THE FUTURE OF INFRASTRUCTURE: DAMS AND THE INTERNET OF THINGS

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ABSTRACT

Engineers and owners been monitoring dams for a long time; first with dam tenders and visual inspections, then piezometers and with the advent of electrical techniques, Carlson gages, vibrating wire, MEMs, and now smart sensors, fiber optics, and remote sensing. The objective of measurement has always been, at it's core, risk management.

Historically, dam safety has been a leader in infrastructure instrumentation practice but there are things going on outside the dam safety community that will impact us and the way that we do our work. There is increasing political pressure to be better stewards of our resources. There is a social expectation, carried especially by young engineers entering the field and the public at large that data should be available in real time for almost anything. Good reasons for this include improved efficiencies in infrastructure management, improved visibility for budgeting, and improved operational management.

This paper presents some of these trends and opportunities and provide awareness to the larger dam engineering community of what is going on in moving some of our infrastructure data into more visible locations, some of the advantages and expectations, and some of the challenges that we will face as we do so.

1. INTRODUCTION

There is a confluence of technologies that is changing the way that we look at infrastructure. For civil engineers, there is a gap between our understanding of natural and designed systems, and the way that the people funding that infrastructure expect to be able to manage their assets. In this paper, we review the evolution of engineering practice, where we are headed with design, operation, and asset management, the three principal challenges to engineers working in this area, and what we need to do to adapt and endure that our work continues to be relevant, or rather that Civil Engineer continue to be relevant to the work that needs to be done.

2. THE EVOLUTION OF ENGINEERING DESIGN

The first building technologies were likely for basic shelter; when we think of “designed” structures that would require special knowledge or skill to construct, archaeologists have identified sites that date back as far as 10,000 years BCE (Curry, 2008), and continued through the industrial revolution. For the purposes of this discussion, I’ll refer to these as monumental structures—structures that are impressive in their complexity and size, that require special skills and knowledge from artisans, architects, and builders, but not engineers in the modern sense. These structures were essentially scaled up versions of smaller successful predecessors. The builders used principles of geometry and scaling but did not have a fundamental understanding of predictive behaviour of systems.

The next major evolution in design and construction coincided with the spirit of inquiry that rose in the renaissance and, at least for Civil Engineers, found a set of guiding principles in Newtonian Mechanics. These principles allowed us to make systematic observations of physical phenomena and properties, and apply those to methods along with the geometry of their predecessors to calculate forces, determine load paths, and estimate capacities and demands.

These techniques opened the door to physics based design of structures, a period that began about 1800 with the work of such luminaries as Watt, Roebling, and Brunel, and predominated until the second half of the 20^{th} century.

Advances in computing technology after the Second World War led to the development of computer methods in design of engineered structures. Concepts that would not be economical or perhaps even possible to evaluate using hand methods became routine, and the progression of increasingly efficient use of materials and resources continued, not just in the calculation of loads and capacities, but also in the use of CAD, word processing, and project management software and techniques to improve the process itself.

The most recent evolution is the integration of data from non-traditional sources into our engineering work. Google Earth, GIS, and GPS have fundamentally changed the way that we design and operate, and while we have not fully embraced the potential of those practices in dam safety, we are moving in that direction. There are three technologies that, as we adapt them to our needs, will fundamentally change the way that we interact with our watershed management infrastructure:

Technology 1: Performance Monitoring for Risk Management

Technology 2: Project and Process Management

Technology 3: Electronic Measurements

Technology 4: The Internet and the Internet of Things

3. PERFORMANCE MONITORING FOR RISK MANAGEMENT

Performance monitoring provides a cost-effective way to reduce the risk of dam failure. For the purposes of this paper, failure is considered to be the uncontrolled release of stored contents from the dam. By indicating undesirable performance early, a performance monitoring program can provide time to perform mitigation measures to reduce the probability of a failure, or reduce the consequences of a failure, or both.

Performance monitoring consists of information from visual inspections and quantitative data from instruments. Both elements are important and the two are complementary. Visual inspection may reveal poor performance not detected by instruments. Loss of fines by piping may be detected by visual inspection while instrumentation may provide no clue that piping is occurring. Contrarily, visual inspections are limited to exposed surfaces and cannot detect conditions that may be deteriorating within the structure. Pore water pressures may be increasing within the dam and lowering the global stability but without surface manifestation until failure develops quite suddenly.

Though only a small percentage of dams develop problems and even fewer of those fail, the highly indeterminate nature of each dam makes it impossible to accurately predict which dam will develop a problem. The many unknowns about the properties of the materials and the large number of possible variations in conditions can never be fully revealed. Therefore, it is prudent that any dam that may affect public safety have a performance monitoring program to monitor its vital signs.

Performance monitoring by itself does not reduce risk. It must be accompanied by an action plan that when put in effect counteracts the factors driving the dam toward failure and stops or reverses the course of deteriorating safety. The invoked action plan mitigates risk. Performance monitoring for dam safety is an instrumentation, monitoring and mitigation program, or I-M-M program in short.

Dams fail because of unknowns about their condition and performance, wrong actions by people, deterioration of materials over time, or loading conditions that exceed those used in the design. An I-M-M program is used to detect these conditions with the aim to intervene and correct them before the dam fails. Dam safety programs repeatedly detect developing problems in time for corrective actions to be completed and, as a result, serve as a highly effective risk management strategy for owners of dams. Most of these actions are never published so we don't have a record of the effectiveness of this approach. An exception is the USBR-USACE (2012) report which indicated that intervention following the detection by visual observations of the initiation of internal erosion resulted in less than 1% of the observed cases causing a dam breach.

A dam safety program aims to protect life, property, and the environment by ensuring that a dam is designed, constructed, operated, and maintained as effectively as possible. It consists of activities to continually inspect, monitor, evaluate and document the design, construction, operations, maintenance, rehabilitation, and emergency preparedness of each dam, as well as the coordination with the potentially affected public agencies having responsibility for public safety. It also includes a clear plan that defines responsibilities for each component and communicates the state of the dam safety program to all with responsibility. Visual inspections and monitoring of instruments are vital parts of many dam safety programs.

There is widespread agreement about the safety benefits of surveillance and monitoring. Regan, Nettle and Zygaj (2008) noted that "a surveillance and monitoring plan is designed to assure that appropriate surveillance and monitoring procedures are in place to identify a developing failure mode as soon as possible so that the maximum time is available for intervention or warning and the chances of success are greatest." They advocate the development of a failure mode sequence to clarify the points where surveillance and monitoring can be successfully implemented and definition of the risk reduction steps that could be taken at each step. A USSD white Paper, "Why Include Instrumentation in Dam Monitoring Programs?" (USSD, 2008), states two important points in the foreword: "There are many historical cases of dam failures where early warning signs of failure might have been detected if a good dam safety-monitoring program had been in place," and "A good dam safety monitoring program should be a key part of every dam owner's risk management program." A recent document by USBR related to dam safety and risk also refers to the use of a monitoring program to help manage risk, (USBR, 2011) and notes that additional risk management activities are recommended when risks are of practical concern. These may include, "visual inspections, instrumentation monitoring (underlining added for emphasis), inundation mapping, exercising of Emergency Action Plans, periodic examinations and evaluations, and similar measures considered to be 'good practice.'"

In draft guidelines, FERC (2012) indicated the role of instrumented monitoring in risk management. In a graphic showing the relationship among risk analysis, risk assessment and risk management, "Monitoring" is included as a Risk Reduction option. The document also states: "Risk management encompasses activities related to making risk-informed decisions, prioritizing evaluations of risk, prioritizing risk reduction activities, and making program decisions associated with managing a portfolio of facilities….These included potential structural and non-structural actions on a given dam or project, but also include such activities as routine and special inspections, instrumented monitoring and its evaluation, (underlining added for emphasis), structural analyses, site investigations, development and testing of emergency action plans and many other activities." FERC is continuing to develop this draft document. Also FEMA is working on a document the draft of which includes the same graphic from the FERC (2012) report (FEMA, 2014).

The Corps of Engineers (USACE, 2014) has recently published comprehensive guidance on dam safety. This guidance states (underlining added for emphasis):

Successful risk management requires a healthy routine monitoring program, including maintenance, repair and staff who are trained in data collection and interpretation. […]. in some cases where data is (sic) relied on for life safety risk reduction decisions, it is appropriate to utilize independent expert consultants to review instrumentation data analyses and help validate conclusions."

Risk management for dams includes short-term Interim Risk Reduction Measures (IRRM), long-term structural risk reduction measures, and strengthening recurrent activities – such as monitoring and surveillance, emergency action planning, operations and maintenance, and staff training.

4. PROJECT VS PROCESS MANAGEMENT

All Civil Works water control projects must have an adequate level of instrumentation, as appropriate to address potential failure modes and risks, to enable design engineers to monitor and evaluate the safe performance of the structures during the construction period and under all operating conditions….Where it is determined that instrumentation is a necessary monitoring component, instrumentation will be utilized to enable designers and operators to verify performance is within tolerable limits relative to potential failure modes.

terms of instrumentation, we tend to think of dams as projects, possibly because of the scale of the effort required for design and construction of facilities that can take decades. There is a shift in thinking, however, that takes advantage of the increased availability of information about system performance to realize the goals and intentions of watershed-wide water management systems. Engineers have been looking at dams as interrelated networks of storage and energy management systems since the early 1900s, but it's only been in the last 10 years that we have begun to have the tools to actively and predictively manage watersheds.

Dams are tools and components in larger systems that have overriding goals of economic development, and risk reduction, water storage, recreation, and power generation are all subsets of the larger goal of managing a watershed for the long term maximization of economic value. Depending on the goals and mandates of the infrastructure owner, the prioritization of these criteria may vary, but overall, the central concept is that maximization of economic value.

The consequence of this emphasis is the need to manage the watershed as a single machine with individual structures as components rather than as an inventory of projects. Historically, this has been difficult, if not impossible because of the difficulty of integrating measurement data into models, and the additional difficulty of aggregating and presenting the data in a way that can be efficiently interpreted. The physical limitations to collecting, aggregating, processing, interpreting, disseminating, and contextualizing dam safety data have been beyond the reach of dam owners. Evolution in data acquisition, management, and promulgation techniques in other fields, however, have opened doors to dam safety managers.

5. ELECTRONIC MEASUREMENT

Electronic Measurement has been a part of dam safety since Roy Carlson (stretched wire resistance) and Andre Coyne (vibrating wire) (ASCE 2000) began installing sensors in dams over 80 years ago. Coupled with the understanding of geotechnical engineering pioneered by Terzaghi and Peck, electronic measurement of dam performance parameters has given us the ability to look into the fundamental behaviour of structures and use those data to validate performance against design assumptions.

When we build a dam, we do our best to mitigate risk through siting, design, and monitoring. There are however things about sites and structures that are unknowable in the investigation and design phase, and can only be observed and quantified after construction is complete and after a facility has been in operation. At the same time, the public perception and trust in dam designers and operators is such that the very idea of failure seems too remote to consider.

Often, we install instrumentation because we know that we should, but without a real plan for long term operation and maintenance. At a high level, there is awareness of the importance of monitoring (ASCE, FEMA, FERC, Regan, USACE, USSD) but in execution, there seems to often be a disconnect between the plans for measurement, and pragmatic access to the data.

Over the past 170 years we have evolved from simple measurements of open standpipe pore water pressure and optical surveys of dam crests (ASCE) to fully automated measurement systems, tracking the same evolutionary process that has driven all of engineering practice as discussed previously. In doing so, we have opened doors into comprehensive system wide management structures that take advantage of the measurements and allow us to put them into context for infrastructure and public safety professionals, and to communicate risks and condition in ways that allow us to make better decisions.

The fundamental problem is that there is an increasing demand for actionable data, and for data driven asset management. We have the tools to make the measurements that are required, and the systems to collect and transmit the data exist. We also have the ability to automate the processes in the context of integrated watershed management. What we lack is guidance on how to pull all of those components together, and how to secure the resources to make that happen.

The components that are required are simple and commercially available or available as a function of the design process:

1) Design models
2) Sensors
3) Power

4) Communications
5) Data storage
6) Analysis
7) Visualization

6. THE INTERNET AND THE INTERNET OF THINGS

The essence of the Internet is that it is a widesperead, almost ubiquitous information infrastructure (Leiner et al). Outside of dam safety, the internet has revolutionized the way that we access and manage data and has made it possible to coordinate activity and work on a scale unprecedented in human history. Its development parallels the development of instrumentation and risk management practice, but until recently, there have been other methods that were better suited to our objectives.

Historically, connecting dam safety sensors to the people responsible for doing something about the data had been done using whatever techniques were currently available or convenient at the time the systems were designed. First manual collection with paper and pencil, then automated collection with dataloggers, then automated collection using radio networks or telephone lines, then satellite or cellular collection, but always with the data ending up in isolated databases for analysis and distribution.

Over the past decade, however, the Internet has solidified a position as the nexus for data collection, processing and distribution. There are real security issues to be resolved, but TCP/IP is the standard for electronic communication and across infrastructure monitoring practice, systems are being designed to move the measurement from the sensor to the internet as efficiently and safely as possible. This introduces challenges, but it also creates opportunities for standardization that lead to improved monitoring, communication and risk and asset management techniques.

6.1 The Internet of Things

It is important to first clarify that the Internet of Things means different things to different people. In the information technology and security world, it carries with it implications of consumer grade internet enabled devices, minimal security, and high risk to data security. But for a working definition, the Internet of Things represents the internet today, and is defined by the transition from an intenrte where the majority of the connections are people to an internet where more things or objects are connected (Evans).

For the non-IT professional, it may just mean that everything seems to have an IP address. Increasingly, we are seeing infrastructure instrumentation systems where the goal is to get the data from the sensor to the internet as quickly as possible, effectively putting an IP address on the dam.

The potential of the IoT is that today, the Internet is a collection of purpose built networks that share information, but not always as efficiently as possible. This provides a framework and a backbone to begin to see what we can do with the internet to first build the networks and work out the details of function, then optimize those networks for their specific purposes. As we begin to build networks that incorporate watershed, weather, energy production and dam safety data, with security, analytics, and management capabilities, we will begin to realize the true power of the IoT in physical infrastructure.

7. SUMMARY

For the past 150 years, we have been trying to figure out how to efficiently use data to understand and manage our dam inventory. Our techniques have evolved on parallel but separate paths, but there is a convergence of technologies that will change the way that we see our work

Sensors and monitoring electronics will continue to evolve, but we can measure most of the parameters that we understand to be critical in dam safety. By shifting our paradigm from project to process, we can look at dams at a watershed lifecycle scale. By integrating risk management processes into our models, we can improve operational efficiencies and budget priorities. And by using the tools made available by the standardization of the internet as the information repository of choice, we can begin to offload what used to be specialized civil engineering functions to data analytics and security professionals.

We also need to recognize the importance of other specialized fields, including electronics technicians, sensor specialists, and software providers as team members with the civil engineer to help us to bring the vision for a comprehensive dam safety system to a reality.

There is a convergence of techniques and tools that will give us the opportunity to be more efficient stewards of infrastructure, but in order to capture the value, we need to be aware of them, and begin to incorporate them into our practice. It all starts with acceptance that there is value in monitoring performace of dams, that they need to be evaluated in the context of their contribution to regional economic stability, and that the data derived from risk based management needs to be delivered to decision makers in a format that allows them to do their jobs effectively:

1) We can improve infrastructure performance through measurement
2) The design engineer or dam safety engineer needs to specify critical parameters and thresholds
3) The design engineer needs to work with the owner to understand feedback, control, and risk management requirements
4) The design engineer needs to work with specialists to develop appropriate measurement systems
5) Specialty contractors will install systems
6) IT and informatics professionals will work with infrastructure managers and design engineers to develop systes to monitor and reduce data
7) Owners will be empowered to make decisions and prioritize funding decisions based on data

8. REFERENCES

American Society of Civil Engineers Task Committee on Instrumentation and Monitoring Dam Performance, *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance*, ASCE, Reston, VA, USA (2000).

Leiner, BM, Cerf, VG, Clark, DD, Kahn, LK, Lynch, DC, Postel, J, Roberts, LG, Wolff, S. "Brief History of the Internet". Internetsociety.org. Retrieved February 19, 2017.

Curry, Andrew (November 2008). "Gobekli Tepe: The World's First Temple?". Smithsonian.com. Retrieved February 17, 2017.

Evans, D (April 2011) "The Internet of Things: How the Next Evolution of the Internet Is Changing Everything," Cisco Internet Business Solutions Group White Paper, Retrieved February 19, 2017

FEMA (2014). "Federal Guidelines for Dam Safety Risk Management – Draft," United States Federal Emergency Management Agency. May.

FERC (2012). "Draft - Federal Guidelines for Dam Safety Risk Management", United States Federal Energy Regulatory Commission, Version 3.0, September 2012. (www.ferc.gov/industries/hydropower/safety/guidelines/draft-guidelines.pdf accessed on November 2, 2014)

Regan, J.J., Nettle, J.D. and Zygaj, J.A. (2008). "Managing Dam Safety Risks Through Surveillance and Monitoring Plans and Surveillance and Monitoring Reports," *Proceedings of 28th Annual USSD Conference on the Sustainability of Experience – Investing in the Human Factor*. Portland, Oregon, April 28 - May 2, 951-965.

USACE (2014). "Safety of Dams – Policy and Procedures," United States Army Corps of Engineers ER 1110-2-1156. March 31.

USBR (2011). "Dam Safety Public Protection Guidelines: A Risk Framework to Support Dam Safety Decision-Making." U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Office, Denver, CO, August.

USBR/USACE (2012). "Best Practices in Dam and Levee Safety Risk Analysis," Chapter 21, p 75. 7 Dec 2012 from usbr.gov/ssle/damsafety/risk accessed on 1/27/15.

United States Society on Dams (2008). “Why Include Instrumentation in Dam Monitoring Programs?” Version 1.00 November. ISBN 978-1-884575-45-7.Von Thun, J. L. (1985). *Application of statistical data from dam failures and accidents to risk-based decision analysis on existing dams*. U.S. Bureau of Reclamation.