

Does Your Dam Measure Up? – Developing an Effective Instrumentation Program for Small Earth Dams

Introduction

An effective dam surveillance and monitoring program is an important component to any dam safety program. The goal of a dam surveillance and monitoring program is to detect if the dam is not performing per the design or if the dam is developing a condition that could lead to adverse performance of the dam. These conditions, if left undetected, could culminate in a dam safety incident or failure and may present a risk to the public, property, or environment. There are two necessary elements of an effective program: surveillance (visual observations) and monitoring (instrumentation measurements). This article focuses on developing an effective instrumentation program for small earth dams based on identifying a clear set of objectives and selecting the right instrument for the job.

Surveillance

The article [Dam Safety Inspections...A Closer Look \(Volume 3 Issue 2 Western Dam Engineering Technical Note\)](#) presented the aspects of visual inspections. Surveillance is the most important component in a dam safety program and consists of the routine visual inspection of the dam. However, not every potential deficiency can be detected or understood by visual surveillance alone. The need for both instrumented and visual monitoring exists for nearly every dam.

For example, while visual inspections for slides, slumps, cracking, and bulging are important visual indications of a potentially unstable slope, additional water pressure data from piezometers and sediment traps will help the owner and engineer understand the extent and possible cause of any observed abnormality.

Instrumentation provides the necessary quantitative data to support a safety evaluation on a dam's performance. These data are used to detect changes in dam behavior and potential slowly developing problems.

Monitoring

The main objectives of a monitoring program are to verify the performance of the project structures with respect to the design parameters, quickly identify any change in conditions that has a potential for safety concerns, and develop data for analytical assessment and prediction of future performance. Detecting a developing problem early through active monitoring can allow for successful intervention, thereby reducing the risks of economic loss and downstream consequences.

A good monitoring program should include monitoring for potential failure modes (PFMs) of the dam as well as monitoring for general health of the structure. General health monitoring refers to implementing best-practices to gather data vigilant dam owners should know about their structure, regardless of specific failure modes, such as reservoir level and periodic measurement of crest elevation. Monitoring for identified PFMs requires that specific defects or conditions that could lead to failure be identified by a thorough review of the design, construction, operation, and performance history of the dam. This review helps establish the objectives of any measurement device and identify the best instrument and location to obtain the targeted measurement. This will be described throughout this article.

Typical Instruments for Small Earth Dams

The information below focuses on common instrumentation that may be appropriate for small earth dams. Information on all the possible types of instrumentation can, and has, filled books (see References [2] and [3]). This section provides a basic overview of the most commonly used instruments. Typical instrumentation appropriate for small earth dams includes means for measuring water levels; weirs to measure seepage flow and turbidity; observation wells/piezometers to measure pore water pressure, and survey monuments to measure settlement and crest elevation. The reader is encouraged to review the references at the end of this article for more details regarding the proper selection, design, installation, and readings for each instrument they plan to implement into their monitoring program.

Reservoir and Tailwater Levels

For most dams, it is important to know the water level in the reservoir and downstream pool or channel. This information can help correlate other monitoring data for a better understanding of the response of the structure at varying pool levels as well as provide useful information for documenting typical operating conditions for each dam. Typical instruments and tools used to determine reservoir levels include staff gauges, slope stakes, or a tape measure. A graduated staff gauge can provide accurate and repeatable water level measurements for reservoir pools, tailwater, and within weirs or flumes. They can be permanently mounted on any flat surface and bolted directly to a structure. The gauge should be made with indelible graduations and markings, so it is resistant to sun bleaching, rusting or other forms of deterioration.

Staff gauges can be mounted on a vertical surface such as a pier or post or on an inclined surface such as the embankment slope. The gauge should be carefully surveyed to accurately mark the elevation graduations.

A typical staff gauge is shown in Photograph 1.



Photo 1: Staff Gauge

Slope stakes are another common method of measuring reservoir level. These consist of stakes that are installed in a line along a slope with a consistent grade and can be used to interpolate reservoir level. Typically, the slope stakes cannot be installed on the embankment, as wave protection is often present. The water level measurement is recorded relative to the known position of the stakes and using a correlation table to interpret the reading. If the potential for movement is detected or suspected, regular resurvey

of the stakes is required to maintain an accurate water level reading. An example of a typical slope stake system table is shown in Figure 1.

The 0+00 pin is located at the upper left (north west) corner of the west boat ramp slab. The alignment is down the left side of the slab. The slab surface is the datum for the slope distance elevations. Pins installed and elevations established by GPS on October 19, 2000. A top of cap elevation is listed for the 50 foot pins. Elevations listed for top left end center of the boat ramp sections below the solid slab. Storage volumes from the March, 1965 active storage table; storage volumes above 4315.9 ft were extrapolated by HKM Engineering (2007).

DISTANCE feet	ELEVATION feet	STORAGE acre-feet	DISTANCE feet	ELEVATION feet	STORAGE acre-feet
0+00 CAP	4319.61	6.124	34	4315.32	5.052
1	4319.49	6.094	35	4315.20	5.022
2	4319.38	6.066	36	4315.07	4.990
3	4319.26	6.036	37	4314.94	4.957
4	4319.14	6.006	38	4314.82	4.927
5	4319.02	5.976	39	4314.69	4.895
6	4318.90	5.946	40	4314.56	4.862
7	4318.78	5.916	41	4314.44	4.833
8	4318.66	5.886	42	4314.31	4.800
9	4318.54	5.856	43	4314.18	4.768
10	4318.42	5.826	44	4314.06	4.738
11	4318.29	5.794	45	4313.93	4.706
12	4318.16	5.761	46	4313.81	4.676
13	4318.03	5.729	47	4313.68	4.643
Spillway	4318.00	5.721	48	4313.55	4.611
14	4317.90	5.696	49	4313.43	4.582
15	4317.77	5.664	50	4313.30	4.549
16	4317.64	5.631	51	4313.17	4.517
17	4317.51	5.599	52	4313.04	4.484
18	4317.38	5.566	0+50 CAP	4313.01	4.477
19	4317.25	5.534	53	4312.91	4.454
20	4317.12	5.501	54	4312.79	4.427
21	4316.99	5.469	55	4312.66	4.398
22	4316.86	5.436	56	4312.53	4.370
23	4316.73	5.404	57	4312.40	4.340
24	4316.61	5.374	58	4312.27	4.311
25	4316.48	5.341	59	4312.14	4.282
26	4316.35	5.309	60	4312.01	4.253
27	4316.22	5.276	61	4311.89	4.227
28	4316.09	5.244	62	4311.76	4.197
29	4315.96	5.212	63	4311.64	4.171
30	4315.83	5.179	64	4311.51	4.142
31	4315.70	5.146	65	4311.39	4.115
32	4315.58	5.116	66	4311.26	4.086
33	4315.45	5.084	67	4311.14	4.059
DISTANCE	ELEVATION	STORAGE	DISTANCE	ELEVATION	STORAGE

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Figure 1: Slope Elevation Storage Table

The third and obviously simplest means of measuring reservoir and tailwater level, is by dropping a weighted tape measure from a reference mark with a known elevation. Similar to the consideration for locating a permanent staff gage, the measurement location should consider effects of drawdown caused by entrance flow into a gate, structure, or weir. For this reason measurements should not be performed into a drop structure or near a spillway with an open gate as the head losses at the inlet can cause significant error.

Seepage Flow Measurements

Weirs are frequently chosen to measure seepage rates, monitor turbidity, and monitor sediment transport. Common weir shapes are square, trapezoidal, and V-notch. The appropriate shape and size of a weir depends mainly on the volume of flow to be measured. Some weirs are more capable and accurate at

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measuring small, or large, flows than others. A weir can be installed to measure seepage flow and sediment transport out of a toe drain system or known surface seep that can be concentrated into a channelized path. A V-notch weir is shown on Figure 2 and Photograph 2. V-notch weirs are efficient at measuring low flows (less than about 450 gallons per minute (1 cubic foot per second)). The depth of water is typically measured with a staff gauge installed within the upstream pool, away from velocity drawdown effects as shown in Figure 2.

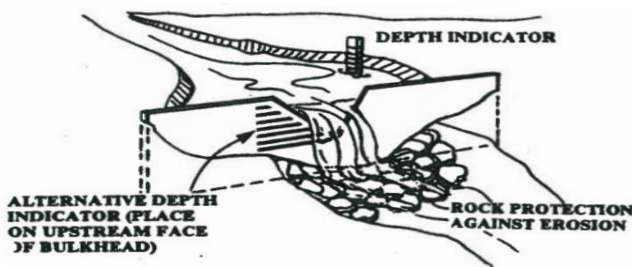


Figure 2: V-Notch Weir and Staff Gauge

Reference: FEMA, *Dam Safety: An Owner's Guidance Manual*, 1987



Photo 2: V-Notch Weir

Other seepage monitoring devices and methods include parshall flumes, pipes (toe drains), timed-bucket methods, and flow meters. Internal erosion can be detected by observing the water for increased turbidity and sediment. The Bureau of Reclamation provides a useful reference for details on methods to measure seepage in the [Water Measurement Manual](#). Reclamation also provides [download links](#) for obtaining the USBRWeir.xls spreadsheet, used to determine rating tables and equations for sharp-crested weirs.

Piezometers

Piezometers installed in the abutments, foundations, and embankments of a dam are used to monitor phreatic surface levels, uplift pressures, and seepage gradients (through the use of piezometer groups). A line of piezometers installed at the dam crest, mid-slope and toe provides information to create a profile of the phreatic surface through the dam. A set of piezometers installed at different elevations in one location (nested piezometers) provides pore pressures in different soil strata and can be used to estimate vertical seepage gradients.

Some common types of piezometers include open standpipe, fiber optic, and vibrating wire piezometers. The open standpipe, or observation well, installation offers the added benefit of being able to manually confirm the water level reading versus sole reliance on a digital instrument. A standpipe piezometer is shown in Photograph 3. Fiber optic piezometers are generally contained within a stainless steel tube and separated from the environment by a porous filter material. Some advantages include their immunity to vibration, lightning damage, and radio and electromagnetic noise interference.

Vibrating wire piezometers contain electrical pressure transducers that read and record the pore-water pressure automatically, allowing for easier and more frequent data acquisition. Each of these types of piezometers has specific design specifications and a qualified engineer should be involved in specifying the appropriate piezometer type, location, and installation procedures.

Piezometers, when strategically placed, can provide useful information on the overall seepage regime within and below the dam. However, since they are a single point measurement, they are not often effective at detecting or characterizing potential concentrated seepage paths unless they are installed to monitor an already known location of a defect.



Photo 3: Standpipe Piezometer

Settlement Monitoring

Typically, movement in dams is monitored to detect settlement or deformations in the dam. These conditions may be due to consolidation, creep, or subsidence or other factor. Settlement within an embankment dam may lead to loss of freeboard or cracking due to differential settlement. Depressions, sinkholes, scarps, sloughs or bulges, which may be indicative of slope instability or internal erosion, are often localized features that are more effectively detected through frequent visual surveillance rather than relying on periodic reading of instrumentation. However, once identified, the known condition can be more quantitatively monitored with instrumentation. Instruments commonly used to monitor settlement include survey monuments, settlement plates/sensors, extensometers, piezometers, and inclinometers.

More Sophisticated Instruments

A large selection of instrumentation is available to measure ground water and pore pressures; seepage, flow, and turbidity; stress and strain; load; temperature; precipitation and wind; reservoir and tailwater levels; water quality; seismic measurements;

and deformation. Details of these types of instruments are included in the ASCE Task Committee Guidelines for Instrumentation and Measurements for Monitoring Dam Performance (2000).

Planning an Effective Monitoring Program

Identifying the Need for Instrumentation

Planning a monitoring program should begin by identifying the need for instrumentation. The need may be based on an observed condition or a known vulnerability. Site conditions such as underground mine workings, deep groundwater pumping, soft foundation, or abrupt changes in the subsurface profile could be known vulnerabilities that may lead to subsidence or differential settlement. Observed seepage, sediment deposition, or depressions, may all be observed conditions that would warrant seepage monitoring through collection and measurement, or piezometers to evaluate seepage gradients. Signs of slope instability (cracking, scarps, bulges) may be justification to install piezometers to estimate internal pore pressures for stability analyses. The need for instrumentation is based on a comprehensive understanding of the design and performance of the dam. If an observed condition or known vulnerability is identified, then one must assess whether it can be reliably and efficiently monitored with instruments. If so, which instrument is best suited for the specific objective?

Selecting the Right Instrument

Once the need and specific monitoring objective is identified, selecting the proper instrument is the next step. Instrumentation should be selected based on the answers to several pertinent questions:

- What is the observed condition, known vulnerability, or PFM?
- What parameter would best monitor the condition (flow, pore pressure, gradient, deformation, etc)?
- Where would the instrument need to be located to monitor the condition?
- How would the instrument need to be installed?

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- What method should be used for collecting data?
- What threshold level should be established for each instrument as a guideline for recognizing an usual reading?

Answers to these questions will guide the decision to which instrument is best suited for the job. Selecting the right instrument includes having an idea on the known parameter. Do I need a 90-degree v-notch weir or a parshall flume? Should my piezometer be an open standpipe or a nest of fully grouted vibrating wires?

The following table is one example that can be used in selecting the right instrument. This assessment is recommended to insure selection of the correct instrument to serve the required purpose. Note that the examples shown in the table are for illustration purposes only; actual information and recommendations would be very site specific depending on the potential deficiency and site specific conditions of the dam.

Table 1: Instrument Planning Table

Problem / Deficiency / PFM	What information/parameter does the instrument need to provide?	At what location is the parameter best measured? (e.g. where is the source of water?)	Construction Recommendation	Potential Problems with Installation	Reading Method and Frequency ¹
<i>Example: Saturated foundation, dry embankment</i>	<i>Are foundation uplift pressures present? Is a confining layer present? If so, how extensive?</i>	<i>Fractured bedrock Water present at approximately 20 ft deep in boreholes</i>	<i>2 piezometers in same 6" borehole 1 in fractured bedrock 1 in presumed cap layer</i>	<i>Isolating strata, can bedrock be augered through?</i>	<i>Manually read with water probe, monthly</i>
<i>Example: Seepage observed at downstream toe</i>	<i>Flow rate of seepage Is sediment present within the flow? What is the relationship or time lag with pool level – does it stop or increase at different pool levels?</i>	<i>Collect seepage at a location near downstream toe</i>	<i>90° v-notch weir Collect into an upstream basin to monitor for sediment Install water level gauge</i>	<i>Collect and convey seepage to single point, avoid seepage bypassing weir. limit adjacent runoff if possible</i>	<i>Manually read water level and convert to flow (gpm), monthly</i>

1. Record reservoir level and recent precipitation at every reading

Implementation (Overview of Design Considerations)

Key design considerations when implementing a monitoring program include:

- Instrument Location
- Instrument Design
- Installation and Protection

The following are some considerations for picking the best instrument location. Limiting impacts of the existing structure should be considered when selecting the preferred location. For example, in order to monitor the phreatic level within the foundation, is it necessary to drill the piezometer through the embankment or can it be installed at the toe?

The location should consider both the existing conditions as well as the post-installation conditions. For example, toe drain outlets that look great during installation, may become inundated over time if installed in a location that does not allow positive drainage.

The ability to measure the instrument should be considered when selecting the installation location. Can you get a bucket underneath the outlet pipe to measure outflow using the timed-bucket method? Staff gauges need to be easily visible from the shore, and within calm water, far enough away from any water intake gate, channel, weir or flume to avoid inaccurate readings due to drawdown effects. A staff gauge should be placed in a sheltered area that is not influenced by wave action or susceptible to ice damage.

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The location should also be chosen such that the instrument does not become a target of vandalism. Instruments in areas accessible to the public are better placed in discreet locations. Piezometers and weirs are common targets of vandalism.

Installation methods of intrusive instruments such as piezometers should be carefully considered, as they can be costly and may impose a risk of damaging the structure in the process. Shallow piezometers (less than about 10 feet) in fine grained sands, silts and clays can be installed with a hand auger as shown in Photograph 4. A video describing the method for installing a piezometer by hand auger can be viewed here: [Installing Piezometers in Your Dam](#). Deeper piezometers, or those to be installed in dense or coarse grained material usually require an auger drill rig as shown in Photograph 5.



Photo 4: Installing Piezometer by Hand Auger



Photo 5: Auger Drill Rig

Reservoir level and seepage conditions should also be considered prior to installing intrusive instrumentation. Installing these instruments can impose conditions that may increase seepage risks for the dam if not accounted for properly. The Bureau of Reclamation provides a guidance document on the installation of piezometers in their [Embankment Dam Instrumentation Manual](#).

Design and installation considerations for all instruments are beyond the feasible scope of this article. However, the effectiveness of the monitoring system is dependent on, and very sensitive to, the correct selection, design, and installation of the instrument. Therefore, an experienced engineer, manufacturer, and/or regulator should be consulted.

Data Collection

Staff should be trained to collect and field-evaluate data and maintain the instrumentation. The collection method and frequency will depend on the parameter being measured and the expected variation. The monitoring frequency is usually based on the expected rate of change, reservoir level variations, time of year, observed variability in reading, and collection method.

The individual reading the instrument should have the historical data or threshold levels accessible in the field. Any spurious reading that deviates from the historical trend or threshold level should be immediately checked by an additional field measurement to confirm the reading. Instrument data are influenced by external factors such as reservoir level, temperature, and recent precipitation. Therefore, this information should be documented along with the instrument reading.

The individual reading the instruments (and performing visual observations) should be trained in detecting unusual or adverse conditions and how to respond. Response may be to call a pre-identified dam safety engineer or regulator, and in severe conditions, such as observing an active sand boil, be prepared to implement immediate risk reduction measures such as lowering the reservoir, placing sand bags, or installing a reverse filter, as well as, when required, activating the Emergency Action Plan.

Manual data collection is most common for small dams. In some rare cases data collection using

automated data acquisition systems (ADAS) is warranted on small dams if there is a high risk associated with changes in the measured parameter and the dam is not observed frequently. On larger dams, the trend is away from manual measurements and mechanical recorders and toward electronic measurements and ADAS. Potential benefits of automated data acquisition include:

- A current and continuous data record
- Repeatability of data acquisition
- A variety of data processing options to improve accuracy
- Potentially lower costs to collect a large volume of data
- Reallocation of labor resources to the more valuable functions of analysis and decision-making
- The ability to assess real-time data remotely
- The ability to automatically initiate alarms and other actions if critical thresholds are exceeded

Data Interpretation

The purpose of data interpretation is to evaluate what the data indicate about the performance of the dam. In order for instrumentation and monitoring to be effective, data needs to be evaluated in a timely manner and with respect to project conditions including reservoir elevation, temperature, precipitation, operational changes, and loading conditions. All data should be compared with expected behavior based on engineering concepts of dam behavior. Expected behavior may be based on analyses, historic readings, or educated judgment. Expected behavior of the data may follow trends, such as decreasing or increasing with time or depth, seasonal fluctuation, variation with reservoir or tailwater level, or a combination of such trends. Trends are best identified through plotting of the data.

Variations from expected behavior may suggest development of conditions that should be evaluated further. If no unusual behavior or evidence of problems is detected, the data should be filed for future reference. If data deviate from expected behavior or design assumptions, action should be

taken. The action to be taken depends on the nature of the problem, and should be determined on a case-by-case basis. Possible actions may include more frequent readings, detailed visual inspection, analysis using the new data, or risk reduction measures such as lowering the reservoir, or designing remedial measures. ASCE Task Committee Guidelines for Instrumentation and Measurements for Monitoring Dam Performance (2000) provides more detail on instrumentation interpretation for dam safety.

Conclusions

A robust and effective surveillance and monitoring program is well designed, proactive, and well understood. Every dam is unique and there is not a “one size fits all” approach to determining the appropriate level of instrumentation. Not every dam warrants a robust instrumentation program. The required monitoring is dependent on the size and type of the dam, the hazard potential classification of the dam, the site conditions including the foundation conditions, existing deficiencies or problems, design of the dam, and any identified PFMs. Table 2 presents a list of common potential failure modes and their associated monitoring instruments. This list can be used as a guide to get started on planning and implementing a monitoring program appropriate for each dam. The monitoring program should be determined by the dam owner/operator, designer, and regulator, should be related to the design criterion and reflect the needs based on the observed behavior, known vulnerabilities, and identified PFMs. Every instrument should address a specific need. While the right instrumentation can be essential in identifying potential problems, in the words of Dr. Ralph Peck, “An instrument too often overlooked in our technical world is a human eye connected to the brain of an intelligent human being.” Routine visual inspection of the dam is of the utmost importance and should always be the primary means of monitoring the dam. It is important to know how to recognize and respond to adverse conditions. Proactive, effectively designed and implemented programs have been successful in detecting a developing adverse condition in sufficient time to allow for successful intervention preventing a dam safety incident or failure.

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Table 2: Typical Instrumentation and Monitoring Used in Evaluating Causes of Common Problems/Concerns
[Reference taken from Table 9-4c in FERC Chapter 9 (FERC, 2005)]

Problem/Concern	Typical Instrumentation
Seepage or leakage	Visual observation, weirs, flow meters, flumes, calibrated containers, observation wells, piezometers
Boils or piping	Visual observation, piezometers, weirs
Uplift pressure, pore pressure, or phreatic surface	Visual observation, observation wells, piezometers
Drain function or adequacy	Visual observation, pressure and flow measurements, piezometers
Erosion, scour, or sedimentation	Visual observation, sounding, underwater inspection, photogrammetric survey
Dissolution of foundation strata	Water quality tests
Total or surface movement (translation, rotation)	Visual observation, precise position and level surveys, plumb measurements, tilt meters
Internal movement or deformation in embankments	Settlement plates, cross-arm devices, fluid leveling devices, pneumatic settlement sensors, vibrating wire settlement sensor, mechanical and electrical sounding devices, inclinometers, extensometers, shear strips
Internal movement or deformation in concrete structures	Plumb lines, tilt meters, inclinometers, extensometers, joint meters, calibrated tapes
Foundation or abutment movement	Visual observation, precise surveys, inclinometers, extensometers, piezometers
Poor quality rock foundation or abutment	Visual observation, pressure and flow measurements, precise surveys, extensometers, inclinometers
Slope stability	Visual observation, precise surveys, inclinometers, extensometers, observation wells, piezometers, shear strips
Joint or crack movement	Crack meters, reference points, plaster or grout patches
Stresses or strains	Earth pressure cells, stress meters, strain meters, over coring
Seismic loading	Accelerographs
Relaxation of post-tension anchors	Jacking tests, load cells, extensometers, fiber-optic cables
Concrete deterioration	Visual observation, loss of section survey, laboratory and petrographic analyses
Concrete growth	Visual observation, precise position and level surveys, plumb measurements, tilt meters, plumb lines, inclinometers, extensometers, joint meters, calibrated tapes, petrographic analyses
Steel deterioration	Visual observation, sonic thickness measurements, test coupons

¹ Appropriate remedial measures should be taken for all problems and concerns. Possible remedial measures for a wide variety of problems and concerns are discussed in EPRI (1986), National Research Council (1983), ASCE (1975 and 1988) and USACE (1986a).

Useful References

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- [10] United States Department of the Interior, Bureau of Reclamation. (1990). [Design standards no. 13. Embankment Dams. Chapter 11: Instrumentation.](#)
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