A GEOPHYSICAL INVESTIGATION OF THE GEOLOGICAL CONTROLS ON LANDSLIDING AND SOFT DEFORMATION IN SENSITIVE MARINE CLAY NEAR OTTAWA

J.M. Aylsworth, Geological Survey of Canada, Ottawa, Ontario, Canada
J.A. Hunter, Geological Survey of Canada, Ottawa, Ontario, Canada

ABSTRACT
Although most critical factors controlling sensitive marine clay landslides are known in theory, to date little was known of the actual geospatial distribution of these parameters or the interaction of these distributions in the Ottawa area. In two study areas near Ottawa, 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 be rapid and cost-effective tools that provide regional-level reconnaissance surveys for landslide hazard assessment and contribute to modeling ground response to earthquake shaking.

RÉSUMÉ
Bien que les facteurs critiques contrôlant les glissements de terrains dans les argiles sensibles soient connus en théorie, a ce jour la distribution géographique de ces paramètres ou de l'interaction de ces distributions est peu connue dans la région 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.

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.

A regional geological, geotechnical and geophysical investigation of the critical geological controls on landsliding and surface deformation in Leda clay was conducted in the Ottawa Valley near Ottawa. Although most critical factors controlling sensitive clay landslides are known in theory, to date little was known of the actual geospatial distribution of these parameters or the interaction of these distributions in the Ottawa area. 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. Several critical soil conditions were mapped over a large area, and the most vulnerable areas identified, using geophysical survey techniques which 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 to 1) a regional assessment of geological factors and interactions controlling earthflow locations in the Bourget area and 2) a detailed investigation of the earthquake-induced, soft-sediment deformation and lateral spreading in the Lefaivre area (Fig. 1b). The rational, methodology and results of each technique are briefly summarized and examples are presented.

The Bourget study area (Fig. 1b) is characterized by 2-10 m of sand overlying 20-45 m of Leda clay. Broad paleochannels of the proto-Ottawa River, now abandoned, cut 20-30 m into these sediments. Most modern earthflows occur along a critical 25 km stretch of the South Nation River which experiences a large landslide recurrence interval of 20-25 years (Lawrence et al. 1996). The most recent occurred at Lemieux in 1993

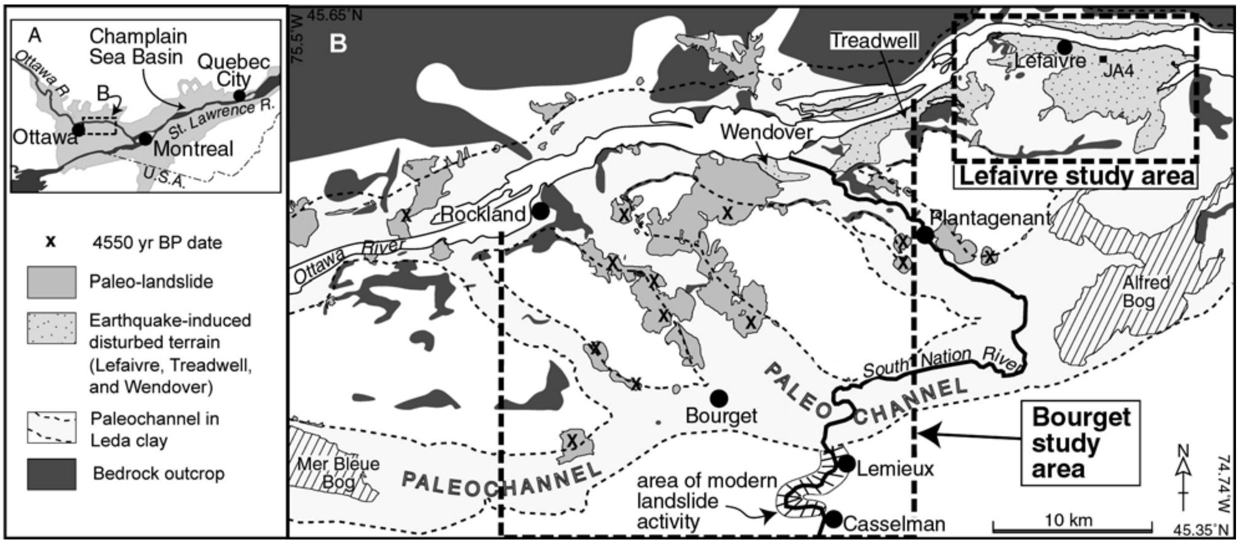

Figure 1. (a.) Location of the Champlain Sea Basin in eastern Canada. (b.) Map of study areas showing paleochannels, paleo-landslides and areas of earthquake-induced disturbance.

(Evans and Brooks 1994). The paleochannel slopes are characterized by numerous, very large, prehistoric earthflows that coalesce and overlap, forming vast failure complexes. Evidence that most paleo-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; Aylsworth and Lawrence 2003). Yet in the immediate area, other slopes with similar topography remain unaffected. In part, the purpose of this investigation was to determine why some slopes failed and others stood in the face of this shaking event. 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 electrical, ground probing radar and seismic geophysical surveys augmented with borehole information.

The Lefaivre study area (Fig.1b) includes 46 km^2 of severe ground deformation, characterized by irregular, hummocky topography and severely deformed sediments. Local relief varies from 3 to 8 m and individual hollows are 100-300 m in diameter. Sections and borehole cores reveal disturbances ranging from brittle shear to liquefaction to a depth of 50 m. Sand dykes and blows occur at surface. The disturbance has been attributed to a massive earthquake, *ca*. 7060 yr BP, which produced strong ground motion amplification effects in thick (150 m) soft soils, resulting in severe near-surface sediment deformation, irregular subsidence, and possibly some lateral spreading in an otherwise-flat erosional plain in marine sediments (Aylsworth and Lawrence 2003). Estimates of earthquake magnitude range from a minimum magnitude of 6.5, with the epicentre occurring within a distance of 40- 60 km (Benjumea et al, 2003) to a low 7 magnitude (J. Adams, pers. comm.). In the Lefaivre area, 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.

2. GEOPHYSICAL APPLICATIONS

2.1 Electrical Methods

Although electrical resistivity of most unconsolidated 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), in marine deposits, 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 local borehole geophysical measurements. In this study, electrical resistivity measurements were used to map the sub-surface occurrence and distribution of saline and non-saline sediments and therefore to infer possible sensitivity of clay throughout the Bourget study area (Figs. 2 and 3). Low resistivity values (high conductivity and salinity) are associated with zones of stable clay. Higher resistivities generally correlate with low salinities that reflecting the leached clay conditions underlying areas of sand cap. In many cases, where salt-leaching has occurred, clay conditions are “sensitive”. Laboratory testing of core from GSC boreholes in the area have confirmed both the variations in pore water salinity as well as the associated variation in clay sensitivity. Both the paleo- and modern landslides occur in zones exhibiting higher resistivity values. However zones with shallow bedrock or thick overlying sand may have similar high resistivities, and more detailed investigations of the anomalous areas using other methods (ERI, GPR) are necessary.

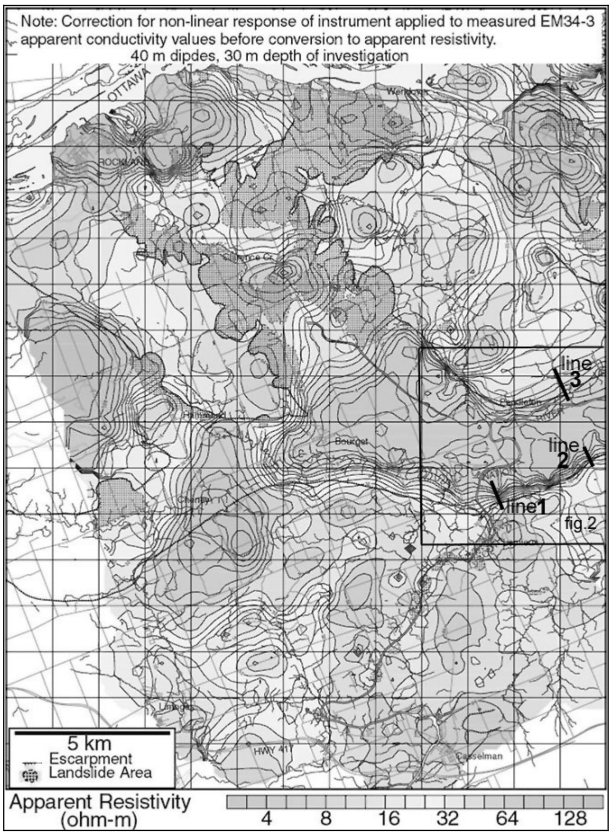

Figure 2. Average soil resistivity (from ground surface to a depth of 30 m) in the Bourget area. Constructed from EM-34 conductivity soundings at 800 m intervals along. roads. Courtesy of T. Calvert. Location of figure 3 and lines of figure 4 are indicated.

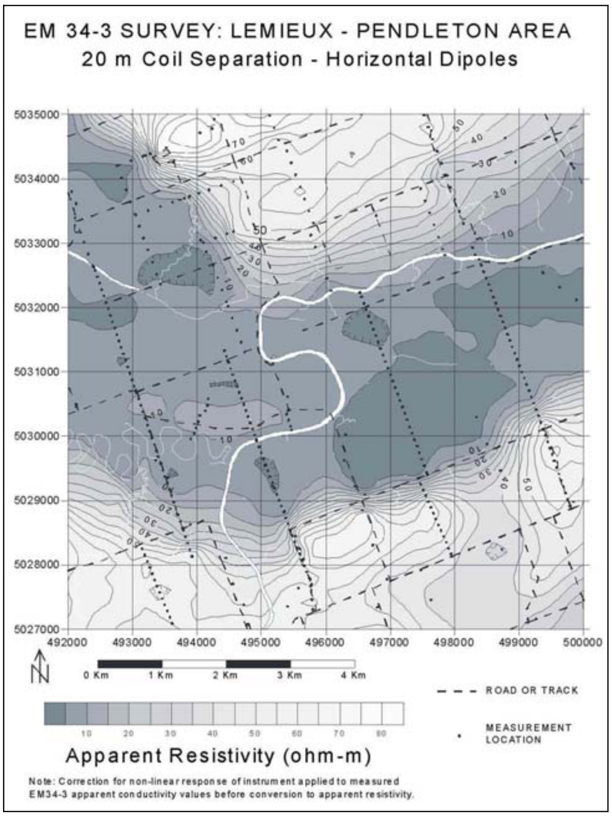

Figure 3. Average soil resistivity to a depth of 15 m. Low values are associated with stable Leda Clay. Higher values correlate with the presence of a sand cap and low saline (leached) clay conditions.

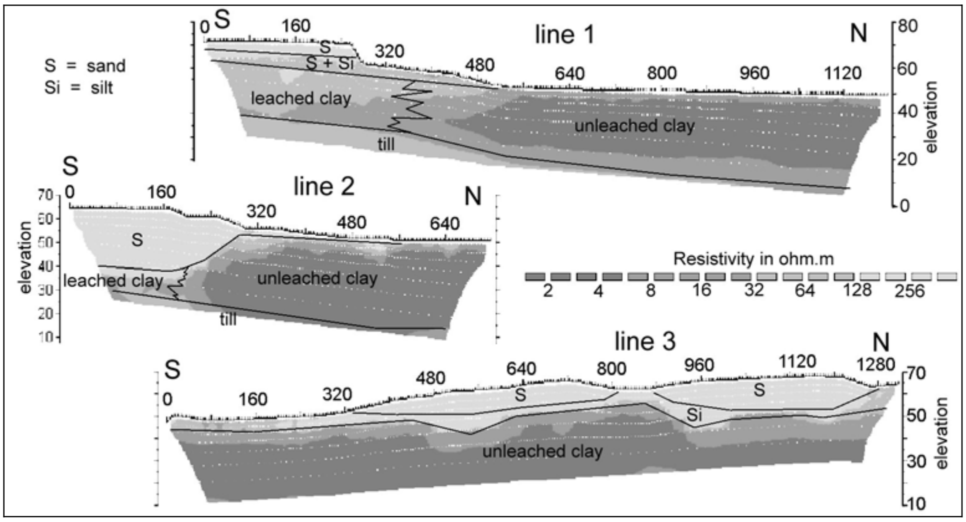

Fig. 4. ERI modeled with topography. Geological interpretation shown. Courtesy of T. Calvert.

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 these surveys can be considered as a cost-effective preliminary phase in regional studies of the stability of Leda clays. Other electrical methods such as DC methods using multielectrode earth-contact or capacitive-coupled arrays 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.

Electrical resistivity imaging (ERI) was used for high-resolution investigations of specific slopes (Fig. 4). Two-dimensional modeling of ERI of a slope near the 1993 Lemieux landslide indicates that only 2-3 m of sand overlies leached, sensitive clay. Therefore over 15 m of clay is exposed in the slope and there is a potential for movement. In contrast, 4 km away, ERI along lines 2 and 3, which occur in similar topographic conditions, revealed that the sand cap thickness is 15-20 m and little clay outcrops in the slope, thus explaining the absence of landslides in these locales. A strong resistivity contrast can be seen in line 2 between unleached clay underlying the paleochannel floor and leached clay underlying the sand terrace.

2.2 Ground Penetrating Radar

Ground probing radar (GPR) surveys were used in several locations in the Bourget area 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 (Fig. 5). 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, virtually eliminating landslide hazard in those zones. GPR was

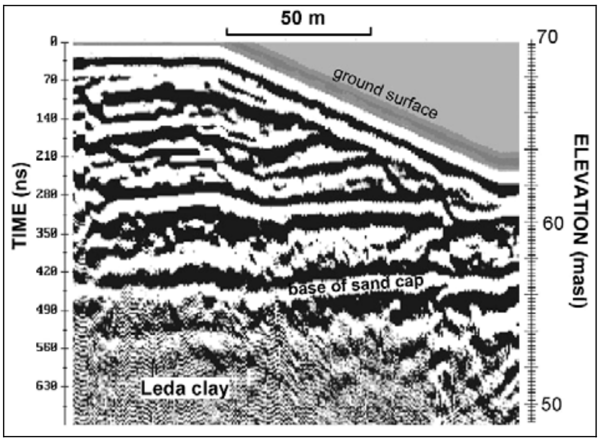

Figure 5. GPR profile across stable edge of the Bourget paleochannel showing sand cap over Leda clay. Although electrical methods indicated that the clay has been leached, the base of the sand cap is below the channel floor, so no landslide hazard exists at this site.

shown to provide a reliable, non-invasive tool in the absence of borehole coverage.

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. Major factors affecting ground motion response to earthquake shaking in soft soil sites include three-dimensional overburden stratigraphy, topographic variability of the buried bedrock surface, shear wave velocity structure, and soil attenuation properties. Seismic reflection and refraction methods have been applied to determine these critical subsurface parameters.

Over 150 1-dimensional seismic reflection soundings were made to augment sparse data from water well records. 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, and average Vs estimates of the total thickness of soft sediment, and also to compute the fundamental site period for resonance amplification studies. Details on the survey parameters and locations are given in Benjumea et al. (2003).

The quality of P and S reflection seismic data obtained within Leda clay is excellent (e.g. Fig. 6). From such measurements, maps of overburden thickness and fundamental site periods for the Lefaivre basin were obtained (Fig. 7a). Thick overburden, infilling a small, deep (150 m) bedrock basin, and large fundamental site periods correlate directly with areas of known surface disturbance.

A high resolution P 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 (Fig. 8). However, the resolution (~1 m) 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. Sub-bottom acoustic profiling in the Ottawa River confirmed that both folding and faulting of marine sediments could be observed to at least a depth of 30 m below river bottom and that deformed sediments seen offshore were restricted to zones adjacent to onshore "disturbed" terrain. Figure 9 shows an acoustic profile of an *in-situ* rotational displacement in layered marine sediments with subsequent truncation by river

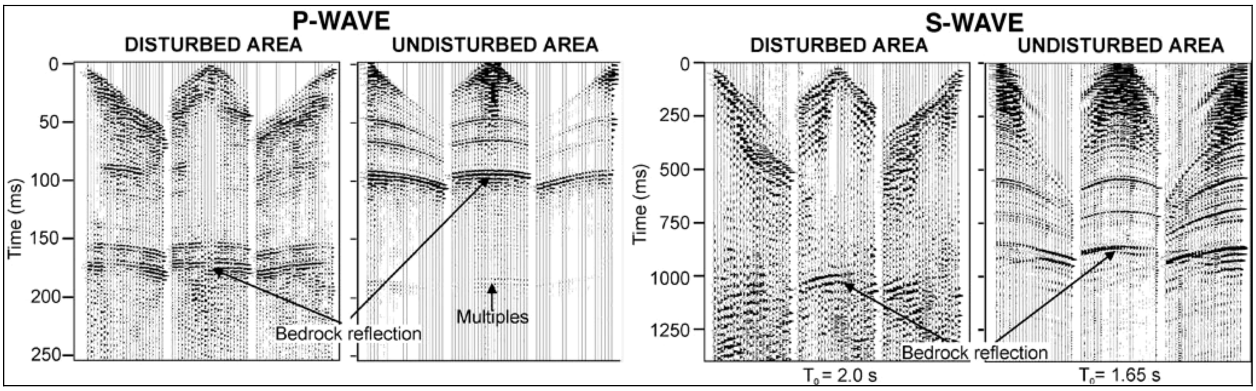

Figure 6. Example P and S wave reflection field recordings for a 24 channel seismic array for two sites in the Lefaivre area showing reflections from stratigraphy within the overburden as well as from the bedrock surface (after Benjumea et al. 2003). The fundamental resonance periods for the sites are 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.

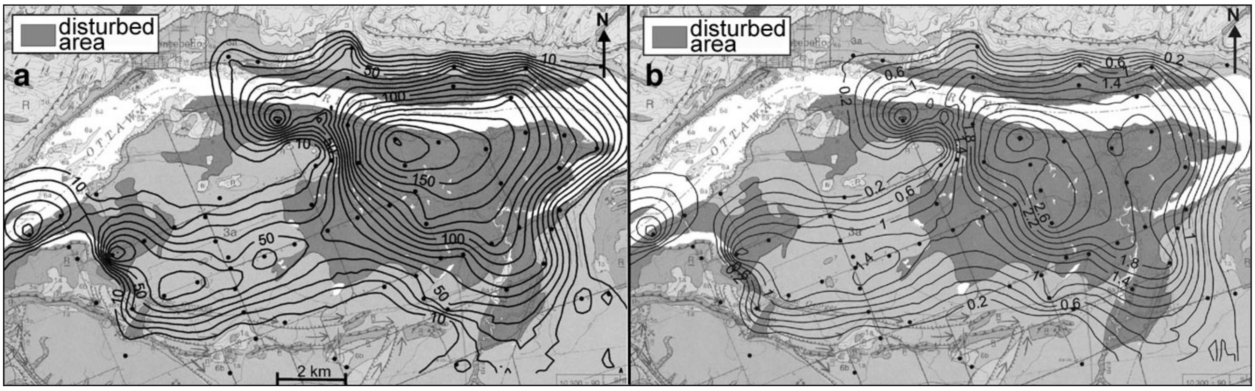

Figure 7 a) Overburden thickness map of the Lefaivre area from combined water-well and seismic reflection soundings. Contours in metres. Note correlation between "disturbed" ground and thick overburden. b) Fundamental resonance period variations derived from 2-way shear wave reflection travel times to bedrock. Contours in seconds. (after Benjumea et al. 2003)

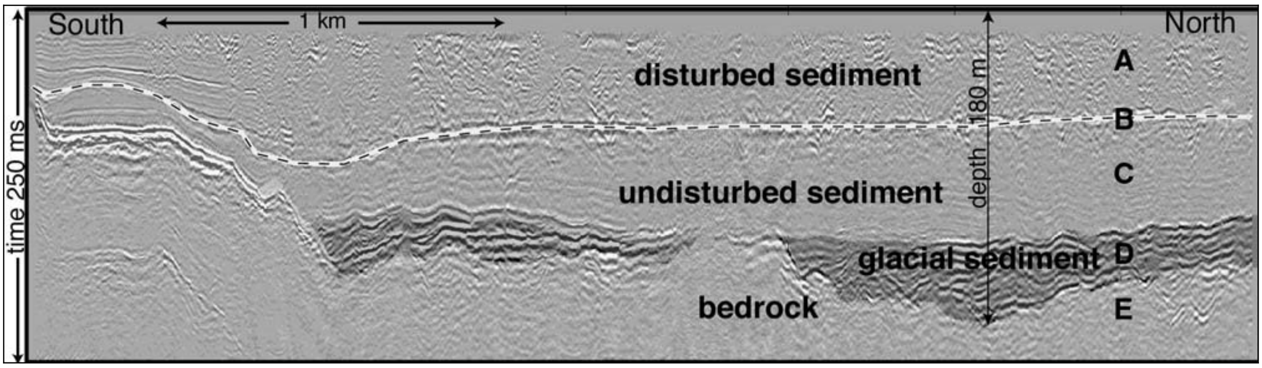

Figure 8. P wave seismic section across the Lefaivre basin. Unit A is disturbed sediment with poor record. Line B is a strong reflector that is interpreted to be the base of disturbance over most of the section. (after Benjumea et al. 2003.)

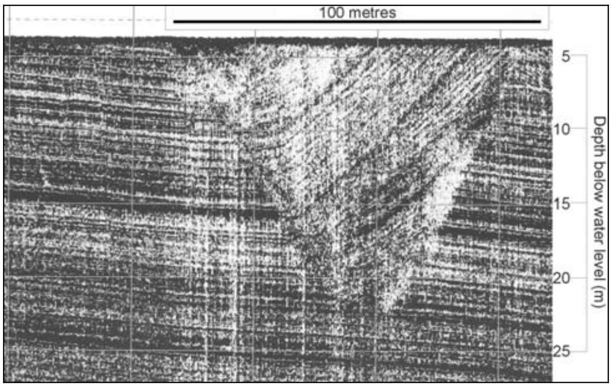

Figure 9. Single channel, high-resolution seismic profile of a rotated block of marine sediments. Detailed profiles across the feature show that the glide plain is spoon shaped and overall plane view is eliptical and measures about 100 x 200 m. VE: 4x.

erosion. The horizontal size compares with surface hollows with inclined bedding seen onshore. These acoustic 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.

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 shown in Figure 7b.

P-wave refraction and reflection data were also used to develop a map of overburden thickness for the paleo-landslide area of the Bourget area (Fig. 10). 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. This suggests that thickness of overburden may be a critical factor in earthquake-induced landsliding.

During earthquake shaking, thick soft sediments (low Vs) promote broad-band amplification of ground motion due to large near-surface shear wave velocity gradients within the soil column. There may also be resonance amplification at specific earthquake frequencies due to significant seismic impedance contrasts within the overburden or at the overburden-bedrock boundary. The ground motion spectral characteristics of earthquake

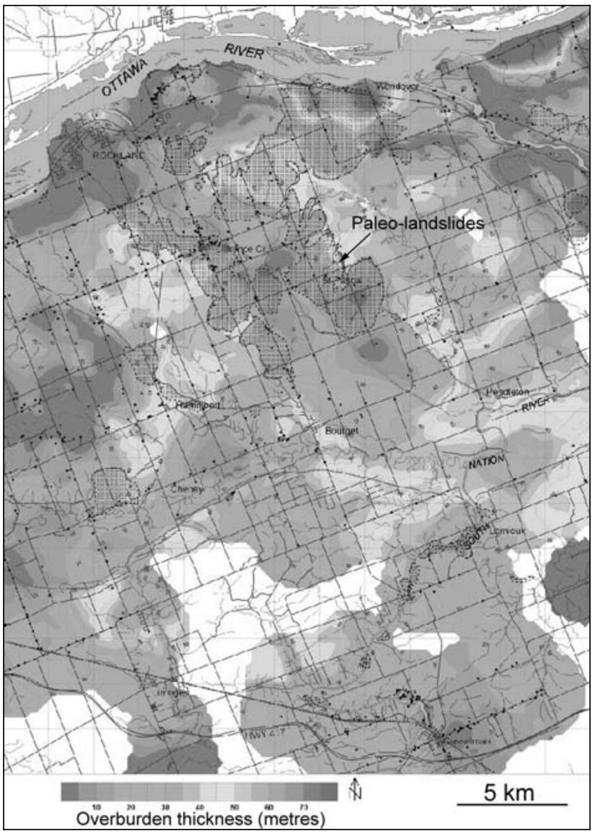

Figure 10. Map of overburden thickness for the Bourget area developed from a combination of water-well records and P wave refraction and reflection data.

shaking can 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 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. Results can provide detailed physical property information which can be used as a guide in geological logging and sub-sampling, and as high-resolution data between sub-samples, as well as providing ground truth for surface

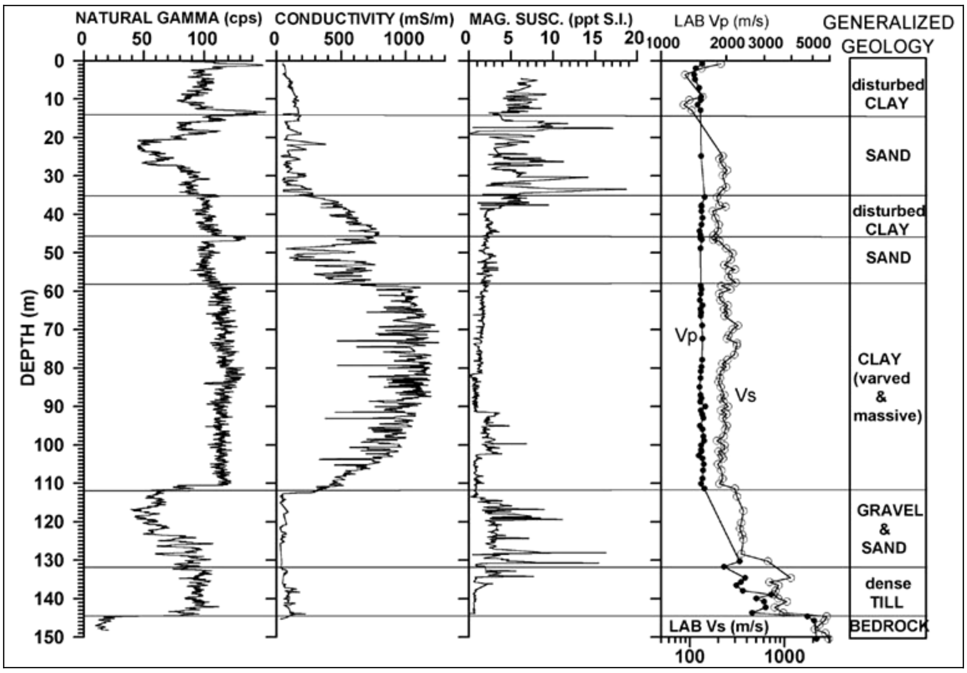

Figure 11. Example of geophysical logs for GSC borehole JA4. Holocene sediments have very low shear wave velocities in contrast to the higher Vs of the basal Pleistocene materials.

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 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 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 11 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 offers a qualitative estimate of average grain size of materials, with fine-grained silts and clays yielding a high count rate. The magnetic susceptibility sonde responds primarily to ferromagnetic materials (e.g. magnetite) which are generally associated with coarser-grained sediments. The electrical conductivity log shows a typical curve for the Champlain sea sediments with lower electrical conductivity in the upper 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. 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 Ottawa area. 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, times 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 a minimum magnitude of 6.5 within a radius of 40- 60 km of these field areas occurred in the past. These events generated ground motion amplification sufficient enough to trigger paleo-landslides and to 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 the geotechnical, geological, and geophysical parameters and the disturbed ground.

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 areas of similar geology and greater population within the St. Lawrence Lowlands.

4. ACKNOWLEDGMENTS

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