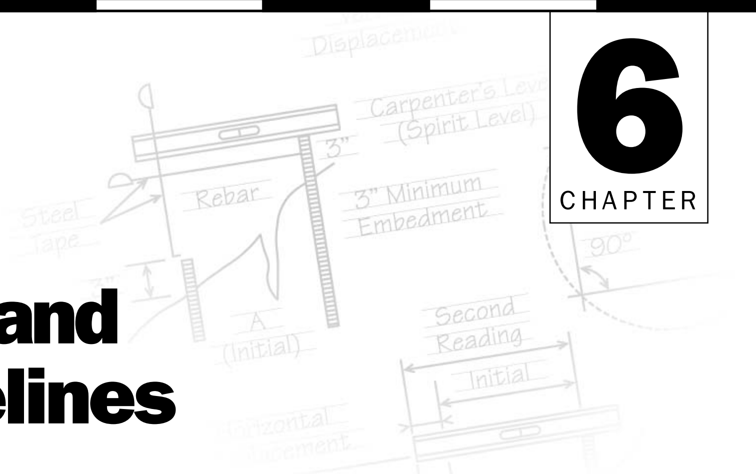
Chapter 6: Instrumentation and Monitoring Guidelines



6.0 General

Widespread attention is now being given to the installation of more expensive instrumentation for study of the behavior of dams and reservoirs and forecasting of any adverse trends.

—Jansen (1980: 25)

The means and methods available to monitor phenomena that can lead to dam failure include a wide spectrum of instruments and procedures, ranging from very simple to very complex. Any program of dam safety instrumentation must be properly designed and consistent with other project components, must be based on prevailing geotechnical conditions at the dam, and must consider the hydrologic and hydraulic factors present both before and after the project is in operation. Every instrument should have a specific purpose and expected design response.

Instruments designed for monitoring potential deficiencies at existing dams must take into account the threat to life and property that the dam presents. Thus, the extent and nature of the instrumentation depends not only on the complexity of the dam and the size of the reservoir, but also on the potential for loss of life and property downstream.

An instrumentation program should involve instruments and evaluation methods that are as simple and straightforward as the project will allow. Beyond that, the dam owner should make a definite commitment to an ongoing monitoring program or the installation of instruments probably will be wasted.

This chapter discusses deficiencies in dams that may be discovered and the types of instruments that may be used to monitor those deficiencies. Increased knowledge of these deficiencies acquired through a monitoring program is useful in determining both the cause of the deficiencies and the necessary remedies. Continued monitoring is important to determine that the remedy remains effective.

Involvement of qualified personnel in the design, installation, monitoring, and evaluation of an instrumentation system is of prime importance to the success of the program.

6.1 Reasons for Instrumentation

Instrumentation and proper monitoring and evaluation are extremely valuable in determining the performance of a dam. Specific reasons for instrumentation include:

- **Warning of a Problem**—Often, instruments can detect unusual changes, such as fluctuations in water pressure within the dam, that are not visible. In other cases, gradual progressive changes in seepage flow, which would go unnoticed visually, can be monitored regularly. This monitoring can warn of the development of a serious seepage problem.
- **Analyzing and Defining a Problem**—Instrumentation data are frequently used to obtain engineering information necessary for analyzing and defining the extent of a problem. For example, downstream movement of a dam because of high reservoir-water pressure must be analyzed to determine if the movement is uniformly distributed along the dam; whether the movement is in the dam, the foundation, or both; and whether the movement is constant, increasing, or decreasing. Such information can then be used to design corrective measures.
- **Proving Behavior Is as Expected**—Instruments installed at a dam may infrequently (or even never) show any anomaly or problem. However, even that information is valuable because it shows that the dam is performing as designed, offering peace of mind to you, the owner. Also, although a problem may appear to be extant or imminent, instrument readings might show that the deficiency (for example, increased seepage) is normal (merely a result of higher than normal reservoir level) and was foreseen in the dam's design.
- **Evaluating Remedial Action Performance**—Many dams, particularly older ones, are modified to allow for increased capacity or to correct a deficiency. Instrument readings before and after the change allow analysis and evaluation of the performance of the modification.

6.2 Instrument Types and Usage

A wide variety of devices and procedures are used to monitor dams. The features of dams and dam sites most often monitored by instruments include: [throughout chapter: lowercased bullet items]

- movements (horizontal, vertical, rotational and lateral)
- pore pressure and uplift pressures
- water level and flow
- seepage flow
- water quality
- temperature
- crack and joint size
- seismic activity
- weather and precipitation
- stress and strain

A thorough treatment of instrument types and their usage is presented in Dunnicliff 1993. Both the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers publish guides specific to the instrumentation and monitoring of dams. The Association of State Dam Safety Officials <www.damsafety.org> and the U.S. Society of Dams <www.USSDams.org> offer technical conferences, reports, and papers related to instrumentation and dam-safety monitoring.

6.2.1 Observations

As discussed in Chapter 5, observations by you, the dam owner , or your representative may be the most important and effective means of monitoring the performance of a dam. An inspector, upon each visit to the dam site, should inspect it visually—at a minimum, walking along the dam alignment and looking for any signs of distress or unusual conditions.

6.2.2 Movements

Movements occur in every dam. They are caused by stresses induced by reservoir water pressure, unstable slopes (low shearing strength), low foundation shearing strength, settlement (compressibility of foundation and dam materials), thrust due to arching, expansion resulting from temperature change, and heave resulting from hydrostatic uplift pressures. They can be categorized by direction:

- **Horizontal** or **translational movement** commonly occurs in an upstream-downstream direction in both embankment and concrete dams. It involves the movement of an entire dam mass relative to its abutments or foundation. In an embankment dam, instruments commonly used for monitoring such movement include:
  - extensometers, including multi-point extensometers
  - inclinometers
  - embankment measuring points
  - shear strips
  - structural measuring points
  - time-domain reflectometry (TDR)

Installation of simple measuring points is illustrated in Figure 6.1, a and b, a simple crack monitoring system is shown in Figure 6.2, and inclinometer systems and plots are shown in Figures 6.3a–c.

Figure 6.1a
Installation of Permanent Points

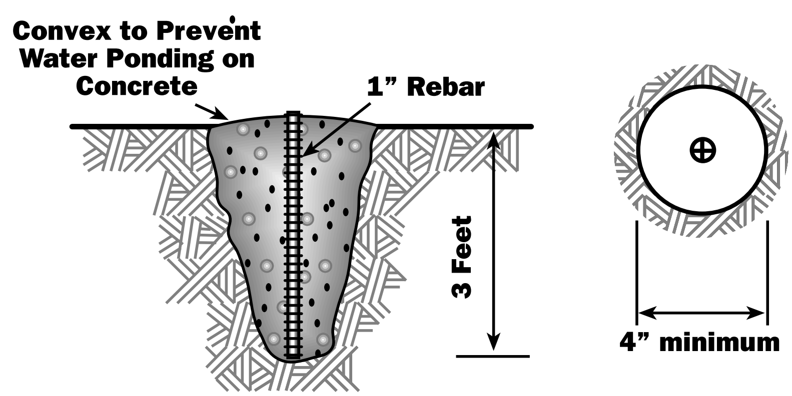


Figure 6.1b
Plan of Alignment System

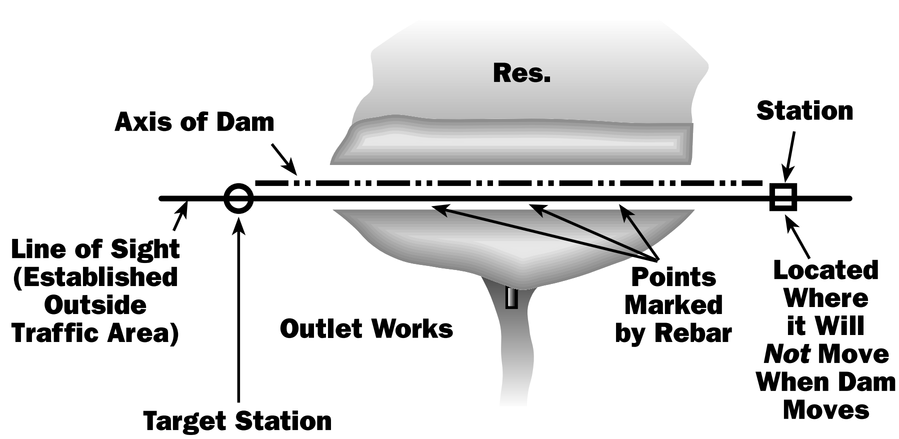
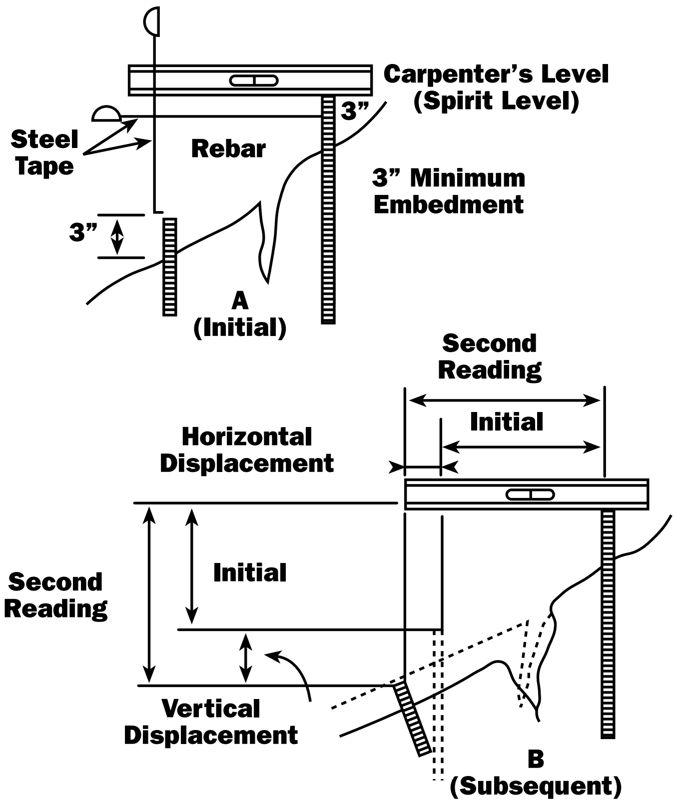


Figure 6.2
Monitoring Cracks on Embankment



For a concrete dam or concrete spillway, instruments for monitoring horizontal movements may include:

- crack measuring devices
- extensometers, including multi-point extensometers
- inclinometers
- structural measuring points
- tape gauges
- strain meters
- plumb lines
- foundation-deformation gauges
- tilt meters
- 2D or 3D joint-movement indicators
- electro-level beams
- a GPS monitoring system

Examples of monitoring of concrete structure movements are shown in Figures 6.4a-d.

- **Vertical movement** is commonly a result of consolidation of embankment or foundation materials resulting in settlement of the dam. Another cause is heave (particularly at the toe of a dam) caused by hydrostatic uplift pressures.

Figure 6.3a
Inclinometer—
Detail at Surface

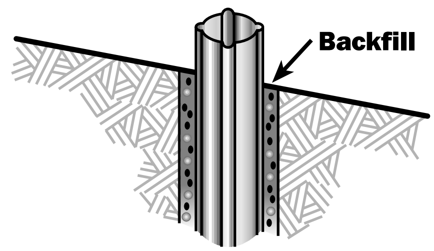


Figure 6.3b
Plot of Inclinometer Readings

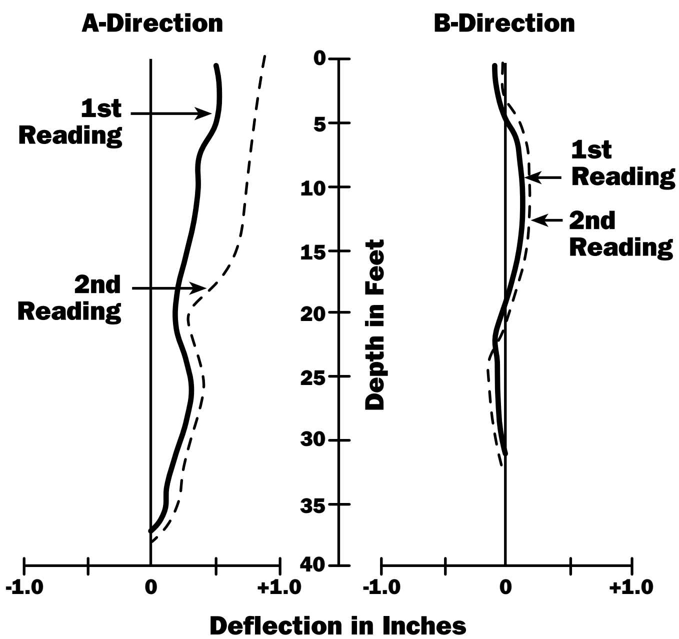


Figure 6.3c
Inclinometer and Casing

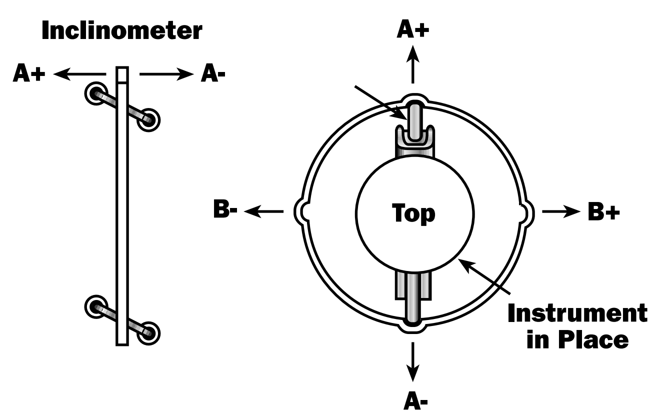
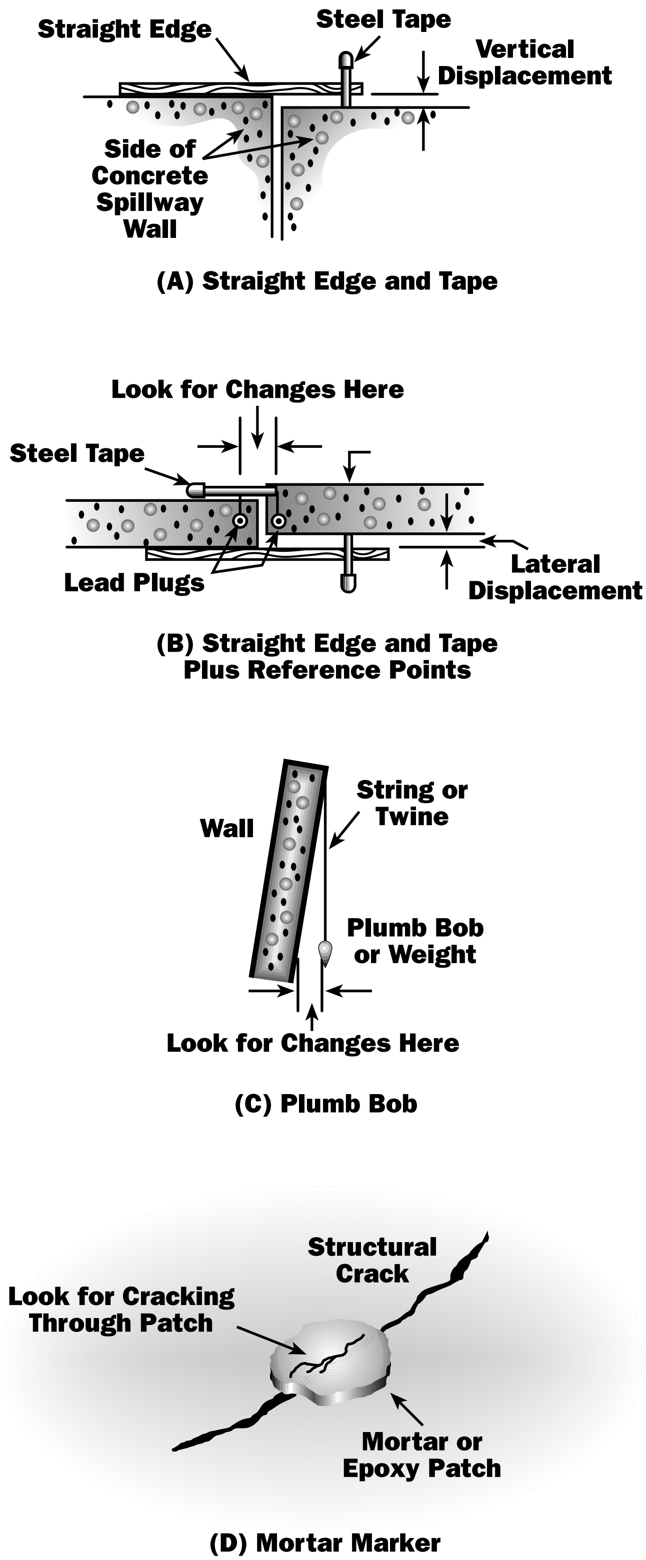


Figure 6.4
Measuring Displacements



In an embankment dam, vertical movements may be monitored by:

- settlement plates and sensors
- extensometers
- embankment survey monuments
- structural measuring points
- inclinometer casing measurements

In a concrete dam or concrete spillway, vertical movement monitoring devices may include:

- settlement sensors
- extensometers
- a GPS monitoring system
- structural measuring points
- foundation-deformation gauges

■ **Rotational movement** is commonly a result of high reservoir water pressure in combination with low shearing strength in an embankment or foundation; it may occur in either component of a dam. This kind of movement may be measured in either embankment or concrete dams by instruments such as:

- extensometers
- inclinometers
- tilt meters
- surface measurement points
- crack-measurement devices
- electro-level beam sensors
- foundation-deformation gauges
- plumb lines (concrete only)

■ **Lateral movement** (parallel with the crest of a dam) is common in concrete arch and gravity dams. The structure of an arch dam causes reservoir water pressure to be translated into a horizontal thrust against each abutment. Gravity dams also exhibit some lateral movement because of expansion and contraction due to temperature changes. These movements may be detected by:

- structural measurement points
- tilt meters
- extensometers
- crack-measurement devices
- plumb lines
- strain meters
- stress meters
- inclinometers
- joint meters
- load cells

6.2.3 Pore Pressure and Uplift Pressure

As discussed in Chapter 2, a certain amount of water seeps through, under, and around the ends of all dams. The water moves through pores in the soil, rock, or concrete as well as through cracks, joints, etc. The pressure of the water as it moves acts uniformly in all planes and is termed *pore pressure*. The upward force (called *uplift pressure*) has the effect of reducing the effective weight of the downstream portion of a dam and can materially reduce dam stability. Pore pressure in an embankment dam, a dam foundation, or an abutment reduces that component's shear strength. In addition, excess water, if not effectively channeled by drains or filters, can result in progressive internal erosion (piping) and failure. Pore pressures can be monitored with the following equipment.

- piezometers
- electrical
- open well
- pneumatic
- hydraulic
- porous tube
- slotted pipe
- pressure meters and gauges
- load cells

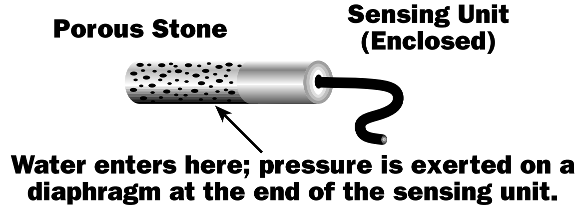
Pore-pressure measurements and monitoring can supply critical information regarding the overall stability of an embankment dam following a major earthquake.

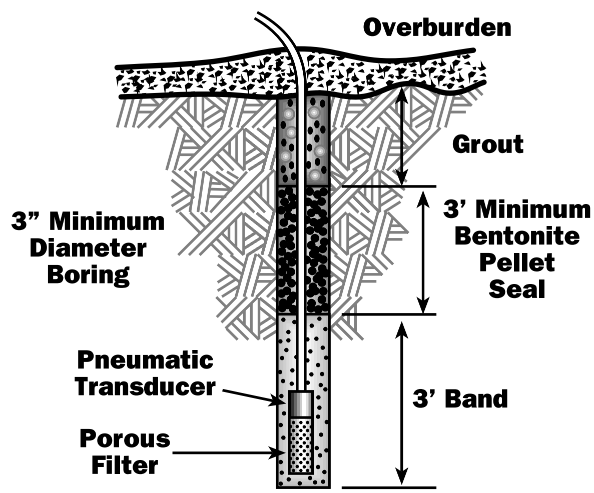
Simple piezometers may resemble the illustration in Figure 6.5; a basic observation well is shown in Figure 6.6.

6.2.4 Water Level and Flow

For most dams, it is important to monitor the water level in the reservoir and the downstream pool regularly to determine the quantity of water in the reservoir and its level relative to the regular

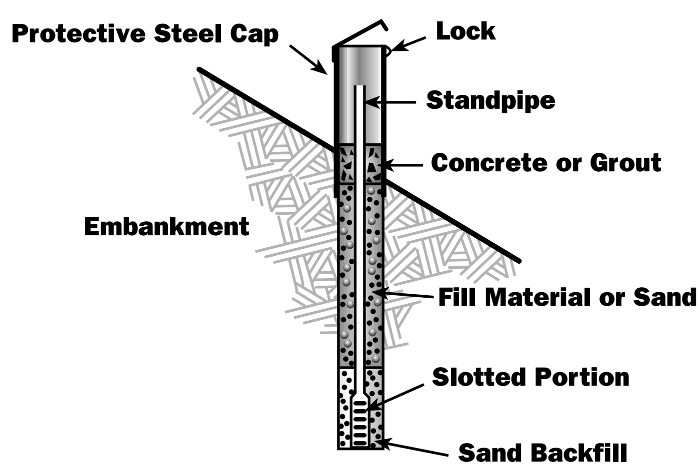
Figure 6.5
Porous Stone Piezometer





Installation Detail (Typical)

Figure 6.6
Installation of Typical Observation Well



outlet works and the emergency spillway. The water level is also used to compute water pressure and pore pressure; the volume of seepage is usually directly related to the reservoir level. It is also important to establish the normal or typical flow through the outlet works for legal purposes.

Water levels may be measured by simple elevation gauges—either staff gauges or numbers painted on permanent, fixed structures in the reservoir—or by complex devices that sense water levels. Flows are often computed from a knowledge of the dimensions of the outlet works and the depth of flow in the outlet channel or pipe.

6.2.5 Seepage Flow

Seepage must be monitored on a regular basis to determine if it is increasing, decreasing, or remaining constant as the reservoir level fluctuates. A flow rate changing relative to a reservoir water level can be an indication of a clogged drain, piping or internal cracking of the embankment. Seepage may be measured using the following devices and methods:

- Weirs (any shape such as V-notch, rectangular, trapezoidal, etc.)
- Flumes (such as a Parshall flume)
- Pipe methods
- Timed-bucket methods
- Flow meters

Examples of weirs, flumes, and bucket measuring installations are illustrated in Figures 6.7a–c, 6.8, and 6.9.

6.2.6 Water Quality

Seepage comes into contact with various minerals in the soil and rock in and around the dam, which can cause two problems: the chemical dissolution of a natural rock such as limestone and the internal erosion of soil.

Dissolution of minerals can often be detected by comparing chemical analyses of reservoir water and seepage water. Such tests are site specific; for example, in a limestone area, one would look for calcium and carbonates; in a gypsum area, calcium and sulfates. Other tests, such as pH, can also sometimes provide useful information on chemical dissolution.

Internal erosion can be detected by comparing turbidity of reservoir water with that of seepage water. A large increase in turbidity indicates erosion.

6.2.7 Temperature

The internal temperature of concrete dams is commonly measured both during and after construction. During construction, the heat of hydration of freshly placed concrete can create high stresses which can result in cracking later. After construction is completed and a dam is in operation, very significant temperature differentials are not uncommon, depending on the season. For example, during winter, the upstream face of a dam remains relatively warm because of reservoir-water temperature, while the downstream face of the dam is reduced to a cold ambient air temperature. The reverse is true in summer.

Temperature measurements are important both to determine causes of movement due to expan-

Figure 6.7a
Standard Weir Installation

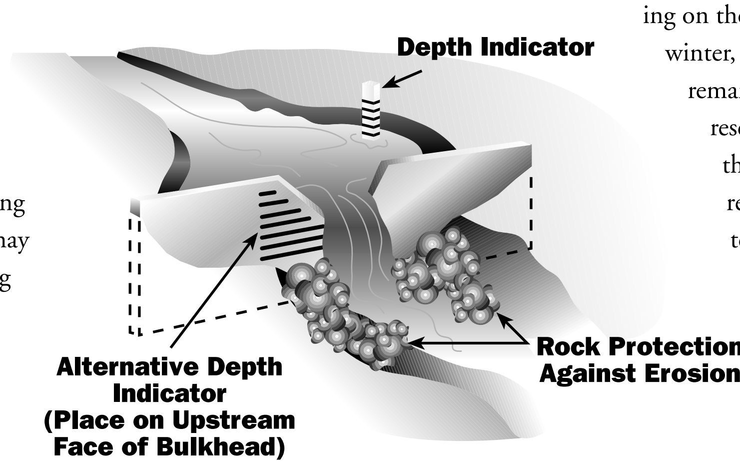


Figure 6.7b
Standard Weirs: 90˚ V-Notch Weir

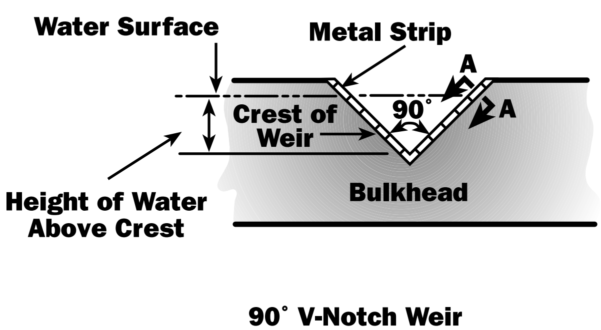


Figure 6.7c
Standard Weirs: Rectangular Weir

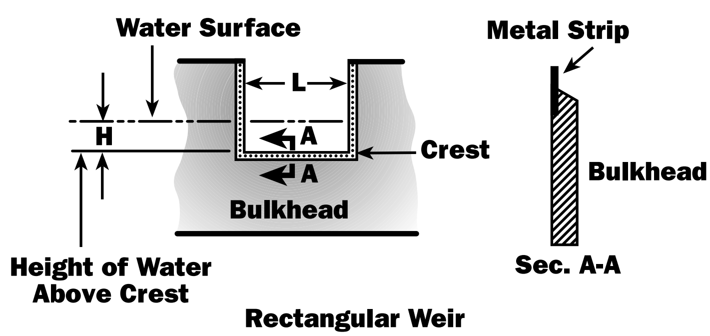


Figure 6.8
Parshall Flume

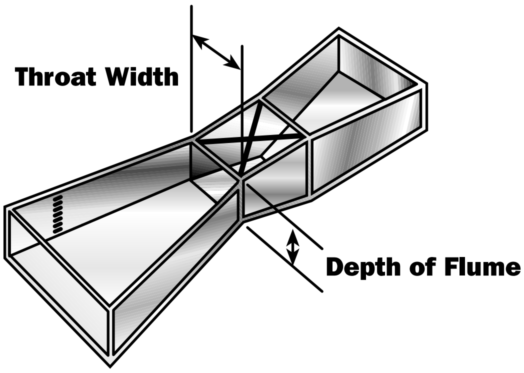
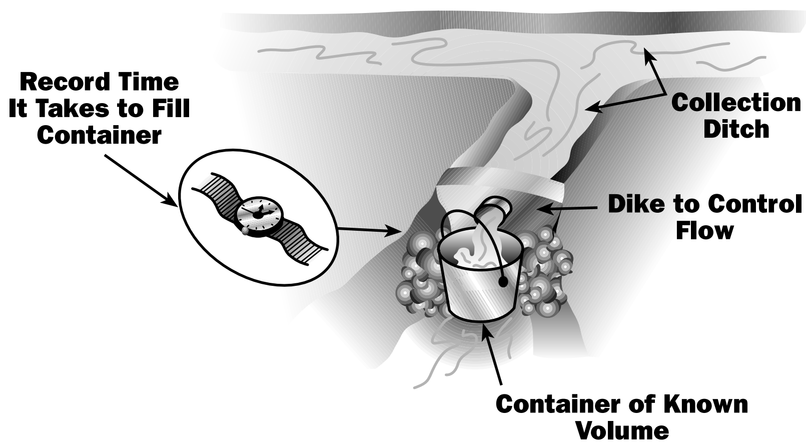


Figure 6.9
Bucket-and-Stopwatch Method



sion or contraction and to compute actual movement. Temperature may be measured using any of several different kinds of embedded thermometers or by simultaneous temperature readings on devices such as stress and strain meters, which allow for indirect measurement of the temperature of the mass.

6.2.8 Crack and Joint Size

Knowing the locations and widths of cracks and joints in concrete dams and in concrete spillways and other concrete appurtenances of embankment dams is important because of the potential for seepage through those openings. It is even more important to know if the width of such openings is increasing or decreasing. Various measuring devices are available for cracks and joints, most allowing very accurate measurement. Some use simple tape or dial gauges; others, complex electronics.

6.2.9 Seismic Activity

Seismic measuring devices record the intensity and duration of large-scale earth movements such as earthquakes. Many federal and state dams use these instruments because they are part of the U.S. Geological Survey's network of seismic recording stations. It may or may not be necessary for a private dam to contain seismic devices depending upon the area's seismic risk. Seismic instruments can also be used to monitor any blasting conducted near a dam site.

6.2.10 Weather

Monitoring the weather at a dam site can provide valuable information about both day-to-day performance and developing problems. A rain gauge, thermometer, and wind gauge can be easily purchased, installed, maintained, and monitored at a dam site.

6.2.11 Stress and Strain

Measurements to determine stress and strain are common in concrete dams and, to a lesser extent, in embankment dams. The monitoring devices previously listed for measuring dam movements, crack and joint size, and temperature are also appropriate for measuring stress and strain. Monitoring for stress and strain permits very early detection of movement.

6.3 Automated Data-Acquisition Systems

Over the last 20 years, there have been significant efforts, primarily led by federal dam-safety organizations, to advance the state of practice in automating dam-safety instrumentation. These projects were initially targeted towards high hazard dams that posed significant potential risk to downstream communities. These two decades have seen many advances in sensor technology, data acquisition equipment, and data management that have made automated data acquisition more reliable, cost-effective, and readily available for broader applications in dam-safety monitoring.

An automated data-acquisition system (or ADAS) can range from a simple data logger temporarily connected to one or more instruments to a permanent system that automates up to several hundred instruments at a dam. Generally, an ADAS for dam-safety monitoring includes the following key components:

- one or more electronic sensors (for water levels, displacements, etc.)
- a remote data logger (permanent or portable)
- a communication link to the dam for remote access (cell phone, landline, radio, or satellite)

An ADAS usually consists of one or more solar-powered remote monitoring units (RMUs) located on the dam connected to key instruments to be automated. The RMUs communicate via radio, hardwire, or cell phone with a central network monitor—a conventional desktop PC with vendor-supplied interface and communication software to provide access to the on-site RMUs by remote users. Typically, the monitor is located on-site; however, it can be located at a remote location (such as a district or administration building). Instrument readings are stored in memory for either manual or automatic downloading for plotting and tabular reporting.

These systems can send out an alarm via cell phone, pagers, or e-mail if user-defined instrument thresholds are exceeded. More recently, ADASes now incorporate remote digital still or video cameras.

Since these systems are employed outdoors, it is important to use only data-acquisition equipment that is designed for geotechnical instrumentation and dam-safety monitoring. Pay special attention to lightning protection and grounding, surge protection, and backup power supplies. You would be wise to contact engineering companies and vendors that are experienced in this area if you are considering an ADAS for your dam-monitoring requirements.

A properly designed and installed ADAS can provide cost-effective and reliable instrumentation data acquisition and presentation to assist dam safety personnel in both long-term monitoring and during safety events. These systems provide the ability to adjust the frequency of instrument readings and provide the ability to quickly assess trends from remote locations. When coupled with downstream warning sirens, ADAS can provide early warning to downstream residents during a safety problem.

For more information on ADASes for dam-safety monitoring, refer to U.S. Society of Dams (2002).

6.4 Frequency of Monitoring

The frequency of instrument readings or making observations at a dam depends on several factors including:

- the relative hazard to life and property it represents
- its height or overall size
- the relative quantity of water impounded
- the relative seismic risk at the site
- its age
- the frequency and amount of water-level fluctuation in the reservoir

In general, as each of the above factors increases, the frequency of monitoring should increase. For example, very frequent (even daily) readings should be taken during the first filling of a reservoir, and more frequent readings should be taken when water levels are high and after significant storms and earthquakes. As a rule of thumb, simple visual observations should be made during each visit to the dam and not less than monthly. Daily or weekly readings should be made during the first filling, immediate readings should be taken following a storm or earthquake, and significant seepage, movement, and stress-strain readings should probably be made at least monthly.

Source for information in this chapter: Jim Hummert, URS Corporation. St. Louis