THE OTTAWA VALLEY LANDSLIDE PROJECT: A GEOPHYSICAL AND GEOTECHNICAL INVESTIGATION OF GEOLOGICAL CONTROLS ON LANDSLIDING AND DEFORMATION IN LEDA CLAY

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ABSTRACT
The Ottawa Valley Landslide Project is, in part, a pioneering study of the capabilities of geophysical techniques to provide regional-level reconnaissance surveys of several critical parameters or factors related to landsliding and surface deformation of sensitive marine (Leda) clay near Ottawa. In two study areas, variations in pore-water salinity and soft-sediment stratigraphy, as well as definition of the bedrock topography, and potential ground response to seismic shaking were determined using electrical conductivity, electromagnetic resistivity, high-resolution seismic, and ground penetrating radar surveys. Results were confirmed at strategic boreholes through downhole geophysical logging and geotechnical testing. The geophysical techniques were shown to offer rapid and cost-effective tools to contribute to regional hazard assessment and modeling ground response to earthquake shaking.

RÉSUMÉ
Le projet sur les glissements de terrain de la vallée de l'Outaouais est une étude de faisabilité portant sur l'utilisation des méthodes géophysiques à la reconnaissance regionale de plusieurs paramètres ou facteurs reliés aux instabilités et aux déformations de surface dans les zones d'argiles sensibles (argiles Leda) à proximité d'Ottawa. Les variations de la salinité de l'eau interstitielle, la stratigraphie des dépôts non consolidés, la topographie de la roche en place, et la réponse potentielle du sous-sol à des sollicitations sismiques, ont été déterminées dans deux zones d'étude, à l'aide des méthodes suivantes: conductivité électrique, résistivité électromagnétique, sismique haute résolution, et géoradar. Les résultats ont été confirmés à des emplacements stratégiques, à l'aide d'essais géotechniques et de diagraphies géophysiques effectuées dans des forages. Il a ainsi été montré dans cette étude que les méthodes géophysiques offrent des outils rapides et peu coûteux qui peuvent contribuer, d'une part, à évaluer l'aléa à l'échelle régionale, et d'autre part, à modéliser la réponse du sous-sol lors d'un séisme.

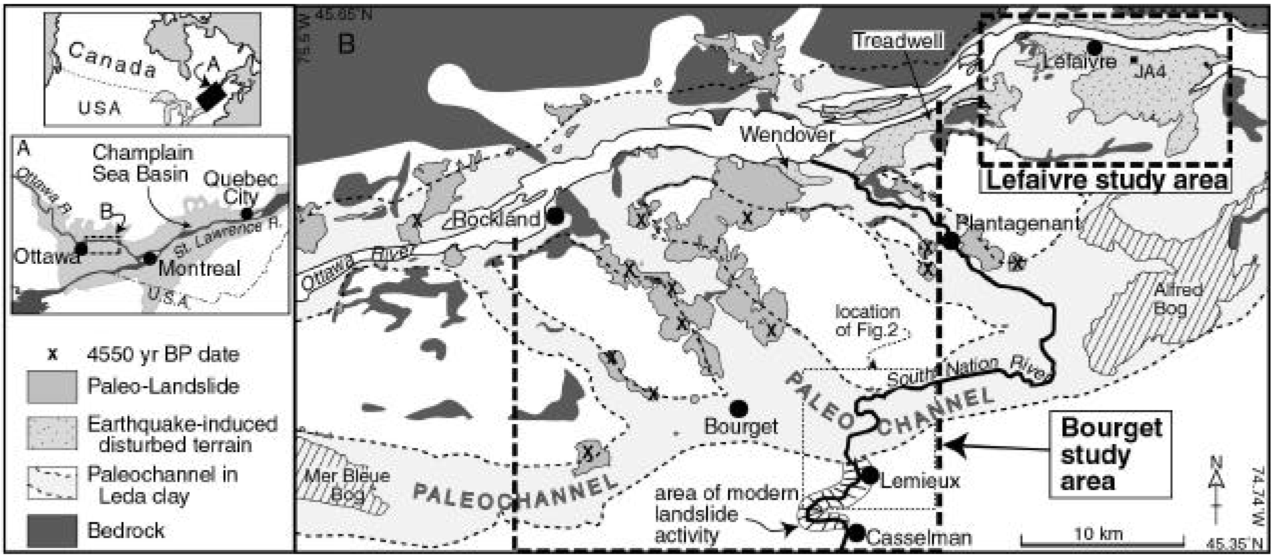

Figure 1. (a.) Location of the Champlain Sea Basin in eastern Canada. (b.) Map of study areas showing paleochannels, paleo-landslides and areas of earthquake-induced disturbance.

1. INTRODUCTION

Landslides in Eastern Canada are primarily associated with sensitive marine (Leda) clays of the Champlain Sea basin (Fig. 1a). These landslides pose a serious hazard to the safety of the local population and have caused costly property damage.

Leda clay is a clayey-silt composed of glacially-ground, non-clay minerals, held together in a loose structural framework capable of retaining a high water content. Marine salinity originally contributed to the bonding of the minerals, and salt leaching now influences structural strength (Torrance 1988). If disturbed, these sediments can lose strength, collapse, and behave like a liquid. Catastrophic earthflows can rapidly destroy large areas of flat land lying behind the unstable slope and the debris may flow great distances from the original failure.

The Ottawa Valley Landslide Project (OVLP) is a regional geological, geotechnical and geophysical investigation by the Geological Survey of Canada (GSC) of the critical geological controls on landsliding and surface deformation in Leda clay near Ottawa. In part, the project is a pioneering study of the capabilities of geophysical techniques to provide regional-level reconnaissance surveys of critical parameters related to landsliding. These techniques include electrical and electromagnetic surveys, high-resolution seismic methods, ground penetrating radar, and downhole geophysical logging. Geophysical results have been confirmed at strategic boreholes through geological logging of continuous core and geotechnical testing of core sample at regular intervals. This paper focuses on the application of geophysical techniques. The rational, methodology and results of each technique are briefly summarized and examples are presented.

The OVLP has two major thrusts:

i) a regional assessment of geological factors and interactions controlling earthflow locations in the Bourget area (Fig. 1b). Pore-water salinity, bedrock topography, stratigraphy, and variation in thickness of sensitive sediments and the sand cap were mapped over a large area, and the most vulnerable areas identified, using geophysical surveys augmented with borehole information.

ii) a detailed investigation of the earthquake-induced, soft-sediment deformation and lateral spreading in the Lefaivre area (Fig. 1b). Seismic surveys offshore and onshore, augmented by borehole data, were used to establish bedrock surface, stratigraphy, and depth of disturbance. In addition, passive ground site response measurements were used to establish ground motion amplification.

1.1 The Bourget Area

The Bourget study area (Fig. 1b) is characterized by a 2-10 m thick sand cap overlying Leda clay generally ranging from 20 to 45 m thick. Broad paleochannels of the proto-Ottawa River, now abandoned, cut 20 to 30 m into these sediments. In this study area, most modern earthflows occur along a critical 25 km stretch of the South Nation River which experiences a landslide recurrence interval of 20-25 years (Lawrence et al. 1996). The most recent event was the 1993 Lemieux landslide (Evans and Brooks 1993). The paleochannel slopes are characterized by numerous, very large, prehistoric earthflows that coalesce and overlap in places, forming vast failure complexes. Evidence that most landslides occurred simultaneously, ca. 4550 yr BP, long after channel abandonment, has been interpreted as slope response to a massive earthquake (Aylsworth et al. 2000). Yet in the immediate area, other slopes with similar topography and geology remain unaffected. In part, the purpose of this geophysical investigation was to determine why some slopes failed and others stood in the face of this shaking event.

1.2 The Lefaivre Area

The Lefaivre study area (Fig.1B) is a broad flat erosional plain underlain by Leda clay. Within this area is a 46 km^2 area of severe ground deformation, characterized by irregular, hummocky topography and severely deformed sediments (Aylsworth and Lawrence this volume). Local relief varies from 3 to 8 m and individual hollows are 100-300 m in diameter. Sections and boreholes reveal disturbances ranging from brittle shear to liquefaction to a depth of 50 m. Several sand dykes and blows occur at surface. Here, the disturbance has been attributed to severe shaking and lateral spread, leading to irregular ground subsidence and deformation, due to severe earthquake shaking, perhaps with a local epicenter. Buried trees have established the date of the event at 7060 yr BP (Aylsworth et al. 2000).

2. GEOPHYSICAL APPLICATIONS

2.1 Electrical Methods

Electrical resistivity measurements have been applied in the Bourget channel area to map potential high hazard areas for earthflows resulting from the sensitive condition of the “Leda” clay. Electrical resistivity of most unconsolidated overburden sediments, above or below the water table, is commonly an indicator of material type (e.g. high resistivity associated with sand and gravel and lower resistivities associated with clays). However, since much of the Champlain Sea sediments were deposited in a brackish water or a marine environment, the pore-water salinity of the sediments generally dominates the formation resistivity response.

A relationship between pore water salinity and electrical conductivity (the inverse of resistivity) has been previously established by Hyde and Hunter (1998) for Leda clays from borehole geophysical measurements in the Ottawa area. As a result, electrical resistivity measurements have been used to map the sub-surface occurrence and distribution of saline and non-saline sediments throughout the Bourget study area (Fig. 1b). In many cases, where salt-leaching has occurred, “sensitive” clay conditions exist and are associated with high values of formation electrical resistivity.

Figure 2 shows a portion of the electrical resistivity map constructed from EM-34 conductivity soundings over the project area near the abandoned town site of Lemieux (Fig. 1b) in the Bourget study area. The electrical resistivity is an average from ground surface to a depth of 15 m. Along the embankments of the South Nation River within the area shown, there are both zones of high hazard due to sensitive clay, as well as zones of low hazard having stable clays. In the low hazard area within the Bourget channel, the salinity of the Leda clay is high and the apparent conductivities are proportionately low. In contrast, in the high hazard area, the high apparent resistivities result from the presence of a surface sand cap (typically >5 m thick in the South Nation River area) and lower salinities (leached conditions) within the underlying ‘Leda’ Clay. Laboratory testing of core from

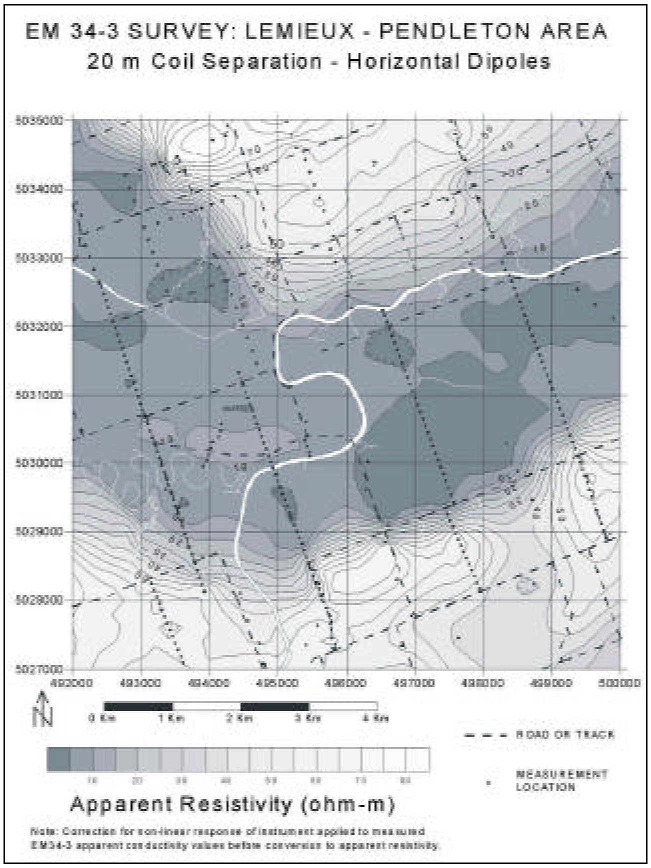

Figure 2. Average soil resistivity (to a depth of 15 m) in the South Nation River area of the Bourget channel. Low values are associated with stable Leda clay. Higher resistivities correlate with the existence of a sand cap and non-saline (leached) clay conditions.

GSC boreholes in the area have confirmed both the variations in pore water salinity as well as the associated variation in clay sensitivity. These types of non-invasive surface inductive conductivity soundings can be rapidly performed (e.g. 10 minutes per site for multiple soundings that measure to 40+ m depth), so that electromagnetic methods can be considered as a cost-effective preliminary phase in regional studies of the stability of Leda clays. Other electrical methods applicable to this type of survey work include DC methods using multi-electrode earth-contact or capacitive-coupled arrays which can provide more detailed vertical and horizontal resolution of the electrical properties. Such techniques are more time-consuming to apply and have been utilized at selected locations to examine conditions at channel edges and other potential hazard zones.

2.2 Ground Penetrating Radar

A key factor influencing the stability of Leda clay slopes in the Bourget area is the thickness and continuity of the overlying sand cap. Ground probing radar (GPR) has successfully been applied in several locations to determine the sand cap thickness associated with both modern and paleo-landslide zones. Depth of penetration is limited to coarse-grain sediments only; the top of continuous Leda clay (either saline or leached) is associated with the deepest radar reflector on the sections (e.g. Fig. 3). Where modern or paleo-landslides have occurred, the base of the sand cap is considerably above the elevation of the channel floor. GPR profiles quickly established that many of the slopes which have not failed have a much thicker sand cap than the regional average. Indeed, in places, most or all of the bank consisted of sand. Hence knowledge of the thickness of the sand cap is critical to assessment of the landslide problem in this area. GPR provides a reliable, non-invasive tool in the absence of borehole coverage.

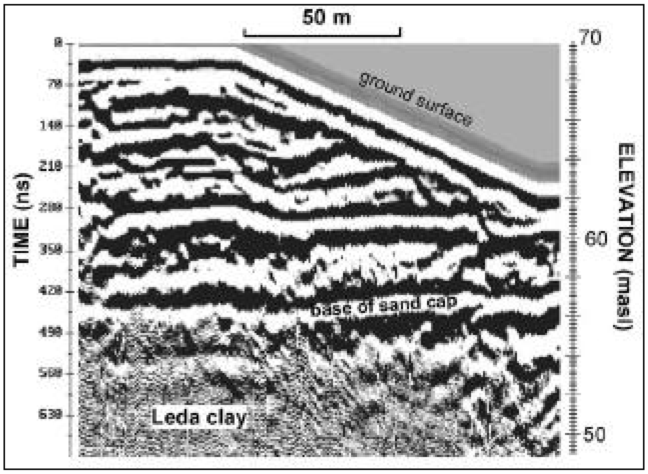

Figure 3. A ground penetrating radar section across a stable edge the Bourget channel showing the sand cap on Leda clay. Although the clay has been leached, the base of the sand cap is below the channel floor, so no landslide hazard exists at this site.

2.3 Seismic Methods

Soft soil may respond to earthquakes in several ways. There may be broad-band amplification of ground motion due to shear wave velocity gradients within the soil column. There may be resonance amplification at specific earthquake frequencies due to significant seismic impedance contrasts within the overburden or at the overburden-bedrock boundary. In addition, there may be bedrock topographic focusing or de-focusing effects and other “basin” effects resulting from large amplitude earthquake surface waves generated at the edges of unconsolidated sedimentary basins and propagated throughout the basin. Some of the major factors affecting ground motion response to earthquake shaking in soft soil sites are: 3-dimensional overburden stratigraphy, topographic variability of the buried bedrock surface, shear wave velocity structure, and soil attenuation properties. Surface and borehole seismic methods are particularly suited to provide information on the necessary geotechnical parameters for ground response modeling (Hunter et al. 2002).

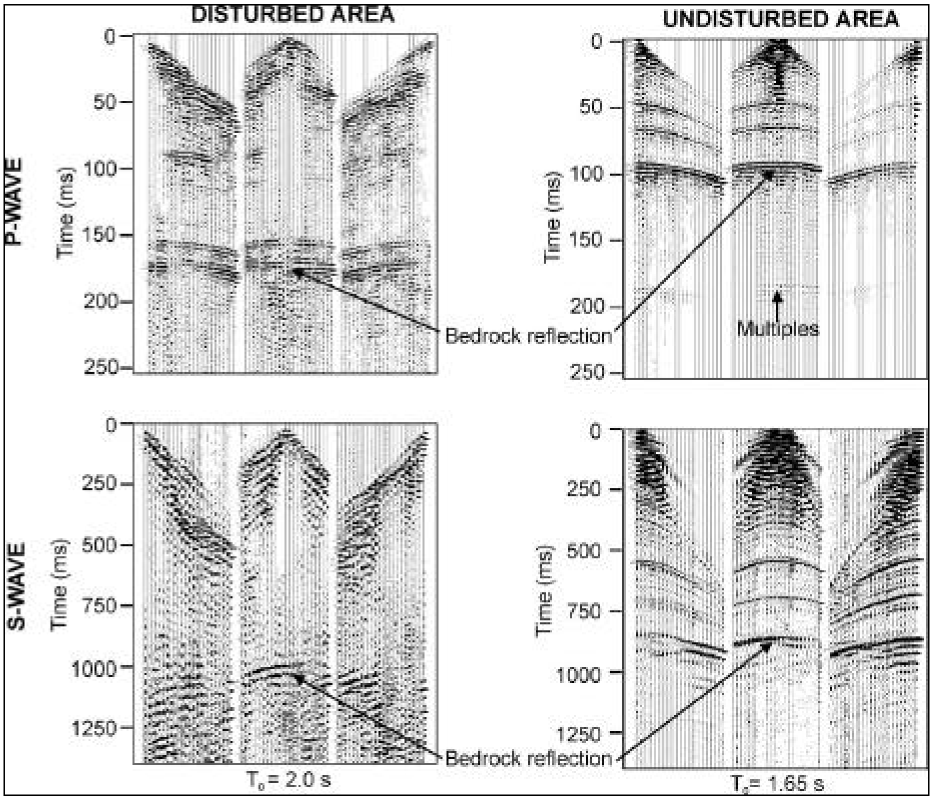

Figure 4. Example P and S wave reflection field recordings for a 24 channel seismic array for two sites in the Lefaivre area showing reflections from stratigraphy within the overburden as well as from the bedrock surface (after Benjumea et al. 2003). The fundamental resonance periods for the sites are computed as T_0= 2 x the two-way S-wave travel time to the bedrock surface. S wave reflection quality is adversely affected by ground surface disturbance.

In the OVLP, seismic reflection and refraction methods have been applied to determine these critical subsurface parameters. Since there was very little existing information on the 3-dimensional overburden structure of the project area (chiefly from widely scattered water wells), over 150 1-dimensional seismic reflection soundings were made to provide regional coverage. Compressional (P) and shear (S) wave reflection and refraction methods were used routinely to establish the depth to firm ground (top of bedrock or glacial till), near surface shear wave velocity (Vs) distribution with depth, average shear wave velocity estimates of the total thickness of unconsolidated overburden, and to compute the fundamental site period for resonance amplification studies. Details on the survey parameters and locations are given in Benjumea et al. (2003). Figure 4 gives an example of P and S reflection seismic quality obtained within and outside the disturbed zones near Lefaivre. From such measurements, maps of overburden thickness and fundamental site periods for the Lefaivre basin were obtained as shown in Figure 5. Thick overburden and large fundamental site periods correlate directly with areas of known surface disturbance.

Recent work with broad-band earthquake monitoring systems has been directed towards ambient seismic noise measurements. The so-called “Nakamura” method measures the horizontal to vertical spectral components of teleseismic noise resulting in spectral peaks associated with the fundamental resonance periods of soft soil sites (Dravinski 1996; Lachet and Bard 1994). Their technique was tested at over 30 sites in the Lefaivre area; the results showed a close correlation between spectral peaks and fundamental site periods predicted from shear wave reflection soundings.

A similar map of overburden thickness has been developed from a combination of water-well, P-wave refraction, and P-wave reflection data for the paleo-landslide area of the Bourget region. As an example of the use of such maps, the interpolated overburden thicknesses at the head-scarps of the paleo-landslides in the Bourget channel were examined at 200 metre intervals for a total length of approximately 34 kilometres. A histogram of the thickness data indicated a strong peak at 43 m thickness, yet the average overburden thickness from all borehole and seismic measurements throughout the survey area (excluding bedrock outcrop locations) was 21 m. Hence, the results suggest that one of the characteristics associated with these paleo-landslides is relatively thick overburden. It is suggested that the soil amplification response to earthquake shaking (due to low Vs values in the Leda clays) may be more pronounced in areas of thicker soils, and that the greater ground shaking during

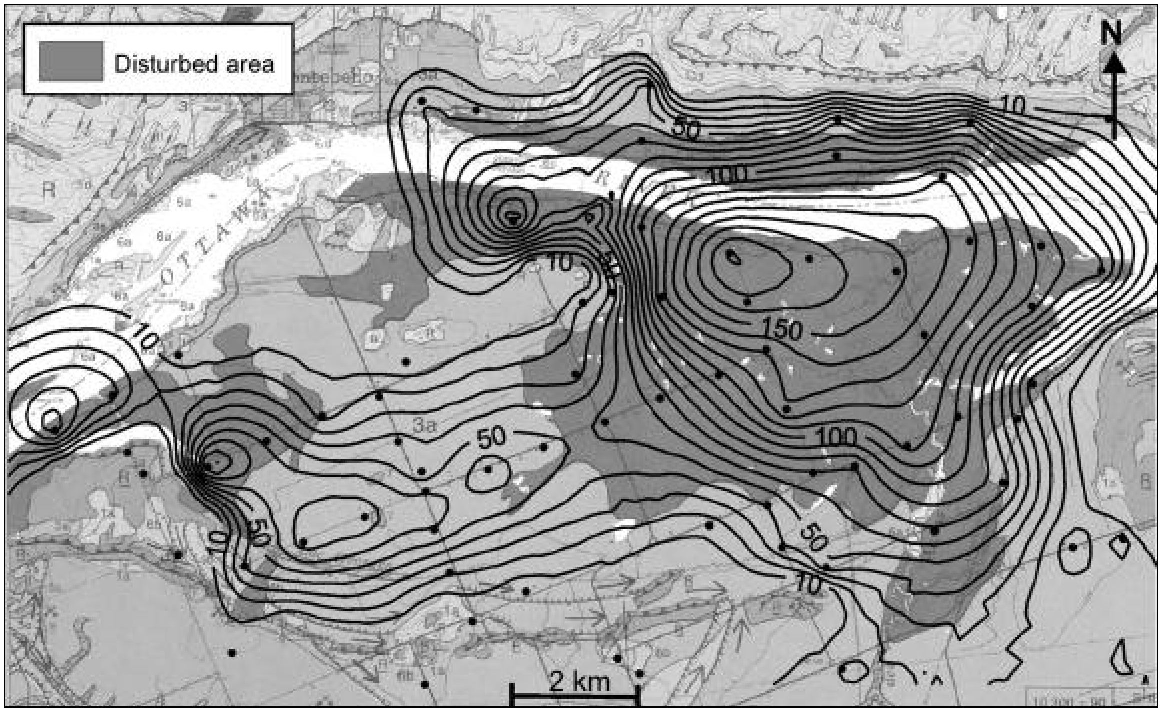

Figure 5(a). Overburden thickness map of the Lefaivre study area from combined water-well and seismic reflection soundings (after Benjumea et al. 2003). Contours are in metres. Note the correlation between “disturbed” ground and thick Champlain Sea sediments.

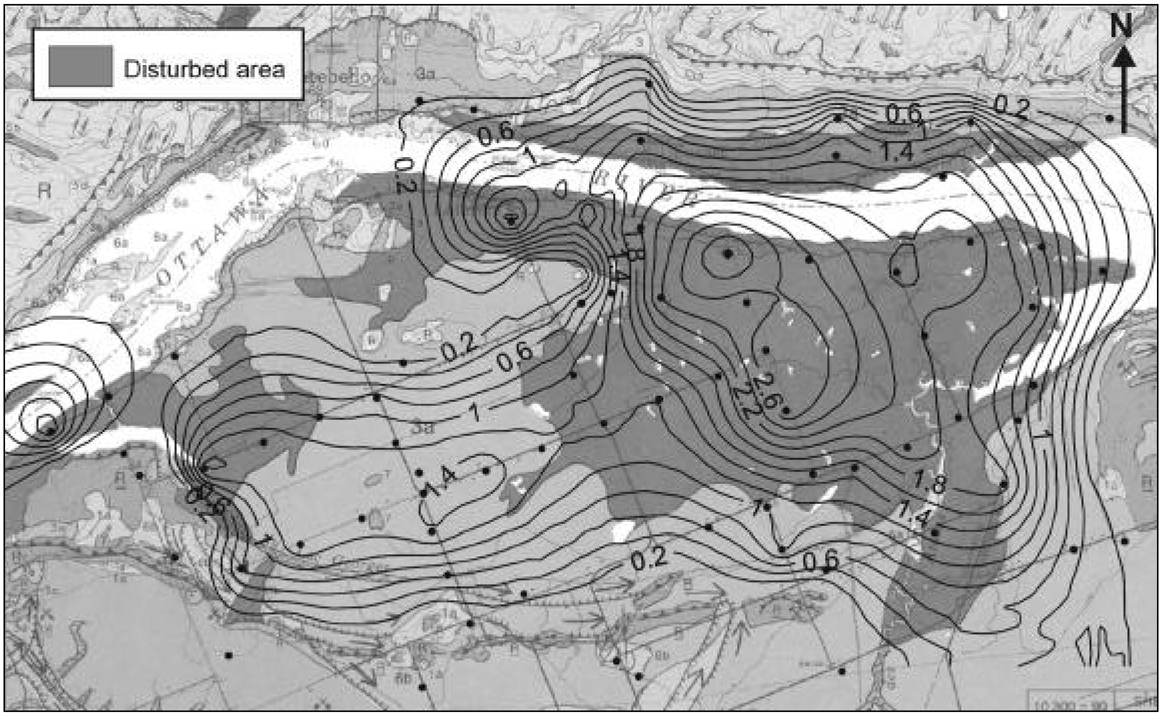

Figure 5(b). Fundamental resonance period variations for overburden sites in the Lefaivre study area. Values are derived from two-way shear wave reflection travel times to bedrock (after Benjumea et al. 2003). Contours are in seconds.

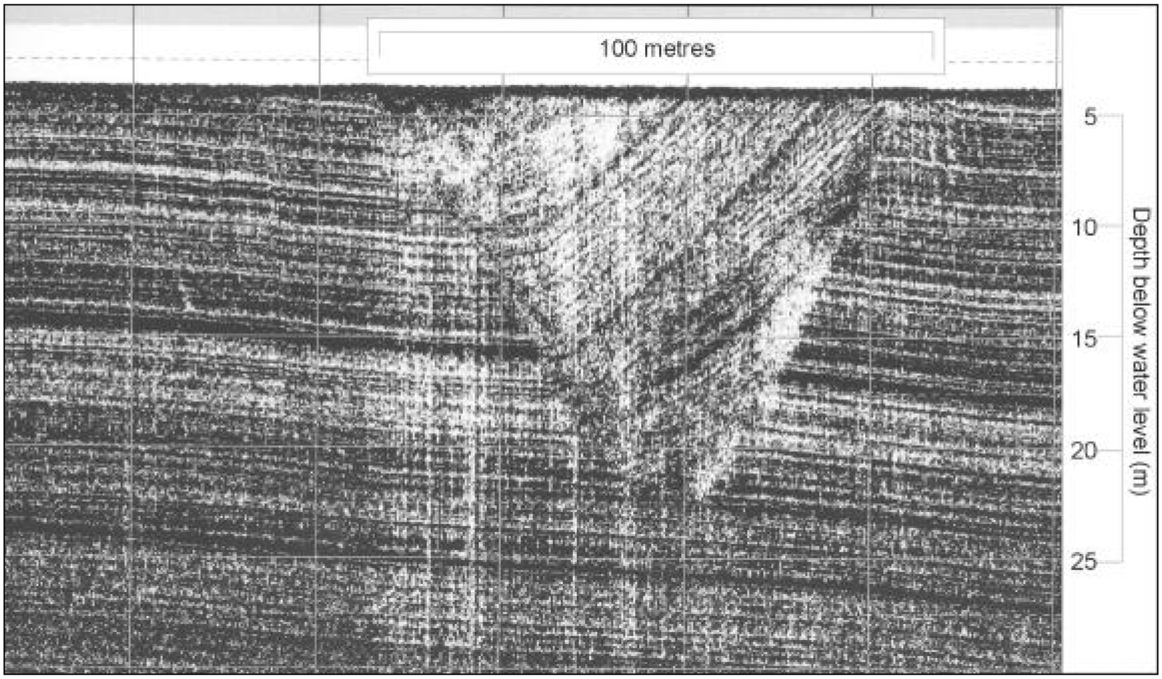

Figure 6. Single channel, high-resolution seismic profile of a rotated block of glaciomarine sediments, near Pt. Filion, in the Ottawa River (Lefaivre survey area). A series of detailed profiles show that layering of the sediments in the block remained largely intact, and that the glide plane is ‘spoon’ shaped. The overall plan view of the block is elliptical, and measures about 100 x 200 m. The vertical exaggeration of this image is 4X.

an earthquake in these areas may have triggered the landsliding.

The ground motion spectral characteristics of earthquake shaking can also be altered by strain-dependent damping within the soil column. Attenuation of high frequency components of ground motion are most prominent in very soft soils such as Leda clay. Although near-surface seismic methods cannot directly address large strain non-linear effects, small-strain attenuation can be measured to obtain initial values for modeling. Several seismic analyses methods have been tested to measure the specific attenuation factor Q (where the damping ratio = 2/Q) using data recorded from surface or downhole shear wave measurements. Preliminary results suggest that the near-surface Champlain sea sediments have low Q values in the range of 10-20, indicating the possibility of significant attenuation of higher (> 1Hz) frequency components of earthquake shaking.

2.4 Sub-Bottom Marine Acoustic Methods

Sub-bottom acoustic profiling was carried out in the Ottawa River in the Lefaivre area in order to examine the river bottom for evidence of continuation of “disturbed” ground mapped on land. For land surveys, under the best of circumstances, high resolution P-wave seismic reflection methods can yield dominant pulse frequencies in the range of 300-500 Hz and yield vertical resolution of acoustic boundaries in the 1 m range. A high resolution compressional wave seismic section across the Lefaivre basin (Benjumea et al. 2003) delineates infra-overburden and bedrock structure and suggests the presence of sediment disruption to a depth of 50 m. However, the near-surface resolution is not high enough to image the disturbance structures. Due to better transmission and coupling characteristics in water, marine acoustic methods can yield resolutions in the decimeter range. In this project area, surveys were conducted using both pulsed, and “chirp” (swept frequency/de-convolved) acoustic sources working over the effective frequency range of 2 kHz and 28 kHz. Regional traverses of the Ottawa River confirmed that deformed sediments were present beneath the river bed and associated only with the zones of “disturbed” ground on land. They suggest a possible catastrophic event. Both folding and faulting of Champlain Sea sediments could be observed to at least a depth of 30 m below river bottom. In some places, a series of closely-spaced traverse lines were run to define structures. Figure 6 shows an example of a rotational displacement of a layered Leda clay sequence. A 3-dimensional analysis developed from the traverse lines over this feature (Douma and Aylsworth 2001) indicated an “in-situ” rotational displacement of sub-bottom sediments with truncation due to subsequent erosion of the river bed. The horizontal size of the feature is comparable to the lower relief areas on shore where inclined bedding have been observed. These acoustic profiling results, with such excellent horizontal and vertical definition of disturbed features, are a significant contribution towards developing models for the process of surface disturbance onshore.

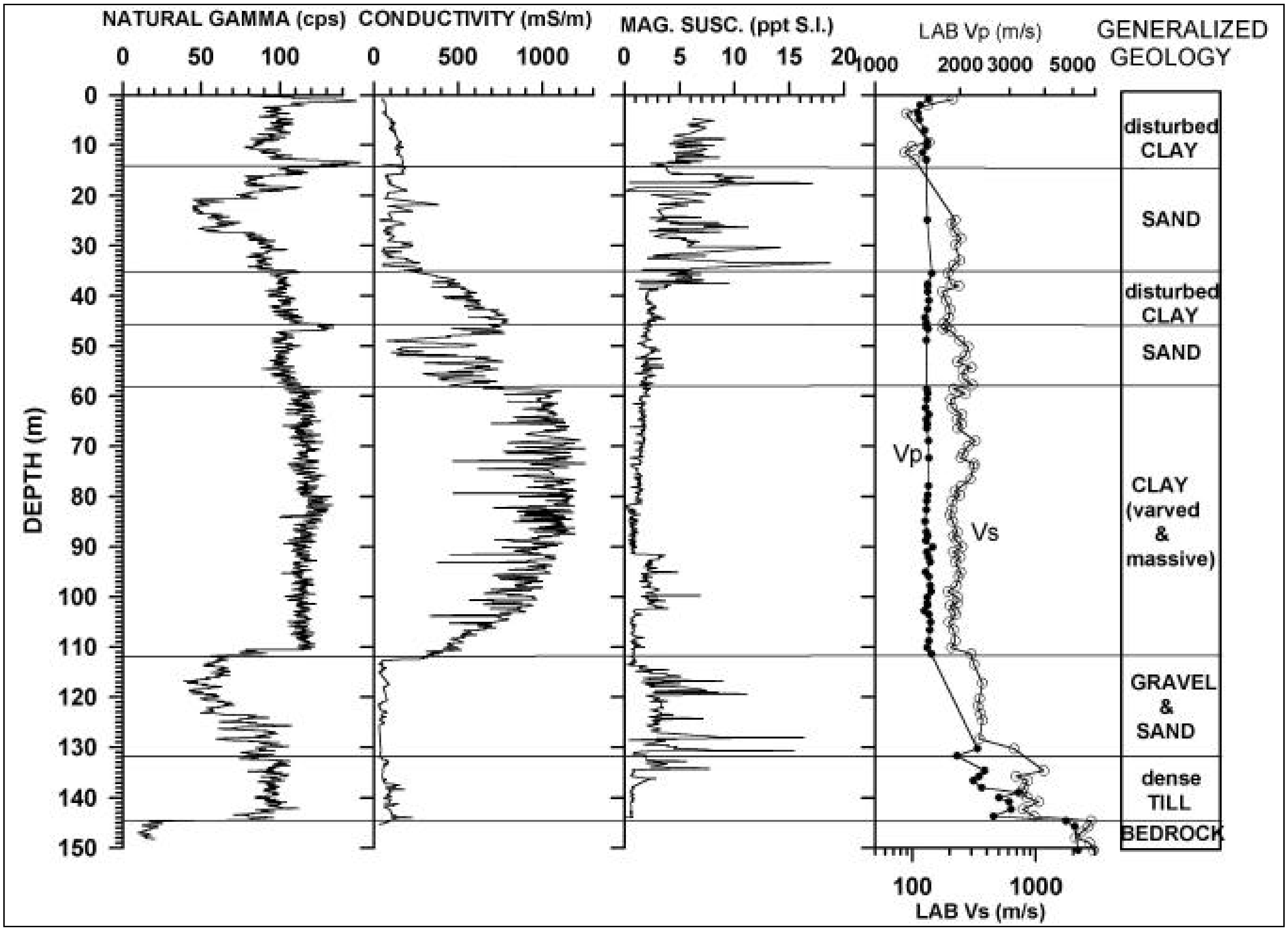

Figure 7. Combined in-hole and laboratory geophysical logs for GSC borehole JA02-4 in the central portion of the Lefaivre sediment basin. Note the presence of sand layering at shallow depths. Holocene Leda clay and sand are associated with very low shear wave velocities in contrast to the higher velocities of the basal Pleistocene materials.

2.5 Borehole and Laboratory Geophysical Testing

For most GSC borehole drilling programs in surficial deposits, provision is routinely made for geophysical logging and, as well, for specific geophysical tests of core samples in addition to geotechnical testing. Such information can provide detailed physical property information which can be used as a guide in geological logging and sub-sampling, as well as providing ground truth for surface geophysical measurements (e.g. seismic and electrical methods). Commonly, for such borehole completions, plastic casing, with a minimum 6.35 cm inside diameter, is inserted in the open hole and grouted to the formation from surface down to and into bedrock prior to logging. Typical geophysical borehole logs consist of the conventional ones such as natural gamma, inductive electrical conductivity, magnetic susceptibility, gamma-gamma density, and temperature gradient, as well as less-well known techniques consisting of down-hole seismic P and S wave velocity measurements. Within the current survey area, all GSC boreholes were continuous cored, and sub-sampled for laboratory measurements of engineering properties as well as P and S velocity measurements. In addition, resistivity and magnetic susceptibility measurements were made at 15 cm intervals along the split core.

Figure 7 is a compilation of some of the geophysical borehole logs and laboratory measurements from borehole JA4, in the central basin area of the Lefaivre disturbed zone(Fig. 1b), along with a generalized geological log based on continuous coring. The natural gamma log is used as a qualitative estimate of average grain size of materials, with fine-grained silts and clays yielding a high count rate. The electrical conductivity log shows a typical curve for the Champlain sea sediments with lower electrical conductivity in the upper, ‘leached’ clay and increasing conductivity (increasing pore-water salinity) with depth, and a “roll-over” towards the base of the Holocene indicating deposition in a less saline environment. The upper two sand units, whose depositional environment are associated with bursts of freshwater, also have lower electrical conductivity. The magnetic susceptibility sonde responds primarily to ferromagnetic materials (e.g. magnetite) which are generally associated with coarser-grained sediments. Both the P and

S wave velocity logs indicate strong velocity contrasts between the Champlain Sea sediments and the older gravels, till and bedrock below. Such direct measurements of these velocity contrasts confirm the measurements made from surface seismic surveys which indicated the possibility of earthquake ground motion amplification and resonance effects. The level of lithological detail which can be interpreted from these combined logs suggests that they can be used in place of continuous coring (e.g. intermittent sampling only) resulting in a substantial decrease in borehole drilling and logging costs.

3. CONCLUSIONS

Applications of various seismic and electrical geophysical techniques have established the geological/geotechnical framework for landslide studies in the OVLP areas. Beneath the “disturbed” zones of Lefaivre, Treadwell, and Wendover lie unusually thick Champlain sea sediments which fill significant basin-like depressions of the bedrock surface. Such thick sequences of low shear-wave velocity sediments can lead to broad-band amplification of earthquake ground motion. Although attenuation of high frequency spectral components may occur due to the high attenuation properties, significant low frequency amplification may result (over a 4 month monitoring program, x 6 amplification has been recorded for small quakes, M. Lamontagne, pers. comm. 2002). In addition, because of thick sequences of sediments (especially in basin areas) and low shear wave velocities, resonance amplification of earthquake ground motion in the 0.3 to 1 Hz range could also occur (> 8 times amplification at the fundamental site period).

Currently, one-dimensional and two dimensional ground response modeling is being conducted for the Lefaivre basin and the Bourget paleo-landslide areas using information derived from these geophysical surveys, as a first attempt to estimate earthquake surface motions and to explain the observed features. At this time, it is suggested that significant earthquakes of the order of M = 6.5 within a radius of 40- 60 km of these field areas might have occurred in the past. These events may have generated ground motion amplification sufficient enough to trigger paleo-landslides and develop liquefaction phenomena in sand bodies within the clay, which could result in the observed surface disturbance of the Champlain Sea sediments (Benjumea et al. 2003). In future, more complete 3-dimensional ground motion modeling, utilizing earthquake-induced surface wave generation, may further help to explain the relationship between disturbed ground and geotechnical/geological/geophysical parameters within the study areas of the OVLP.

Finally, the geophysical techniques have been shown to offer rapid, cost-effective, and non-invasive tools that can be of valuable assistance in assessing regional hazards. Methodologies developed for delineating subsurface conditions and modeling of ground response to earthquake shaking at Lefaivre can be applied to other high-hazard areas within the St. Lawrence Lowlands.

4. ACKNOWLEDGMENTS

The authors wish to thank S.E. Pullan for insightful comments on this manuscript.

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