Advances in Distributed Fiber Optic Sensing for Autonomous, Real-time Monitoring of Dam Integrity.

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Summary

There are 11,500 large dams in North America (ICOLD 2017) supporting hydropower generation, water supply, storage of mining waste and environmental protection through flood control. Earth and rock embankments comprise 75% of the world's dams and seepage, or piping, is the number one cause of structure failure. Detection of internal movement, settlement and seepage that is measurable at the micro-scale can reduce or prevent risks to environment, economy and public safety at the macro-scale. This talk will describe the challenges associated with risk analysis in dam safety and explain the application of fiber optic distributed sensing for continuous monitoring of structure integrity and advance warning systems.

Dams & Risk Assessment

In general, a "dam" is a barrier constructed from earth, rock and/or concrete for the retention of water (and other substances) that has a minimum height of 2.5 m, with the capacity to impound at least 30,000 m^3 of fluid (CDA 2019) (Figure 1). A "large dam" has a minimum height of 5-15 m and the capacity to resist the forces of 3,000,000 m^3 of impounded fluid (ICOLD 2011). In the case of mining dams, the impoundment comprises tailings, often with overlying supernatant water (Figure 2). Tailings add a layer of complexity in assessing risk, since they contain chemical reagents and mobilization is a function of rheology and liquefaction.

Dam design, construction, and installation of monitoring sensors differ depending on purpose. A water dam is built to full height prior to operation, while a tailings storage facility is built in stages and operated during its incremental building phase which may span the entire life of the mine it serves. In both cases, stability is a function of permeability of the materials used in the dam construction, slope, compaction, saturation, and foundation strength. Monitoring designs consider key failure modes, like seepage, for effective detection of breach potential.

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 (CDA 2021). Both methods use event trees, dam failure modes, calculated probabilities and a risk matrix, but struggle with the acquisition of adequate field data beyond hydrologic and tailings characterization. In February 2017, the Oroville Incident (France et al. 2018) 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 (Rigbey & Hartford 2019).

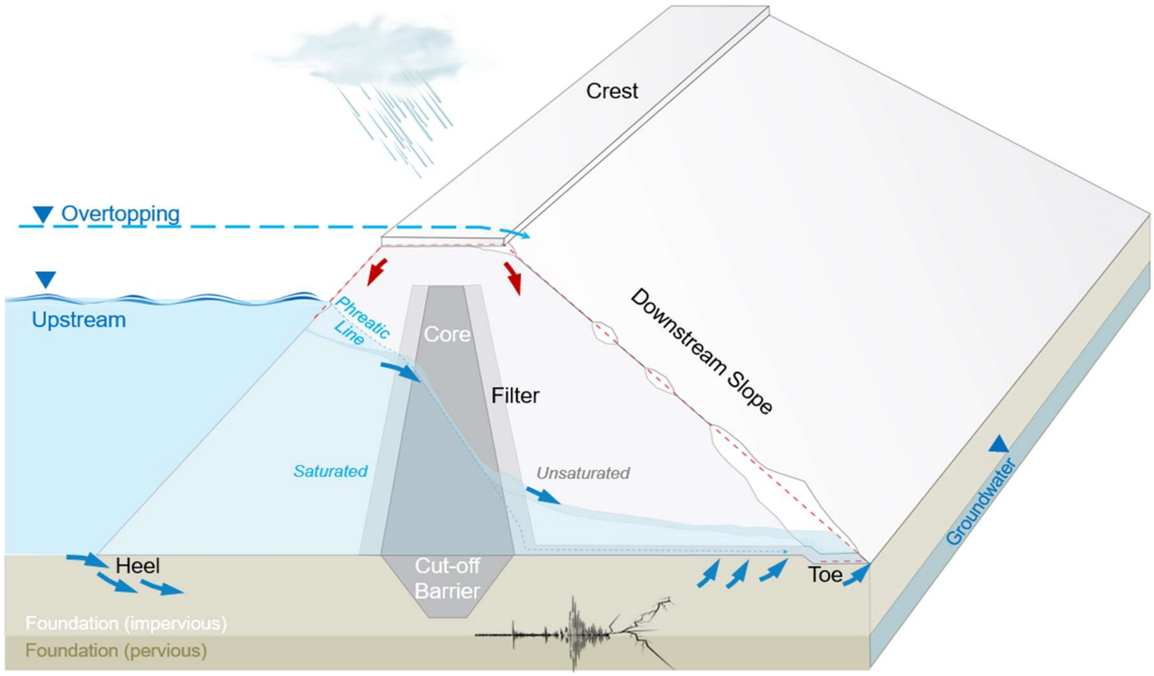

Figure 1. Schematic of a representative water dam, where the goal is not to have the phreatic surface reach the toe drain with enough pressure behind it to flow with destructive force. Continuous monitoring systems should have the capacity to measure direct and indirect parameters of failure modes such as: (1) surface erosion from upstream wave action, overtopping and rain wash; (2) seepage and internal erosion causing particle movement, a change in material properties and uplift at the toe; and (3) settlement, sliding, and structural failure due to erosion or seismicity.

Distributed Fiber Optic Sensing for Monitoring Dam Integrity

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 methods that rely on individual sensor measurements at predetermined points (such as extensometers, inclinometers, piezometers and geophones), distributed sensing utilizes optical fiber as the sensing element without any additional transducers along its path (Silixa 2022). 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. Most dams can be monitored using similar cable installations, customized to their reservoir capacity and environment (Figure 3). 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, or along concrete dam structures and spillways. Application of a single fiber optic cable containing multiple optical fibers can provide complementary DTS, DAS and DSS datasets for rigorous risk analysis and predictive modelling.

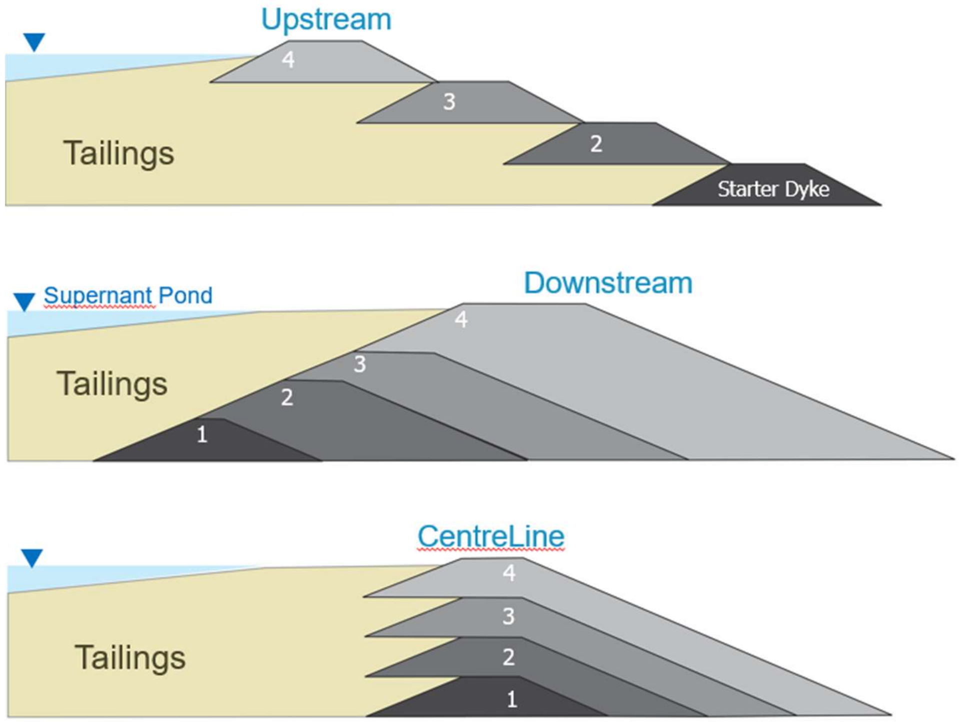

Figure 2. Schematic of sequentially raised tailings dam designs, where the name reflects the direction the crest moves relative to the starter dyke #1. The upstream version results in a dam crest constructed on a larger profile of fine tailings, which have low permeability and are susceptible to liquefaction, compared to that of the more desirable downstream and centreline designs.

Silixa 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. Intelligent DAS (iDAS) detects natural or induced microseismic events to evaluate seismic risk. It can also 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. 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 $\mu\varepsilon$. An increase in strain values at a specific location over time can indicate vertical or horizontal movement of a structure. This talk will describe near-surface horizontal and vertical applications of distributed fiber optic cable to detect seepage flow, surface movement, settlement and seismicity.

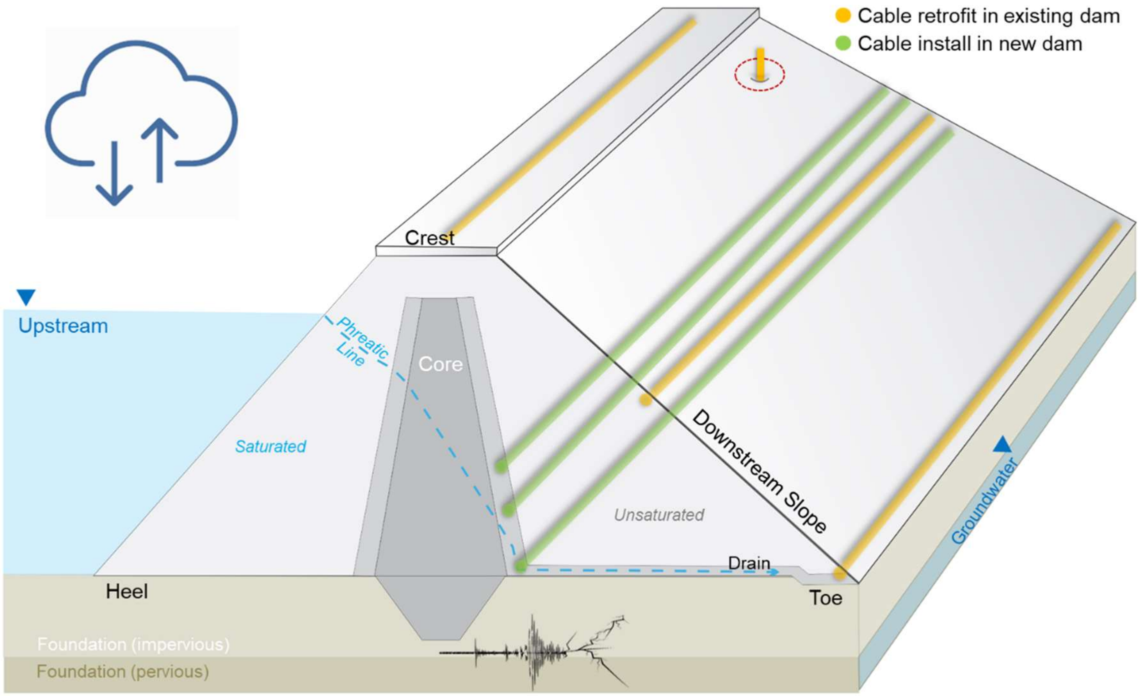

Figure 3. Schematic of a basic distributed fiber optic monitoring design, comparing DAS-DTS-DSS cable installation for an existing dam with limited retrofit capacity (represented by yellow lines), to that of a new dam under construction (represented by green lines), where access to the filter accommodates a more comprehensive install. Most cable is installed horizontally to maximize spatial coverage, detect anomalous settlement, and allow for tomographic imaging; however, vertical installations have useful applications in monitoring structure integrity. Data is remotely accessible using cloud applications and a small (solar) power source (< 80 Watts).

Takeaway

A cost-efficient fiber optic 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 for structure integrity, including dams.

References

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