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Commissioning an Electrical Resistivity Imaging System for Long Term Seepage Monitoring at a Dam Abutment

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Summary

As embankment dams age, one of the most common failure modes is internal erosion – a gradual washing out of fine grained material in a dam's core that is difficult to detect on surface in early stages and can accelerate over time. The Mactaquac Generating Station is a large (660 MW) hydroelectric facility approximately 19 km upstream from Fredericton, New Brunswick. The concrete structures on site are now differentially expanding due to an alkali-aggregate reaction, leading the dam's operator, NB Power, to be proactive in monitoring for any signs of concentrated seepage leading to internal erosion that could arise where the dam's clay till core abuts a concrete diversion sluiceway.

Repeated or time-lapse resistivity surveys have proven to be an effective non-invasive approach for investigations of seepage in dam interiors elsewhere. Unlike most previous reports, we are employing a 3D resistivity array and focusing on the interface region between the embankment dam and its concrete abutment. Following experimentation with various electrode arrays and measurement parameters necessitated by high noise levels, we began to obtain reliable resistivity data in June, 2019 to approximately 20 m below the dam's downstream face. Fully autonomous monitoring began in late November. Early comparisons of data are encouraging, as we see coherent spatial and temporal changes in resistivity in surveys from June, October, November and December. The clay-till core of the dam, and concrete dipping below the array are evident as regions of low resistivities (< 50 Ωm). The overlying rockfill is electrically resistive (>500 Ωm) and heterogeneous by comparison. Temporal changes in resistivity, as revealed by an October:June resistivity ratio image, are well correlated with the internal structure of the embankment. The most prominent change - an increase in resistivity of the uppermost core and of the filter/transition zone and rockfill directly above the inclined core – is tentatively attributed to drying and/or washing out of road salt from the embankment over the summer. Two other shallow temporal anomalies, more subtle in nature and located close to the abutment, will need to be tracked further over time to assess their significance. Resistivities generally appear more consistent at depth. Ongoing monitoring of how anomalies evolve seasonally, and with respect to reservoir temperatures and total dissolved solids, will help us to assess seepage conditions in the interface region.

Theory / Method

Seepage is a leading cause of dam failures (Foster et al., 2000). The use of electrical resistivity imaging (ERI) surveys is emerging as a popular, effective and non-invasive method to seek evidence of seepage through dams and levees (Binley et al., 2015). ERI as a method is sensitive to earth properties that facilitate or hinder charge transport: degree of water saturation, porosity, clay content, temperature and ionic content or amount of total dissolved solids (TDS) in the pore water. Provided that seepage has not advanced to the stage of producing internal erosion, the material properties of a dam or levee are expected to remain constant over time. In that case, localized rapid or seasonal variations in subsurface resistivity are proxies for changes in saturation, temperature and/or ionic content, all of which can be indicators for anomalous seepage (Johannson and Dahlin, 1996; Sjödahl et al., 2008).

Use of time-lapse resistivity data to successfully evaluate seepage has taken place at hydroelectric facility embankments (e.g., Johannson and Dahlin, 1996; Sjödahl et al., 2008; Rahimi et al., 2019), earthen tailings dams (Sjodahl et al., 2005; Mainali et al., 2015) and dykes (e.g., Bievre et al., 2018). The common approach of data collection is to install electrodes along a dam's crest and collect repeated 2D resistivity surveys focused on the core. Magnitudes of seepage velocities have been estimated based on seasonal variations in temperature and TDS in the reservoir and comparing those to resistivity in the embankment (Johannson and Dahlin, 1996). The resistivity of water-saturated sediments varies inversely by ~2.5% per °C, so dams best suited for the use of ERT to look for seepage are located in locations with seasonal climates.

The resistivity array at Mactaquac consists of 100 electrodes arranged in five lines in the coarse rockfill on the downstream face of the dam as show in Figure 1. This includes 30 $Pb/PbCl_2$ electrodes which were used for a prior study examining self-potential variations in the embankment (Ringeri et al., 2016), and 70 stainless steel electrodes, 90 cm in length, installed into hammer-drilled holes with bentonite mud. Each line consists of 20 electrodes at 3 m intervals with lines spaced 5 m apart. In contrast to the 2D arrays used by prior studies, a 3D grid is employed at Mactaquac as we are most interested in the possibility of seepage at the interface of the embankment and its concrete abutment. The lines have recently been extended across the dam crest by adding electrodes beneath the crest road, but the results shown here are from the downstream face only. A remote electrode was also installed at the opposite end of the embankment, 500 m away. Pole-dipole arrays are used to increase depth of investigation along the relatively short, 57 m long lines. The resistivity meter is a low power single-channel instrument (Lippmann 4ptlight10w) providing up to 180V and 100 mA current subject to a maximum power of 10W. It is connected to four 24-electrode switchboxes connected to the electrodes via individual 16 AWG wires. All instrumentation operates autonomously and is housed in an enclosure. A compact 17 Ah 12V lead-acid battery has been sufficient to collect four surveys of 3400 measurements each day for up to 10 days at a time, after which the data are manually downloaded.

Quality control/editing of data is accomplished using custom scripts (in MATLAB). Usually several days to a week of data (10 or more surveys) are averaged to mitigate noise issues. A smart stacking script is used to discard outlier measurements before averaging. The data are subsequently inverted to obtain a maximally smooth model in 3D using the DCIP3D algorithm (Li and Oldenburg, 2000; University of British Columbia Geophysical Inversion Facility, 2014). We currently evaluate temporal changes in resistivity by comparing the results of independent inversions on different dates, though we ultimately intend to use simultaneous time lapse improved robustness in the presence of noise. ultimately intend to use simultaneous time lapse inversion for improved robustness in the presence of noise.

Results, Observations, Conclusions

Data collection began in late December, 2018. Data quality was variable initially, as we lost connection to our remote electrode, and saw contact resistances rise significantly (to as much as 30 kOhm on some electrodes) during the depth of winter. During summer, 2019, we made an important discovery that repeatability issues with pole-dipole measurements employing low transmitter voltages were a consequence of current regulation problems associated with the high powerline noise voltage across our 500 m long current dipole. This was overcome by forcing the transmitter to use higher voltage settings for pole-dipole measurements. We also began to calculate weekly average measurements, with outlier rejection, which improved data quality significantly. Major features such as heterogeneity in the rockfill shell and its contact with the conductive clay-till core became highly repeatable and we have begun to observe more subtle seasonal changes in resistivity.

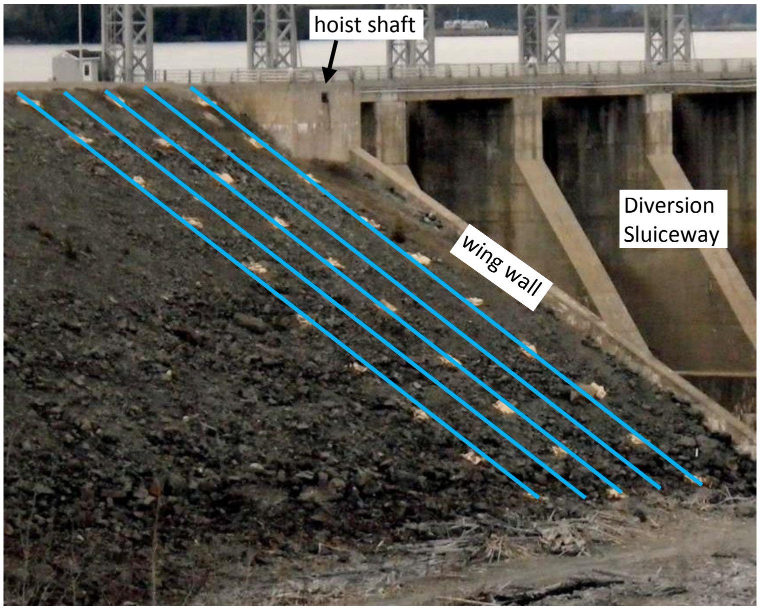

Figure 1: Electrode array on downstream face of the dam, consisting of 70 stainless steel rods and 30 $Pb/PbCl_2$ electrodes (under beige tarps) arranged in five 57-m long lines spaced 5 m apart.

Five vertical slices through the 3D resistivity model obtained by inverting late October data can be seen in Figure 2. The division between conductive clay till core (blue) and the overlying resistive rockfill (red) is clear. The anomalously high conductivities at depth along lines 1 and 2 can be attributed to the presence of the inclined concrete abutment which dips below those two lines. Heterogeneity within the rockfill can most likely be attributed to variability in the lifts of material used to build the dam.

Figure 3 shows the ratio of resistivities between late June and late October, 2019. As expected, the deeper features, light green in colour representing a ratio of 1, remain relatively consistent. Just above the core, resistivity of the filter zone and rockfill increased as much as 3x in some places from June to October. We suspect that this is due to materials above and just inside the core losing moisture through the summer and into fall, although it might alternatively be due to dilution of road salt which runs off the dam crest road during the winter. A small area of slightly less resistivity increase is located at roughly 6 m depth on lines 1 and 2, closest to the abutment. This lines up well with an anomaly found in previous work examining temperature variations just inside the concrete at the abutment (Yun et al, 2018). We also note an anomalous reduction (~25%) in the resistivity of the core near the dam crest below line 2, which would be consistent with more summer-warmed water from the reservoir moving through that region. However, it is too early to draw any conclusions. The areas of higher conductivity in October in the shallow

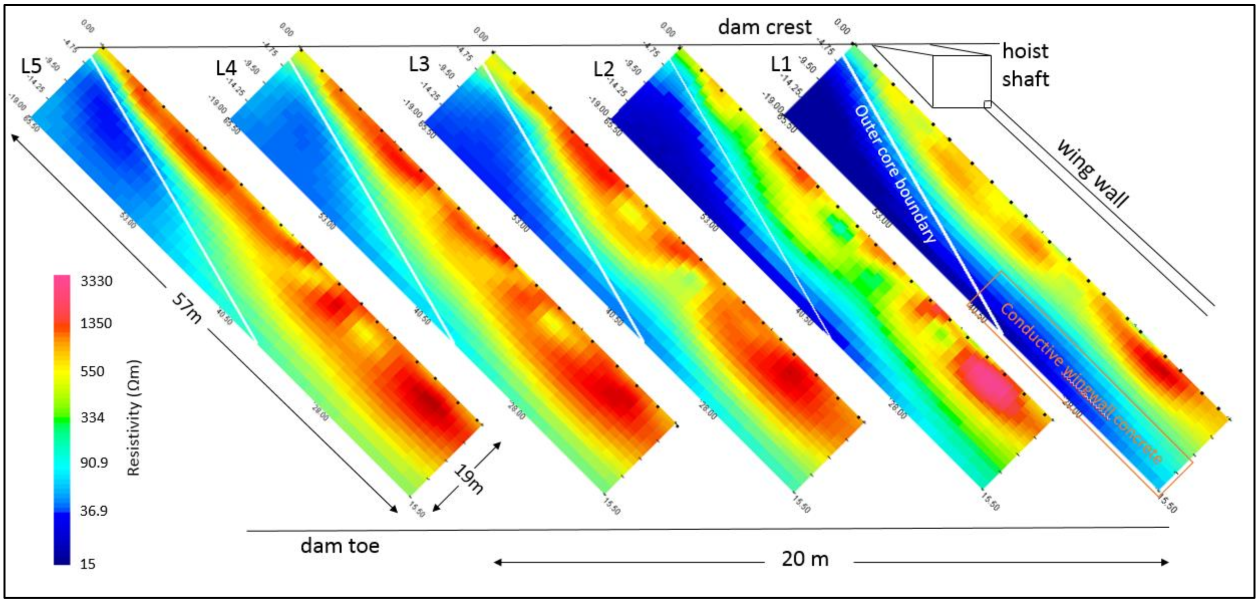

Figure 2: Five vertical slices (horizontally exaggerated) through a 3D resistivity image of the embankment adjacent to the diversion sluiceway based on data collected Oct 21-24, 2019.

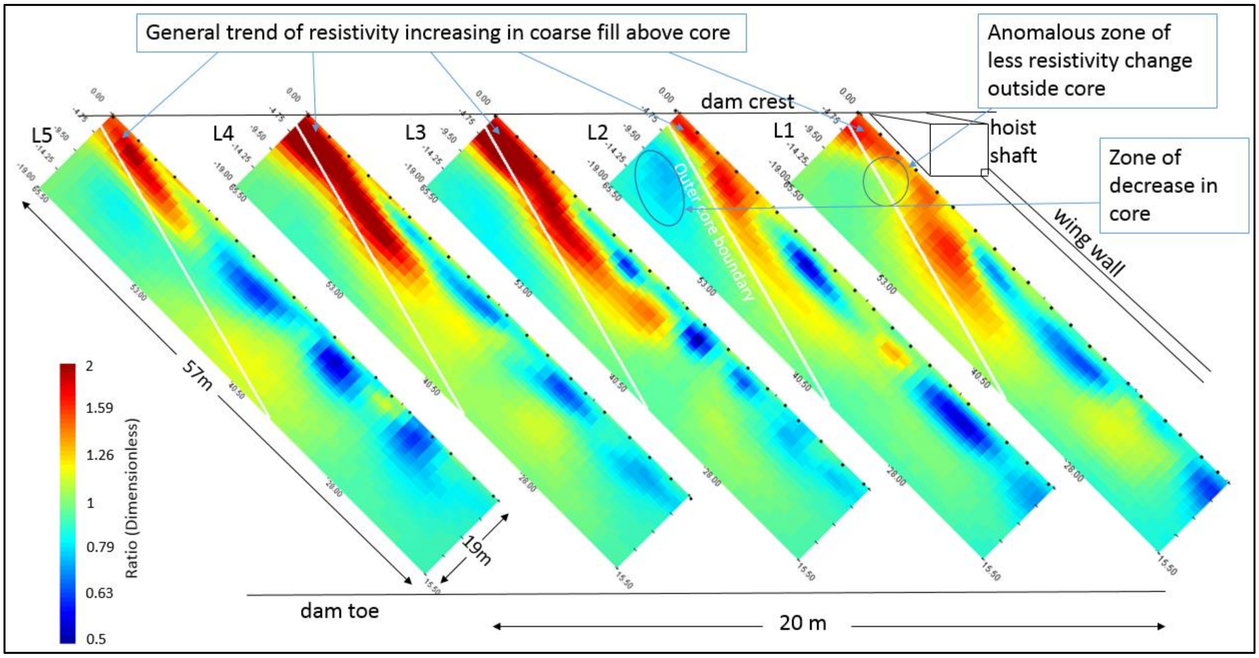

Figure 3: Ratio of resistivities obtained in late Oct compared to those measured four months earlier in late June, 2019.

rockfill are difficult to explain, but are most likely pockets of moisture in October or localized dryness in June.

The power of this type of installation will be shown when comparing this year's data to next year. We will seek to identify anomalous changes in resistivity that evolve seasonally and can be explained in terms of anomalous changes in moisture content, temperature or TDS consistent with concentrated seepage. Future work will involve incorporating the cross-crest electrodes, and dam topography to improve imaging of the core, and experimentation with electrode array measurement sequences to improve spatial resolution beyond what we are now achieving using in-line measurements only. Modeling will be done to investigate the expected effects of road salt runoff and any inversion artifacts they might generate at greater depth (within the core). Also the precise location of concrete wall dipping below the array will be determined and used to constrain future modelling and interpretations.

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