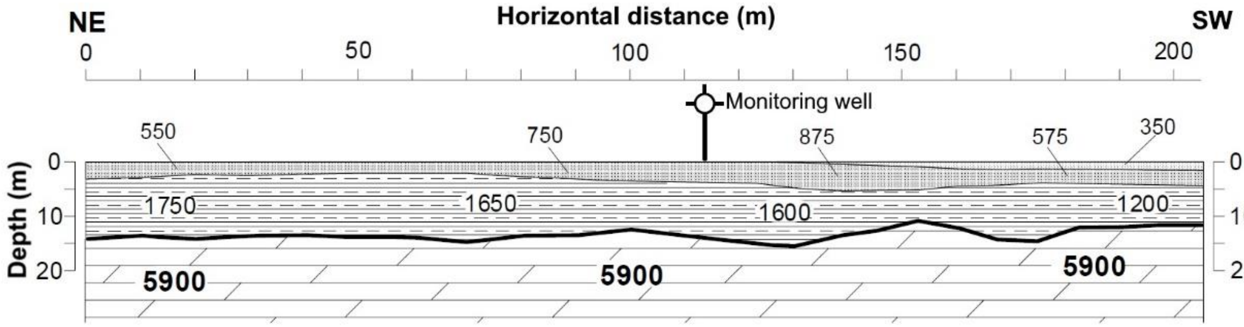

Figure 6. Geological model generated by seismic refraction.

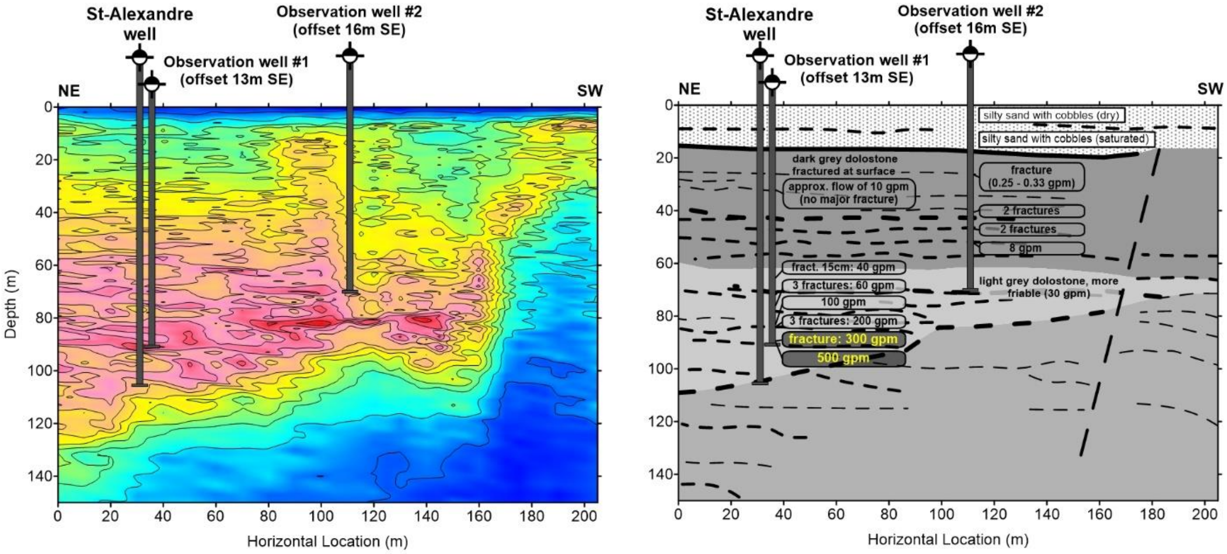

Figure 7. Hydro-TISAR profile with corresponding geological interpretation.

4.2 Precisely locating a landslide slip plane, Fredonia, Colombia

Landslides are frequent in Colombia due to the steep topography and significant rainfall during the rainy seasons. While most of these occurrences do not have a significant impact on the population, in some cases, major infrastructures are damaged by such events. A main road was cut off near Fredonia due to a landslide event in May 2018. In order to conduct a proper risk assessment and to plan subsequent corrective measures, the landslide slip plane had to be precisely identified.

A geophysical program was established in order to image the landslide structure using Hydro-TISAR as the main investigation technique, complemented with seismic refraction, ERT and SP data. Particular attention was given to the duration of the surveys since time was of the essence for the road rehabilitation and safety of the workers (the landslide was still active and further rainfall could become a risk for the workers on site).

Figure 8 shows the Hydro-TISAR profile on which were added the geological interpretation from the electrical methods. In this case, the geophysical methods used allowed to image the landslide slip plane in accordance to field observations and theorical assessments made by the geotechnical engineers and to provide data for groundwater modelling.

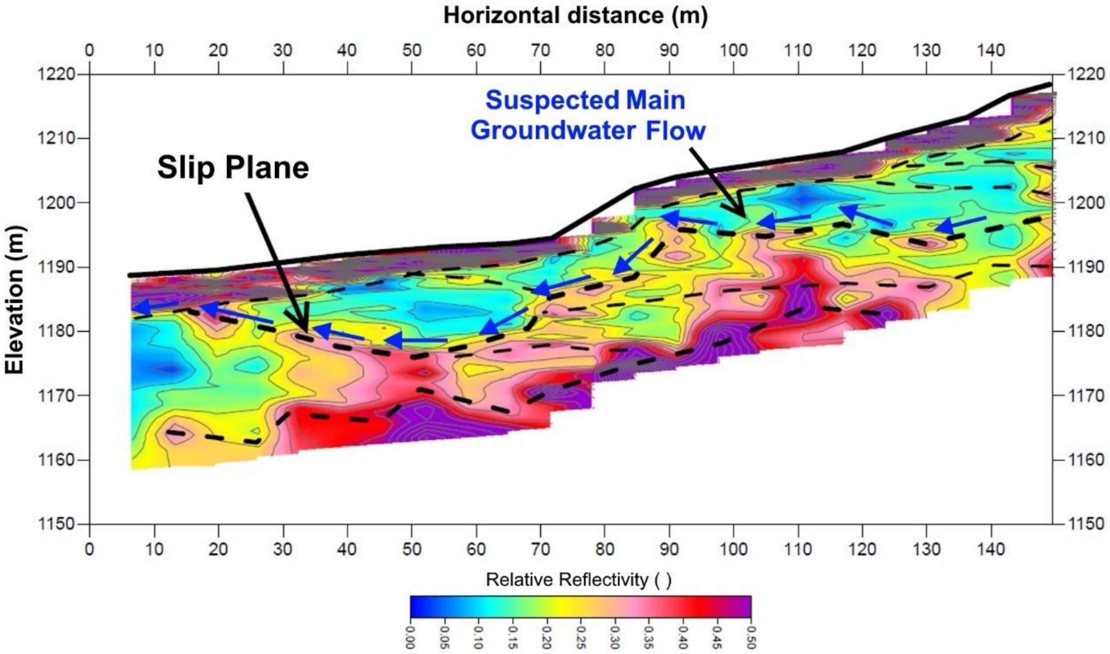

Figure 8. Hydro-TISAR profile locating a landslide slip plane.

4.3 Locating preferential groundwater flow pathways in a former mine tailings pond dam, Rouyn-Noranda, Canada

Groundwater seepage through tailing pond dams is a common phenomenon in older works. These occurrences are contained with waste water catchment and treatment systems, but complete remediation is not possible unless the embankment is assessed and repaired.

The purpose of these surveys was to locate preferential flow pathways in the embankment in order to determine the processes involved in water escaping the tailings impoundment upstream. The Hydro-SEEp methodology was considered in this case, since a cost-effective investigation program was needed to gather geophysical data and correlate it with existing geotechnical and monitoring well data. ERT surveys were carried out to determine a stratigraphic model for the embankment, while the SP method allowed locating low voltage areas associated with fluid flow. The Hydro-SEEp analysis favored these methods for their ability to obtain field efficient data and identify major structural trends.

Detailed coverage of an area of approximately 17 ha was performed using industry standard geophysical equipment. Non-polarizable lead-based electrodes were used to take the SP readings at constant intervals. Figure 9 shows the bedrock topography map obtained from the seismic and ERT data. Figure 10 shows a contour map of the SP data draped on the bedrock topography model and the groundwater preferential flow pathway identified with the SP method.

The bedrock topography map showed the presence of a possible cut-off trench along the dyke axis that was excavated in the bedrock.This shows off as a blue depression in figure 9. Correlation with surface water occurrences and exhaustive monitoring well data suggested that fluid seepage in the embankment could be related to bedrock topography. The presence of coarser materials, characterized by higher electrical resistivities, right above the bedrock supports these conclusions. Corrective measures were recommended along the main seepage pathway within the higher resistivity layer above the bedrock.

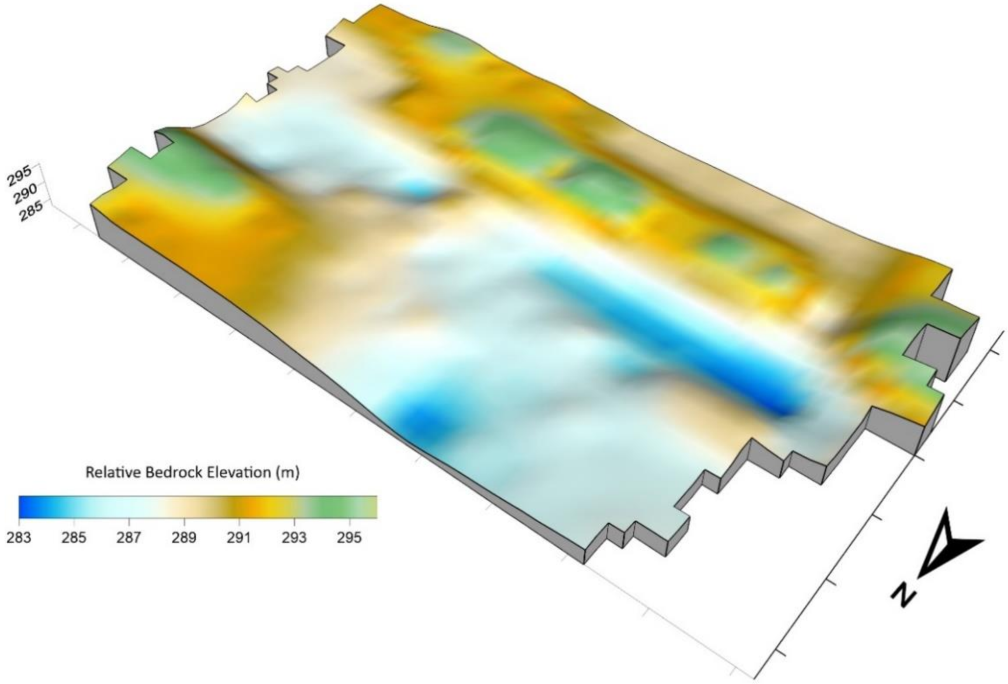

Figure 9. Bedrock topography model generated with geophysical data.

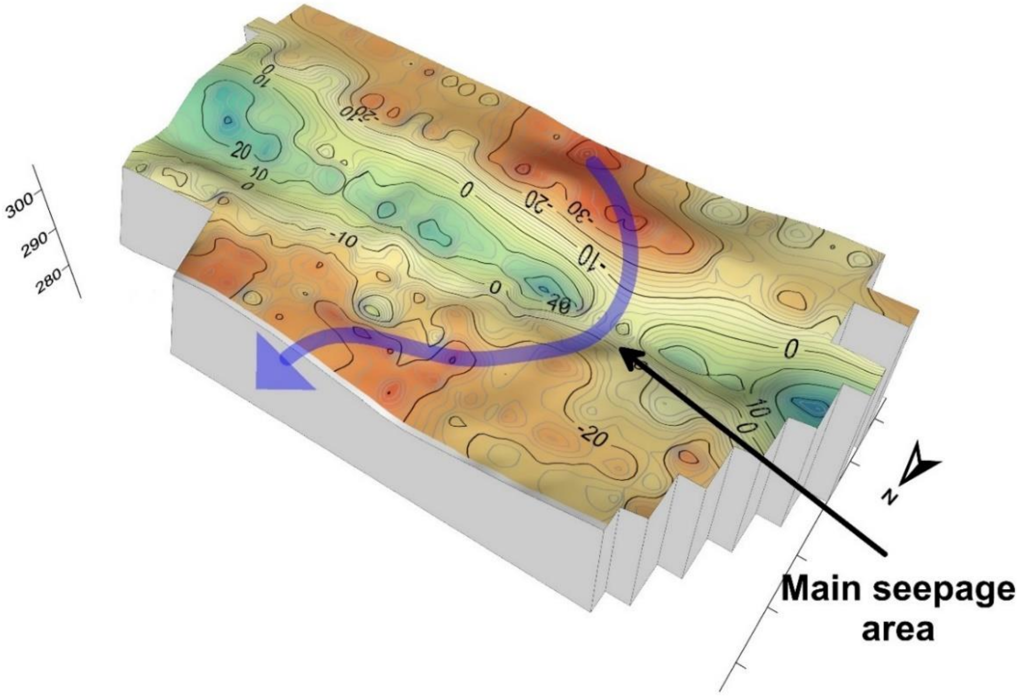

Figure 10. Main seepage pathway identified with Self Potential measurements draped over bedrock topography map.

4.4 Structural imaging of an earth dam, Eastern Townships, 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 11 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 12 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.

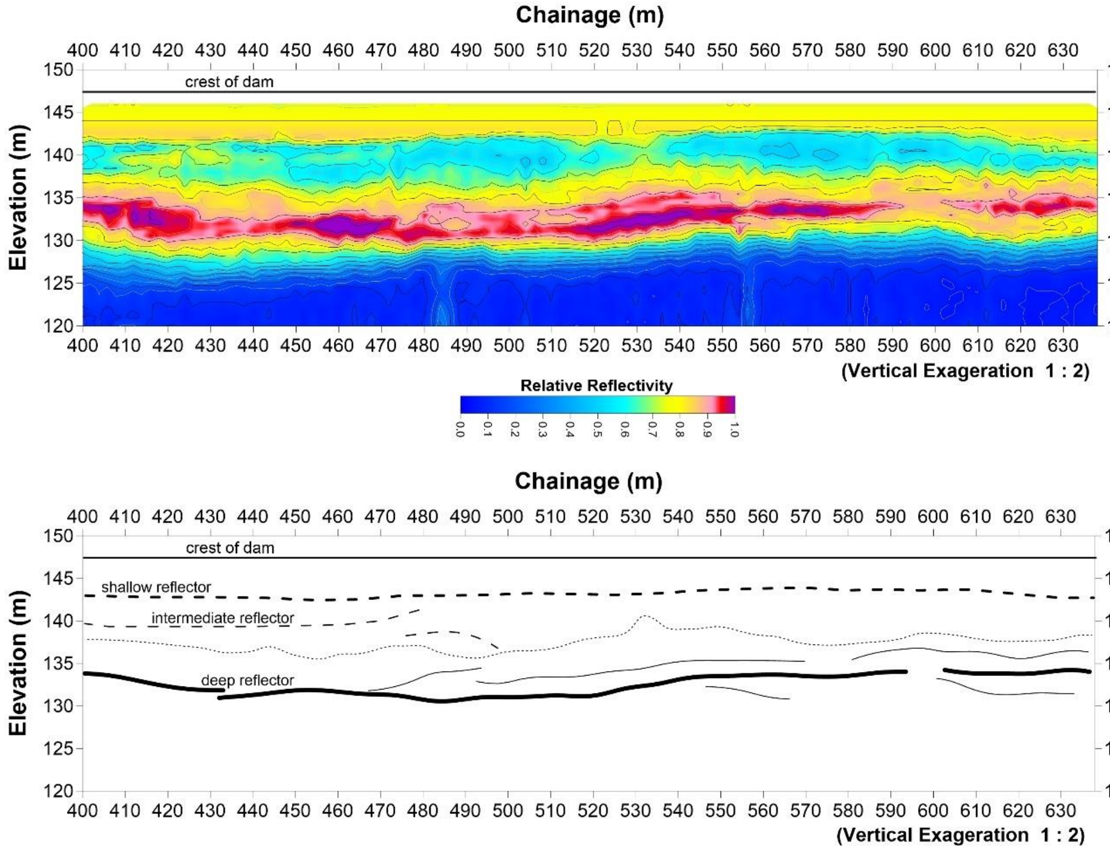

Figure 11. Hydro-TISAR profile and corresponding structural interpretation along the surveyed area.

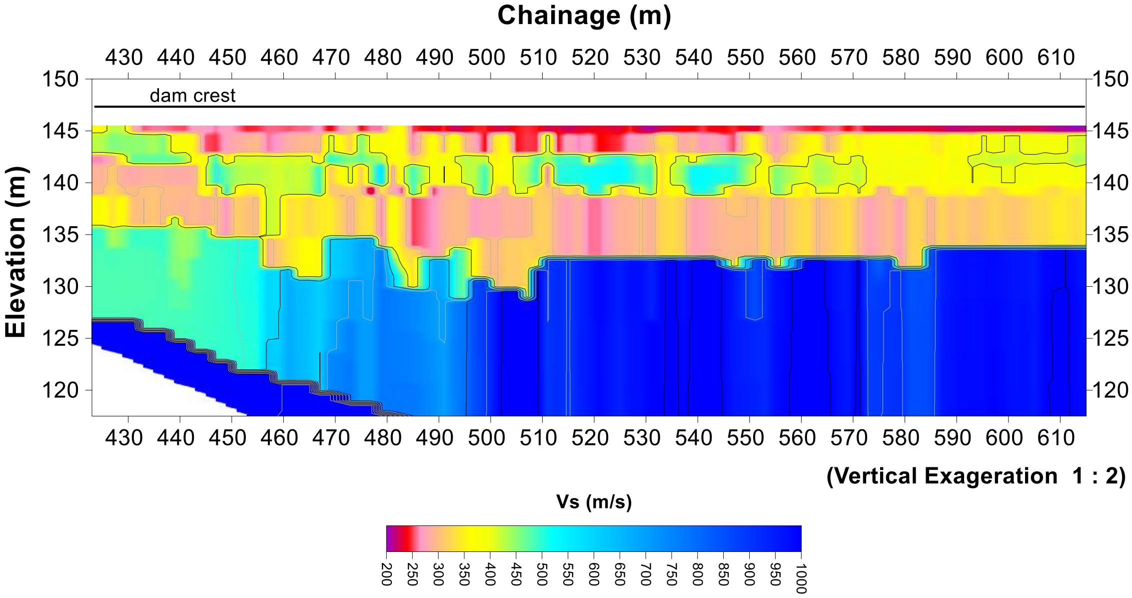

Figure 12. 2D-MASW section along the surveyed area.

5 CONCLUSIONS

The Hydro-TISAR method was developed to offer an alternative to GPR and as a complimentary method to other geophysical methods. Case studies show that this method can be very useful for geotechnical and hydrogeological investigations. It was demonstrated that the use of this method in superficial geological contexts produces accurate and high-resolution results; however, a precise geological model is necessary, which is possible to obtain by using conventional seismic refraction surveys. It is important to consider its limitations, which are mainly its qualitative nature, its inability to correlate with physical properties of the materials and to accurately measure the detected features thickness.

The Hydro-SEEp methodology uses Hydro-TISAR's capabilities combined with other geophysical methods in order to produce a detailed conceptual model for groundwater seepage studies. This methodology allows a more robust approach compared to the "one method" perspective.

Geophysical investigations cannot replace geotechnical and hydrogeological studies but allow optimizing their planning and targeting critical investigation areas. The results of the several case studies presented in this article demonstrate the versatility of Hydro-TISAR and Hydro-SEEp for different applications and in different geological contexts. One can foresee the usefulness of these methods to other sectors, such as dam safety investigations, mineral, oil and gas exploration, mining engineering and infrastructure.

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