DOWN-HOLE SEISMIC SURVEY AND VERTICAL ELECTRIC SOUNDINGS
RABASKA PROJECT, LÉVIS, QUÉBEC

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1. INTRODUCTION

In October 2005, Terratech mandated Geophysics GPR International Inc. to carry out one down-hole seismic survey and two vertical electric soundings (VES) at the Rabaska project site in Lévis, Québec (Can.). The purpose of the seismic survey was to provide the seismic shear wave velocity of the soil and the rock, as well as the dynamic elastic properties. The VES were performed in order to measure the grounds apparent electrical resistivity for grounding purposes. This work was required to complement the methane storage tanks site feasibility studies. The survey location is presented in Figure 1.

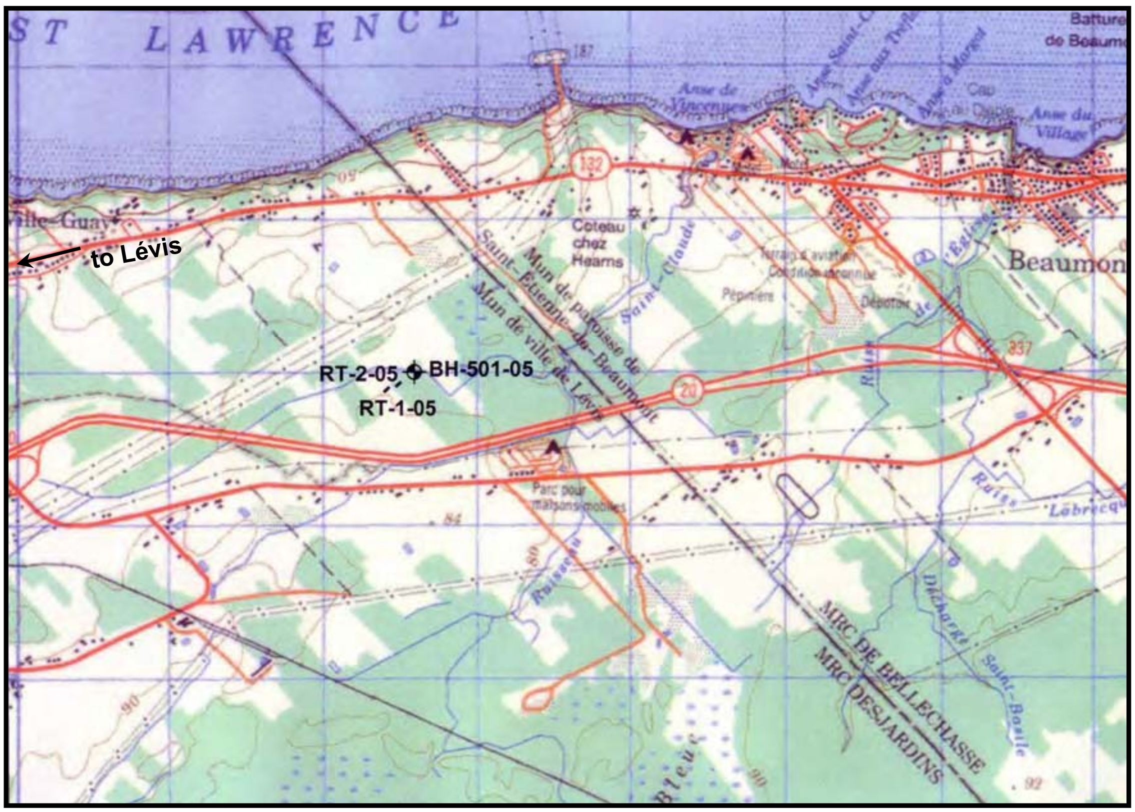

FIGURE 1
Approximate survey location

2. METHODOLOGY

This section summarizes the field procedures and interpretation methods used for the down-hole seismic survey and VES surveys. The field work was executed on November 3 and 4, 2005 by Mr. Daniel Campos, Eng., M.A.Sc. and Mr. Benoit Maillé, Sr. Tech. The borehole investigated for the seismic survey (BH-501-05) is about 20 meters deep. This borehole was previously drilled by Terratech.

Down-hole seismic survey

The down-hole seismic survey was executed using a surface seismic source and an in-hole seismic receiver. Figure 2 shows a schematic diagram of the set-up.

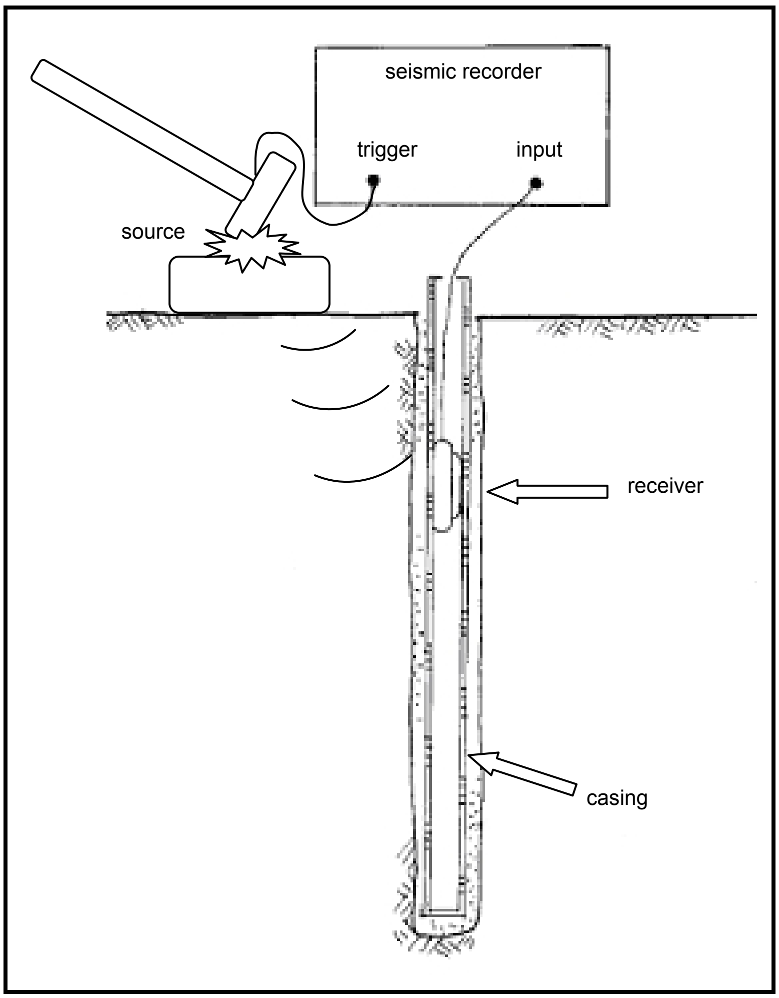

FIGURE 2
Schematic diagram of the down-hole seismic survey

The borehole had 63.5 mm inner diameter PVC casing. These boreholes were used to measure the seismic wave arrivals with a 3D geophone, held in firm contact with the casings by lamellar springs. The seismic records were acquired with a Terraloc Mark VI seismograph from ABEM. In order to have a good resolution and to be sure to record some eventual very slow shear waves, the sampling interval was set to 50 μs. Thus, every record was 410 ms long, and a pre-trig delay of 10 ms ensured to always record the entire seismic signal at the geophone.

Compression “P” and shear “S” waves were produced by hitting a 10 pound sledgehammer vertically on a steel plate and laterally on a wooden beam that was coupled to the ground using metal studs. To facilitate the picking of the shear “S” wave arriving time, the wooden beam was hit on both extremities to obtain inverse polarities of the wave signal. An electrical switch system was used to trigger the seismic recorder. Seismic records were produced every 1.0 meter along the borehole. The travel times from the source to each receiver (geophone) location are determined by measuring the elapsed time from the time break to the seismic wave manifestation within the record. The distance between each geophone location was then divided by the time elapsed for the different seismic waves travel time, to obtain local seismic velocities in function of depth. The down-hole method presents the advantages of being free from the seismic velocities inversion in depth, as well as not being affected by refraction effects in opposition to the crosshole method.

The "P" wave velocity depends mainly on volumetric elastic ratio of the constituent soil particles and pore water. The "S" wave velocity depends more on the structural elasticity of the material, which is influenced by the size, form and tightness of the particles.

Mechanical dynamic moduli

The main objective of the down-hole seismic survey was to provide the in situ measurement of the shear wave velocity of the soil and rock, and also to evaluate the dynamic elastic properties of the overburden and rock. Two types of seismic waves were required for this purpose. These are the compressional wave velocity ("Vp") and the shear wave velocity ("Vs"). The propagation of this second seismic wave is always slower than the one produced by the compression action by almost a factor 2 to 6 in the case of an unconsolidated material. Both seismic waves are assumed to propagate into an isotropic material according to its elastic mechanical parameters and density as shown below:

$$Vp = \sqrt{\frac{E(1-\nu)}{\rho(1-2\nu)(1+\nu)}}$$

and

$$Vs = \sqrt{\frac{E}{2\rho(1+\nu)}}$$

where :

Vp :	seismic compressional wave
Vs :	seismic shear wave
E :	Young modulus
υ :	Poisson ratio
ρ :	density of the material

Knowing the "Vp", "Vs" and the density of the material, one can directly derive its elastical properties (Poisson ratio, Young, bulk and shear moduli).

The Poisson ratio is determined directly from the compressional and shear waves data. It is expressed by the ratio of transverse strain to longitudinal strain. Its dynamic determination can be noted as:

$$\nu = \frac{Vp^2 - 2Vs^2}{2(Vp^2 - Vs^2)}$$

The Poisson ratio usually varies from 0.05 for a very hard and rigid rock, to 0.48 for a soft and poorly consolidated material, the value 0.5 being characteristic of a non-solid (liquid) material where "Vs" is non-existent.

The Young, bulk and shear moduli calculations require the material density (ρ). Their dynamic determination can be expressed as follows:

The Young modulus is the uniaxial stress-strain ratio. It is also sometimes known as the stretch modulus or modulus of elasticity, and can be calculated as:

$$E = \frac{\rho Vp^2 (1+\nu)(1-2\nu)}{(1-\nu)} = 2\rho V_S^2 (1+\nu)$$

The bulk modulus, also known as the incompressibility modulus, is the stress-strain ratio under simple hydrostatic pressure (pressure change on volumetric dilatation). Its dynamic evaluation can be obtained by the following equation:

$$K = \frac{E}{3(1-2\nu)}$$

The shear modulus is the stress-strain ratio for a simple shear. It is also known as the rigidity modulus and its dynamic value is obtained by:

$$G = \rho Vs^2 \quad \text{or} \quad G = \frac{E}{2(1+\nu)}$$

Nevertheless, all of these mechanical moduli are named "dynamic moduli" as opposed to the usual "static moduli" measured from laboratory tests. Dynamic moduli are then generally higher than static ones. The dynamic moduli of elasticity are also the instantaneous deformation moduli under the natural state of stress. The main differences between the dynamic and the static tests are the time factor of the load and the low strain level applied to the material for the dynamic case.

Vertical electric soundings (VES)

VES were performed at two locations (RT-1-05 and RT-2-05). Data acquisition was carried out using a SAS1000 resistivity meter from ABEM. In order to perform the electric soundings, four (4) stainless steel electrodes are distributed along a line, centered about a midpoint that is considered the location of the sounding. The Wenner electrode array which consists of four (4) evenly spaced electrodes (shown at Figure 3) was used for the soundings.

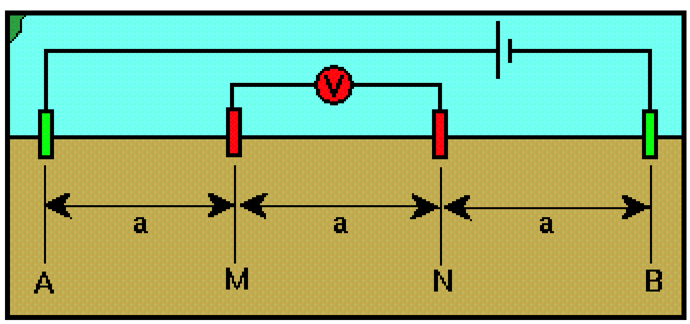

FIGURE 3
Wenner electrode configuration

In order to measure the ground apparent resistivity, a known current is injected through the ground via the two outer electrodes and the potential difference is measured between the two inner electrodes.

The ground apparent resistivity is calculated using the following formula:

$$\rho_a = 2\pi\ a\frac{\Delta V}{i}$$

Where ρ_a is the ground apparent resistivity, a is the electrode spacing, ΔV is the measured potential difference and i is the injected current.

The ground apparent resistivity is measured for several electrode spacings (a) in order to generate a plot of apparent resistivity versus electrode spacing from which it is possible to interpret the resistivity variation with depth. For soundings RT-1-05 and RT-2-05, the maximum electrode spacing (a) was 40 meters (AB = 120 m).

VES soundings are interpreted using 1D inversion and forward modelling programs. The purpose of data inversion is to determine the thickness and resistivity of the layers for a 1D model, which response matches the measured values.

3. DOWN-HOLE SEISMIC SURVEY RESULTS

Borehole BH-501-05 was 19.84 m deep while the surveys were carried-out. The rock surface was 13.21 m deep, according with the boring log. Figure 4 presents two seismograms constructed with some seismic records from this borehole, showing the P and S waves with increasing time with depth. The rock presents a good shear wave reflection signature on the vertical component seismogram.

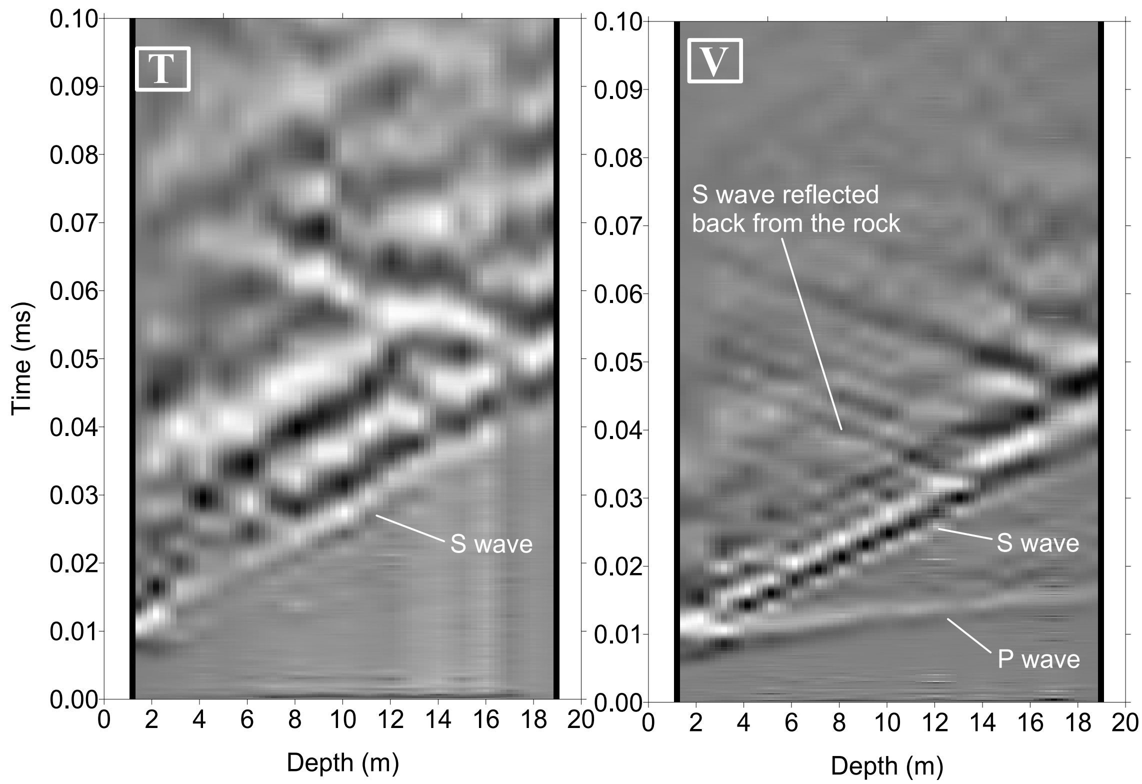

FIGURE 4
Seismograms (Transversal and Vertical components) from BH-501-05

The measured seismic velocities are presented at the Table 1. For the dynamic moduli calculations, we have assumed two material densities that could be within a reasonable range for the surface sediment (1900 kg/m^3), and for the rock (2600 kg/m^3).

High “Vp” values, generally ranging from 1100 to 2000 m/s, were recently obtained in the overburden (Borehole BH-501-05) between depths of about 3.5 and 13.2 m, thus suggesting a stiff and/or dense state of relative density of the soil. In shallow overburden, i.e. at less than 3.5 m depth, lower “Vp” values in the range of 599 to 820 were recorded thus suggesting a lower soil relative density. Relatively low “Vp” values close to 2500 m/s were measured in the bedrock.

In the overburden, corresponding shear wave velocities “Vs” values ranged from 425 to 620 m/s between depths of about 3.5 and 13.2 m, whereas a Vs value of 268 m/s was obtained at less than 3.5 m below ground surface. In the bedrock, “Vp” values of the order of 761 to 972 m/s were determined.

The above “Vs” and “Vp” values were generally found to be in good agreement with the range of velocities previously measured on rock (in Boreholes BH-101-05 and BH-109-05) by means of down-hole seismic surveys (Reference: Geophysics GPR International Report M-05043 dated April 2005).

TABLE 1

Seismic velocities measured and calculated dynamic moduli at BH-501-05

Depth (m)	Vs (m/s)	Vp (m/s)	Vol.mass.* (kg/m3)	Poisson (GPa)	G dyn. (GPa)	E dyn. (GPa)	K dyn. (GPa)
1.6		599	1900				
2.6	268	820	1900	0.44	0.14	0.39	1.10
3.6	425	1550	1900	0.46	0.34	1.00	4.11
4.6	574	1793	1900	0.44	0.63	1.81	5.27
5.6	496	1107	1900	0.37	0.47	1.29	1.71
6.6	536	1995	1900	0.46	0.55	1.60	6.84
7.6	482	1248	1900	0.41	0.44	1.25	2.37
8.6	499	1248	1900	0.40	0.47	1.33	2.33
9.6	620	1998	1900	0.45	0.73	2.11	6.61
10.6	518	1427	1900	0.42	0.51	1.45	3.19
11.6	481	1998	1900	0.47	0.44	1.29	7.00
12.6	592	2498	1900	0.47	0.67	1.96	10.97
13.6	761	2499	2600	0.45	1.51	4.36	14.22
14.6	821	2837	2600	0.45	1.75	5.10	18.59
15.6	821	2499	2600	0.44	1.75	5.05	13.90
16.6	925	2499	2600	0.42	2.22	6.32	13.27
17.6	839	2499	2600	0.44	1.83	5.26	13.80
18.6	972	2855	2600	0.43	2.46	7.05	17.92

* : “assumed” density values.

The principal information from this survey is probably the very low seismic waves velocities measured in the limestone-shale bedrock, which agrees with the low RQD values (indicated on the borehole log).

The calculated Poisson ratios are generally high in the overburden and also in the bedrock with values close to 0.44 and corresponding to values previously obtained in Boreholes BH-101-05 and BH-109-05. The dynamic shear modulus (“G”) varies around 0.5 GPa for the overburden, and from 1.5 to 2.5 GPa for the rock.

4. VERTICAL ELECTRIC SOUNDINGS (VES) RESULTS

The interpretation of the field data was carried out using the RESIX v3 DC resistivity data interpretation software from Interpex Ltd. Figures 5 and 6 show the results from the data inversion for soundings RT-1-05 and RT-2-05.

Sounding RT-1-05 shows an alternation of two resistive layers and a conductive layer within the first meter from the surface. This variation may be due to local heterogeneities in the topsoil. Depths ranging from 1 meter to about 11.5 meters show a constant apparent resistivity layer of 108 ohm•m. This value is representative of Quaternary sands and clayey sands. The apparent resistivity slightly increases to 174 ohm•m below a depth of 11.5 m. This interface probably corresponds to the top of the bedrock. The RMS error from the 1D inversion for soundig RT-1-05 is 1.5%.

Sounding RT-2-05 also shows an alternation of two resistive layers and a conductive layer near the surface. Again, this variation may be due to local heterogeneities in the topsoil. Depths ranging from 2.2 meters to about 8.3 meters show a constant apparent resistivity layer of 35 ohm•m. The lower apparent resistivity observed in this layer may be due to high clay content in the overburden at this location. The apparent resistivity slightly increases to 220 ohm•m beyond a depth of 8.3 m. This interface could correspond to the top of the bedrock. Borehole BH-505-05, located at the southeast of RT-2-05, shows the top of the bedrock at about 1.5 meters beneath the surface while borehole BH-401-05, located at the northwest of RT-2-05, indicates that the depth of the bedrock is greater than 20 meters. This appears to be in good fit with the bedrock depths inferred by means of the VES survey. The RMS error from the 1D inversion for sounding RT-2-05 is 2.4%.

The calculated apparent resistivities at depths of interest for each site are presented in Table 2.

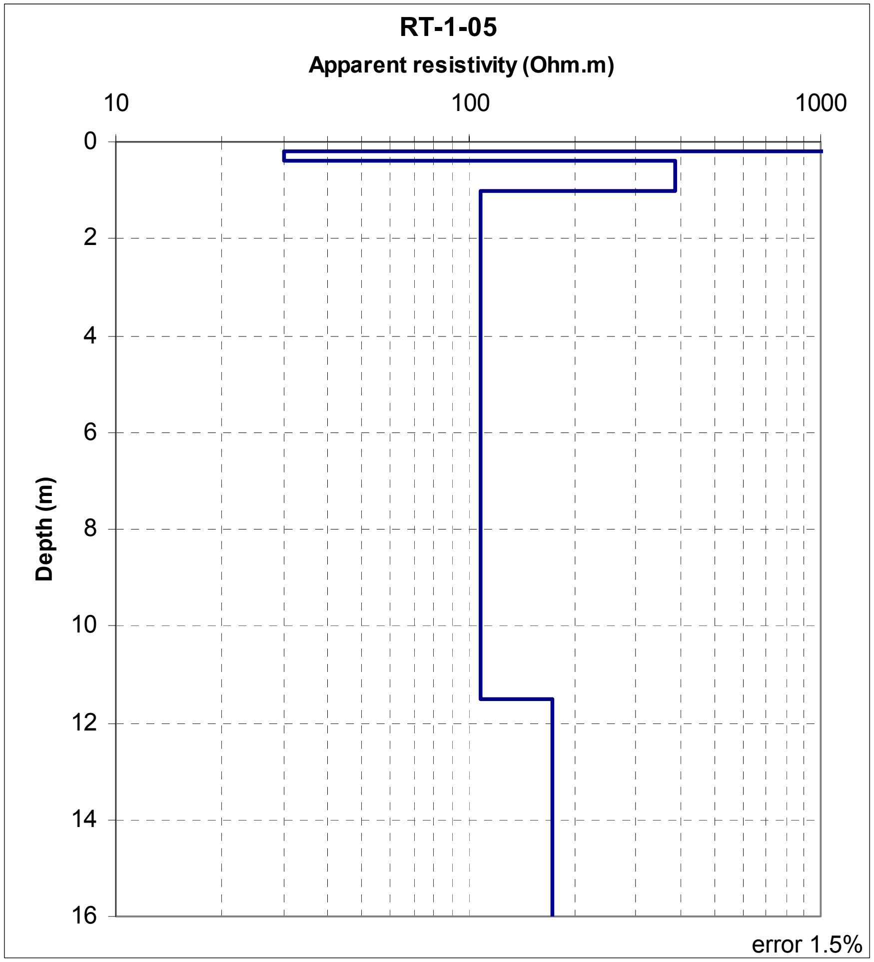

FIGURE 5
Data inversion results – sounding RT-1-05

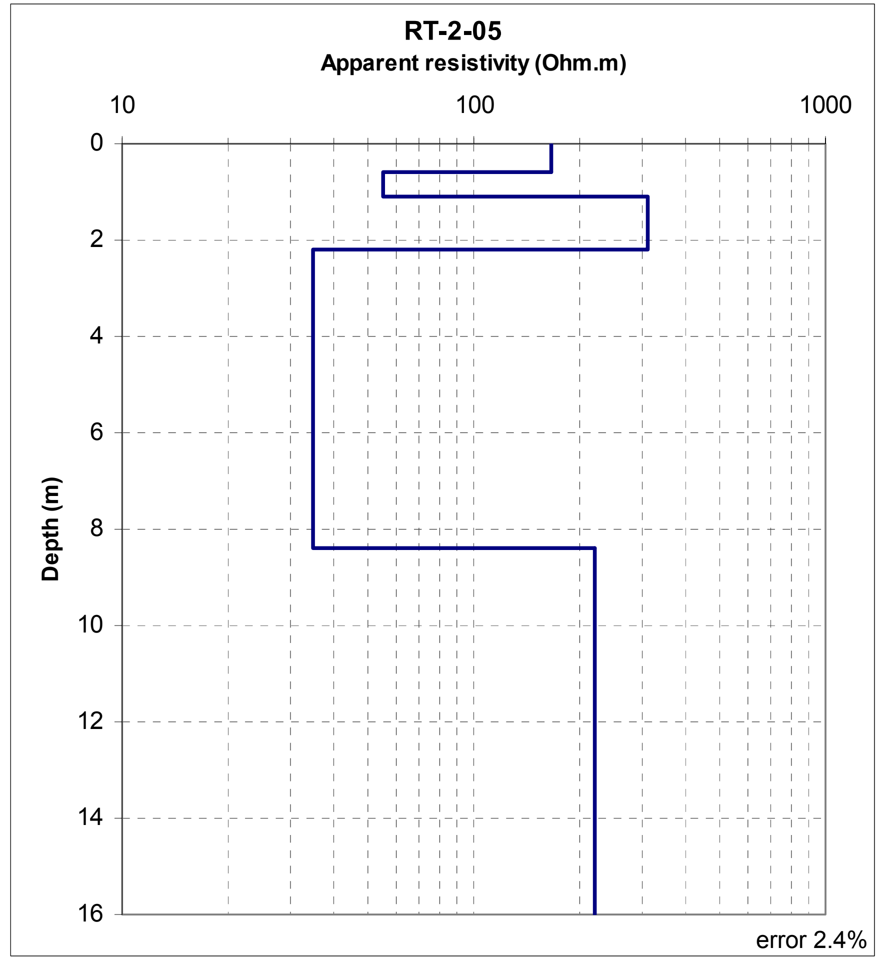

FIGURE 6
Data inversion results – sounding RT-2-05

TABLE 2
Calculated apparent resistivities at depths of interest for each site

Depth (m)	Apparent resistivity (ohm•m)	
	RT-1-05	RT-2-05
1.5	108	312
3.0	108	35
4.5	108	35
6.0	108	35

As with all numerical inversion techniques, the calculated solution for the inversion of VES data is not unique. For example, by increasing the thickness and apparent resistivity of a layer it is possible to obtain the same convergence error than a thinner but less resistive layer. This means that the apparent resistivity model can be different from the true apparent resistivity in the ground. This is why it is important to use all the knowledge (relative to the site) in our disposition to constraint the model during the inversion process.

VES techniques assume that the ground is homogenous and has a horizontal stratigraphy between layers. The presence of heterogeneities in the overburden and dipping soil and/or bedrock interfaces may result in a difference between the true apparent resistivity in the ground and the calculated apparent resistivity of the model obtained by the 1D inversion.

5. CONCLUSION

The down-hole geophysical surveys carried out at the Lévis site, specifically in Borehole BH-501-05, revealed that the rock (a limestone with layers of shale) presents low seismic velocities for its seismic compressional nature ("Vp"), and also some very low values for its shear seismic waves velocities ("Vs"). Generally, as well as for BH-101-05 as BH-109-05, the representative shear wave velocity appeared to be of the order of 800 m/s, which is very low for a sound sedimentary rock. The calculated Poisson ratio was high (around 0.44) in the overburden and also in the bedrock.

The shear modulus "G" was estimated considering a hypothetic but realistic volumetric mass of 2600 kg/m^3 for the bedrock. The computed "G" values range from 1.5 to 2.5 GPa, which is low for a sedimentary rock.

VES soundings carried out at the Lévis site showed alternate high and low resistivity values in the topsoil, relatively low resistivity values in the overburden (108 Ohm•m for RT-1-05, and 35 ohm•m for RT-2-05) and higher resistivities for the underlying bedrock (174 ohm•m for RT-1-05, and 220 ohm•m for RT-2-05). Resistivities obtained in the bedrock are typical of the shale/siltstone/limestone formations present in this region.

This report was prepared by Jean-Luc Arsenault, Eng., M.A.Sc., and Daniel Campos, Eng. M.A.Sc., and approved by Réjean Paul, Eng., Geoph.

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