Borehole Geophysical Logging in Unconsolidated Sediments – An Aid to 3-D Mapping

Hunter, J.A.
Geological Survey of Canada, Ottawa, Ontario, Canada; E-mail: James Hunter at jhunter@nrcan.gc.ca

Over the last two decades, several advances have been made in the development and application of slim-hole geophysical sondes for use in groundwater, engineering, and environmental applications. This equipment is commonly used to provide qualitative (but detailed) estimates of grain size, sediment type, porosity, density, pore-water salinity, as well as bulk and shear moduli, to supplement geological/geotechnical sampling in boreholes. The goal of this paper is to illustrate the enhanced information that geophysical logs provide about a borehole and the utility of geophysical logging in unconsolidated sediments as a tool for 3-D mapping.

Some of the earliest geophysical logs used in conjunction with water-well drilling were the natural gamma and single-point electrical resistivity logs; these are run in “open hole” conditions, and can be quite definitive for lithologic studies (Maathuis, 2001). As open holes are difficult to maintain in unconsolidated sediments, PVC-cased boreholes have become more common in conjunction with shallow geophysical logging and a considerable number of specific sondes have been developed for such applications. The Geological Survey of Canada (GSC) routinely operates a suite of slim hole (<60mm diameter) sondes: natural gamma, inductive conductivity, magnetic susceptibility, gamma-gamma density, and temperature gradient. In addition, two downhole seismic arrays for compressional and shear wave velocity measurements are commonly run. Another significant tool (in use by other groups for porosity measurements) is the compensated neutron sonde. Emerging technologies at the GSC include the passive gamma-spectral sonde and the capacitive-coupled resistivity tool.

Geophysical properties of unconsolidated materials, using the various sondes mentioned above, are given by Hunter et al. (1998), Douma et al. (1999), and Pullan et al. (2002). In short, as a rule of thumb: natural gamma responds to grain size, with high count rates associated with clay materials; inductive conductivity measures the combined electrical conductivity of the pore-water and the matrix; magnetic susceptibility responds primarily to magnetite content; neutron absorption is inversely proportional to water content; the count-rate of the gamma-gamma tool is inversely proportional to density variation; a derived log, the spectral density ratio, compares the high- to low-energy portions of the spectral gamma-gamma log and is proportional to the average atomic number of the formation; temperature gradient is a function of thermal conductivity of materials with sharp vertical fluctuations in the curve associated with thermal disturbance from water flow; P- and S-wave velocities vary directly with bulk modulus and shear modulus respectively (function of compactness and porosity of the materials).

Although measurements from a single geophysical sonde can be used for stratigraphic characterization, a suite of geophysical logs is a significantly more powerful tool. Figure 1 shows a composite log suite from the Waterloo Moraine area in southern Ontario, which is used here to illustrate the additional information, at both the detailed and unit scales, that the geophysical logs can provide, even when a borehole has been continuously cored. The drillers’ log shows that several tills were encountered in the hole, inter-layered with clay, silt, and gravel. From inspection of the changes in natural gamma, conductivity, and P-wave velocities, the till units can be subdivided based on interpreted changes in grain size, provenance, and elastic moduli. Commonly, abrupt changes in geophysical properties occur between units; such changes can
serve to adjust interpreted depths in continuously cored holes and can be utilized to establish unit boundaries in boreholes with limited sampling. Note that though the lowest till unit in Figure 1 (T4) would be interpreted as the most coarse-grained on the basis of the gamma, conductivity, and magnetic susceptibility logs, it also appears to have the lowest porosity as shown by the neutron, gamma-gamma density, and spectral density ratio, and suggested by the P and S wave logs. This till has been identified as the Catfish Creek till (A. Bajc, Ontario Geological Survey, pers.comm.) and is known to be a regional aquitard.

Geophysical borehole logs can be important tools for regional stratigraphic correlation. An example using comparisons of anomalies within the electrical conductivity and magnetic susceptibility plots is shown in Figure 2. These data come from an area east of Ottawa, Ontario, where four boreholes spanning a total distance of ~60 km, were drilled within a Holocene basin consisting of Champlain Sea sediments. The fine-grained sediments (Leda clays) that make up most of the unconsolidated sequence were deposited in a marine environment, and some portions retain the original brackish-saline pore-water (e.g., boreholes A and D) yielding higher electrical conductivities. In other areas, modern (fresh) water is found in the pore spaces and the conductivities are relatively low (e.g., boreholes B and C). All boreholes, however, show two thin coarser-grained layers with lower conductivity than the surrounding material and distinct concentrations of magnetite; on some logs (not shown here) there are also indications of slightly higher densities and a slight increase in grain size. These anomalies are visible on the geophysical logs in many boreholes throughout the Ottawa area, and also from some boreholes as far away as Montreal. It is suggested that they represent widespread contemporaneous depositional events in the early history of the Champlain Sea.

Figure 1. Geophysical log suite from a borehole in unconsolidated sediments near Waterloo, Ontario.
Non-standard logs such as seismic velocity or gamma-gamma also show value in subsurface stratigraphic mapping. The P-wave downhole log can be used as a stratigraphic indicator in concert with other conventional logs, but is also extremely useful in providing vertical velocity control for high-resolution seismic surveys. As well, recent work is showing that seismic velocities can be used to provide total porosity estimates. Figure 3 shows an example of the use of velocity logs as a stratigraphic indicator from the Oak Ridges Moraine area near Toronto. The Newmarket Till is not well defined by most geophysical logs, since many of its geophysical characteristics are similar to formations above and below it. However, one distinguishing feature is its unusually high P-wave velocity (commonly > 2500 m/s), postulated to result from partial cementation of pore spaces.

Figure 3 shows a N-S section of P-wave downhole logs across the Oak Ridges Moraine area north of Toronto showing the interpreted thickness of the Newmarket Till. The presence or absence of the Newmarket Till and its role as an aquitard is very important in the development of the hydrogeological framework of the Toronto area; hence the P-wave downhole log is considered to be an important tool in such studies.
The GSC is establishing a number of “golden spike” boreholes (Sharpe et al., 2003) in various surficial geological areas across Canada. As well as being geophysical logged, these PVC-cased and preserved boreholes have been continuously cored, sampled, and geologically logged. Such “golden spikes” serve as reference data for surficial geological deposits in the area, and are also available as test sites for future developments in borehole or surface geophysical techniques.

Figure 3. A suite of P-wave downhole logs across the Oak Ridges Moraine showing the regional correlation of high velocities associated with the Newmarket Till aquitard.

References


