BOREHOLE INVESTIGATION OF EARTHQUAKE-INDUCED SOFT-SEDIMENT DEFORMATION AT LEFAIVRE; A CONTRIBUTION TO THE OTTAWA VALLEY LANDSLIDE PROJECT

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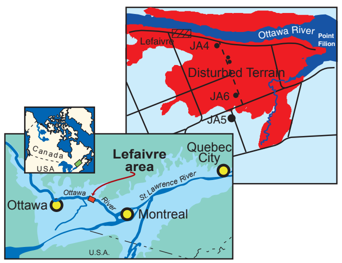
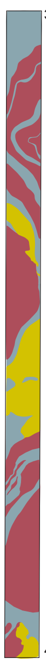
Abstract

A 46 km2 area near Lefaivre, Ontario, east of Ottawa, shows evidence of severe near-surface deformation of Champlain Sea marine sediments, lateral spreading towards the Ottawa River, and irregular surface subsidence on an otherwise flat erosional plain. Geological evidence suggests this disturbance was caused by a large (≥6.5 M) earthquake about 7060 yr BP. Seismic surveys have mapped the existence of a small deep bedrock basin (max. depth 180 m) underlying the disturbed area. Earthquake-induced ground motion amplification and resonance effects caused liquefaction of the buried saturated sand bodies, leading to loss of shear strength, deformation, and possible liquefaction of the clay.

Three boreholes were drilled through thick Quaternary sediments to bedrock. Borehole JA4 is in the deepest part of the bedrock basin where surface disturbance is greatest. Borehole JA6 is near the edge of the disturbed area where topographic expression is muted. Borehole JA5 lies 1 km outside the disturbed area. Continuous core was collected, logged and tested for geotechnical and geophysical parametres. The boreholes were cased for downhole geophysical measurements.



39.9 m



40.4 m

grey clay
red clay
fine sand

Geological Description

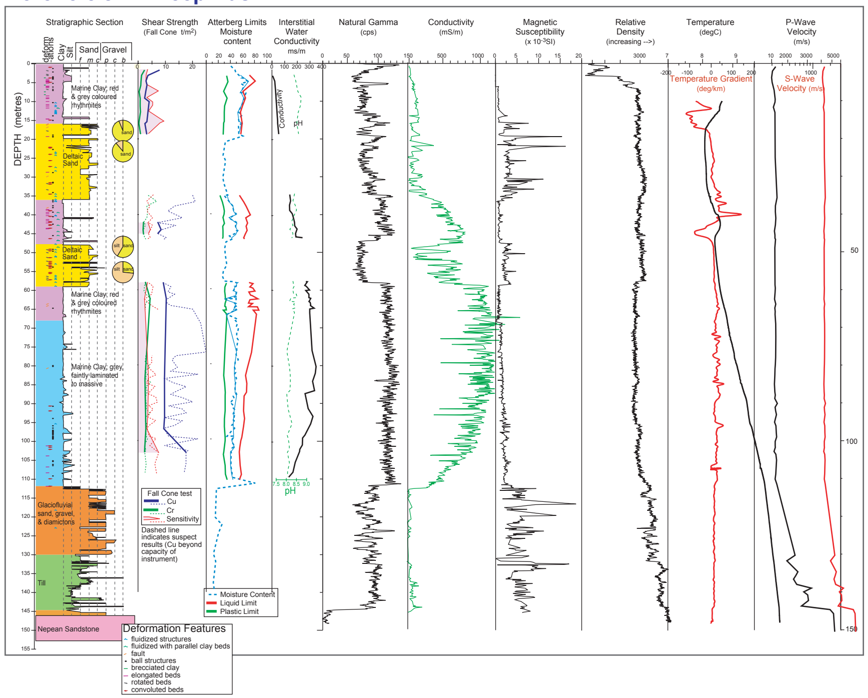
Within the deep borehole (JA4) two significant units of saturated, fine to medium sand occur within the thick marine sequence. Within the sand layers, liquefaction, intrusion and other fluidized structures were found, although lengths of core with intact fluvial bedding also exist. Within the clay units above and between these sand units, evidence of extreme sediment deformation ranges from brittle shear to extreme plastic deformation and liquefaction. Deformation decreases in intensity with depth below 35 m, but extends to > 50 m depth in the deep borehole.

Deformation is less, both in depth and intensity, in the shallower borehole (JA6), in which the two sand layers are minor (<0.5 m thick). Outside the disturbed area (borehole JA5), bedrock is closer to the surface, sand layers absent, and no sediment deformation exists.

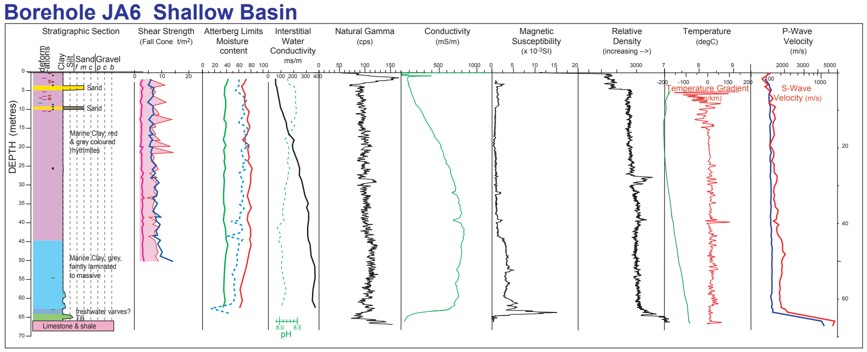
Example of Deformation

Borehole JA4 (run 27)
In the upper clay unit, at 40m depth, a 5 cm wide sand dyke extended through a 2.5 m length of core, and the surrounding red and gray clay layers were vertically inclined, convoluted, and folded, — dragged upward with the dyke.

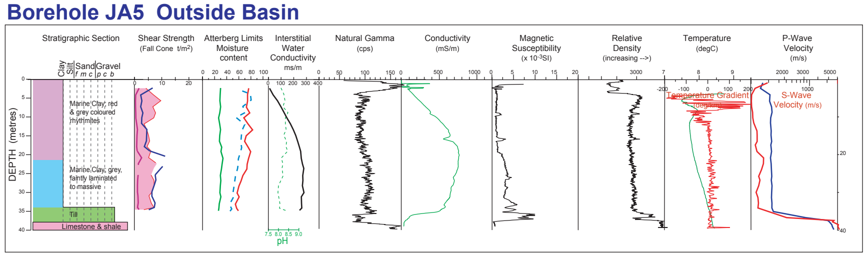
Borehole JA4 Deep Basin



Borehole JA6 Shallow Basin



Borehole JA5 Outside Basin



Geophysical Techniques

Natural gamma log

The natural gamma log is used as a qualitative estimate of average grain size of materials, with fine-grained silts and clays generally yielding a high count rate and sand and gravel generally yielding a low count rate. Gamma radiation is measured, using a sodium iodide scintillation detector, from the earth material immediately surrounding the borehole (out to a distance of approximately 30 cm from the sonde).

Spectral gamma-gamma density log

Density variations are relative (non-calibrated) and values are given in units of count rate (e.g. high count rate is equivalent to low density). In overburden, the tool is run in a small diameter PVC casing.

Magnetic susceptibility log

The magnetic susceptibility sonde responds primarily to ferromagnetic materials (e.g. magnetite) which are generally associated with coarser-grained sediments. In overburden, the magnetic susceptibility can help identify layer boundaries (e.g. clay vs sand) and, in some cases, help identify differing origins of similar materials (e.g. magnetite-rich sand).

Electrical conductivity log

The electrical conductivity of a porous unconsolidated material is a function of the combined electrical conductivity of the matrix and the pore fluid. If the pore fluid conductivity is low (such as in the water in the pore spaces) then the bulk conductivity mainly reflects that of the matrix material (eg. sand vs clay). If, however, the pore fluid is highly conductive (e.g. saline water) and porosity is 40-50%, then the bulk conductivity mainly reflects that of the pore fluid, and the conductivity differences between clay and sand may be subdued. In Champlain Sea sediments, high or low conductivity values are associated with presence or absence of saline pore water, and are correlatable with stable or "sensitive clay" conditions.

The electrical conductivity logs show typical curves for the Champlain Sea sediments with lower electrical conductivity in the upper, 'leached' clay and increasing conductivity (increasing salinity) with depth, and a "roll-over" towards the base of the Holocene indicating deposition in a less saline environment. In JA4, the upper two sand units, whose depositional environment are associated with bursts of freshwater, also have lower electrical conductivity.

Induction electromagnetic (EM) conductivity loggers do not require contact with the formation or fluid in the borehole. A high frequency EM signal is transmitted from and received by two coils in the sonde. Conductivity averages a large volume of material around the sonde, the extent of which is governed by the inter-coil spacing. Sondes are relatively insensitive to near effects (such as change in hole size or saline drilling fluids) and most of the conductivity response comes from 15-100 cm out from the tool. At relatively low conductivities, magnitude of the induced EM field is proportional to formation electrical conductivity. At high formation conductivities, >200 mS/m, response is non-linear (measured values 20% less than actual ones), and post-acquisition corrections are necessary.

Temperature and temperature gradient logs

Absolute temperature can provide regional variations of the geothermal gradient, which is affected by thermal conductivity variations and near-surface thermal disturbances due to water-bodies, insulation effects of ground cover etc.

Thermal gradients can be used to determine the presence of small thermal disturbances in the formation resulting from flow of water within a formation. These effects can commonly be associated with changes in lithology related to changes in permeability.

Seismic logs

Compressional (P) and shear wave (S) velocities in unconsolidated formations can be used to identify moisture content (top of water table) and strengths of materials, and to provide qualitative estimates of over-consolidation. These parameters are also used in ground-response modeling due to earthquake shaking where (initial) small strain estimates of shear modulus and Poissons ratio are required.

P-wave velocity values can yield a qualitative estimate of material type and geological history. For normally consolidated sediments of Holocene age, the P-wave velocity range is only slightly greater than water (1460 m/s); whereas, in older,overconsolidated sediments (e.g. Pleistocene glacial deposits), velocities can vary directly with consolidation and grain-size to values exceeding 4000 m/s.

In Champlain Sea sediments, unusually low S-wave velocities exist in the near-surface sediments, indicating low shear moduli. Shear wave velocities are sensitive to loading effects and significant increase of velocity can be seen with depth. On the other hand, S-wave velocities are relatively insensitive to soil type (e.g. sand or clay). Small-strain shear wave velocities can be used directly in calculations for earthquake ground motion amplification. The presence of large near-surface shear wave velocity gradients can yield substantive amplification. The presence of large velocity contrasts across geological boundaries (e.g. the Holocene-Pleistocene boundary) can also trigger earthquake resonance effects at one (or more) frequencies, a major factor in some building construction practises (e.g. high-rise buildings, bridges, towers, etc).

Both the P and S wave velocity logs indicate strong velocity contrasts between the Champlain Sea sediments and older gravels, till and bedrock. 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.

Relatively undisturbed core was sub-sampled at ~ 1 m intervals for measurement of P and S waves at sonic frequencies using an OYO Sonicviewer system. The sample was extracted using a PVC container and subjected to uniaxial pressures equivalent to the particular load pressures at the sample depths. No samples were measured in the intervals of the core where physical disturbance was obvious (e.g. high water content sands).

Summary of Geophysical Techniques

Geophysical logging of boreholes drilled in overburden can be used to augment the observed geological sample descriptions. Such data can reveal subtleties of grain size, mineralogy and pore-water content that are not readily observable during normal specimen examination in the field. Borehole stratigraphy may be more accurately constrained and hole-to-hole correlations more easily visualized with the aid of geophysical logs. The level of lithological detail which can be interpreted from these combined logs suggests that they may be used in place of continuous coring (e.g. intermittent sampling only) resulting in a substantial decrease in borehole drilling and logging costs.