IMPROVING RISK ANALYSIS IN DAM SAFETY WITH DISTRIBUTED FIBER OPTIC SENSING FOR AUTONOMOUS, REAL-TIME MONITORING AND DATA ACQUISITION

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Dams support two fundamental staples of socio-economic development, energy and water, in adequate supply and quality. They affect the natural magnitude and timing of streamflow, creating a system of managed waterways. With the benefits of managed river systems comes the responsibility of continuous monitoring to maintain the integrity of management structures. There are 11,500 large dams in North America (ICOLD 2017), 3,000 of which provide 60% of the electricity supplied to Canada and the northwestern United States. This talk will describe the challenges associated with risk analysis and explain the application of recent technological advances in fiber optic distributed sensing for continuous monitoring of structure integrity and advance warning systems for existing dam types.

Dam safety in North America has been managed using two methods of risk analysis. The *Failure Modes and Effects Analysis (FMEA)* and the *Potential Failure Modes Analysis (PFMA),* which follows the US Federal Energy & Regulatory Commission (FERC) Engineering Guidelines for the Evaluation of Hydropower Projects. Both methods use event trees, dam failure modes, calculated probabilities and a risk matrix, but struggle with the acquisition of adequate field data. In February 2017, the Oroville Incident sparked controversy associated with inconsistencies in risk analysis methods. Indeed, a new approach that integrates monitoring, data-tracking, and operational factors is needed, rather than relying on engineer judgment to estimate probabilities and consequences (ICOLD 2019). Advances made in fiber optic distributed temperature, acoustic and strain sensing (DTS, DAS, and DSS) have allowed autonomous and real-time data acquisition at high spatial and temporal resolutions. Unlike traditional sensing that relies on individual sensor measurements at predetermined points (eg. extensometer, pressure and temperature sensors, or geophones), distributed sensing utilizes optical fiber as the sensing element without any additional transducers along its path. Spatio-temporal coverage is continuous, with a single sensor system acting as tens of thousands of independent sensors, each with sensitivity similar to or better than point sensors. Because the optical fiber *is the sensor,* it includes no electronic or moving parts and requires no maintenance.

Embankments comprise 75% of the world's dams. Concrete gravity dams rely on their material weight, while the thinner geotechnical design of arch dams utilizes their material strength. Buttress dams are hollow and rely on vertical projections spaced out along the downstream face. Variations of these fundamental designs, such as those exhibited in dykes, levees and weirs will not be discussed in the interest of conciseness. All dams can be monitored using similar cable installations, customized to their reservoir capacity and environment. Temporally continuous measurements can be collected over tens of kilometers of embankments and structures using robust, direct-bury fiber optic cable installed horizontally and vertically during construction, or via retrofitting processes using trenches and boreholes along concrete dam structures and spillways. Application of a single cable containing multiple optical fibers can provide the following data outputs. DTS interrogators provide independent temperature measurements every 0.25 m along the cable, with temperature resolution as fine as 0.01 °C. Ambient temperature fluctuations throughout the year cause reservoir temperature to change. DTS uses this signal as a tracer to estimate seepage flow through an earthen embankment and identify locations of potential failure. DSS absolute strain data provides a direct measurement of any deformation or settlement occurring along a dam. Strain measurements can be obtained every 0.10 m along the fiber optic cable with a strain resolution of 2 με. An increase in strain values at a specific location over time can indicate vertical or horizontal movement of a structure. DAS detects natural or induced microseismic events to evaluate seismic risk, or to be used for time-lapse seismic imaging based on passive and active methods. The results from these imaging methods are correlated to potential changes in physical properties of the structure material such as density, saturation related to water level and erosion, and shear strength which could also indicate locations with potential failure.

In summary, a single, cost-efficient fiber optical cable can be used to monitor large structures in detail, yielding complementary datasets for analysis in parallel to provide an independent means of evaluation using multiple sources of evidence to identify and locate potential failures. Achievability of large spatial coverage and autonomous operation that requires low maintenance and power makes this technology a cost-effective monitoring solution.