CHAPTER 1
INTRODUCTION

> When you can measure what you are speaking about, and express it in numbers, you know something about it. . . .
>
> Lord Kelvin

Welcome to *Monitoring Dam Performance—Instrumentation and Measurements*. This manual reviews the current state of practice for monitoring dam performance as part of the American Society of Civil Engineers commitment to serve the worldwide community of dam engineering professionals.

Monitoring dam performance is a global enterprise. Almost every country in the world has dams that are monitored for performance by their owners and engineers. Many countries have agencies with monitoring guidelines and regulations for safe practice. These include agencies such as the CWC in India, U.S. Federal Energy Regulatory Commission (FERC), China's Ministry of Energy, Canadian Dam Association, The Environment Agency in England and Wales, France's Permanent Technical Committee, and ANCOLD in Australia. The intent of this manual is to capture the fundamentals and current state of practice of instrumented measurements for monitoring dam performance in the global dam engineering community.

Dam-performance monitoring is a blend of visual surveillance coupled with instruments to measure indicators that answer a basic question: "How is this dam performing?"

Visual surveillance is the backbone of all performance-monitoring programs.

> Monitoring of every dam is mandatory because dams change with age and may develop defects. There is no substitute for

> systematic intelligent surveillance. But monitoring and surveillance are not synonymous with instrumentation.
>
> Ralph Peck

Instruments can supply measurements of performance indicators that evade visual surveillance. It is difficult for the eyes to accurately estimate the flow or amount of embankment settlement. There are instruments to measure both. But are they required?

> Certainly the fundamental rule today should be that no instrument should be installed that is not needed to answer a specific technical question pertinent to the safe performance of the dam.
>
> Ralph Peck

Specific technical questions are unique to every dam. Like people, no two dams are exactly alike. The questions to ask rely upon an understanding of a dam's vulnerabilities. Designs are intended to provide adequate defenses against perceived vulnerabilities. Monitored instrumentation is intended to provide measurements to validate the design or point to performance that could lead to loss of reservoir control. This manual describes the process of using instrumented monitoring to answer the basic question of how a dam is performing.

- First: Understand what sequence of events could cause a dam to fail to retain its reservoir.
- Second: Select which performance indicators to measure and the appropriate instruments to measure them.
- Third: Plan and implement the program to make observations and measurements.
- Fourth: Gather, manage, and present measured data in a form amenable to decision making.
- Fifth: Evaluate the data.
- Last: Make decisions based on the monitoring results and take action as needed.

Chapter 2 reviews the importance of dam safety not only to protect the public but also to sustain the benefits that dams provide. The case for developing a responsible performance-monitoring program is presented.

The vulnerabilities of different types of dams are the subject of Chapter 3. Modes of failure and their performance indicators vary for different types of dams. Understanding a dam's potential modes of failure sets the stage for asking performance questions for which answers may be provided by instrumentation and measurements.

Chapter 4 describes how to plan and implement a monitoring program tailored to provide answers to questions about a dam's performance.

Many new means of measuring have been added to performance-monitoring practice in recent years. Instruments to measure a variety of loads and responses are described in Chapter 5.

Chapter 6 introduces geodetic monitoring and its role in measuring a dam's response to loads.

Chapters 7 and 8 describe data acquisition, presentation, and management to provide a basis for evaluating the measurements from the performance-monitoring program.

Chapter 9 discusses the process of acquiring the measurements to answer the questions asked, evaluating those measurements, deciding what action to take, if any, and then acting on those decisions.

Typical instrumented monitoring of embankment, concrete, and other dams are the subjects of Chapter 10, 11, and 12, respectively.

Sample data forms and plots are illustrated in Chapter 13.

Monitoring dam performance has a long and colorful history. Chapter 14 captures that history.

Four appendices provide a

- List of references about dam-performance monitoring,
- Procedure for conducting failure mode analyses,
- Discussion of precision and accuracy, and
- Glossary.

This manual of practice is not intended to establish a standard for the design, installation, operation, or use of dam instrumentation systems. This manual presents the current state of practice. Each dam is unique in its geologic setting, physical loads, materials of construction, purpose, design life, and method of operation and presents its own distinct set of challenges in understanding its behavior.

Dam instrumentation and measurement provide a key part of the information that owners, engineers, and regulators consider to understand how a dam is performing compared to design estimates and historic performance, to identify any sequence of events that could cause a loss of reservoir control, and to inform decisions about dam safety actions.

This page intentionally left blank

CHAPTER 2
PERFORMANCE MONITORING

> Engineers shall hold paramount the safety, health and welfare of the public and shall strive to comply with the principles of sustainable development in the performance of their professional duties.
>
> Canon 1, ASCE Code of Ethics

Dam-performance monitoring is a key element in preserving public safety and sustaining the benefits that dams provide.

Every dam has an inherent potential for failure, no matter how well it is investigated, designed, constructed, operated, and maintained. Even the best engineering, construction, operation, and maintenance practices cannot completely eliminate the uncertainties associated with a man-made structure constructed on natural materials (the dam foundation), built with natural and manufactured materials, and subjected to the forces of nature. These uncertainties can manifest anywhere within the "system" of a dam (foundation, man-made structures, mechanical, electrical, operations, and maintenance) and can emerge at any point within the life cycle of a dam, as shown in Fig. 2-1.

Uncertainties can take the form of an undiscovered deficiency in the foundation, an incorrect estimate or mistake during design, an undocumented or inappropriate change during construction, poor maintenance, or improper operation. Each uncertainty, on its own or in conjunction with others, can produce a potential mechanism for loss of reservoir control. Although allocating more resources and care during each phase of a dam's life cycle can reduce unknowns, uncertainty is inherent, and no dam is completely without potential for failure.

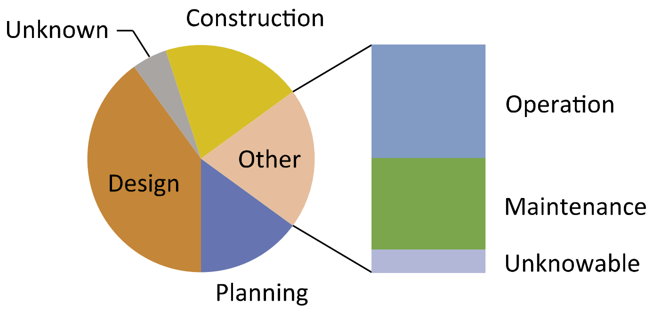

Fig. 2-1. Resolving uncertainty

In the planning phase for a new dam, even the most robust site investigation program cannot completely resolve the uncertainties of how the ground will respond to the dam and reservoir. Geologists and geotechnical engineers base judgments about the quality of a foundation on the evidence and tools available to them. Visually exploring and mapping a site provides surficial evidence of soil and rock quality. If only what is apparent from the surface informs the design, the level of uncertainty will be high, as subsurface conditions may differ greatly. Exploratory drilling and testing within the foundation can reduce the level of uncertainty. The level of uncertainty is reflective of the level of effort in site investigation; however, some uncertainty regarding the condition of the foundation is unavoidable because the resources allocated to an exploratory program are finite, and some uncertainties may defy resolution. At some point, the drilling and testing stop, and the unresolved uncertainties retain the potential to affect dam performance.

Additional uncertainties can arise at the design phase. Engineers not only must rely on the site characterization during the planning phase but also must apply judgment and make estimates regarding the anticipated loads that the structure must resist during its life. Designers must estimate the quality and strength of the materials available for construction. Future operation and maintenance requirements require attention. The accuracy of the engineer's estimates will depend on the quality of the data from the site investigation and the accuracy of the predictions of the loading conditions and the dam's response to imposed loads. Detailed flood studies and seismic hazard assessments may reduce the level of uncertainty regarding the loads a structure must withstand; however, flood and earthquake loadings cannot be estimated with certainty (unknowable), and their application in design must consider acceptable risk. Even with adequate resources and a high standard of care during design, some level of uncertainty remains, as the design relies on the quality of the estimates made to support the design. The goal at the end of design is to reduce the uncertainties (unknowns) to those manageable during construction.

Unforeseen conditions may be discovered during construction, and design changes may be required. An extensive quality control program that oversees and documents construction can greatly reduce the uncertainty associated with construction by reducing workmanship errors that have caused unsatisfactory dam performance.

As dams age, other factors such as inadequate maintenance, improper operation practices, or loading that is inconsistent with estimates made during design may result in unsatisfactory performance. Surveillance and monitoring can provide a basis for deciding whether or not a dam is performing as expected.

Monitoring the performance of dams is necessary because the uncertainties that could introduce a mechanism for failure cannot be fully resolved. The risk of failure, however remote, always exists. Failure has societal and financial consequences that include loss of the benefit a dam provides and the potential for loss of life and property damage.

Performance monitoring as part of a comprehensive dam safety program is a powerful tool for identifying and managing the risk of failure associated with a dam. Instrumented monitoring systems may be among the tools contained in a performance-monitoring program. As with any tool, proper understanding of the purpose and use of a monitoring tool maximizes its benefit.

The guidance contained in this chapter is intended to assist the reader in recognizing the uncertainties generated in the life cycle of a dam, identifying a dam's vulnerabilities associated with those uncertainties, understanding how unacceptable performance may develop, prioritizing those modes of failure by the level of risk associated with them, and developing a dam safety program that effectively incorporates performance monitoring for managing that risk.

2.1 DAM SAFETY PROGRAM

A dam safety program is a dam owner's road map to designing, constructing, monitoring, maintaining, and safely operating a dam. Without a structured dam safety program, the monitoring systems described in this manual lack context. A dam safety program is the framework for those responsible for the safety of a dam to identify and manage the risks associated with the structure. Instrumented monitoring is a valuable tool to reduce the probability that reservoir control will be lost (World Bank 2002).

There is no "one size fits all" dam safety program. The scope of a dam safety program depends on the size, type, complexity, and age involved and the potential consequences associated with the dam. A dam safety program seeks to establish the following:

- Performance criteria—a statement of the purposes and design requirements for the dam;
- Potential failure modes—identification of dam-specific failure modes;
- Performance-monitoring plan—a planned surveillance and monitoring plan tailored to the identified failure modes, including visual inspections and instrumented monitoring;
- Performance evaluation methodology—a comparison of the dam's actual performance to the performance expectations;
- Safety assessment methodology—analyses to determine whether the dam can safely respond to the imposed loads;
- Duties and responsibilities for those responsible for dam safety;
- Procedures for safe operation and maintenance;
- Procedures for identifying, planning, designing, and constructing dam safety improvements, modifications, and remedial measures;
- Access to sufficient technical resources and expertise as necessary;
- Training plan for staff involved in dam safety—the personnel who carry out the routine dam safety monitoring efforts at the dam site; and
- Emergency planning and contingency planning for intervention in the event of a developing failure.
- An effective dam safety program requires (1) a comprehensive understanding of potential sequences that could lead to failure of the dam or appurtenant structures to retain the reservoir and (2) an understanding of the likelihood that those sequences would develop.

2.2 DAM OWNER RESPONSIBILITY

Dam safety requires recognition on the part of the dam owner of the inherent risks associated with the impoundment of large quantities of water and the potential adverse consequences of an uncontrolled release. The owner of a dam has an ethical and legal responsibility to maintain and operate the dam in a safe manner. Failure to do so not only endangers lives, property, and the natural environment but also can expose the owner to substantial loss of revenue, legal costs, and remediation expenses.

Legal liability for a dam owner has typically been imposed under one of two different legal doctrines. Under the standard of strict liability, a dam owner is responsible for any damages caused by a dam incident or loss of reservoir control regardless of the cause. Under the standard of negligence, a dam owner would be liable if the owner did not exercise sufficient care in the design, construction, operation, or maintenance of the dam. In many cases, the appropriate standard of care will include instrumentation and measurements to monitor dam performance and the provision of sufficient resources for the performance monitoring.

2.3 FAILURE MODES

A potential failure mode is described by the U.S. Federal Emergency Management Agency as "a physically plausible process for dam failure resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir" (FEMA 2004). The term "failure" means the loss of reservoir control and does not necessarily mean dam failure. An uncontrolled release of the reservoir such as the gate failure at Folsom Dam (Fig. 2-2) is an example of loss of reservoir control.

The Swift No. 2 embankment breach (Fig. 2-3) is an extreme example of loss of reservoir control—a dam failure.

The key to developing a dam safety program is identifying what could go wrong. In another sense, the term "failure" is a misnomer because loss of reservoir control often occurs as an incident associated with operation and maintenance. With an understanding of what could cause a loss of reservoir control, a surveillance and monitoring scheme tailored to

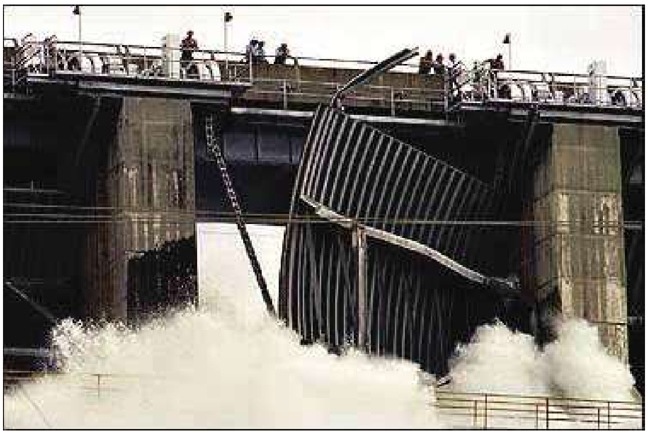

Fig. 2-2. Gate failure at Folsom Dam
Source: U.S. Bureau of Reclamation.

Fig. 2-3. Embankment breach at Swift No. 2

answering the relevant questions informs decisions about what to measure to judge a dam's behavior.

To be credible, a potential failure mode must define an initial condition and follow a progression of events to failure. The initial condition is any combination of material properties and loads that could progress to a failure. Design and construction flaws, operational errors, or unanticipated loads are potential contributors to progression. Changes may occur gradually or suddenly.

For example, the initial condition for a piping failure of an embankment dam could be the lack of a filtered zone downstream from the dam's core. Seepage flow could begin to erode and move soil particles, form a soil pipe into the dam, and erode a void in the dam's core such as the incident shown in Fig. 2-4.

Collapse of the void and subsequent erosion could cause loss of freeboard, breach of the embankment, and dam failure.

A reservoir release does not necessarily have to be a complete structural failure of the dam. Rather, an uncontrolled release may initiate at appurtenant structures such as a penstock rupture, shown in Fig. 2-5, canal break, gate failure, or failure of a diversion tunnel plug.

When evaluating potential failure modes for a dam, it is important to consider the dam as part of an overall system. This "system" includes the

Fig. 2-4. Piping failure at Fontenelle Dam
Source: National Park Service.

Fig. 2-5. Penstock failure
Source: Courtesy of Brookfield Renewable Resources, reproduced with permission.

dam, the foundation and abutments, appurtenant structures, and human factors:

- Pipelines, penstocks, and spillways that pass flow through or past a dam,
- Mechanical features such as gates, valves, and generators that control flow through a dam,
- Electrical systems that provide power to those mechanical features,
- Control and data-acquisition systems that monitor and control those mechanical and electrical features, and
- Human behavior during operation and maintenance, including opportunities to intervene when an emergency arises such as responding to uncontrolled turbid seepage at the toe of an embankment dam.

Every part of the system has the potential to introduce a failure to control the reservoir. Therefore, the entire system is worthy of scrutiny to identify potential failure sequences amenable to instrumented monitoring.

After identifying potential failure modes, the next step is to estimate their likelihood. Whether likelihood of occurrence is expressed as a numeric value or a relative category, the results provide the basis for understanding, communicating, prioritizing, and managing the risks to a dam by allowing the owner to allocate monitoring resources in the most efficient manner to protect public safety and sustain the benefits the dam provides.

The goals of failure mode analysis are to identify and judge the likelihood of any sequence of events that may lead to a loss of reservoir control and to suggest means and methods of surveillance and monitoring to ensure reservoir control. Guidance on how to perform failure mode analyses [potential failure mode analysis (PFMA) or failure mode effect analysis (FMEA)] is provided in Appendix B.

2.4 SURVEILLANCE AND MONITORING

A dam's performance depends on the decisions made to bring it from concept to physical reality. Those decisions were intended to provide answers to the following questions:

- Magnitude—How large are the loads to which the dam and its foundation will be subjected?
- Location—Where will the loads be applied? Where will water go (over, under, around, through)?
- Response—How does the dam support and distribute its load, and how does it manage water?

Assessing the performance of a dam involves evaluating responses to those loads with data collected by visual and instrumented monitoring and then comparing the data against expected performance.

Visual surveillance involves routine site inspections by personnel trained in dam safety and familiar with the design and operation of the dam and its appurtenant structures. That activity is the backbone of any surveillance and monitoring program. Each dam is unique, and visual monitoring must be tailored to capture all visible aspects of a dam's performance. For those aspects of performance that cannot be seen, instrumented monitoring can play an important role.

> Monitoring of every dam is mandatory, because dams change with age and may develop defects. There is no substitute for systematic intelligent surveillance. But monitoring and surveillance are not synonymous with instrumentation.
>
> Ralph Peck

Instrumented monitoring produces quantitative data regarding conditions surrounding the dam (foundation, reservoir, tailwater, precipitation) and within the dam—conditions that are not apparent from the ground surface and may not be detectible through visual inspection. Instrumented monitoring can provide long-term records of data, allowing for detection of time- or load-dependent trends in a dam's performance. The ability to detect a change over time is important because these changes may be indicative of a developing performance problem related to a potential failure mode. When used in conjunction with visual monitoring, instrumentation data can verify visual observations of change in a structure or vice versa, providing a level of redundancy and confidence to the monitoring program. The collection of data can be automated, allowing for monitoring on a more frequent (approaching real-time) basis. Automated monitoring systems can initiate alarms indicating unexpected performance.

Surveillance and monitoring seek to identify conditions suggestive of a developing potential failure mode by blending visual observations and instrumented measurements to form a coherent picture of a dam's performance.

2.4.1 Design

Field investigation is the primary information-gathering method used during the design phase to characterize the geology and materials at and around a dam site. Instrumentation installed as part of this investigation establishes baseline conditions for items such as groundwater levels and downstream spring flow rates. Monitoring during construction and first filling allows detection and evaluation of changes to baseline conditions.

2.4.2 Construction

Instrumentation during construction can confirm design predictions or recognize changed conditions. Instrumentation also provides information about conditions during construction that may affect construction quality. For example, (1) temperature is routinely monitored when placing and curing concrete, (2) measurements of material moisture content and compaction densities are important to confirm the design soil shear strength during embankment construction, and (3) pressure measurements are required during grouting operations. Instrumentation indicating unexpected performance during construction can identify unsafe working conditions. Additionally, instrumentation can be used during construction to help verify compliance with required environmental conditions such as water-quality monitoring.

2.4.3 Postconstruction and First Filling

Instrumentation during construction and first filling provides data regarding performance as the structure receives loads. Reservoir filling tests the seepage resistance of the dam, foundation, abutments, and reservoir rim for the first time. In addition, the reservoir load tests the structural stability of the dam. Instrumentation data during this phase provide early indications of unusual or unexpected performance and establish baseline measurements for future operating conditions.

2.4.4 Operation

Instrumented monitoring supports operations of the dam and provides feedback to operations personnel. For example, measurements of reservoir elevation, downstream flow, water temperature, and dissolved oxygen at a hydroelectric dam provide data to operate the generation equipment and to meet governmental regulatory or environmental requirements.

2.4.5 Maintenance

Some dams will experience unexpected performance, even after many years of uneventful operation. Instrumentation can help identify a problem and confirm the effectiveness of remedial actions. For example, if an embankment experiences an unexpected increase in the amount of seepage as indicated by a high phreatic surface and increasing weir flow measurements, the remedy might include construction of a reverse filter at the toe in the area of the seepage. Instrumentation and monitoring could then be used to evaluate the effectiveness of the remediation.

CHAPTER 3
FAILURE MODES

> It's fine to celebrate success but it is more important to heed the lessons of failure.
>
> Bill Gates

Chapter 2 traced performance monitoring throughout a dam's service life and introduced the importance of failure modes in the design of an effective program for dam-performance monitoring. By first identifying the most significant threats to a dam's performance, a performance-monitoring program can be planned to address key indicators relative to the potential causes of unsatisfactory performance.

This chapter describes the state of knowledge about how embankment, concrete gravity, and concrete arch dams perform. It outlines vulnerabilities that may lead to unsatisfactory performance, and it describes indicators that may signal a developing failure mode.

Knowing how a failure may develop and asking appropriate questions form the basis for planning and implementing an effective performance-monitoring program, the subject of Chapter 4.

3.1 EMBANKMENT DAMS

Constructed using soil and rock, embankments are particularly vulnerable to (1) uncontrolled seepage, (2) overtopping, and (3) slope instability.

3.1.1 Design

Embankment dams rely on mass and foundation strength for stability.

Homogeneous embankments, shown in Fig. 3-1, are mixtures of soil and rock using the low permeability of those materials to keep internal pressure from rising to cause instability. Finer materials are placed in the interior and coarser materials in the shells.

Zoned (central or inclined core) embankments, shown in Figs. 3-2 and 3-3, utilize low-permeability (fine-grained) soil for the core, again to manage internal pressure. Because fine-grained soil in the core is susceptible to transport through the coarser downstream shell, an engineered filter zone is placed downstream from the core to prevent migration of the core. Design practice is to place a drainage layer adjacent to the filter zone to manage internal pressure in the downstream shell. Many embankments have a similar filter arrangement on the upstream slope to manage pressure in the event of a rapid reservoir drawdown.

Foundation seepage management often is achieved with a cutoff trench or grout curtain under the core and a toe drain contiguous with the drain zone behind the filter.

An embankment dam may be designed with an impervious upstream face. One popular design is the concrete-faced rockfill dam (CFRD), shown in Fig. 3-4. Other designs have employed different materials, mainly asphalt (Fig. 3-5), but clay has also been used. An upstream impervious face for a rockfill dam has the advantage of a free-draining downstream shell, thereby reducing or eliminating the potential for problems of uncontrolled seepage or slope instability.

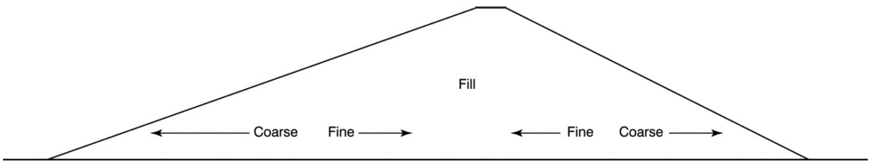

Fig. 3-1. Homogeneous embankment dam

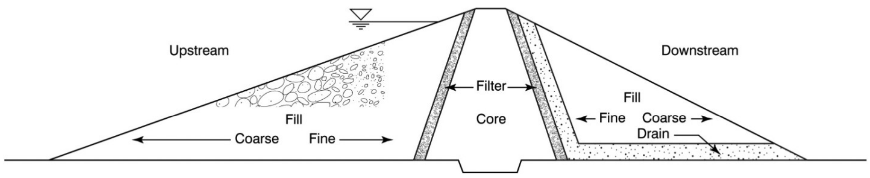

Fig. 3-2. Central core embankment dam

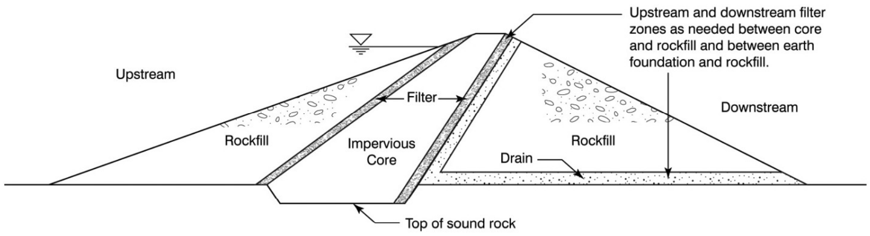

Fig. 3-3. Inclined core embankment dam

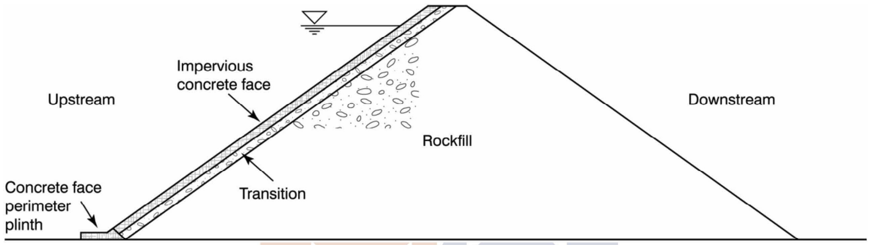

Fig. 3-4. Concrete-faced rockfill dam

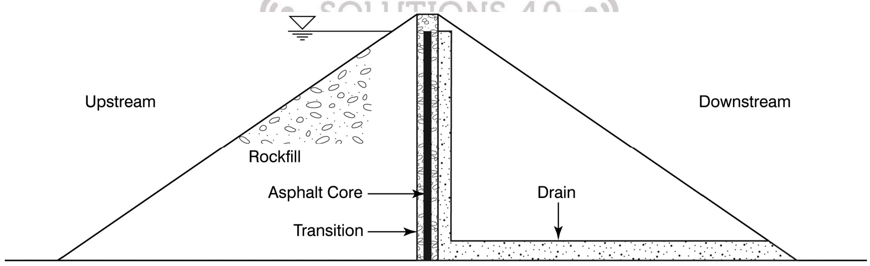

Fig. 3-5. Asphalt core embankment dam

3.1.2 Vulnerabilities

3.1.2.1 Uncontrolled Seepage. Internal erosion (piping) may initiate in many ways. Design may have failed to include appropriate provisions for filters and drains or to lengthen the seepage path. Construction practice may leave poorly compacted or pervious material, offering a privileged path of seepage. Abrupt changes in abutment slopes against which fill is placed may cause core cracking, allowing flow to overwhelm the drains.

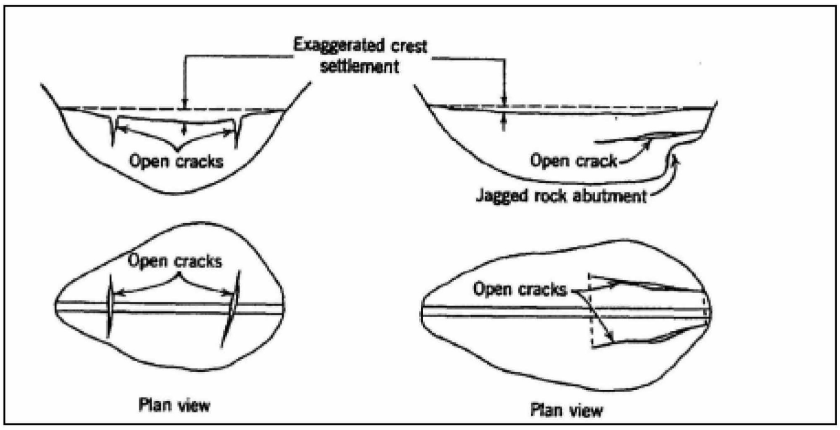

Fig. 3-6. Settlement-induced cracks that can initiate internal erosion
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Foundation settlement can initiate core cracking as well. Poor compaction around conduit penetrations in the fill may allow a seepage path to develop. Or a conduit may leak, allowing seepage path development along the conduit exterior. Fill placed against rigid structures such as a spillway training wall requires care in design to include granular materials that can stop seepage from exploiting the soil/wall contact. The foundation may contain a defect such as an open joint that communicates with the reservoir and passes under the embankment, bringing reservoir pressure to the embankment toe, as shown on Fig. 3-6.

Internal erosion initiates when one of the causes of piping allows the seepage flow velocity to increase fast enough to transport soil. The first indicator is seepage on the downstream slope or at the toe. If the seepage force is strong enough, it begins to transport soil by eroding backward from the toe toward the core, creating a void that begins to enlarge provided that the soil is strong enough to support the upstream progression of the void. Fig. 3-7 illustrates a serious case of internal erosion. Rapid erosion follows that leads to embankment slumping and loss of freeboard and reservoir control, resulting in a breach and embankment failure.

Embankments with an impervious upstream face or with an asphalt central core resist piping through the embankment, but they may be vulnerable to uncontrolled seepage in the foundation, along the abutments, or by leakage along embedded conduits, as shown in Fig. 3-8.

Key indicators that signal development of a piping failure sequence are

- Increasing seepage along abutments, conduit penetrations, and/or at the toe,
- Turbid seepage,

- Change of embankment shape such as bulging, sinkholes, unexpected crest settlement, and
- Longitudinal or transverse cracking along the crest.

3.1.2.2 Overtopping. Flow over the crest of an embankment has caused many failures, as shown in Fig. 3-9. The design may lack sufficient freeboard to accommodate the inflow design flood (IDF).

All types of embankment dams are susceptible to failure by overtopping because downstream shells are likely to be eroded, ultimately leading to a loss of freeboard. Judgment is required to estimate whether the duration and depth of overtopping is likely to initiate failure.

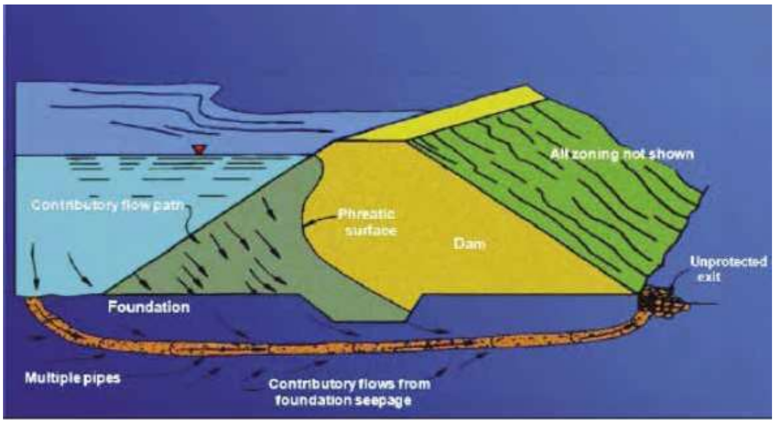

Fig. 3-7. Internal erosion through foundation
Source: FEMA (2015).

Fig. 3-8. Internal erosion along training wall
Source: Courtesy of ND State Water Commission.

Fig. 3-9. Overtopping failure sequence
Source: FEMA (2013).

The only indicator that signals development of an overtopping failure sequence is the progressive loss of freeboard.

3.1.2.3 Slope Stability. Embankment slopes are designed to remain stable under all loading conditions. Slope failure, either downstream or upstream, may reduce freeboard to the point where the reservoir is exposed, allowing discharge to erode the downstream slope until a breach forms and failure ensues.

Understanding the foundation conditions, properties of embankment materials, and quality of construction are key to identifying whether embankment slopes will remain stable under all loading conditions. Slope performance may be affected by

- Material quality (density, shear strength, moisture content, and plasticity),
- Reservoir operation,
- Slope aspect,
- Seepage gradient,
- Susceptibility to liquefaction (embankment and foundation),
- Time-dependent strain, and
- Strong shaking during an earthquake.

Slope failure may initiate because a slope is too steep to remain stable against a rising seepage gradient or rapid drawdown (upstream slope) without adequate time or provision for drainage or because of liquefaction in the foundation during an earthquake. Judging the adequacy of a slope to remain stable requires review not only of its design but also of its performance history. If vulnerability is discovered, then appropriate monitoring can be planned.

Figs. 3-10 and 3-11 show an upstream slope failure at Fort Peck Dam and a downstream slope failure at the Mount Polley tailings dam, respectively.

Figs. 3-12 and 3-13 show downstream slope erosion from seepage and upstream slope erosion from wave cutting, respectively.

Key indicators that signal development of a slope stability failure sequence are

- Increasing seepage gradient (elevated phreatic surface),
- Turbid seepage,
- Change of embankment shape—slumping, scarp development, unexpected crest settlement, and
- Longitudinal cracking along the crest.

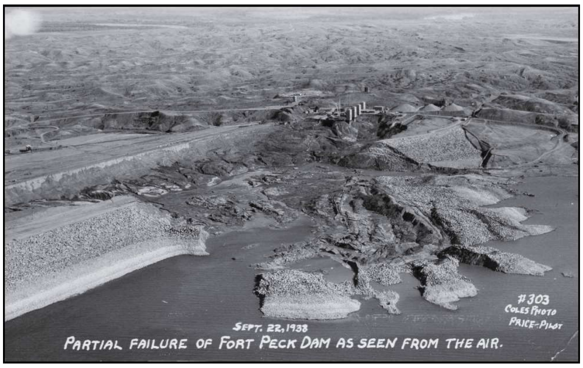

Fig. 3-10. Upstream slope failure at Fort Peck Dam
Source: USACE Fort Peck, http://www.nwo.usace.army.mil/Missions/Dam-and-Lake-Projects/Missouri-River-Dams/Fort-Peck/.

Fig. 3-11. Downstream slope failure at the Mount Polley tailings dam
Source: Imperial Metals, reproduced with permission.

Fig. 3-12. Downstream slope erosion from seepage
Source: Courtesy of Texas Commission on Environmental Quality, reproduced with permission.

Fig. 3-13. Upstream slope erosion from wave cutting
Source: U.S. Army Corps of Engineers.

3.2 CONCRETE GRAVITY DAMS

Conventional and roller-compacted concrete gravity dams are vulnerable if they lack adequate resistance to sliding and/or overturning. Sliding and overturning or combinations of both motions are the dominant concrete dam failure modes. A failure sequence may initiate from a design error, poor workmanship, concrete deterioration, or loss of foundation integrity. A failure sequence may progress by exploiting the lack of appropriate operation or maintenance procedures.

3.2.1 Design

Concrete gravity dams rely on their mass and foundation strength for stability. The forces acting on a gravity dam are well understood. How those forces are resisted is also well understood. The weight of the dam must overcome all the applied forces. Typical designs employ features that promote stability, such as

- Proper foundation preparation and treatment to support the weight of the dam and ensure that no foundation rock blocks capable of displacement are stabilized or removed and replaced with concrete,
- Grout curtains or cutoff walls that lengthen the seepage path in both the foundation and the abutments,
- Drainage curtains downstream of the grout curtain or cutoff wall to reduce uplift on the base of the dam,
- Internal drainage within the dam body to relieve uplift that may form along lift lines,
- Provision of waterstops and/or keyed contraction joints, and
- Careful spillway layout to reduce scour potential.

Fig. 3-14 illustrates the importance of effective drainage to limit uplift on the base of the dam.

3.2.2 Vulnerabilities

3.2.2.1 Drain Design. If drains are effective, headwater pressure will be reduced at the line of drains and provide a stabilizing effect. Similarly, effective drainage within the body of the dam serves to reduce the probability that a threat to stability will develop along a lift line.

If drains are ineffective, a crack may form at the heel, introducing headwater pressure across a larger area of the base and creating a destabilizing effect. Similarly, a failure sequence may initiate along a lift joint in the concrete if it cracks and uplift exceeds the tensile strength of concrete. Once a crack develops, seasonal temperature changes may "rock" the joint, allowing deeper uplift penetration along a lift joint. Drainage within the dam body can be effective in reducing the probability that tension will develop.

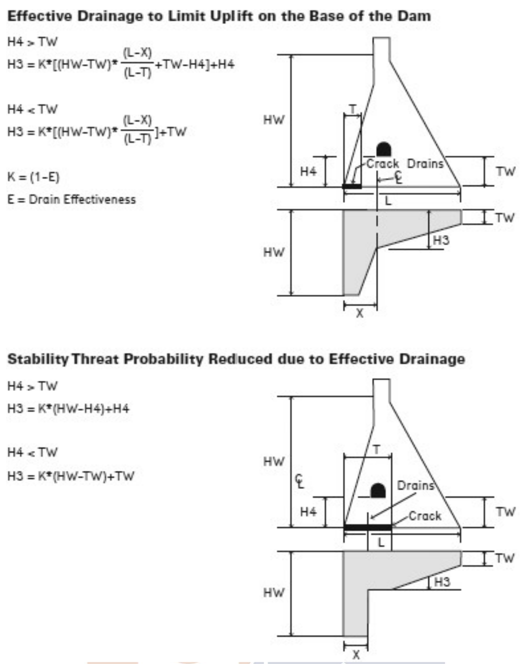

Fig. 3-14. Uplift reduced by effective drainage
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Design errors may take many forms. The error most often encountered in aging dams is failure to provide for positive drainage at the foundation and within the dam body. An indicator of a design error is unexpected movement.

3.2.2.2 Workmanship. Poor workmanship may be a contributing factor that allows a threat to progress. The failure of Gleno Dam, shown in Fig. 3-15, was attributed in part to the poor quality of cement used to produce the concrete.

Poor workmanship was also cited as a contributing factor in the failure of Teton Dam. A common indicator of poor workmanship is heavy weeping visible along lift joints on the downstream face.

3.2.2.3 Concrete Deterioration. Concrete deterioration may contribute to failure if it adversely affects the concrete strength and reduce its resistance to sliding or overturning.

Freeze–thaw (F/T) damage, shown in Fig. 3-16, is common in older concrete placed prior to the advent of air-entrained concrete. F/T damage begins shallow and superficially. Left untreated, it will continue to reduce

Fig. 3-15. Gleno Dam post-failure
Source: Wikimedia Commons, en.wikipedia.org.

Fig. 3-16. Freeze–thaw damage

concrete thickness and strength, but it is not usually considered a contributor to a failure sequence.

Concrete produced with aggregates reactive with the alkalis and carbonates in cement is likely to develop through the entire concrete section, gradually causing expansion and cracking, as seen in Fig. 3-17. The expansive reaction is referred to as an alkali–silica reaction (ASR) or an alkali–aggregate reaction (AAR), and, depending on the degree of severity, may contribute to a failure sequence.

Fig. 3-17 shows an expanding aggregate particle and the cracks induced in the surrounding cement paste. An indicator of ASR is cracking and crazing pattern of cracks on the downstream face, as shown in Fig. 3-18.

3.2.2.4 Foundation and Abutment Integrity. A gravity dam failure sequence initiates when uplift reduces shear resistance at the foundation, allowing the dam to move or slide downstream, as shown in Figs. 3-19 and 3-20.

Leakage around and/or under the dam can initiate a sequence that allows uplift pressure to rise, causing displacement of the foundation or abutments, and then progress until the concrete loses support, cracks, and moves downstream, causing a breach that leads to failure.

Slope instability in an abutment from gravity alone (Fig. 3-21) may initiate without uplift and cause damage, threatening reservoir control.

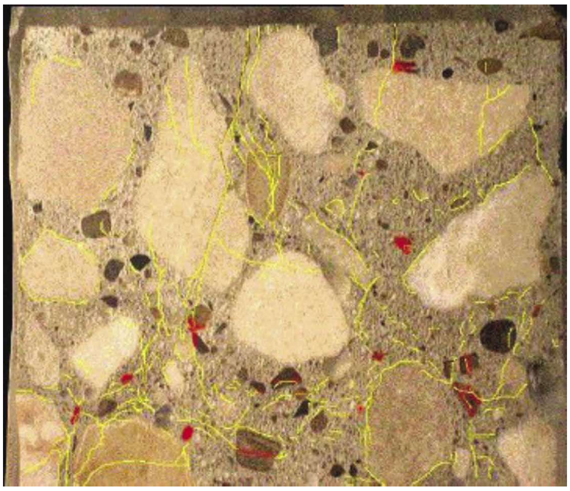

Fig. 3-17. Alkali–silica reaction (ASR) in aggregate
Source: U.S. Department of Transportation (2008).

The only known failure involving fault rupture and offset during an earthquake occurred at Shih-Kang Dam in Taiwan during the 1999 Chi-Chi earthquake, shown in Fig. 3-22. Judging the probability of such an event at another dam evades rational analysis. A fault in the foundation of a gravity dam is addressed during design and treated during construction. Instruments measuring movement may detect fault displacement for a dam in service.

Fig. 3-18. ASR in downstream face of a gravity dam

Fig. 3-19. Abutment failure, Camara Dam

Fig. 3-20. Foundation/abutment failure, St. Francis Dam

Source: Regan (2009, left); Wikimedia Commons (2018, right).

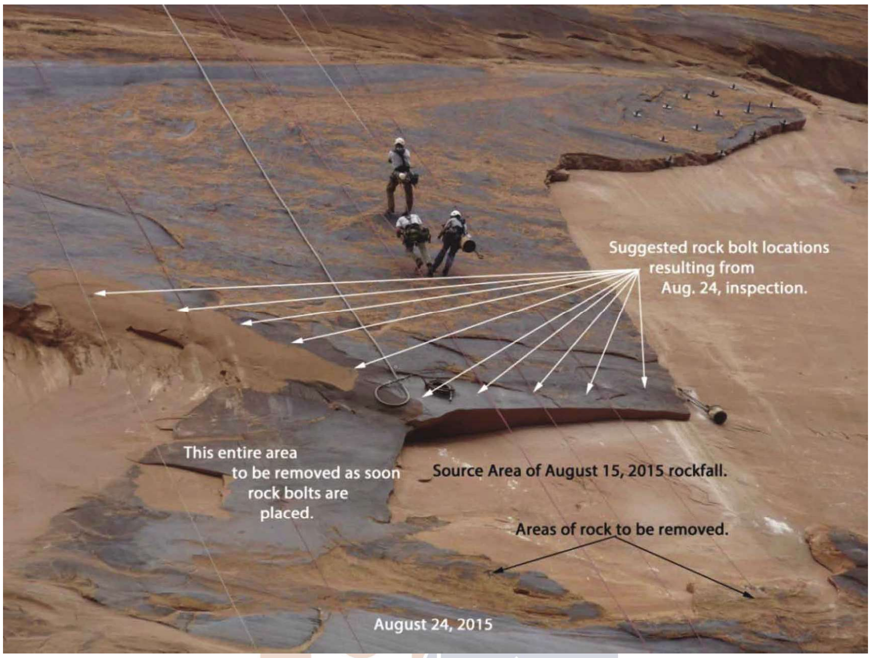

Fig. 3-21. Stabilizing left abutment at Glen Canyon Dam
Source: U.S. Bureau of Reclamation.

Indicators that may signal foundation or abutment instability are (1) displacement of abutment rock blocks, (2) leakage along the abutments, (3) loss of drainage capacity to reduce uplift under or within the dam, and (4) elevated uplift pressure at the heel.

Spillway arrangements vary widely. Spillways may be through the dam, over the crest of the dam on an abutment, or remote from the dam, as shown in Figs. 3-23 and 3-24.

Spillway discharges deliver enormous amounts of kinetic energy that must be dissipated at the foundation. In the process, erosion often scours the rock, creating a "scour hole."

Spillway discharge or overtopping of a concrete dam can cause scour that undermines the toe and reduces a dam's resistance to sliding and overturning, as shown in Fig. 3-25.

Spillways are concrete structures and can thus develop instability indicators similar to those of a dam. Cavitation of concrete surfaces exposed to high-velocity flow merit attention. Both gated (Fig. 3-23) and uncontrolled spillways are susceptible to scour. An indicator that scour threatens the toe of a dam or spillway requires interpreting profiles of scour depth. Scour undercutting the toe of a dam or spillway requires positive intervention.

Fig. 3-22. Fault rupture at Shih Kang Dam
Source: Courtesy of Robin Charlwood, reproduced with permission.

Fig. 3-23. Ogee-gated (left) and chute-gated (right) dams
Source: Wikimedia Commons (right); Courtesy of Seattle City Light, reproduced with permission (left).

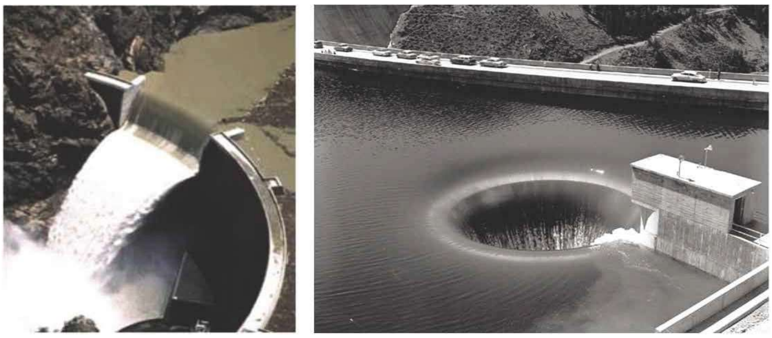

Fig. 3-24. Uncontrolled overflow (left) and Morning Glory (right)
Source: U.S. Bureau of Reclamation (left); U.S. Army Corps of Engineers (right).

Fig. 3-25. Scour hole at base of arch dam

3.3 CONCRETE ARCH DAMS

3.3.1 Design

Concrete arch dams derive their strength by transferring the imposed loads to their abutments and foundations. Valley shape is a key consideration in design that seeks to drive the arch loads as deeply into the abutments as possible to accept the loads and limit the effect of those loads on

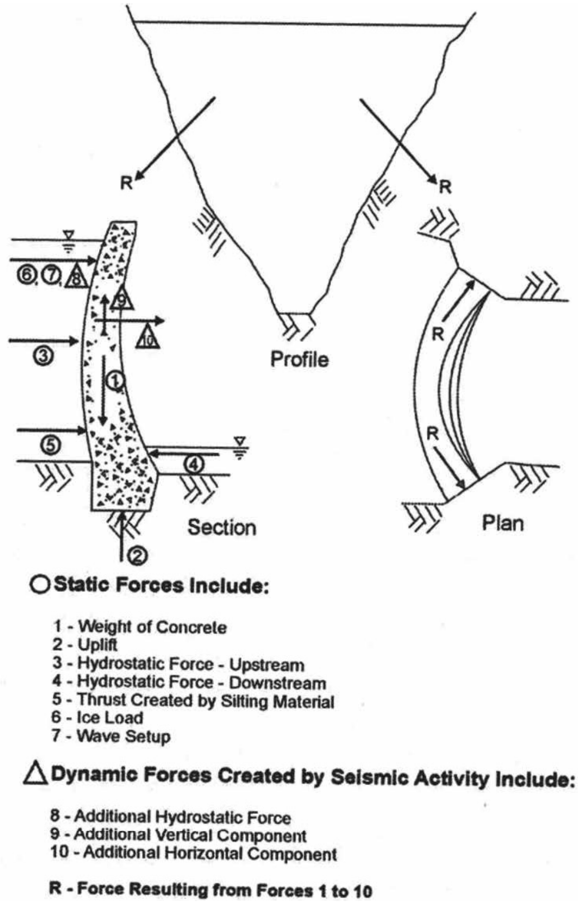

Fig. 3-26. Forces acting on an arch dam
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

the abutment itself. A narrow valley makes that easier to accomplish. In addition to the reservoir, thermal stresses affect how the arch dam transfers load to the abutments seasonally. Arch dam stability relies upon the stability of the abutments and foundation, as indicated in the distribution of forces shown in Fig. 3-26.

Typical arch dam designs employ features similar to those of gravity dams to promote stability, such as

- Proper foundation preparation and treatment to provide adequate support for the dam,
- Grout curtain or cutoff wall that lengthens the seepage path,

- Drainage curtain downstream of the grout curtain or cutoff wall to reduce uplift on the base of the dam,
- Internal drainage within the dam body to relieve uplift that may form along lift lines,
- Provision of waterstops and/or keyed contraction joints,
- Grouted contraction joints, and
- Careful spillway layout to reduce scour potential.

Not every arch dam has either a drainage curtain or internal drains within the dam. An example of measuring drain discharge is shown in Fig. 3-27.

Because positive abutment support is required to resist arch loads, concrete thrust blocks may be required to accept the loads if an abutment cannot furnish adequate resistance.

Typical designs divide the structure into monoliths separated by contraction joints that are fitted with waterstops and often keyed between monoliths to provide shear resistance. The contraction joints are grouted to promote monolithic action from abutment to abutment. An example of this design is the Glen Canyon Dam, shown in Fig. 3-28.

Arch dams are resistant to earthquake forces, and there are no recorded failures of arch dams from earthquakes. The few recorded arch dam failures from any initiator have involved defects in the abutments or foundations. The most frequently cited is Malpassat Dam in France, shown

Fig. 3-27. Measuring toe seepage with V-notch weir

Fig. 3-28. Glen Canyon Dam
Source: U.S. Bureau of Reclamation.

Fig. 3-29. Malpassat Dam after failure
Source: Michel Royon / Wikimedia Commons.

in Fig. 3-29, which failed during first filling because of a foundation defect that went undiscovered during design and construction.

3.3.2 Vulnerabilities

Unlike gravity dams, arch dam performance is not very sensitive to uplift; however, it may be a consideration if the base is thick. Abutment and foundation stability are keys to acceptable performance.

Indicators that may signal foundation or abutment instability are (1) displacement of abutment rock blocks and (2) leakage along the abutments.

A developing threat to stability may be indicated if loss of drainage capacity to reduce uplift under or within the dam is measured or if measured uplift pressure at the heel increases unexpectedly.

3.4 OTHER DAMS

This chapter described the most common dam types (embankment, concrete gravity, and concrete arch), their designs, vulnerabilities, and performance indicators that may signal a developing threat to safety and initiation of a failure mode. There are several other types of dams, each with its own design and vulnerabilities, and they are described in Chapter 11.

CHAPTER 4

PLANNING AND IMPLEMENTING A MONITORING PROGRAM

> Dam surveillance aims to detect, by visual observation and monitoring, any phenomenon that can compromise the structural and operating integrity of a structure or its related operating equipment.
>
> ICOLD 1988

Chapter 3 explained how monitoring of performance indicators is linked to questions about a dam's performance relative to its potential failure modes. This chapter provides guidance for planning and implementing a monitoring program to provide data alerting dam owners of potential threats to safety by measuring key performance indicators. A well planned and implemented monitoring program recognizes the consequence of loss of reservoir control, not only for potential loss of life and property damage but also for the loss of the benefit the dam provides. Properly implemented, surveillance and monitoring reduce risk.

The two integral components of a dam-performance monitoring program are (1) visual surveillance and (2) instrumented measurements. Visual surveillance employs the eyes of informed and motivated inspectors. Instruments help fill the gaps of what cannot be seen by providing measurements of quantifiable responses such as pressure, flow, movement, stress, strain, and temperature.

Dam instrumentation by itself has no particular value. The best instrument does not enhance dam safety if it is not working, is recording irrelevant information, is in the wrong place, is not monitored with appropriate frequency, or if the acquired data are not evaluated. Monitoring is the collection, processing, and evaluation of the measurements recorded by the instruments, combined with information from visual observations.

The following are discussions of a program's overall objectives and key factors that need to be considered in each step to plan and implement an effective program that integrates the interests of the owner, regulator, engineer, and technician. The first step in planning is to ask the key questions concerning a dam's performance, i.e., what aspects of performance require answers? The next step is to decide what, where, and when to measure performance indicators to provide answers to those questions.

4.1 PLANNING

To the extent practical, the key to a successful program is simplicity in planning, installation, monitoring, data collection, and evaluation. Simplicity is served by limiting the number of interfaces between an instrument, data logger, transmitter, and database and through the use of simple, robust instruments and sensors that are easy to install, calibrate, operate, and maintain. There will be cases when delicate and sophisticated instrumentation is required; however, when given a choice: keep it simple!

Tailoring a monitoring program requires some soul-searching to answer another question:

"Just because I can measure a performance indicator, should I?"

Should dams exhibiting no indication of unexpected performance require monitoring other than visual surveillance? This manual cannot provide an answer to that question because (1) each dam is different, (2) each owner is different, and (3) each dam may be subject to regulations that have specific requirements. Many dams are monitored only by visual surveillance, a staff gauge, and crest monuments. Some dams have complex instrumented monitoring in addition to visual surveillance. Most dams fall in between those two extremes.

Agencies with jurisdiction and expertise throughout the world have different regulations for monitoring and reporting that require planning for compliance.

A systematic plan is required to design, procure, install, operate, and maintain the monitoring system; to acquire, evaluate, and interpret information; and to take appropriate actions in a timely manner to ensure safe performance of a dam.

Most dams have monitoring programs balanced to observe and measure only those performance indicators of concern. It is important to understand that the need for observations and measurements may change during the life of a dam. The monitoring plan anticipates those changes and provides sufficient flexibility to address unexpected changes.

During planning and design, measurements are helpful to establish baseline conditions such as existing groundwater levels and any evident ground movements. Site evaluation prior to the start of construction can provide a baseline that will be helpful in measuring responses during and after construction. For example, the potential for settlement may result from measurements and tests made during site investigation.

Monitoring during construction is required to understand ground response to changing loads, to provide construction safety, and to measure the quality of the work. The results can be used to confirm key design assumptions in comparison with actual site conditions, to comply with regulatory monitoring (where applicable), and to determine when specific conditions are met to allow construction to continue (e.g., hold points).

Filling of a reservoir following construction or following a prolonged drawdown is probably the most severe test of a dam and its appurtenant structures. Both visual and instrumented monitoring are vital because the structural stability of the project, as well as the seepage resistance of the dam, foundation, abutments, and reservoir rim, is tested. Observations made during filling can provide an early indication of unexpected performance and also confirm satisfactory performance. Frequent measurements are planned during filling and drawdown. Once steady-state conditions are reached and a stable set of baseline measurements is acquired, measurement frequencies are established for continued long-term monitoring.

Pumped storage projects present a special case of reservoir fluctuation because filling and drawdown occur frequently. Planning for measuring the performance and response of a pumped storage scheme may require continuous monitoring.

Planning for long-term monitoring requires flexibility to provide measurements of performance indicators that may change with time. Procedures are planned to detect trends in responses over the life of the project. Monitoring is tailored to answer the basic question, "Is this dam performing as expected?" Surprises are not uncommon. An effective monitoring plan describes the actions required in the event that measurements suggest monitoring error or unexpected behavior.

Often overlooked in the planning process is the need to provide adequate funds to acquire, install, maintain, and measure all the instruments for the service life of a dam.

Summarizing, the scope of a monitoring program depends on

- Type, purpose, and size of dam;
- Hazard classification;
- Consequences of failure;
- Age and condition of dam;

- Performance indicators to be measured;
- Regulatory requirements; and
- Commitment to funding program life-cycle costs.

How each of these factors affects overall program costs will differ from project to project.

The success of a monitoring program depends on developing objectives, verifying site conditions, complying with regulatory requirements, and understanding measuring requirements. A successful program will meet the objectives of the designers, owners, operators, and regulators. The program is reviewed and updated periodically. Data evaluation may reveal needed modifications to the program because of changes in estimated loading conditions (floods and earthquakes). Instruments may fail. Dedicated staff and regular training are required to maintain an effective program.

A monitoring plan can be a stand-alone document or incorporated into a set of standard operating procedures (SOPs) for a dam. In addition to defining the monitoring needs, effective planning requires specific and detailed answers to the following questions:

- What questions need to be answered?
- Which performance indicators are to be monitored?
- Why are they monitored?
- How are they monitored?
- Where will they be monitored?
- How often will they be monitored?
- How much will the measurement system cost?
- Who will do the work (install, maintain, operate, interpret, report, and take action and responsibility)?

Planning for the life cycle of a monitoring system, both visual and instrumented, begins with design, procurement and installation, and commissioning. Finally, it must address operation, maintenance, continual training, rehabilitation, replacement, placing on inactive status, and abandonment. These activities cost money. A successful monitoring program requires development of a realistic estimate of both initial capital costs and the operational life-cycle costs. An adequate budget is needed for design, engineering, and oversight during procurement and installation, as well as for calibration and commissioning. Annual budgets for operations, maintenance, and training are estimated during the initial planning phase to allow for a realistic assessment of total long-term facility operation and maintenance and capital costs for monitoring. Over the longer term, software updates may be needed. Eventually, instruments will reach the end of their operational life and require replacement.

4.1.1 Visual Surveillance

The performance of many small dams and dams with low consequences is often monitored visually with little or no instrumentation. Most dams are monitored by a combination of visual observations and instrumented measurements.

> An instrument too often overlooked in our technical world is a human eye connected to the brain of an intelligent human being.
>
> Ralph Peck

Visual surveillance is the most important element of a dam safety program. Thorough visual inspection by an individual knowledgeable about a dam's vulnerabilities can provide first warning of unexpected performance or response of a dam.

The frequency and extent of surveillance is a function of the complexity of the site, the consequences of failure, past performance, and staff requirements to perform other duties.

Results from routine and special visual inspections are recorded and captured on simple reporting forms, emails, or memoranda. Documentation of the observations made during inspections is important to develop a baseline understanding of the project performance and observable changes.

A trained operator on the crest of the dam might observe an area along the dam abutment contact where the color of the vegetative slope protection on the embankment has changed. This pattern difference may or may not indicate a potential initiator of a failure sequence. It may require additional evaluation as the cause might be simple intended differences in the vegetation type in that area, or it may reflect the development of a wet spot due to seepage through the dam or the abutment.

With high-quality cameras and the low cost of high-speed communications, it is possible to supplement on-site visual monitoring with monitoring via remote cameras. These tools are useful for monitoring areas of concern or providing surveillance of remote areas. However, cameras do not replace the need for regular observations by a qualified inspector.

4.1.2 Instrumented Monitoring

A simplified eight-step approach for planning and implementing a monitoring program, summarized in Table 4-1, follows:

Step 1: Review information about the project.

Review site investigations, siting studies, design and construction documents, construction photos, operations history, and monitoring

Table 4-1. Eight-Step Approach.

Steps	Description
1	Review information about the project.
2	Identify the vulnerabilities and questions that need to be answered.
3	Identify what measurements can and should be made.
4	Design appropriate monitoring system, including installation, calibration, maintenance, and data acquisition and management.
5	Procure, test, install, and commission program.
6	Operate and maintain instruments.
7	Collect, process, and evaluate data.
8	Take action when indicated.

data. Understand project conditions such as stratigraphy, foundation structure, material properties, groundwater conditions, ambient conditions, appurtenant structures, past construction issues, or proposed future construction.

Step 2: Identify sequences of events that could lead to a loss of reservoir control and the questions that require observations or measurements to answer. Develop an understanding of vulnerabilities and potential failure mechanisms.

Step 3: Identify performance indicators. Decide whether visual observations will be sufficient or whether instrumented measurements are required. Establish the frequency of measurements. Estimate instrument and dam behavior. Establish a range of expected values.

Step 4: Design an appropriate monitoring system including installation, calibration, maintenance, and data management. Provide sufficient financial resources for life-cycle monitoring costs.

Key factors requiring consideration during program design include

- Instrument purpose and location;
- Instrument range, resolution, accuracy, and repeatability;
- Environmental and climatic conditions;
- Instrument site accessibility and ease of installation;
- Availability of replacement parts;
- Reputation of vendor;
- Compatibility with other instruments in a dam-monitoring portfolio;
- Protection during and after installation;
- System power requirements;
- System reliability requirements;

- Need for redundancy and backup; and
- Training requirements.

Select instruments and optimal instrument locations based on the questions that need to be answered. Keep in mind accessibility of instruments for ease in reading, verification, repairs, or replacement. Choose locations that provide the best representation of the conditions of performance, whether at representative sections or specific potential problem areas. Consider the reliability of the instruments. Durable and simple instruments are sometimes the best choice. Establish data-collection procedures and frequencies. Consider the need for manual readings versus automated or semi-automated readings. Include the collection of complementary data to support response and performance interpretations. Establish threshold and action limits. Describe actions required when readings or observations reach these levels. Identify the type and amount of data to be acquired. Define who will be using the data and for what purpose.

Step 5: Procure, test, install, and commission the program. Chapter 5 contains a description of various instruments for monitoring. Once the goals of the program have been documented in a design and procurement package, the various components can be procured, tested, and installed per manufacturer guidance. Vendors also provide technical specifications, as well as operation and maintenance instructions.

Commissioning involves training of staff to implement the program from maintenance of the system to data collection to data evaluation.

Step 6: Operate and maintain instruments.

The instrumentation design report, an SOP, or other similar documentation contains the procedures to take readings, repair instruments, and reduce and evaluate data. Procedures are updated regularly as needed.

Plan to provide for labor and material costs. Acquiring data, scheduling maintenance, repair, or calibration, responding to instrument malfunction, instrument replacement, and technology and software updates, stocking backup supplies, preparing reports to meet reporting requirements, and evaluations and training all have life-cycle costs.

Step 7: Acquire and manage data.

Establish the means and methods for data acquisition and management. To the extent possible, avoid drowning in data.

Means for storage and retrieval of the data are dependent on the size and complexity of the program. Chapters 7 and 13 discuss data acquisition and presentation.

Step 8: Take action when indicated.

Configure the program to alert the owner when measurements suggest behavior of a developing failure sequence. Chapter 8 provides guidance for evaluating the data and taking action.

Overall simplicity is considered when finalizing the design for monitoring because an uncomplicated program is more likely to produce reliable measurements with fewer errors and less cost than a complicated system. This does not mean that having many instruments is a bad idea. The number of instruments is dependent on the number of performance indicators requiring measurement to answer questions about behavior. There may be many instruments, but they will produce best results if they possess as many of the following attributes as possible:

- Simple,
- Robust,
- Accurate,
- Reliable,
- Insensitive to environmental conditions, and
- Easy to read, access, and replace.

These attributes are applicable to small and large monitoring programs All instruments are manufactured to operate within a specified range, resolution, accuracy, precision, and repeatability. Instrument manufacturers and vendors supply their technical specifications. Selection of instruments is matched to program needs and weighed against cost, reliability, and ease of operation.

Instruments and appurtenant parts, including cables, cabinets, power sources, and connections, are designed to operate properly in the environmental conditions to which they will be exposed. In remote areas, batteries or solar collectors used to power instrument data loggers and transmitters may need to operate through dark, cold, hot, wet, dry, or corrosive conditions. For example, battery draw will be affected by sampling frequency data transmission. Incorporation of an automated system can provide continuous readings and the ability to continue to evaluate performance of the project under all conditions. Chapter 7 describes automated data-acquisition systems and their advantages and disadvantages.

Access to the instruments is an important consideration because installation, operation, and maintenance costs increase for sites that are difficult or dangerous to reach. The use of fully automated or semi-automated systems can reduce problems, but challenges will remain for calibration, maintenance, or repair if access is difficult. Other considerations include safety regulations when installing instruments in confined or enclosed spaces. Where instruments are needed in difficult locations, redundant instruments and special measures to protect appurtenances (cables and power) are con-

Fig. 4-1. Protecting cabling
Source: Courtesy of DG-Slope Indicator, reproduced with permission.

sidered to reduce the chances or consequences of unplanned maintenance and repair; however, power will still be required. An example of protecting cabling is shown in Fig. 4-1. Instrumentation in locations that are difficult to access requires careful evaluation to determine if there are alternative means to collect similarly useful data.

Instruments and their appurtenances require protection during and after installation. Damage during construction commonly occurs from traffic with heavy equipment. Locating instruments during construction requires consideration of the changes that will occur to the site over the course of construction. Care is needed to plan instrumentation to avoid heavy traffic and still serve areas that will change during construction. Durable installation materials will reduce the risk of damage.

Common protections include bollards, special coatings, exclusion fences, and burial in vaults.

Design of a system considers other instrumentation already installed. If there are similar instruments in an owner's portfolio, a sense of familiarity with types of instruments, instrument vendors, and possibly installation techniques are beneficial. Contact with other owners and operators or soliciting ideas through technical users' groups also may provide helpful information.

4.2 IMPLEMENTATION

Once the desired system has been designed, the next step is implementing the system to meet the established objectives. Procurement will be based on a set of drawings and specifications that reflect the design intent. Development of the estimate of the initial capital investment for procurement, installation, and initial calibration of the monitoring system is improved if consideration for costs includes the price of all system components and appurtenances such as cable, conduit, protective devices, hardware, software, and facility outages (lost revenue). Vendor mark-up and shipping costs are considered in the initial estimate, as well as labor, material, and equipment costs to properly install and calibrate the system.

A contingency is helpful in the planning-level cost estimate to provide flexibility for future refinements to the system or changes during installation to accommodate site conditions or other unanticipated events such as delays caused by bad weather. Examples of various approaches to procurement, as well as considerations in the development of the procurement package (or drawings and specifications) of the planned system, are discussed in the following sections.

4.2.1 Procurement Approaches

Items to consider as part of the procurement phase include identification of the parties responsible for

- Procurement of the instruments,
- Pre-installation review,
- Installation and calibration of the system, and
- Collection, management, and review of the data.

Procurement services typically involve instrumentation hardware and appurtenant equipment, software, and factory calibration provided by the instrumentation manufacturer or vendor. Construction oversight and review prior to installation are necessary to confirm that the intended and requested instruments will be appropriate for the site. Installation and calibration of the instrument system also includes pre-installation acceptance tests on both hardware and software, commissioning of the hardware and software, and calibration and development of a baseline set of data for the system to confirm successful operation. This, along with troubleshooting of the system to bring it in line with the services requested in the procurement package, is typically provided by the vendor and can also be supplemented or complemented by the owner's representative.

An important aspect of the planning process includes adequate budget and time to effectively schedule transition of the operation and maintenance aspects of the monitoring system after it is installed. A contractor or the owner may be responsible for instrument installation, maintaining installation records, and delivering operation and maintenance information.

If a contractor installs the system, an effective way to minimize challenges associated with the transition of a monitoring program to the owner is to involve the owner's personnel directly in the instrumentation installation and initial monitoring during construction. When direct owner involvement in the construction phase of the monitoring program is not possible, the contractor may provide on-site training for the owner's personnel. Either approach allows for the preparation of a detailed instrumentation operation and maintenance manual for future reference.

Once the system has been installed successfully, the responsibility for continued readings and maintenance is transferred to the owner. Depending on the extent and complexity of the system, some systems can be monitored on remotely accessed systems and others may be monitored locally. Some systems may be monitored by the owner or other entities as specified by the owner. These responsibilities need to be outlined in the plan for monitoring.

The same considerations apply for the installation of new instruments or for repairs to existing instruments at an existing dam. However, existing dams are being actively operated by their owners. When new instrumentation needs arise, direct contact between the owner and the instrumentation vendor is common. When instrumentation is to be added during a retrofit or other new construction phase, procurement through a general contractor can be used. For existing projects, the lessons learned from the prior plan should be taken into consideration.

Other procurement approaches include contracts through an engineering consultant or third-party design–install–operate firm. The advantage and disadvantages of any procurement method require evaluation based on the specifics of each particular project.

For complex monitoring requirements, it is recommended that a qualified instrumentation engineer be involved not only during the planning and design phase but also during procurement, installation, and initial calibration and testing of the system. Engineering expertise may be available from the owner's staff, engineering consultants, instrumentation vendors, or regulatory agencies. This collaboration is important for successful procurement and implementation. A contract package should be developed that includes specifications and drawings for the system. A part of the contract package may be a plan document to identify the specifics of the program, reading frequencies, reporting requirements, and requirements for backup equipment, replacements, and remedial actions. This type of documentation can be beneficial to the owner. Its inclusion in the contract package depends on the owner's intent to involve a third party in the overall monitoring. Also, bidding entities may provide comments and suggestions on the overall plan and program. It is suggested that at least two vendors be contacted during the acquisition process to confirm that the instruments specified will, in fact, be capable of measuring the required performance indicators.

4.2.2 Procurement Package—Drawings and Instrumentation Specifications

The preparation of drawings and specifications that clearly establish the system requirements and define the intent of the instrument monitoring system is important early in the process and should be developed in conjunction with the owner, designer, and instrumentation vendor(s). Early collaboration in the development of drawings and specifications allows for creative solutions and planning, as well as potential cost savings. As emphasized previously, site conditions at the dam such as remoteness, availability of power, dam size, access, and reporting needs must be considered. These criteria define the type and distribution of the instruments that will be used, the nature of the data-acquisition system required (manual, semiautomated, or fully automated), data transmission methods (cable, radio telemetry, fiber optics, distributed data loggers, etc.), data transmission regulations and security, power sources for the system (AC, batteries, solar, microhydro), and data collection, processing, and storage requirements.

In many cases, multiple vendors will be able to supply functionally equivalent instruments, and therefore the specification should not be so specific as to exclude qualified products on the basis of nontechnical issues or minor resolution or accuracy differences. Drawings and specifications should clearly describe the system requirements, as well as the installation, calibration, and testing to provide a working system that meets the objectives of the program. Many vendors include guidance specifications on the instruments themselves, as well as guidance documents on installation needs, procedures, and maintenance required for their systems. This information can be used in the development of the procurement package.

Most of the information that the dam owner requires to operate an instrument and apply its readings is contained in the specifications provided by the manufacturer. A complete set of specifications includes a description of the environmental and electrical conditions under which the instrument will operate and defines the characteristics of the signal that the instrument produces. The performance characteristics of each instrument's resolution, range, repeatability, and accuracy (outlined in Appendix C) belong in the specifications.

The performance characteristics provide the user with the conditions under which the instrument can be reliably used and the performance that can be expected. The manufacturer's specifications should be verified by performing a full-scale calibration check prior to installation; if this is not possible, the instruments' zero outputs should be checked.

Knowledge of instrument power requirements and signal output characteristics is also essential for ensuring compatibility with an automated data-acquisition system if one is needed. Each data-acquisition system (see Chapter 7) has its own signal input requirements, which must match the output of the monitoring instruments that will be connected to it. The hardware and software vendors will provide necessary advice and guidance in this area.

The following is an example of the key elements and considerations for an instrument specification; it follows Section 10 00 00 of the Construction Specifications Institute format:

- Establish general contract conditions.
- State known access restrictions and available utilities.
- Describe known special conditions related to dam safety, e.g., care with heavy equipment, access restrictions, etc.
- Describe the product.
- Provide either performance requirements (e.g., must report water level within 5-mm accuracy), the preferred instrument or equivalent, or the physical attributes of the instrument (amps, wiring, conversions).
- Require drawings to owner standards.
- Describe the execution.
- Require vendor presence during installation, calibration, and commissioning.
- Specify standards for acceptance of work including testing.
- Require instrument operation and maintenance manual that includes calibration and troubleshooting.
- Require instrument training in maintenance, readings, software use, and troubleshooting.

Installation and implementation of a new monitoring system at new or existing projects require adherence to the approved drawings and specifications, but they also include appropriate oversight and procedures to facilitate timely in-field decision making during installation as challenges arise.

4.2.3 Installation in New Dams

Installation of a new instrumentation system at a new dam or at an existing dam requires explicit procedures and should include interface with the instrumentation vendor(s). If possible, the instrument vendor should be present during instrumentation installation, testing, and commissioning and should also provide the owner or operator with training and documentation on the installed system that includes operation and maintenance procedures. If possible, the instrument or data management vendor should visit the site to acquire some familiarity with the site, its challenges, unique situations, limitations in access, or other issues to be able to tailor the system to the specific site. This is crucial not only for selection of proper instruments but also for proper installation techniques, accurate calibration, and testing, as well as the ability to troubleshoot anomalies or problems in the system with the vendor or manufacturer's representative present.

Continued contact with the vendor or manufacturer's representative once the system has been successfully installed will streamline troubleshooting and discussions on necessary repairs, upgrades, and maintenance issues over the life of the system. This will provide the necessary quality assurance and quality control for an effective system. Many vendors will provide training for correct installation, calibration, and testing of instruments. Vendors of data management systems often offer training so that the installed system is optimized for the specific project and its objectives. Successful operation of the instruments and data management system must be verified before components are buried or encased and inaccessible. Coordination with installation specialists, such as drillers for piezometers or inclinometers, also will need to be considered and managed.

Records of instrument installation should include the following information:

- Instrument type,
- Instrument identification,
- Readout type,
- Equipment and personnel responsible for installation,
- Initial measurements,
- Calibration results,
- Noted calibration constants,
- Site conditions,
- Changes from specifications,
- Changes from manufacturer's recommendations,
- As-built locations and dimensions,
- Complementary data and observations, and
- Anomalies in installation or construction, especially those that may affect data interpretation.

Responsibility for the collection and documentation of these data is often assigned to the vendor but it should be supplemented by the owner. This requirement should be included in the specifications as part of the procurement package and will become part of the instrumentation monitoring program, as it will be needed when recalibration or troubleshooting of the system is required.

4.2.4 Installation in Existing Dams

In some instances, instrument installation in an existing dam can be more straightforward than that at a new dam because identification of instrument location and type are dictated by the identified performance indicators. The need to install new instruments at an existing dam should be evaluated carefully and the actual installation and testing closely monitored, in addition to the overall performance and response of the dam and appurtenant features.

4.3 RESPONSIBILITY AND AUTHORITY

The following quotation captures the importance of owner engagement in dam safety monitoring:

> To provide the best basis for securing reliable and high-quality data, hence for securing best value, the people who have the greatest interest in the answers to the questions should have a major role in obtaining the data.
>
> John Dunnicliff

Clearly defined responsibilities are necessary for the development, implementation, and maintenance of a monitoring program. Responsibility should be linked to established decision-making authority for decisions related to dam safety.

The classification of personnel varies widely with different organizations. Small projects may assign several responsibilities (e.g., plan development, data collection, calibration and maintenance, and data analysis) to a single person. Larger organizations operating multiple projects with individuals for every facet of a monitoring program may including personnel responsible for

- Dam safety;
- Interfacing with regulatory agencies;
- Development, implementation, and maintenance of the program, including
  - Training and communication;
  - Review and analysis of information;
  - Operation and maintenance and data collection; and
  - Data entry, reporting, storage, and plotting.

The owner is ultimately responsible for the safe operation of the dam. This is an important concept for dam owners to understand when setting priorities, allocating funds, and assessing risk. The absence of specific regulatory oversight or instruction does not negate this responsibility. The owner establishes clear dam safety responsibilities and decision-making authority. Responsibilities can be delegated among individuals with diverse skills and backgrounds, but in all cases owner responsibilities are clearly understood.

Responsibilities include reporting and backup, which will be documented in a project's emergency action plan (EAP). Typical responsibilities are well defined by agencies with jurisdiction for dam safety and include decisions to notify the public, owners in key positions, dam safety engineers, and the media and on how to secure help in an emergency.

In general, regulatory agencies provide oversight and enforce rules, but they are not responsible for the safety of the structures they administer. For example, the responsibility of the U.S. Federal Energy Regulatory Commission (FERC) include

- Issuance of licenses for the construction of a new project;
- Issuance of licenses for the continuance of an existing project (relicensing);
- Oversight of all ongoing project operations, including dam safety inspections and environmental monitoring; and
- Enforcement of dam safety regulations.

Other agencies may operate differently. Whatever the degree of regulatory oversight and requirements, it is important to have the dam safety responsibilities outlined, assigned, and understood to minimize confusion or redundancy.

Regardless of the size of the project, it is best if a chief dam safety engineer is responsible for the program. Responsibilities include plan development, selection, procurement, and installation and commissioning of instrumentation and automation equipment design, as well as training and delegation of responsibilities when required. Large organizations will typically have internal staff to manage these activities, whereas smaller dam owners may rely on engineering consulting teams or another third party to provide guidance, recommendations, evaluation, and, in some cases, oversight.

The chief dam safety engineer responsible for the success of the monitoring plan oversees monitoring tasks such as data collection, instrument calibration, training, and reporting to confirm the program is being completed as planned. Communication of the content and intent of the program to other staff also is part of this responsibility. Delegation of responsibilities to a third party, whether to an engineering consultant or otherwise, does not relieve the owner of his or her dam safety responsibility to the public.

The dam safety engineer may also assist in data interpretation and analysis and provide technical guidance to other staff responsible for final data analysis. Depending on the complexity of the monitoring program, the owner may either have staff on hand for detailed technical evaluation or consider a partnership with consulting engineers to provide this analysis. Regardless, the data collected must be reviewed in a timely manner to identify possible problem areas and allow enough time to address these issues. Regular data review, report preparation, and distribution to appropriate personnel are required.

Data collection, field inspections, and reporting are assigned to staff familiar with the entire project. The benefits of using staff familiar with the project and areas of concern are familiarity with site conditions and the ability to notice changes over time. For these reasons, visual inspections are often assigned to current operating personnel, dam tenders, or dam operators. For projects with multiple staff levels, senior-level technical personnel train project personnel responsible for collecting and reporting of data, maintaining and calibrating instruments, and identifying action(s) to take based on field observations. Emphasis is placed on the importance of the task and the link between monitoring and dam safety.

Some owners with multiple projects choose to use a group of knowledgeable staff that rotate between projects and who then develop a familiarity and understanding of the performance of each project. This is an acceptable method of project staffing and, as long as staff training is kept current, it has the advantage of redundancy and multiple experienced observers.

In all cases, it is important to have continuity in personnel so that knowledge of historic trends is not lost. Often those with detailed knowledge of project conditions can quickly identify data-collection or observable anomalies in the field. Personnel responsible for data collection in the field must be reliable, dedicated, and motivated. Attention to detail is required because mistakes or omissions can result in lost information or even delays in warning of developing conditions. The opposite is also true where lack of experience or knowledge leads to the idea that an irregular reading automatically suggests a dam safety issue. Field personnel need to understand how the dam functions, its expected behavior, and the purpose of instrumentation and monitoring. The maintenance and calibration checks of an instrument and other automated equipment during their service life are best done by data-collection personnel who are able to notice potential problems, malfunctions, deterioration, or damage.

Data-acquisition personnel also may perform data entry. This can prevent data entry errors or misinterpretations. The need for data entry by hand is decreasing as more and more instruments are automated. However, automation of data collection is no substitute for thoughtful review and analysis.

Large organizations with a portfolio of projects may be able to assign a single person to the job of storing data, developing data plots, and preparing reports. Such a person must work closely with other individuals responsible for surveillance and monitoring. Tasks can include coordination between software programs, data transfer from remote sites, simple programming, creating reports, and making presentations. It is recommended that such a person also be trained in data collection and field maintenance to better understand not only the instruments and automation equipment in use but also to understand the data being evaluated.

Avoid drowning in data! Critically evaluate sampling frequency, storage, and processing. Swollen data-collection files can become filled with large quantities of partially processed data or useless and redundant data. Implementing the surveillance and monitoring plan requires adequate time and funds for data storage, maintenance, and evaluation following installation of the system. This requires staff or external sources to collect, store, and evaluate data and to assess polling frequency.

4.4 OPERATION AND MAINTENANCE

An effective monitoring program requires an adequately funded operation and maintenance program with well-defined responsibilities and procedures. It is often incorporated into the day-to-day project operation.

The basis for developing an operation and maintenance program takes into account several important factors that affect reliability and sustainability, such as

- Frequency of inspections (visual monitoring);
- Frequency of inspections of equipment (especially automated systems that may not regularly be inspected visually);
- Maintenance and service tasks especially calibration, testing, repairs and correction for drift or other malfunction that can affect performance or accuracy such as settlement, vandalism, or impact;
- Performance tests;
- Spare parts or repair/replacement of aging systems/components;
- Upgrades to software technologies and equipment;
- Labor and time required to record, review, and analyze the collected data; and
- Training needs.

Redundancy in staff knowledgeable in the systems is important to account for absences or additional staff needed in time of unusual conditions such as large floods.

The operation and maintenance program is needed for the life of the project. It is regularly reviewed for changing conditions. Reductions require justification. A summary of typical maintenance activities for common instruments is provided in Table 4-2.

The decision to repair, replace, remove, deactivate, or abandon an instrument or component of a monitoring system is based on an evaluation of

Table 4-2. Common Maintenance Activities.

Instrument type	Maintenance activity	Frequency of maintenance
Borehole extensometer	Inspection for corrosion or damage	Annually then less frequently
Inclinometer (manual)	Recalibration	Per manufacturer direction
	Maintain clean tube	As required
Inclinometer (in-place)	Recalibration	Per manufacturer direction
Pressure transducers	Recalibration	Per manufacturer direction
Joint or crack meter	Inspection, cleaning	Annually
Load cells	None	N/A
Weirs or flumes	Remove debris, vegetation, sediment, and algae	Monthly to annually (or more frequently as required)
	Remove chemical precipitation or iron bacteria sludge	Annually (or as required dependent on conditions)
	Clean gauge orifice	Annually (or more frequently as required)
Piezometer (standpipe)	Flush standpipe to remove accumulated sediment (exercise care to prevent hydraulic fracturing)	As required
	Repair any damage to aboveground protective casing or cap	As required
Piezometer (pneumatic)	Check connection valve fitting and replace as required	Annually
	Check air vent from pressure test for clogging	Annually

Common maintenance activities for instrumentation

Table 4-2. (*Continued*) Common Maintenance Activities.

Common maintenance activities for instrumentation		
Instrument type	Maintenance activity	Frequency of maintenance
Piezometer (vibrating wire)	Check lightning protection device in terminal box or cable leads holder	Annually (or following a lightning storm)
Plumbline, inverted pendulum	Maintain full damping oil reservoir	As required
	Remove calcium deposits from line	As required
Settlement gauge	Check for impacts, settlement	As required
Strain gauge	None	N/A
Thermometer	Calibrate	N/A
Tiltmeter, beam sensor	None	N/A
Total pressure cell	None	N/A
Readout instruments	Recalibration	As required by manufacturer
	Replace batteries	As required by manufacturer
	Check fluid tank of pneumatic readout	As required
General	Check strip heaters in readout boxes for proper functioning	Annually and prior to onset of cold weather
	Check for vandalism	Regularly
	Maintain access to monitoring locations	As required
	Power source maintenance	As required

the overall program, the purpose of the specific instrument, the added value of maintaining the instrument, the possibility of the instrument being useful at some future date, and the effect of possible removal or abandonment on the overall monitoring program. These decisions will likely arise in the life cycle of any monitoring program. Consult the instrument manufacturer for instructions prior to disabling an instrument if the possibility of reactivation in the future is anticipated. Instruments that may be reactivated are not considered abandoned and can be referred to as inactive.

Instruments will need to be replaced when they reach their design life. Instruments that consistently malfunction because of wear or site conditions such as settlement, corrosion or other environmental damage, vandalism, vehicular impact, or even irreversible instrument drift should be replaced. Careful review of and familiarity with the historic performance of instruments will help identify when an instrument can no longer be relied upon to provide accurate measurements. Before replacing an instrument, consider how technology evolved since the original installation. Better instruments may be available.

Replacement of instruments or appurtenant components including cables, readout devices, and power sources can be economical. Updates or improvements to the instrument systems require regular review. Instrument manufacturers and vendors can help with a review.

Dam safety concerns may require the abandonment of an instrument that might create a source of a potential failure mechanism (e.g., an abandoned piezometer casing that provides a piping path in an embankment).

Instruments may be retired by simple removal of the device or by abandoning it in place. For example, resistance thermometers, thermistors, joint meters, and other similar instruments are often abandoned in place in concrete dams because their measurements are no longer required.

Next, Chapter 5 presents an array of instruments capable of measuring performance indicators to complete the implementation of a successful performance-monitoring plan.

This page intentionally left blank

CHAPTER 5

INSTRUMENTATION AND MEASUREMENT TOOLS

> The expectations of life depend upon diligence; the mechanic that would perfect his work must first sharpen his tools.
>
> Confucius

Chapter 4 described planning and implementation of a performance-monitoring program. This chapter provides information to select appropriate instrumentation for a monitoring program based on the measurements required to answer performance questions.

Instruments used for measuring different dam-performance parameters are described by physical description, measured quantity, sensor options, advantages and disadvantages, output options, operation and maintenance requirements, and typical application in dam monitoring. References are made to manufacturer websites that provide additional information, including photographs and figures.

Explicit direction or equations on how to read or calculate the measured parameters are left to other references, including manufacturer materials, which are easily obtained. The following instrument descriptions are intended to provide the reader with enough information to select instruments but not necessarily how to install, read, or evaluate the data.

Qualities such as precision, accuracy, robustness, cost, reliability, and longevity are discussed; however, the ever-changing nature of instrument specifications and costs suggests that the reader refer to current manufacturer-published data on those qualities that are also discussed in greater detail in Appendix C.

The emphasis here is on the most commonly installed contemporary instruments. Less attention is given to "legacy" instruments that may still be in use or that may serve to provide redundancy to their contemporary counterparts. A legacy instrument is one that was used in previous eras and may still be active on sites today; however, it is not commonly installed in new-use applications in modern practice. An example of a legacy instrument is a pneumatic piezometer.

The next section begins with the present state of practice and future trends in instrumentation and measurement tools. Subsequent sections are organized by measured performance indicators.

5.1 INSTRUMENTATION

Instruments may measure a dam's geotechnical, structural, hydraulic, or geohydrologic performance indicators. A generalized schematic of the flow of information from the physical world to the instrument user is shown in Fig. 5-1. Instrumentation is a general term used to refer to mechanical, electromechanical, or electronic instruments. A mechanical instrument measurement is converted to a visual reading by purely mechanical means. Some mechanical measuring methods are extremely simple, such as the use of a bucket and stopwatch to measure volumetric flow rate or seepage. Electromechanical devices convert mechanical movement into a measurable electronic signal. One example is an extensometer, in which movement of a rod anchored in a borehole operates an electronic transducer. In purely electronic instruments, the measured parameter generates an electrical signal without an intervening mechanical step. A thermocouple is an example of an electronic instrument.

Most new instruments today are electronic or electromechanical. The electronic part of these instruments combines a sensing element (sensor and transducer) and an electronic circuit (signal-conditioning electronics), as illustrated in Fig. 5-1. The transducer converts the sensed parameter into an electrical signal. The electronics excite the transducer and transform its signal into an amplified output that can be recorded at the end of a cable. The signal-conditioning electronics are typically packaged as close as possible to the transducer in the same housing.

Some transducers, such as vibrating-wire or fiber optic types, produce a signal that is relatively immune to electrical noise even when transmitted over cable lengths of many hundreds of feet. Where such transducers are used, the signal-conditioning electronics may be located near or within the recording or display unit.

Instrument readings may be recorded manually (by writing down or photographing the value displayed on a mechanical scale or digital readout), mechanically (typically by pen-and-ink lines on a circular or strip chart recorder), or electronically by a data logger or computer. The trend today is away from manual measurements and mechanical recorders and increasingly

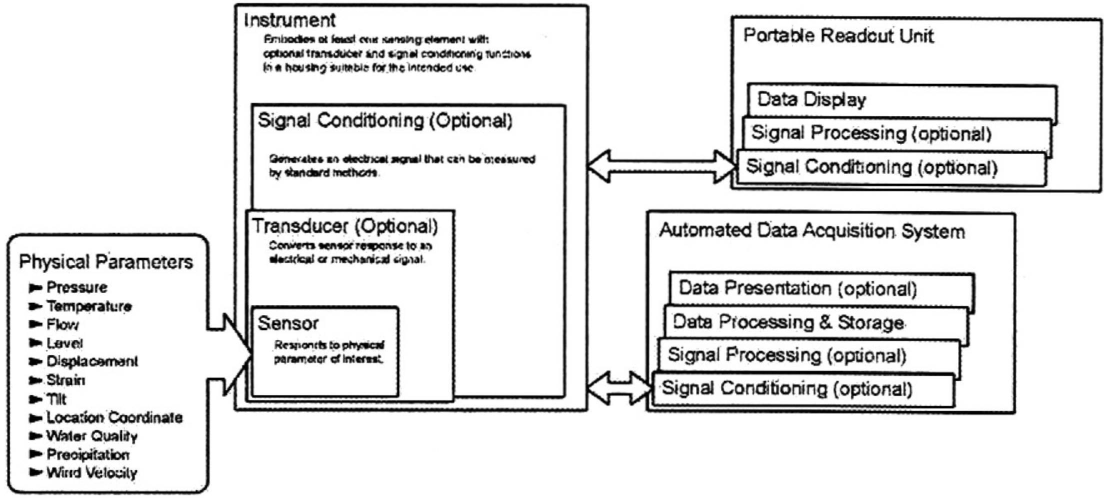

Fig. 5-1. Block diagram of generic instrumentation systems
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

toward electronic measurements and Automated Data-Acquisition Systems (ADASs). Potential benefits of automated recording and reporting include

- A current and continuous data record;
- A variety of data-processing options to improve accuracy;
- Lower costs to collect data and reallocation of labor resources to the more valuable functions of analysis and decision making;
- Ability to assess real-time data remotely in an office that may be located hundreds of miles from the site through web-based applications; and
- Ability to automatically initiate alarms and other actions if critical thresholds are exceeded (refer to Chapters 7 and 8 for more information).

The features and application of each instrument as a whole are the focus of this chapter. The instruments described are as inclusive as possible, but some devices may have been omitted in the array of instrumentation for dams. This oversight is unintentional. Furthermore, as technology advances, valuable new instruments will enter the market. For these reasons, the choice of instrumentation for a particular project will continue to evolve and is not necessarily limited to the devices described in this chapter.

The names used for the instruments described in this chapter are the common names used in the trade. Many of the names have been assigned by the instrument manufacturers or by long tradition. In some cases, more than one name may be used for the same type of instrument. Different names may refer to the specifics of the application and not to differences in the instruments or the fundamental measured parameter. For example, the terms "tiltmeter," "clinometer," and "inclinometer" all describe an instrument that measures angular rotation with respect to the vertical gravity vector. "Piezometers," "pressure transducers," and "pressure gauges" all measure pressure.

5.2 FUTURE TRENDS

Beyond the long-standing manual methods that are still in use, dam monitoring has embraced the technologies of sensors, electronics, computers, and information technology, all of which continue to rapidly advance. These current and future advances will more than likely affect the ways that dam monitoring is performed in the future. A few "crystal ball" predictions of future trends follow; however, it is certain that new technologies will emerge, changing the methods employed by our successors.

5.2.1 Sensors and Electronics

Most electronic instruments used on dams today output an analog signal, a voltage, current, or frequency that is proportional to the measured pressure, tilt, displacement, or other parameter. This output is transmitted in analog form and is then digitized and recorded at a data logger or computer.

However, in an emerging trend over the last decade, more instruments on the market have the required electronics to process and digitize the signal at the transducer level and produce an output in a standard digital protocol such as RS-485, allowing the measurements to be transmitted without being affected by electrical noise and electromagnetic interferences over distances that can reach several hundred feet. An additional advantage of digital transmission is that several sensors can be mounted along a single 4-conductor cable in what is often called a sensor array, as discussed in the next section. This development is further accelerated by the rapid development of micromachined sensors, known by the acronym MEMSs (microelectromechanical systems). In these devices, the mechanical components of the sensor are photo-etched into a silicon chip, along with much of the signal-conditioning circuitry. Accelerometers, strain gauges, and pressure sensors have already been produced using this method. Interestingly, MEMS accelerometers can now be produced with a low full-scale range of $+/-1g$ or less, which makes them suitable to be used as high-accuracy inclination and tilt sensors in inclinometer probes, in-place inclinometers, and tiltmeters when read in static mode. The main advantages of MEMS sensors are their low temperature influence, high resolution, linearity and repeatability, and low zero drift, in addition to high-impact resistance (Sellers et al. 2008). A MEMS sensor itself can sustain impacts of several hundred g's without damage.

5.2.2 Fiber Optic Sensors

Fiber optical data transmission is now widespread in the telecommunications industry, and it is being introduced and used in other industries such as transportation and water supply; however, cost-effective fiber optical sensors have been slower to develop. As a result, fiber optical sensors are not commonly used in dam monitoring because other technology can currently monitor similar parameters more cost-effectively. Exceptions are found in the use of fiber optics to monitor water-temperature changes and to locate movement in long structures such as dikes. As explained in more detail further in this chapter, optical fibers can be used for distributed temperature and strain sensing. This opens the possibility for long fiber optic cables to be embedded in earth and concrete dams and to be used for distributed sensing at numerous locations in the dam. Practical considerations arise because the installation of long fiber optical cables can obstruct construction, and there is a risk of losing all measurements if the cable is accidentally cut or sheared in the structure at an inaccessible location where it cannot be repaired. Nevertheless, fiber optic sensors will probably be used more widely for dam safety purposes in the future. As an example of an application that could benefit from these techniques, piping detection in embankment dams lends itself to distributed-temperature fiber optic instrumentation, using water-temperature changes sensed by the optical fiber as an indicator. Accumulation of information and data from this approach could help to develop a better understanding of piping mechanisms and improve its prediction. Another advantage of fiber optic sensors is their immunity from electrical noise and transients. With continuing advances and price reductions, fiber optic sensors are likely to be used more frequently for dam-monitoring work in the future.

5.2.3 Sensor Arrays

Sensor arrays can be defined as strings of multiple sensors along the same signal cable, which can be electric or fiber optic. With the numerous recent technological advances in sensors with digital output and fiber optic sensors discussed previously, along with price reductions, the logical evolution is to integrate more sensing points along the signal cable. Examples of sensor arrays are strings of tilt inclination sensors based on MEMS accelerometers that can be used as in-place inclinometers, strings of digital thermistors points, strings of pressure sensors or piezometers, and optical fibers read using distributed strain and temperature-sensing methods. Strings of mixed types of sensors could certainly be feasible as well.

5.2.4 Computers and Data Acquisition

Although data transmission from instrument to acquisition system has generally been performed by copper wires, distribution through radio telemetry has become much more commonplace. Radio telemetry reduces the infrastructure traditionally used for networking the instruments to data-acquisition systems, especially signal cables in trenches. Lower-power and lower-cost radios, which make it possible to transmit on license-free spread-spectrum frequencies, together with lower-cost data loggers, have become more available and make it now very cost effective to transmit signals wirelessly between loggers as small as single-channel loggers, enabling the placement of data loggers at each instrument or small cluster of instruments. Additionally, within the past five years, the trend has moved toward wireless internet protocol communication between instruments and acquisition systems. Wireless internet protocol (IP) routers allow for more seamless communication of instrument data to the IP database system.

Automated collection and dissemination of monitoring data are now common practice. The continued increase in power and affordability of personal computers, the availability of digital instruments, the proliferation of low-cost data loggers with networking capabilities, and the availability of wireless telecommunication have all contributed to the trend toward real-time digital data acquisition and PC interfacing of monitoring data.

Use of digital cellular and satellite technology is starting to become a popular means of data transport also. Chapter 6 expands on the various current practices and trends in data-acquisition technologies.

5.2.5 Information Technology

The term "information technology" refers to how information is processed, distributed, and used. This is an area where some of the most important advances in dam monitoring have been made, and they are expected to continue to develop rapidly in the future. Advancements in computing power, internet-based databases, graphics programs, and higher internet speeds have greatly reduced the inefficiencies in the analysis and decision-making processes of previous monitoring systems. Databases now allow monitoring data to be organized, filtered, and graphed automatically—putting the data into forms that can be quickly and meaningfully evaluated by all concerned parties. Readily available internet communication schemes make secure dissemination of these results nearly instantaneous. Recent developments have allowed more efficient and effective automated warning systems and decision-making processes.

Over the past decade, continual upgrades in mobile communications have led to the development of powerful mobile peripherals. Smartphones and tablets have changed the way people send and receive information, and they allow for more remote usage. At present, mobile broadband is accessible at many dams, and the broadcasting infrastructure is growing rapidly on a global scale. It is expected that the trend toward handheld peripherals will continue, with a corresponding trend in databases and graphics programs that run on new operating systems. The portability of the tablet computer allows for convenient input of data directly into a digital database from the field. Data can then be wirelessly transmitted to a digital database. Although this trend is just emerging, it will continue to grow in the industry.

5.2.6 IP-Based Video Cameras

IP-based video cameras are being used more frequently for dam monitoring and remediation work. The cost of this technology has decreased in recent years, and improvement in the bandwidth of communication systems from microwaves to wireless local area networks (WLANs) has made this a much more common instrument for dam monitoring. IP-based video cameras are digital, frequently with tilt–pan–zoom (TPZ) capability, and they can be used to make manual backup readings (e.g., read a staff gauge on a weir).

5.2.7 Residual Load and Integrity of Tendons and Anchors

Concrete dams and their appurtenant structures often incorporate anchors to enhance the stability of the structure. The anchors are typically made of solid rods or 7-wire strands, also called tendons, which are tensioned and grouted in boreholes. Anchors have been used in dams for more than 50 years, and the technology regarding installation and long-term corrosion protection has improved over the years. Because of the inability to directly inspect the anchors, questions are arising regarding the long-term integrity of aging anchors.

The traditional approach to evaluating residual load (i.e., the current load capacity of the anchor) is to conduct a lift-off test of the anchor using a hydraulic jack. However, this method is costly and also risky when taking into account the fact that the anchor can fail during the test. In addition, the test may not always be feasible, as the anchor head may not be accessible or very little grip space may be available to mount the jack.

For this reason, there have been a number of attempts at using nondestructive testing (NDT) methods to evaluate existing anchors and tendons. Among others, Holt et al. (2013) described the results of a research project funded by the U.S. Army Corps of Engineers. The resulting method, which was based on dispersive wave propagation, was successfully used at two dams to determine the load in anchor rods used to secure trunnion gates.

In another approach, in 2002, a research effort was funded by the Transportation Research Board under its National Cooperative Highway Research Program (NCHRP) led to a comprehensive report titled, "Recommended Practice for Evaluation of Metal-Tensioned Systems in Geotechnical Applications" (Withiam et al. 2002). This report presented the findings of a research project to evaluate procedures for estimating the design life of metal-tensioned systems in new geotechnical installations and determining the conditions and remaining service lives of systems already in place. It presented a recommended practice for assessing the present conditions and remaining service lives of metal-tensioned systems with NDT techniques and an appropriate prediction model. The report identified several electrochemical tests, including measurement of half-cell potential and polarization current, which can detect the presence of corrosion and gauge the integrity of any corrosion protection systems. However, it found that mechanical NDTs, principally wave propagation methods such as impact and ultrasound techniques, must also be used to determine whether corrosion has caused loss of element cross section in the metal-tensioned system.

The report included a critical literature review on NDT methods and prediction models, as well as a detailed description of the NDT methods selected for use with the associated recommended practices. It should be noted that the Transportation Research Board sponsored additional research afterward on the same theme of evaluation and improved design of metal-tensioned systems.

The other approach is the ASTM standard D 5882–07 titled "Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations" (ASTM 2016), on which pile test procedures are based. Specifically, this standard covers the procedure for determining the integrity of individual vertical or inclined piles by measuring and analyzing the velocity (required) and force (optional) response of the pile induced by an impact device such as a handheld hammer. The test methods covered are the pulse echo method (PEM), where the pile head motion is measured as a function of time and the time-domain record is then evaluated for pile integrity, and the transient response method (TRM), where the pile head motion and force (measured with an instrumented hammer) are measured as a function of time and the data are evaluated usually in the frequency domain. Although not originally intended for rods and tendons, the methods described in the standard or variations thereof certainly hold promise for successful use in this type of application.

Methods for evaluating the residual load and integrity of anchors are not yet mainstream, but there is certainly a need and a demand that will keep increasing with time, especially if rather simple and very efficient methods can be developed and brought to the market.

5.3 CRITICAL PERFORMANCE INDICATORS

5.3.1 Internal Hydraulic Pressure

5.3.1.1 Piezometers - General. Piezometers are used to measure pore water pressures and are by far the most common of all instruments installed in dams. Piezometers installed in the abutments, foundations, and embankments of a dam are used to monitor phreatic levels and uplift pressures and to interpret seepage regimes. Piezometers installed in an earth embankment under construction can also be used to monitor excess pore pressures caused by changes in stress from the weight of the fill. For dam-performance monitoring, a reading accuracy to one-tenth of a foot is generally acceptable for piezometers.

The most common types of piezometers in use today are the open standpipe (open hydraulic) and the vibrating-wire piezometer. Other types include liquid-level, hydraulic, and pneumatic piezometers; however, these are not often installed in current practice. They are covered in this section because working instruments of these types may still be in use. Newer technologies such as resistance strain gauge piezometers, fiber optic piezometers, and quartz pressure sensors are also available but not yet as widely used. The following section describes these various types of piezometers and their advantages and disadvantages.

In situations when knowing the temperature of pore or joint water pressure is required, thermistors may be installed with along with piezometers in most applications.

5.3.1.2 Installation Considerations.

Pressure Sensors. The user needs to keep in mind several considerations regarding pressure sensor installation. The instrument will need to be installed such that the total pressure sensor will always be submerged and that the barometric pressure sensor is never submerged. Should the water level drop below the total pressure sensor, data loss will occur. Should the barometric sensor become submerged, the barometric compensation will be incorrect and the data will be unreliable. Because of drift in pressure measurements as the sensor ages, it is recommended to periodically manually measure the height of water for sensor calibration.

Filters. Piezometers buried in the ground or grouted into boreholes are often surrounded by a sand envelope. In these cases, it is necessary to incorporate a filter into the piezometer housing to permit the entry of water while excluding solid particles. Filters can also prevent the entry of air into the piezometer. Air inside a piezometer causes a lag in the response to a change in pore water pressure. This is especially problematic with hydraulic piezometers, which have long, liquid-filled lines.

Two types of filters are used: High air-entry (HAE) value filters have a pore size of 0.5–2 μm and an air-entry value of approximately 14.5 psi (1 bar). Low air-entry (LAE) value filters have a pore size of approximately 40–60 μm and an air-entry value approaching zero. Air-entry value is defined as the differential pressure that must be applied across a saturated filter before the filter allows air to pass through. The smaller the filter's pore size, the greater the effect of surface tension, which causes a higher air-entry value. HAE filters are generally used in unsaturated soils of low permeability to prevent soil particles from entering the piezometer. In contrast, LAE filters are generally used in coarse-grained saturated soils, where pore gas pressure is not present.

Piezometers installed in wells have the filter replaced by a mesh screen, which is less susceptible to blockage by scaling or crystallization of dissolved salts, especially where the standpipe may periodically become dry.

Venting. Piezometers with pressure-sensitive diaphragms react to changes of barometric pressure in the same way that they react to changing groundwater pressures. Barometric pressure acts directly on the water surface in wells and standpipes, and small fluctuations in barometric pressure affect readings. Barometric effects are eliminated by venting the piezometer. Vented piezometers naturally compensate for barometric pressure changes by allowing the ambient barometric pressure to act on the backside of the diaphragm. Venting is achieved by inserting a small plastic tube within the cable all the way to the inside face of the pressure-sensitive diaphragm. The outer end of the tube is open to the atmosphere.

Vented piezometers are used in standpipes and observation wells, in which the piezometer measures the height of a water column. Nonvented piezometers are normally buried and sealed in fills or boreholes, in which the soil acts as a baffle and prevents pore water pressure from reacting to minor changes in barometric pressure.

A disadvantage is that the vent tube provides a path for moisture to migrate into the inside of the piezometer, which usually shortens the instrument's life. To prevent moisture from entering the vent tube, the open end has a chamber containing desiccant capsules. The desiccant capsules need to be replaced regularly to prevent corrosion and damage to the piezometer. For these reasons, venting is not always advisable, and it is sometimes preferable to correct for barometric pressure based on readings from a barometer. Barometric recordings can be automatically accounted for in digital data collection.

Casing Materials. To retard corrosion, piezometer housings are made of noncorrosive materials. Plastic, stainless steel, and titanium are the most common materials in use. Soil chemistry (e.g., pH and corrosivity) are considerations when choosing the housing materials. Casing material choice requires care if sensors are installed in high-temperature environments (e.g., tailings dams).

Comparative Installations. The four most common installation configurations for piezometers are open standpipe, observation well, zoned, and fully grouted; a comparison of these configurations is given in Table 5-1. All four installation methods can be instrumented to allow automated (digital) readings using pore-pressure sensors, such as vibrating-wire (most common) piezometers, but only two of the installation methods allow manual/physical confirmation of the reading by using a water probe.

The open standpipe piezometer and observation well installation offer the added benefit of supplementing the pore-pressure measuring device with the ability to directly measure or observe the water level in the standpipe. Open standpipe piezometers and observation wells are often installed with a zoned backfill to prevent vertical flow in the area surrounding the pipe or to target a specific subsurface layer.

Table 5-1. Comparison of Piezometer Installation Techniques.

Installation method	Advantages	Disadvantages
Open standpipe and observation well	• Open well allows access to physically confirm water level • Simple to install • Common practice • Longevity • Reliability	• Time lag in pressure equalization
Zoned backfill	• More robust than open standpipe	• No physical confirmation of data
Fully grouted	• Generally lower cost • Simple installation • More immediate response (less lag time to stabilize) in saturated soils • Easier to install multiple piezometers within one well	• Sensitive to grout mix and installation procedures • May not give reliable readings in certain formations or at interfaces with low and high permeable strata • No physical confirmation of data • Separate instrument (i.e., open well) required to confirm reading • May be more susceptible to damage due to settlement of surrounding strata • Requires barometric correction • Likely unsuitable for partially saturated soils • Cannot be replaced

A zoned backfill configuration employs the backfill characteristics of open standpipe piezometers and observation wells without using a pipe. The pore-pressure measuring device is installed in a borehole at a desired depth, with the electric leads, cables, and hoses guided up the borehole to the ground surface. The immediate area above and below the device is then backfilled with a porous material (sand pack). The area immediately above the sand pack is then backfilled with bentonite pellets or chips and hydrated to form a seal above the sand pack. The remaining borehole is then grouted to the ground surface.

Fully grouted installation is a simplified method where the pore-pressure device is lowered into a borehole at a desired depth, with the electric leads, cables, and hoses guided up the borehole to the ground surface. The entire borehole is backfilled with a nonshrinking cement–bentonite grout to prevent vertical flow. Methods for installation and grout mix design are detailed by Mikkelsen and Green (2003). Some of the key considerations are summarized here.

Piezometers have been installed using all four methods since the advent of diaphragm pore-pressure devices. In general, the open standpipe piezometer configuration has been most popular; however, there has been increased use of the fully grouted configuration by some members of the dam-monitoring community. Recent research and reviews by Contreras et al. (2012) and Mikkelsen and Green (2003) have advocated the increased use of fully grouted piezometer systems because they simplify construction and reduce costs, and their research indicates that such systems provide comparable results to the other installation methods. In contrast to this research, there have been practical applications of fully grouted piezometer systems that have reported erroneous or questionable data without the ability to confirm or calibrate the readings. Although no formal case histories or studies have been published regarding these issues, the dam-monitoring community remains divided over the suitability of fully grouted piezometer systems. Perhaps until more confidence is developed in fully grouted piezometers, standard practice might consider installing open-well piezometers adjacent to some of the fully grouted piezometers in such a way that these piezometers record the same data, so that comparisons can be made. This was done during remedial construction at the Saluda Dam in South Carolina (SCE&G Company), and good comparisons were obtained. It is unknown if the comparisons have continued over the years since installation.

If an owner or engineer wishes to capitalize on the cost savings of a fully grouted installation, the following guidance requires careful consideration:

- Proper grout mix is critical to the successful performance of grouted piezometers:
  - Grout needs to be of a creamy or "milkshake" consistency.
  - Cement is added first, then bentonite. It is important to use the proper water/cement ratio.
  - Grout needs to be designed for proper permeability. This ensures the pressures read in the grout reflect a response to hydrostatic pressure similar to that of the surrounding strata. Laboratory and analytical evaluations have indicated that the permeability of the grout can be up to three orders of magnitude greater than the surrounding strata (Contreras et al. 2012).

- Grouted piezometers may have questionable readings when placed near interfaces with strata of significantly different permeability characteristics (i.e., near the interface of a highly pervious filter or foundation zone and a low-permeability core or a concrete structure).
- The settlement or deformation potential of the surrounding soil needs to be considered.
- Grouted piezometers can generally withstand vertical strains of up to approximately 15%.
- Grouted piezometers in partially saturated soil may not provide the intended response.
- Industry experts should be consulted if you plan to install grouted piezometers within partially saturated soils or rock.
- If the system will include numerous grouted piezometer locations, consider installation of one or more open standpipe wells for comparison and data confirmation.

5.3.1.3 Open Standpipe and Observation Well. An open standpipe (also known as an open well or Casagrande piezometer) is the simplest type of piezometer. An example is shown in Fig. 5-2. It consists of a steel or plastic pipe, with a filter at its lower end, installed inside a borehole. The annular space adjacent to the filter is backfilled with sand; backfill above the filter is generally an impermeable material, such as bentonite grout or bentonite chips. Water entering the pipe through the filter rises to a height above the filter, which is equal to the pore water pressure at the filter elevation divided by the average density of the water in the standpipe.

Fig. 5-2 also shows a typical observation well. This differs from the open standpipe piezometer in that the full height of backfill material is permeable, usually sand or gravel. Observation wells provide a vertical connection between all the strata through which they are installed. If artesian

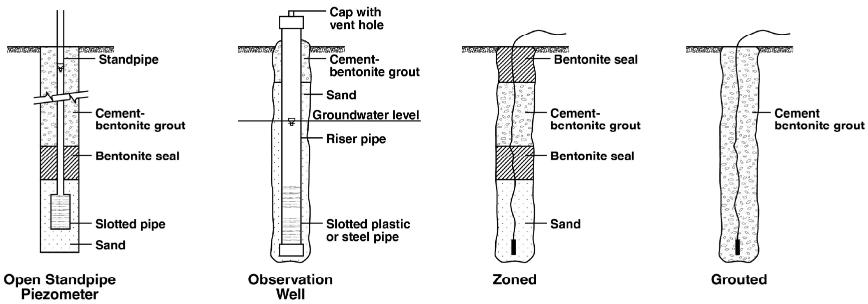

Fig. 5-2. Common piezometer installation techniques

Fig. 5-3. Water-level indicator (left) and pressure gauge (right)
Source: AECOM (left only), reproduced with permission.

conditions occur in one or more strata, interpretation of the water level in the well can be ambiguous. In addition, rain and/or irrigation water can seep in and accumulate in the bottom of the observation well in soils that decrease in permeability with depth. This gives a false indication of the piezometric surface. If infiltration is entirely from one unconfined aquifer, observation wells usually give a reliable indication of the groundwater level and are well suited to measure uplift at the base of a concrete dam.

Open standpipe piezometers and observation wells are not used in clay and other low-permeability soils because the time lag is too long between pore water pressure changes and the corresponding change of water level inside the well.

The water level inside an open standpipe piezometer is easily measured with a water-level indicator (dipmeter) or a pressure gauge, as shown in Fig. 5-3.

Reading an open standpipe piezometer can be automated by installing a pressure transducer or vibrating-wire pressure sensor inside the pipe. It is wise to choose a standpipe with an internal diameter greater than 0.8 in. (20 mm) because many pressure sensors have a diameter of 0.75 in. (19 mm). However, the larger the standpipe, the greater the amount of water that must flow into or out of it for the water level to reach equilibrium with the pore water pressure in the ground. If the ground around the filter has low permeability, the time lag to reach equilibrium could be excessive.

Another method to measure the water level in an open standpipe piezometer or observation well is with a bubbler system, as shown in Fig. 5-4.

The bubbler system consists of a pipe connection to the water level in the standpipe, a pressure transducer, and a small compressor. The compressor

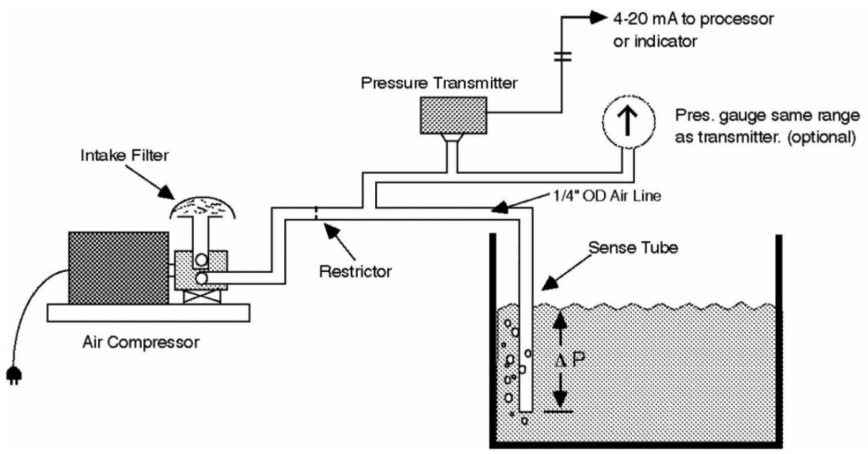

Fig. 5-4. Bubbler system
Source: Kele Associates, reproduced with permission.

pumps air into the well through the pipe, and the "backpressure" is measured. The pressure measured in the air pipe can be correlated to the water level. The advantage of bubblers is that the sensor is located out of the water where it can more easily be protected and maintained. They can also be used to retrofit small-diameter standpipe piezometers (less than 5/8 in. inside diameter), which were very commonly used in earth dams from the 1940s to the 1970s. Bubblers are also suitable for dirty water.

Similar to other manual instruments, the advantages of open standpipe piezometers include their low cost, longevity, simplicity, and reliability. They are typically installed in drilled holes. Major disadvantages are lack of real-time, automated readings. Although the use of pressure sensors can allow remote sensing, the lack of real-time response of the instrument in a low-permeability soil is a disadvantage for embankments in which changes in water levels and pore pressures are important factors in evaluating dam performance.

5.3.1.4 Pneumatic and Hydraulic Piezometers.

Pneumatic Piezometers. A typical pneumatic piezometer and its operating principle are shown in Figs. 5-5A, 5-5B, and 5-5C.

Water entering the body of the piezometer through a filter exerts pressure on a flexible membrane, closing two valve ports. Nitrogen from a pressurized tank at the readout location is metered at a controlled flow rate into one of two plastic tubes. When the nitrogen pressure at the piezometer tip equals the pore water pressure, the flexible membrane lifts off the valve ports, allowing nitrogen to flow into the second tube and vent to the atmo-

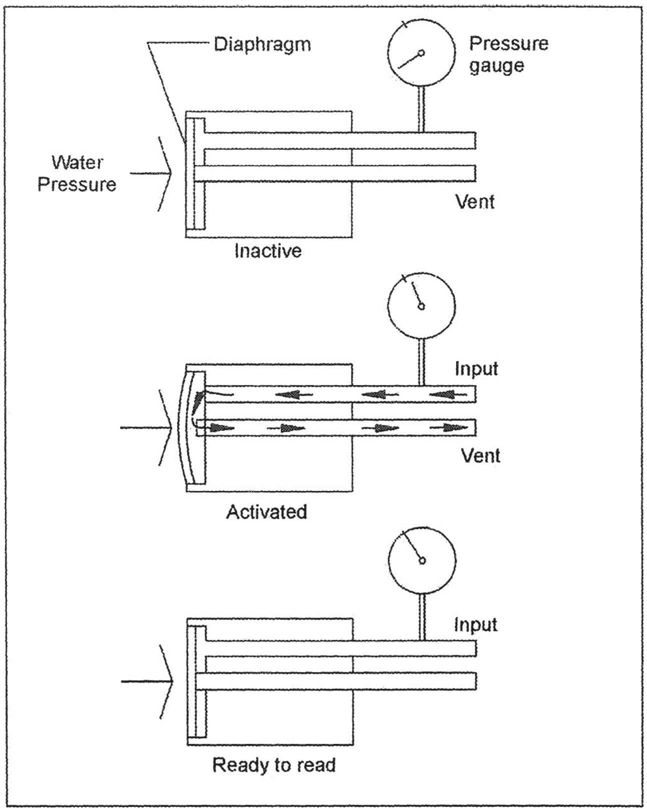

Fig. 5-5A. Operating principle of a pneumatic piezometer
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Fig. 5-5B. Pneumatic piezometer sensor
Source: RST Instruments, reproduced with permission.

Fig. 5-5C. Pneumatic piezometer sensor with protective slotted casing Source: RST Instruments, reproduced with permission.

sphere. The pressure at the inflow tube when the valve opens can be read on a pressure gauge. Alternatively, the nitrogen supply can be shut off, allowing the valve at the tip to close and the static pressure at no flow to be read on the pressure gauge.

The advantages of the pneumatic piezometer include its low cost and its immunity to lightning damage. Disadvantages include the prolonged times required to read piezometers with long tubes, the bulky readout box, the need for a nitrogen supply, and the difficulty of connecting to a data logger. Also, inaccuracies can be caused by leaks in the tubing. Water or dirt entering the tubing may foul the valve seats and cause reading errors.

Pneumatic piezometers are fairly uncommon for new dams, except in some cases where an owner may ask for a redundant technology (e.g., in addition to a vibrating-wire piezometer) that has no risk of being affected by lightning. Most applications for pneumatic piezometers are for short-term embankments such as pre-loads of compressible layers.

Twin-Tube Hydraulic Piezometers. In the past, this type of piezometer was quite common but in recent years it has generally been replaced by pneumatic or, more commonly, vibrating-wire piezometers. The essential components are shown in Figs. 5-6A and 5-6B. Groundwater enters the tubing through a filter element designed to prevent air from entering the tubing. The tubing is usually made from two individual nylon tubes bundled inside a PVC outer jacket. The tubing leads to a readout terminal at a lower elevation, where water pressure in the tubing is measured by a Bourdon tube pressure gauge or a pressure transducer. Because the pressure reading is sensitive to the elevation of the readout terminal, this must be accurately surveyed, and any subsequent settlement or heave of the reference elevation accounted for.

The apparent simplicity and reliability of the system is compromised by operational difficulties. The main problem is the accumulation of air bubbles in the tubing and the need for periodic flushing with de-aired water. A pressure gauge with high accuracy and resolution and made of noncorrosive material is the best choice.

An additional concern about these piezometers is transmission of pore pressure along horizontal reaches of tubing, and, as the tubing ages and breaks, it may also cause piping of fine material.

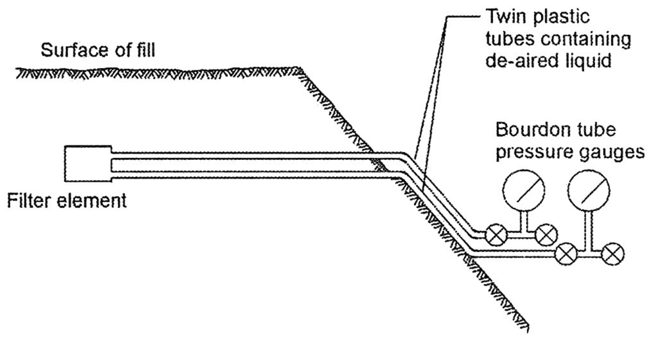

Fig. 5-6A. Twin-tube hydraulic piezometer schematic
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Fig. 5-6B. Twin-tube hydraulic piezometer
Source: RST Instruments, reproduced with permission.

5.3.1.5 Resistance Strain Gauge Piezometers. Resistance strain gauge piezometers and pressure sensors employ stainless steel, titanium, or ceramic diaphragms to sense pressure. Strain of the diaphragm resulting from the application of pressure produces a change in the resistance of an attached strain gauge, as shown in Fig. 5-7. Today most strain gauges are sputtered or plated onto the diaphragm, which results in more economical and reliable instruments. The resistive properties of silicon semiconductors are also used for pressure sensing by bonding a silicon chip to the diaphragm. Such sensors are then called piezoresistive pressure sensors.

Strain gauge and piezoresistive-type pressure sensors are available with internal signal-conditioning electronics that produce 0–5 V output or 4–20 mA output. They are also available without electronics, in which case the output is a millivolt-level signal. Millivolt-level signals are more easily affected by electrical noise and require external bridge completion circuitry. Outputs of 0–5 V or 4–20 mA are readily recorded by almost all automated data-acquisition systems.

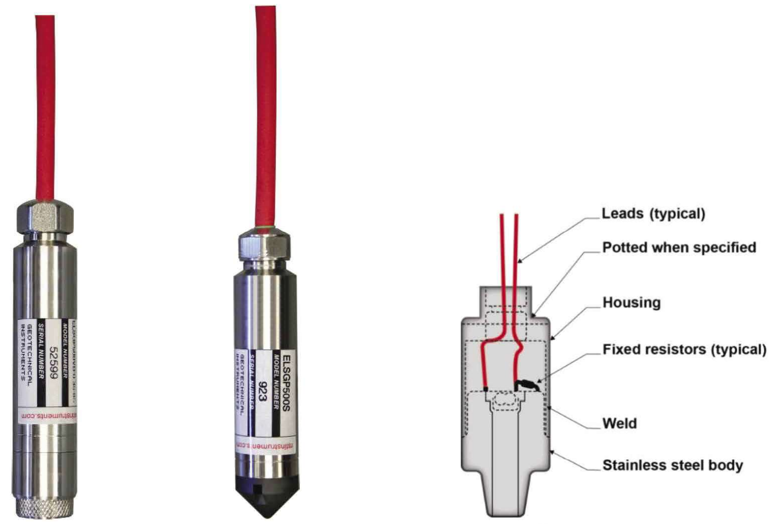

Fig. 5-7. Diaphragm strain gauge piezometers with filter nose and ported nose Source: RST Instruments, reproduced with permission.

Many commercial pressure sensors of this type do not include a filter in the housing and are therefore best suited for use in open standpipes. These are generally referred to as borehole pressure gauges or piezometers with ported noses. Most have a vent tube in the cable to equalize barometric pressure changes. Models with filters can be buried in the ground and are true piezometers in that they directly measure pore water pressures. Most of these instruments have stainless-steel housings. Titanium housings are also available and have superior corrosion resistance in salty or brackish water.

An advantage of this type of pressure sensor is that it is widely used in the industrial market and is therefore available from numerous suppliers. These sensors are also suitable for dynamic measurements. The main disadvantages are susceptibility of the internal electronics to lightning damage and to moisture that enters the instrument through the vent tube. These problems are most critical in piezometers that are buried and therefore nonretrievable. However, some manufacturers include a lightning protection component (gas tube) in the piezometer to improve its reliability.

5.3.1.6 Vibrating-Wire Piezometers. Vibrating-wire piezometers, as shown in Figs. 5-8A and 5-8B, have been used extensively on dams throughout the world and have achieved an excellent reputation for long-term stability and reliability (Bordes et al. 1985; McRae et al. 1991; Choquet et al.

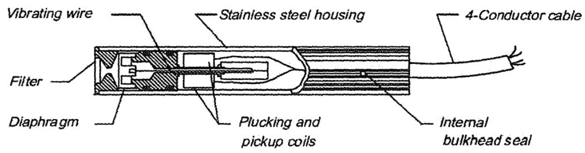

Fig. 5-8A. Vibrating-wire piezometer schematic
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Fig. 5-8B. Vibrating-wire piezometers (standard, heavy-duty, and drive-point models)
Source: RST Instruments, reproduced with permission.

1999). The pressure-sensitive diaphragm is coupled to the vibrating wire, which is plucked and read by an electromagnetic coil. Various styles are available, including small-diameter versions for insertion into small-diameter standpipes, heavy-duty models for use with armored cable in earth dams, and standard models for burial in fill or installation in boreholes.

Vibrating-wire piezometers have the advantage of long-term stability, and the frequency signal can be transmitted accurately over very long cables. Additionally, they can be used in open standpipes, zoned piezometers, and fully grouted piezometers. There is some limitation to the dynamic capabilities for the measurement of rapidly changing pressures (e.g., earthquake effects), although their capability is improving with new data loggers, and they are susceptible to lightning damage but not to the same extent as resistance strain gauge types. Most manufacturers include a lightning protection component (gas tube) in the piezometer to improve its reliability.

5.3.1.7 Fiber Optic Piezometers. Fiber optic piezometers consist of MEMSs (microelectromechnical sensors) or MOMSs (micro-optical mechanical sensors) that send signals to an optical cable. The instrument is generally housed in a stainless-steel tube and is separated from the environment by a porous filter material composed of ceramic or stainless steel. Housings for fiber optic piezometers are generally tubular, with typical diameters around 0.3 to 0.8 in. (8 to 20 mm) and typical lengths of 2.2 to 4 in. (55 to 100 mm). These instruments are relative newcomers to the geotechnical field. As yet, they do not have an extensive history of use and are somewhat expensive. An example using Fabry–Perot Interferometry technology is shown in Fig. 5-9 (Choquet et al. 2000).

Major advantages of fiber optic sensors include their immunity to vibration, lightning damage, and radio and electromagnetic noise interference. Fiber optic piezometers can be used in harsh environments, including gaseous environments, and their optical signals can be sent over several kilometers with little signal loss. As such they can be considered for use in ADASs. Fiber optic piezometers are expected to have good long-term stability, but there are still few case histories to support that claim. Their simplicity of design and small number of parts hold the promise of reduced sensor unit costs in the future. Readout units can also be expected to follow a similar cost reduction trend with further advances in research and number of applications. Fiber optical cables are already less expensive than their copper counterparts with a similar degree of mechanical reinforcement and waterproofing.

5.3.1.8 Quartz Pressure Sensors. The resonant frequency of a quartz crystal changes as a function of the pressure applied to it. This property is used in submersible quartz pressure sensors available from several manufacturers. They are mainly used in dam monitoring for pool-level measurements. These instruments have very high accuracy and precision, but they are typically more expensive than the other types of piezometers discussed previously.

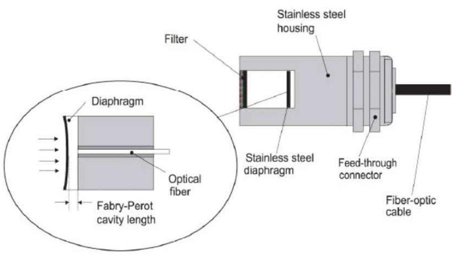

Fig. 5-9. Fiber optic piezometer based on Fabry–Perot interferometry
Source: Courtesy of Roctest, reproduced with permission.

5.3.1.9 Multiple Piezometers in a Single Borehole. Occasionally it is desirable to install more than one piezometer in a borehole. This can be difficult in standpipe and zoned backfill-type piezometers. A sand envelope is required around each piezometer tip. Furthermore, the tips need to be isolated from one another by sealing the borehole space between them with a bentonite grout or other impervious material. Various methods of installation have been used and specialized equipment exists for placing the various materials in controlled amounts in their proper locations (Dunnicliff 1993). The impervious plugs must be longer than imperfections in the embankment or joints in rock that would allow water to bypass the plugs. Fig. 5-10 shows an example installation detail for nested piezometers with multiple piezometers in the same borehole. Alternatively, a number of piezometers can be mounted on a multiconductor cable to ease installation, as shown in Fig. 5-11.

Fully Grouted Piezometers. An advantage of fully grouted piezometers is that they can easily accommodate several pore-pressure measuring devices in a single borehole. The grout column surrounding the instruments allows for the isolation of subsurface layers. The borehole can also accommodate other types of instruments alongside pore-pressure measuring devices, such as inclinometers. Fully grouted piezometers have become the most common form of nested multipoint piezometers. Details of fully grouted

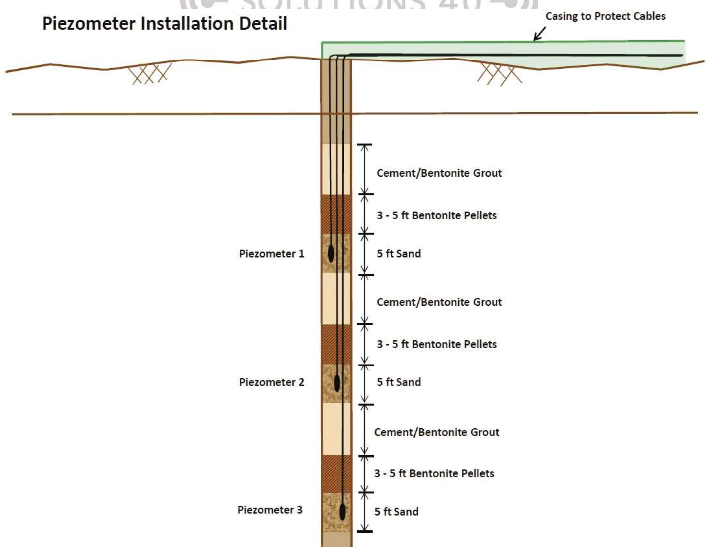

Fig. 5-10. Nested piezometers installation detail
Source: AECOM, reproduced with permission.

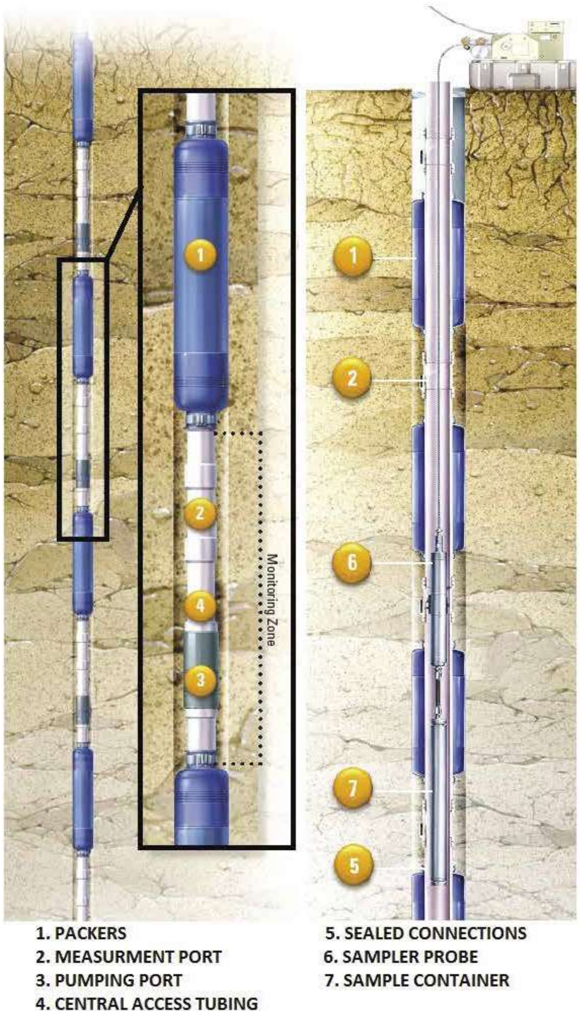

Fig. 5-11. Multiple piezometers in one hole—the Westbay System
Source: Westbay Instruments, reproduced with permission.

piezometers would be similar to those shown in Fig. 5-10; however, the entire column would be grouted.

The Westbay System. The Westbay System, shown in Fig. 5-11, consists of casing, couplers, and independently-inflated packers permanently installed in a borehole. Packers isolate the couplings from their neighbors. Measurement port couplings have a valve, which can be located and operated by a wireline-deployed probe with a pressure transducer lowered into the casing. This port is used for measurement of formation fluid pressure, performance of hydraulic tests, or collection of formation fluid samples.

The Waterloo System. The Waterloo System, shown in Fig. 5-12, uses a series of special double packers connected by a watertight casing. The packers inflate chemically upon exposure to water and remain inflated permanently. The sample entry ports can be connected to pressure transducers located inside the casing (Solinst 2015).

5.3.2 Flow and Water Level

Measurement of seepage quantity is important to estimate the amount of water seeping and leaking through, beneath, or around a dam. Water clarity and quality are also important because high turbidity is a performance indicator that material is being removed from the dam or its foundations, raising the possibility that piping may lead to failure of the dam. Flow quantity is often measured indirectly using water-level devices. Seepage measurement devices described in this section focus on flow quantity and include calibrated containers, Parshall flumes, and weirs. Applications in dam engineering primarily include measurement of flow through seepage collection channels, toe drain outlets, and stream discharges. A reading accuracy of these flows to the nearest gallon is generally considered adequate for dam-performance monitoring. Also included in this section is a description of various liquid-level measuring devices. These are used to measure water levels in reservoirs and also to indirectly

Fig. 5-12. Multiple piezometers in one hole—the Waterloo System
Source: Solinst Waterloo Systems, reproduced with permission.

calculate seepage flows by measuring the water level in a flume bay or weir box.

5.3.2.1 Flow Measurement.

Calibrated Containers. The simplest method of measuring seepage flows is to use a stopwatch to measure the time required to fill a container of known volume. The container volume is then divided by the time to fill the container to calculate a volumetric flow rate.

Parshall Flumes. Parshall flumes are frequently used to measure flow in open channels. The Parshall flume is a specially shaped section of a channel that restricts the flow and creates a gradient at the water surface, as illustrated in Figs. 5-13A and 5-13B. The water surface elevation is measured at two locations using stilling wells. The flow rate can then be calculated based on the difference in water surface elevations in the stilling wells.

Water levels are commonly measured with staff gauges fixed to the walls of a stilling well or the flume itself. Water levels are also measured using ultrasonic-level sensors, bubbler tubes, and submerged pressure sensors. These sensors are described in other sections of this chapter. Several sensor technologies provide the potential for connection to ADAS. The advantages of the Parshall flume are its simplicity, low maintenance, long service life, self-scouring design, and the potential for integration into ADAS for continuous, real-time remote sensing.

Weirs. Weirs, shown in Figs. 5-14A and 5-14B, are often chosen to measure seepage rates. They work better at low flow rates than Parshall flumes and have better precision. The shape of the weir may be square, trapezoidal, or V-notch. The shape and size of the weir depend mainly on the volume of flow to be measured. The depth of water is typically measured with a staff gauge installed near the weir. For best accuracy, vent pipes are attached to the downstream side of the weir plate (not shown) to ensure that the pocket beneath the nappe is fully ventilated. Also, flushing ports can be provided at the bottom of the weir plate and upstream baffles may be used to calm the water flow. They can, however, become filled with sediment or fouled by algae or floating debris, requiring periodic maintenance and flushing. Weir covers can be effective in controlling algae growth. The figures below also show an arrangement for the automatic reading of water levels using a vibrating-wire force transducer.

For large flow volumes, a rectangular or trapezoidal weir may be needed, as shown in Fig. 5-15.

River Flow Gauges. River flow gauge stations are often used for monitoring inflow and outflow from dams and their structures and to calibrate hydrologic predictions for the site. River flow gauges downstream of a dam

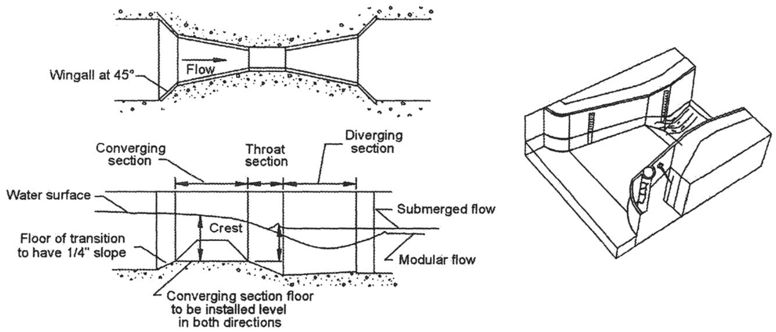

Fig. 5-13A. Parshall flume schematic
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Fig. 5-13B. Parshall flume
Source: AECOM, reproduced with permission.

structure can provide an indication of unexpected releases and may be set to automatically trigger an alarm if an unusual spike occurs in river flows. River flow gauges upstream of a structure can be used as an early indicator of changes in inflow, which may warrant proactive operation of water conveyance features. The U.S. Geological Survey (USGS) maintains a network of publicly available river gauge data that can be accessed on their website. Owners may also decide to install their own gauges in proximity to their site. The USGS provides guidance on stream flow measurement in their manual *Techniques of Water-Resources Investigations of the USGS*, Chapter 8, "Discharge Measurement at Gaging Stations." This chapter can be downloaded for free at http://pubs.usgs.gov/twri/twri3a8/pdf/TWRI_3-A8.pdf.

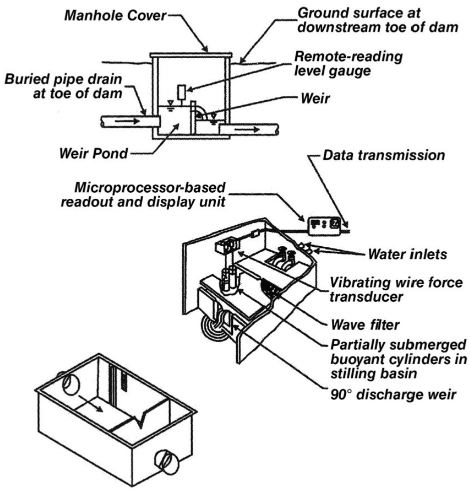

Fig. 5-14A. V-notch weir schematic
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Fig. 5-14B. V-notch weir photo
Source: AECOM, reproduced with permission.

River flow gauge measurements require a staff gauge to measure the river stage, and then the cross section at the gauging site must be calibrated for stage-discharge.

Velocity Measurement. Several instruments that directly measure the volumetric flow rate in pipes are available commercially. Flowmeters use

Fig. 5-15. Rectangular weir

a variety of sensing principles and techniques, including pitot tubes, propeller vanes, paddle wheels, electromagnetic, ultrasonic velocity through the fluid, Doppler, Coriolis mass, and vortex shedding. They typically are built into a short section of a pipe of specified size with attached signal conditioning and display module and sold as a unit. All flowmeter types have inherent advantages and disadvantages. Two well-proven general-purpose types are ultrasonic and vortex shedding.

The vortex shedding-type flowmeter, shown in Fig. 5-16, is suitable for use over a wide temperature range. It is simple, rugged, and maintenance-free. There are no moving parts; no sensor parts are exposed to the water.

When using any type of flowmeter fitted to a pipe, it is essential that the pipe be completely full at the time of measurement if the velocity is to be converted accurately into a volumetric flow (gal./min or L/min). This is sometimes challenging in applications such as toe drain outfalls, which do not always flow full. This stipulation applies to all types of flowmeters and is not only limited to vortex shedding.

Flowmeters may also be used in open channels to measure linear velocity (ft/s, etc.); however, the dimensions of the channel and elevation of the water must be known to obtain a volumetric flow rate. This can be readily accomplished in a hardened channel of known cross section with water-level sensing technology to determine water depth. Portable flowmeters have been used for this purpose, but the accuracy is not great because velocities vary across the stream profile. Paddle wheel- or propeller-type flowmeters require more maintenance than noncontacting types or vortex-shedding types.

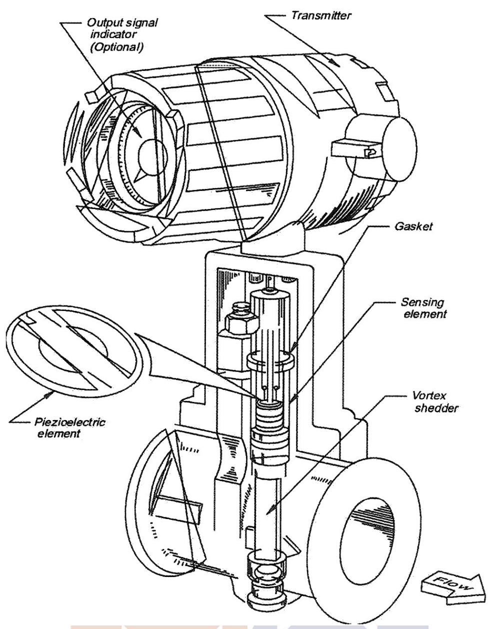

Fig. 5-16. Flowmeter, vortex shedding type
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

5.3.2.2 Water-Level Measurement. Reservoir and tailwater levels are usually recorded even on the smallest dams. Unanticipated rapid increases in tailwater or decreases in reservoir level or both are often linked to activation triggers for operation of gates or valves or the emergency action plan (EAP). There are several ways to measure these water levels. Typically, a stilling well is used to house a measuring device to attenuate wave action. Level-monitoring instruments are located away from the nappe effects of spillways, powerhouses, and other intake and outlet structures. Common devices placed upstream and downstream of the dam to measure reservoir and tailwater, respectively, include staff gauges, float systems, bubblers, or submerged pressure transducers. As described previously, water-level measurement devices are also used to measure water levels in flumes and weirs in order to calculate flow.

Low-Range Pressure Sensors. Low-range pressure sensors are available for measuring shallow fluid depths. The major advantage in using these instruments is greater accuracy when measuring the shallow depths often encountered in low-flow flumes and weirs. One sensor measures the total pressure at the base of the flume or weir and another sensor measures barometric pressure. The net fluid pressure is calculated and then converted to a height of water. The barometric pressure transducer may either be integrated into the top of the flume or weir or housed externally. In some cases, the barometric pressure is conveyed to the instrument through a data cable. In such instruments, extra care must be taken to protect the cable from damage. Pressure sensors are available for a wide range of pressures (i.e., flow depths) and accuracies.

Vibrating-Wire Weir Monitors. The vibrating-wire weir monitor, shown in Fig. 5-17, uses a vibrating-wire force transducer to monitor water levels upstream of a weir. The main component is a cylindrical weight hung from a vibrating-wire force transducer. The cylinder is partially submerged in the basin upstream of the weir. The water level behind the weir is related to the buoyant force on the cylinder, which is reflected in the tension in the wire and its resonant frequency. The depth of water in front of the weir can be used as an input to open-channel flow equations to calculate the estimated volumetric flow of water through the weir.

Staff Gauges. The simplest and most common device for monitoring reservoir elevation is the graduated staff gauge, which can be mounted on any vertical surface and bolted directly to a concrete, timber, or steel structure. Staff gauges are also commonly used to measure water levels within Parshall flumes and weirs. The gauge requires indelible graduations and markings so that it is resistant to sun bleaching, rusting, or other forms of deterioration. The positioning of the gauge is carefully surveyed so that it is easily visible and permits accurate water surface elevation readings. The

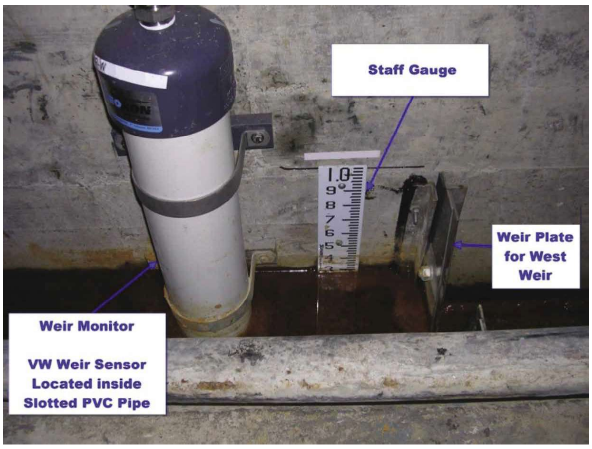

Fig. 5-17. Automated vibrating-wire V-notch weir

best location is one that is not influenced by wave action. In cold climates, protection of exposed staff gauges against ice loads may be necessary.

Many reservoirs, weirs, and flumes that are fitted with automatic water-level sensors are also equipped with a staff gauge that provides a convenient visual check on automatically read data and serves as a backup system in the event of electronic system failure. Also, a staff gauge for visual observation is often required by many regulatory agencies because of its reliability and accuracy. Frequent documented checks of automatic water-level sensors using manual staff gauges are required, including documented cross checks with readings at remote control centers or powerhouses.

A standard staff gauge used by the U. S. Bureau of Reclamation is shown in Figs. 5-18 and 5-19. The gauge is staff graduated in increments of 0.01 ft (5 mm). Typical materials include fiberglass, laminates, type 316 stainless steel, or steel with a coating of porcelain enamel. Staff gauges are simple, but they cannot be automated and must be protected from ice and debris.

Manual Tape Measurement. Steel tapes used for reservoir gauges are typically custom-made and graduated precisely to unique reservoir elevations. A common configuration is a steel tape coiled onto a drum and

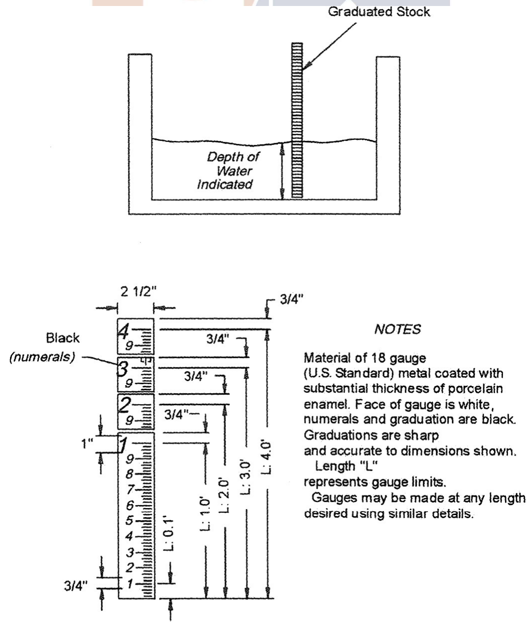

Fig. 5-18. Standard staff gauge
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Fig. 5-19. Staff gauge in measuring weir
Source: AECOM, reproduced with permission.

mounted on the top of a standpipe. The standpipe is open to the reservoir and serves to attenuate wave action. Some steel tape reservoir-level monitoring devices have a tape that is electrically charged with a low current and low DC voltage and an in-line voltmeter to indicate contact with the water. To measure the reservoir elevation, the tape is lowered into the standpipe until contact is made (indicated by the voltmeter) and the tape is read.

Float Systems. A typical float system, which uses a float attached to a chain leading over a sprocket to a counterweight, is shown in Fig. 5-20. As the float rises, the sprocket turns, moving a pen that draws a line on a cylindrical paper chart or activating a rotary encoder for electronic measurements. In the former case, the paper chart is driven by a small battery-powered electric motor or by mechanical clockwork.

Bubbler Systems. Bubbler systems are commonly used to measure reservoir level. This type of system was described earlier in this chapter under the open standpipe section.

Submerged Pressure Transducer. Water levels can be measured by using a submerged pressure transducer to measure the head of water above the transducer elevation. Pressure transducer gauges are usually mounted in a stilling well or a pipe with an open top and connected to the reservoir

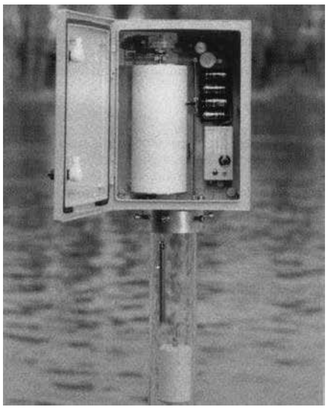

Fig. 5-20. Water-level float recorder
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

at low elevation. The stilling well damps most wave action. Electrical or vibrating-wire pressure transducers require protection from lightning and may become fouled in dirty water. Corrosion of the transducer can be a problem. Transducers made entirely from titanium with very high corrosion resistance are available commercially if needed. Pressure transducers can be vented to eliminate barometric influences, but moisture must be prevented from entering the vent line. This requires the use of desiccant capsules, which must be replenished at regular intervals. Alternatively, nonvented transducers can be used and the barometric pressure can be recorded separately. Pressure transducers are relatively delicate and susceptible to damage. The locations for these gauges are selected strategically to limit the risk of damage due to impact, debris, and environmental exposure. Two different types of transducers are shown in Figs. 5-21 and 5-22, respectively.

Ultrasonic and Radar Sensing. Ultrasonic and radar technologies provide two methods of electronic-level sensing. The methods provide means for continuous level measurement of a fluid surface. The sensors for these technologies may be contacting (sensor is in contact with the measured fluid) or noncontacting (sensor is not in contact with the measured fluid). Noncontacting methods may be complicated by the presence of foams or liquid/liquid interfaces (such as an oil–water interfaces) within the measured fluid. The sensors can be connected to data loggers or ADASs.

The most common contact method is guided wave radar (GWR), which may also be known as time-domain reflectometry (TDR) or micro-impulse radar (MIR). In GWR, a probe extends into the measured fluid. A pulse of

Fig. 5-21. Transducer in secure location

Fig. 5-22. Submerged pressure transducer
Source: Teledyne Isco, reproduced with permission.

microwaves traveling at the speed of light is sent down the probe. When the pulse reaches the air/water interface, a large portion of the microwave energy is reflected back to the transmitter. This technique works well in applications where the liquid surface may not be perfectly flat, such as cases where waves are present. Changes in pressure and temperature do not affect the accuracy of this technique. The equipment typically has no moving parts and involves minimal or no maintenance.

Two techniques are available in noncontacting radar-level sensing (Fig. 5-23): pulse radar and frequency-modulated continuous wave (FMCW). Typical ranges of measured distances are up to approximately 100 ft. The principle in noncontacting pulse radar sensing is to send out a microwave signal that bounces off the surface of the liquid and returns to the gauge. Using the measured time for the return signal, onboard electronics calculate the distance to the liquid surface.

The FMCW technique also sends microwaves toward the liquid surface and receives signals that are bounced back. However, the transmitted

Fig. 5-23. Radar-level transmitter at Roosevelt Dam
Source: U.S. Bureau of Reclamation.

signals are of continuously varying frequency. Electronics within the sensor calculate differences between the transmitted and received frequencies, which are proportional to the distance to the liquid.

Ultrasonic-level sensing is similar to the noncontacting radar-level sensing except that the energy pulse is ultrasonic, which means that the energy travels at the speed of sound. The sonic transducer works by reflecting sound waves off the surface of the fluid back to the instrument. The time traveled for the sound wave is proportional to the distance the wave travels. This distance is subtracted from the known elevation of the transducer yielding the fluid elevation. The advantage of this system is that it can be located above the fluid surface, therefore providing better access for maintenance. Temperature affects the pulse speed, but this is compensated for by onboard temperature sensors and calculations.

In dam engineering, level sensors may be used to continuously measure and record reservoir levels in real time. For contacting sensors, a shield or stilling well may be required to prevent damage to probes by floating debris, waves, and so on. A shield or stilling well could also be provided below a noncontacting sensor to minimize the effects of waves that create a nonlevel water surface. These technologies may also be used as a component part to automate other instruments that require the elevation or depth of water to be known, such as a weir.

5.3.3 Water Quality

5.3.3.1 Turbidity. Turbidity is a measure of the degree to which light traveling through a water column is scattered by suspended particles. A variety of turbidity meters exists to measure this property. Instruments of this type are useful in detecting any changes, sudden or otherwise, in the

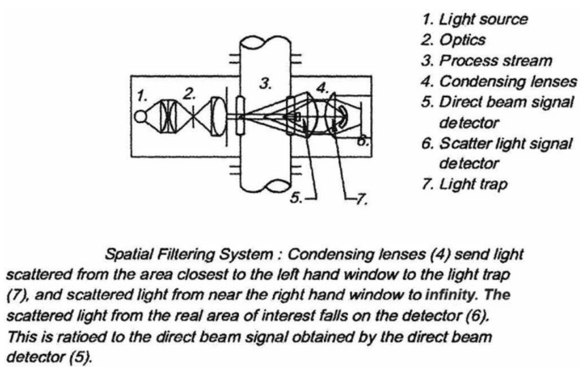

Fig. 5-24. Turbidity meter
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

amount of material being eroded from a dam embankment or a dam's foundation.

Conventional turbidity meters, shown in Fig. 5-24, must be recalibrated for light transmission versus sediment concentration when the sediment-size distribution changes. For heavy sediment loads, more advanced turbidity meters obtain the size distribution of suspended particles by infrared laser multi-angle scattering (laser diffraction). These can measure the total suspended particle concentration and a mean sediment size.

5.3.3.2 Quality. Water-quality measurements at dams are typically made to indirectly assess conditions within the dam, its abutments, and its foundation. For example, increases in the turbidity of seepage water can indicate internal erosion and piping. On rare occasions, changes in water chemistry can indicate changes in the flow paths of seepage water. Changes in seepage water quality generally indicate a condition that requires closer investigation using other, more direct methods.

The most common water-quality measurements made at dams are turbidity, conductivity (resistivity), pH, total dissolved solids (TDS), and salinity. Instruments used today are commonly "multiprobe" instruments, an example of which is shown in Fig. 5-25, that make more than one type of measurement simultaneously. Water-quality instruments currently on the market are capable of measuring temperature, dissolved oxygen, percent saturation, specific conductance, salinity, resistivity, TDS, pH, redox, and depth.

These parameters can be measured by a combination of multiprobe instruments or by a single instrument. Water-quality instruments are typically equipped with their own digital displays. They also are available with

Fig. 5-25. EXO1 Multiparameter Sonde
Source: Photo courtesy of YSI Incorporated, reproduced with permission.

analog or digital outputs that can be recorded by ADASs. Chemical analysis is typically done by collecting water samples and performing laboratory tests.

5.3.4 Strain

Strain is defined as the change in the length of a solid material over a base length divided by the base length. Strain is a nondimensional value and is commonly expressed in units of micro-inches per inch (μ-in./in.) or microns per meter (μm/m). These units are commonly termed "microstrain units" or "microstrain."

Strain normally is the result of applied stress or thermoelastic deformation. The time-dependent strain (creep) can also be generated in soil, rock, and concrete, where strain increases with time under a constant stress. Because it is generally difficult to measure stress directly, strain is usually measured and stress is then calculated using Hooke's Law. Hooke's Law relates strain (ε) to stress (σ) using the Young's modulus (E) of the material ($\sigma = E \times \varepsilon$). There are, however, some exceptions, where stress can be measured directly using pressure cells, stress cells, or stiff inclusions in the solid material.

Instruments for strain measurement are usually referred to as strain gauges or strain meters. They are based on a variety of principles: some are purely mechanical and others are electrical.

5.3.4.1 Strain Gauges for Concrete and Soil. Mechanical strain gauges can only be used at the surface of materials, usually concrete or rock surfaces. They employ two reference studs, fixed a certain distance apart, and a removable micrometer of sufficient accuracy, usually 0.004 to 0.0004 in. (0.01–0.001 mm), to measure the change in distance between the two studs.

Electrical strain gauges can be used at the surface or internally in concrete, rock, and embankment materials. The most common types are strain, optical, and vibrating-wire gauges for use in concrete, where the strain values to be measured generally do not exceed 1,000 microstrains, and potentiometric or vibrating-wire gauges for use in soils where the expected strain values can be higher (i.e., several thousand microstrains). In this latter case, the instrument is generally referred to as a soil extensometer.

Vibrating-wire strain gauges, an example of which is shown in Fig. 5-26, are also used for embedment in concrete. The length of the measuring base of a vibrating-wire strain gauge is defined as the distance between the two end flanges. It is normally recommended that this length be at least three to four times the maximum size of the aggregate. For this reason, these instruments are most often manufactured in lengths of 4–10 in. (10–25 cm). Their measuring range is usually ±1500 microstrains.

Another instrument commonly used as an embedment strain gauge in concrete is the sister bar, shown in Figs. 5-27 and 5-28. A sister bar is a short, usually 3.28-ft (1-m)-long steel reinforcement bar (rebar) with a small diameter in the range of 0.5 to 0.6 in. (12–15 mm) containing a coaxially mounted vibrating-wire strain gauge. The sister bar is installed parallel to a larger-diameter rebar that is part of the normal reinforcement of the concrete. Strain measured in the sister bar, which is cast into the concrete, is then

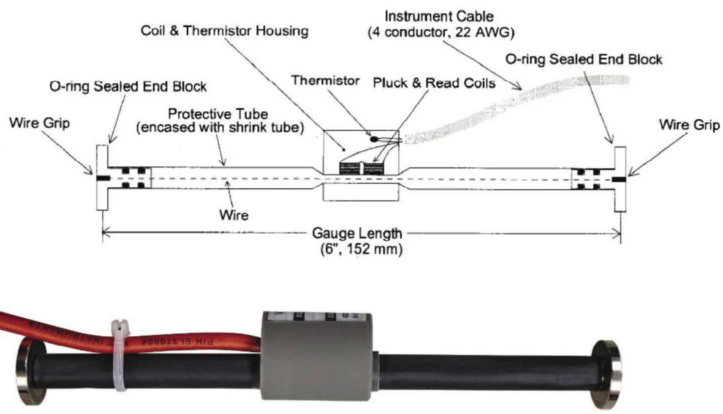

Fig. 5-26. Vibrating-wire strain gauge for embedment in concrete
Source: RST Instruments, reproduced with permission.

Fig. 5-27. Sister bar
Source: RST Instruments, reproduced with permission.

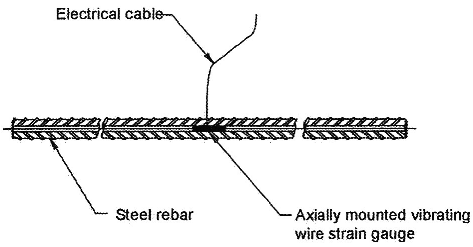

Fig. 5-28. Small-diameter sister bar to be installed parallel to large-diameter rebar
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

assumed to be the same as that in the larger-diameter rebar and in the concrete itself. It is assumed that the small-diameter sister bar has a negligible effect on locally modifying the strain or stress state in the vicinity of the larger rebar.

Figs. 5-29A and 5-29B illustrate a soil extensometer used to measure strain in soils. These are also described later in this chapter under the settlement section. It consists of a central tube with a telescopic coupling in the middle and two end flanges that define the base length. A displacement transducer, either potentiometric, linear variable differential transformer (LVDT) or vibrating-wire, is mounted longitudinally in the tubular piece and attached to the two end flanges to measure the change of distance between the flanges. Soil extensometers have a long base length when used in embankment materials, usually in the range 40 in. (1 m) and can be easily modified for greater base lengths. Measuring ranges of the displacement transducers are generally on the order of 1 to 12 in. (25 to 300 mm) and can be modified for greater ranges. A number of soil extensometers can be installed end-to-end to get a complete strain profile along a measuring section.

5.3.4.2 Multiple Strain Gauges (Rosettes). Concrete-embedded strain gauges are installed either singly, to measure strain in one direction, or in rosettes of two or more gauges to determine the principal strain directions and to obtain the complete state of strain in two or three directions.

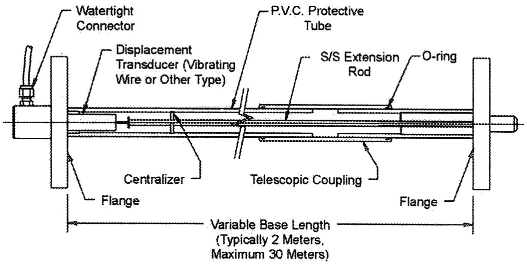

Fig. 5-29A. Soil extensometer schematic
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Fig. 5-29B. Soil extensometer
Source: RST Instruments, reproduced with permission.

In Fig. 5-30, configurations A and B are for simple situations where it is already known that the principal stresses are vertical and horizontal. Configurations C and D are used to determine the state of strain in one plane. The three strain measurements are used in formulae derived from Mohr's circle to calculate the two principal strains in the plane and their orientations.

Configuration E is similar to those of C and D, except that one strain gauge is added in the same plane as the other three to add some redundancy and also in case of malfunction of one of the gauges, to still be able to determine the two principal strains and their orientations. In addition, a fifth strain gauge is installed perpendicular to the main plane of the measurement, where this perpendicular direction is known to be a principal strain direction. This happens when the geometry of the dam or the estimated loading directions make it apparent to the design engineer that a certain direction is a principal strain direction, such as a strain value of zero close to an outer boundary of the dam. Finally, configuration F involves six strain gauges installed in different directions in a pyramid geometry. This configuration is used in the more general case where no principal direction is known. The six strain measurements can be used to derive the complete state of strain at a given location, namely, the three principal strains and their orientations.

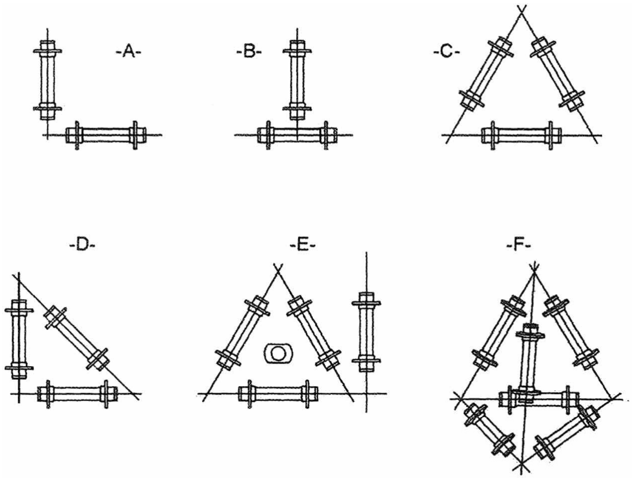

Fig. 5-30. Rosette configurations for installation of strain gauges in concrete Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

5.3.4.3 Concrete Dummy Gauge. It is generally a good practice to install one or more dummy gauges near concrete-embedded strain gauges. The purpose of a dummy gauge is to differentiate between measured strains due to hydration of the concrete and strains resulting from true loading of the concrete. This effect is greatest during the first 28 days of curing of the concrete, but it can be significant over longer time periods, especially in dams where large quantities of concrete are used and the heat of hydration persists longer than 28 days.

An alternative to dummy gauges is simply to accept that the initial state of zero strain occurs 28 days after the date of the concrete pour. However, this may be risky because construction is likely to have advanced enough in 28 days to have applied significant loads at the gauge location.

A dummy gauge is a simple device. It consists of a conventional strain gauge installed in a container with padded sides to prevent external loads from being applied to the dummy gauge. A no-stress enclosure for a dummy gauge is shown in Fig. 5-31.

The dummy gauge is typically installed just far enough from the embedded primary strain gauges to avoid modifying the stress field surrounding the primary gauges. The box is first solidly attached to a support so that it will not move during concrete placement. It is then filled with concrete from the same pour that embeds the primary strain gauges. The open end of the box allows the concrete in the box to experience the same hydration effects as the concrete of the pour, but the dummy strain gauge in the padded box

Fig. 5-31. No-stress enclosure for dummy gauge
Source: RST Instruments, reproduced with permission.

is isolated from the mechanical effects to which the primary strain gauges are subjected.

The usual way to apply dummy gauge readings is to subtract them from the readings of the closest embedded primary strain gauges to obtain the true mechanical strain in the concrete. Usually, strain in the dummy gauge increases significantly in the first few days after concrete placement because of the heat of hydration. The rate of strain then decreases and stabilizes after a few weeks, although hydration effects can continue for months and even years. Therefore, it remains a good practice to always subtract readings of the dummy gauge from the readings of the conventional gauges. A final advantage of this procedure is that it cancels the error induced by the temperature coefficient of the vibrating-wire sensor (the coefficient of thermal expansion of vibrating-wire strain gauges is about 5–10 °C, close to that of concrete).

5.3.4.4 Distributed Strain Measurement Using Optical Fibers. Distributed strain measurement using optical fibers allows the measurement of strain at many points along a single strand of a very long (up to many miles) fiber optic cable. The technique takes advantage of the sensitivity of signals within fiber optic cables to changes in temperature and strain. In short, the technique involves attaching the fiber to the medium to be monitored and sending light pulses of known wavelength into the fiber. Small fractions of the light are scattered at each point along the fiber. The nature of the scattered light varies with local changes in the fiber's temperature and strain. Time- and frequency-domain analyses of the scattered light are performed on the return signal, allowing the determination of strains and temperatures. The result is a profile of strain and temperature along the fiber.

The technology is based on three types of scattering that occurs within the cables: Raman, Rayleigh, and Brillouin. Raman scattering is inelastic and occurs as light is scattered by thermally activated molecular vibrations, allowing a measure of temperature within the fibers. Rayleigh scattering occurs when light is elastically scattered in all directions due to variations in a fiber's refractive index, which is affected by local strain and temperature changes. Brillouin optical time-domain analysis is performed by generating sound waves or introducing two counter-propagating light waves with a frequency difference equal to the Brillouin shift. Using the time of flight of the short light pulse, local variations of strain can be measured along the fiber.

Similar to a strain gauge, strain-sensing fibers must be firmly attached to or embedded into the monitored medium to ensure that fiber strains are similar to strains in the monitored media. Specialized fibers are available with increased resistance to crushing and more effective rodent protection for use in harsh environments, including subterranean, submarine, and tunnel environments.

The technology provides the potential for precise measurements of strain and temperature at many points along great lengths of fibers using a single transducer. A single cable may replace thousands of discrete point sensors, resulting in lower installation and maintenance time and costs. Full sets of measurements can be made in minutes, resulting in decreased costs when compared to manual sensors.

Terms related to the performance of an optical fiber measurement system include distance range, spatial resolution, sampling interval, distance precision, measurement uncertainty, and measurement resolution or repeatability.

Distance range describes the maximum distance over which the system can perform given a set of performance criteria. For optical fiber measurement technologies, this extends for kilometers.

Spatial resolution describes the ability of the system to accurately measure two adjacent locations with different temperatures or strains. The system will be able to measure temperatures or strains that spread over distances greater than the spatial resolution of the system with 100% accuracy. Temperatures or strains that do not span the minimum spatial resolution will not be measured with full accuracy. Optical fiber measurement technologies are capable of providing full accuracy for spatial resolutions on the order of 20 in. (0.5 m).

Sampling interval describes the distance between two measurement points along the fiber and is determined by the number of points along the