RECLAMATION
Managing Water in the West

Design Standards No. 13

Embankment Dams

Chapter 11: Instrumentation and Monitoring
Phase 4 Final

U.S. Department of the Interior
Bureau of Reclamation

March 2014

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Design Standards Signature Sheet

Design Standards No. 13

Embankment Dams

DS-13(11)-9: Phase 4 Final
March 2014

Chapter 11: Instrumentation and Monitoring

Foreword

Purpose

The Bureau of Reclamation (Reclamation) design standards present technical requirements and processes to enable design professionals to prepare design documents and reports necessary to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Compliance with these design standards assists in the development and improvement of Reclamation facilities in a way that protects the public's health, safety, and welfare; recognizes needs of all stakeholders; and achieves lasting value and functionality necessary for Reclamation facilities. Responsible designers accomplish this goal through compliance with these design standards and all other applicable technical codes, as well as incorporation of the stakeholders' vision and values, that are then reflected in the constructed facilities.

Application of Design Standards

Reclamation design activities, whether performed by Reclamation or by a non-Reclamation entity, must be performed in accordance with established Reclamation design criteria and standards, and approved national design standards, if applicable. Exceptions to this requirement shall be in accordance with provisions of *Reclamation Manual Policy*, Performing Design and Construction Activities, FAC P03.

In addition to these design standards, designers shall integrate sound engineering judgment, applicable national codes and design standards, site-specific technical considerations, and project-specific considerations to ensure suitable designs are produced that protect the public's investment and safety. Designers shall use the most current edition of national codes and design standards consistent with Reclamation design standards. Reclamation design standards may include exceptions to requirements of national codes and design standards.

Proposed Revisions

Reclamation designers should inform the Technical Service Center (TSC), via Reclamation's Design Standards Website notification procedure, of any recommended updates or changes to Reclamation design standards to meet current and/or improved design practices.

Prepared by:

3/25/14

Jay N. Stateler, P.E.
Civil Engineer, Instrumentation and Inspections Group

Date

Peer Review

Richard Kelsic, P.E.

3/26/14

Richard H. Kelsic, P.E.
Civil Engineer, Instrumentation and Inspections Group

Date

Security Review:

Robert L. Dewey

3/26/14

Robert L. Dewey, P.E.
Geotechnical Engineering Group 3

Date

Recommended for Technical Approval:

3/26/14

for DeWayne A. Campbell, P.E.
Group Manager, Instrumentation and Inspections Group

Date

Submitted:

Karen Knight

6/19/2014

Karen Knight, P.E.
Chief, Geotechnical Services Division

Date

Approved:

T. A. Luebke

9/23/14

Thomas A. Luebke, P.E.
Director, Technical Service Center

Date

Chapter Signature Sheet
Bureau of Reclamation
Technical Service Center

Design Standards No. 13

Embankment Dams

Chapter 11: Instrumentation and Monitoring

DS-13(11)-9:[1] Phase 4 Final
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Chapter 11 – Instrumentation and Monitoring is a completely revised and updated chapter within Design Standards No. 13 that replaces previous Chapter 11 – Instrumentation. Chapter 11 now includes discussion of visual monitoring issues associated with a dam safety monitoring program, and the use of the Potential Failure Mode Analysis (PFMA) approach with respect to designing dam safety monitoring programs.

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[1] DS-13(11)-9 refers to Design Standards No. 13, chapter 11, revision 9.

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3/25/14

Jay N. Stateler, P.E.
Civil Engineer, Instrumentation and Inspections Group

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Chief, Geotechnical Services Division

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Approved:

T. A. Luebke

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Thomas A. Luebke, P.E.
Director, Technical Service Center

Date

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Chapter 11

Instrumentation and Monitoring

11.1 Introduction

11.1.1 Purpose

The purpose of this chapter is to provide general information regarding important issues associated with instrumentation and dam safety monitoring including: (1) instrumentation and/or monitoring program designs, (2) evaluation of monitoring data and information, and (3) response to unusual monitoring data or information. Continuing technological advancements require this document to be limited to broader principles and generalities about instrumentation equipment to prevent this information from becoming outdated shortly after publication. Professionals working in the instrumentation and monitoring fields need to be consulted regarding the latest developments in these fields.

11.1.2 Scope

This chapter addresses a full range of topics associated with instrumentation and monitoring of embankment dams, and appurtenant structures typically associated with embankment dams, such as spillways and outlet works facilities. Instrumentation and monitoring issues associated with concrete dams, and the concrete portions of composite dams, are not covered in this chapter. *Design Standards No. 2, Concrete Dams*, should be used for this information. Instrumentation and monitoring issues associated with canals and levees are not directly covered in this chapter, but many of the principles and equipment types discussed herein are relevant to these facilities.

11.1.3 Applicability

The guidance and procedures presented in this chapter are applicable to the design of instrumentation and monitoring programs for embankment dams, as well as the evaluation of data and information obtained from such programs.

11.1.4 Deviations from Standard

Design of instrumentation and monitoring programs within the Bureau of Reclamation (Reclamation) should adhere to the concepts and methodologies presented in this design standard. The rationale for deviation from the information presented in this design standard should be presented in technical documentation for the dam and should be approved by appropriate line supervisors and managers.

11.1.5 Revisions of Standard

This standard will be revised periodically as its use indicates, and the state of practice dictates. Comments and/or suggested revisions should be forwarded to the Chief, Geotechnical Services Division (Code 86-68300), Bureau of Reclamation, Denver, Colorado 80225; they will be comprehensively reviewed and incorporated as appropriate.

11.1.6 Overview of Contents

This chapter begins with discussion of some general topics, including the central role that Potential Failure Mode Analysis (PFMA) plays in the design of instrumentation and monitoring programs, as well as the important relationship between instrumented monitoring and visual monitoring. The discussion then turns to the various instrument types, with separate sections regarding instruments used for monitoring: (1) seepage flows, (2) water pressures, (3) earth pressures, and (4) deformations. Discussion is then provided regarding the development of monitoring programs for both new and existing dams, followed by discussion of the design, installation/construction, and maintenance of instrumentation systems. Operational aspects of dam safety monitoring programs are then discussed, including data collection and transmittal (manual and automated), and data review and evaluation. The chapter concludes with a listing of references pertinent to instrumentation and monitoring.

11.2 General Instrumentation and Monitoring Considerations

11.2.1 Use of Potential Failure Modes Analysis for Monitoring Program Design

In the early 1990s, Reclamation realized that in order to put in place a rational, cost-effective instrumentation program for a dam, it is first necessary to identify the potential dam safety threats, or potential failure modes, that the instrumentation program is to be designed to address. A dam-by-dam effort was embarked upon, initially called the “Performance Parameter Process,” which involved the following three steps:

- Identify the potential failure modes (the most likely ways the dam could fail)

- For each potential failure mode, determine the key monitoring parameters that would indicate initiation or progression of the potential failure mode

- For each key monitoring parameter, determine the ranges of expected performance (consistent with satisfactory dam performance)

Reclamation personnel initially prepared Performance Parameters Technical Memoranda (TMs) for Reclamation dams. In time, this activity became part of Comprehensive Facility Reviews (CFRs), which later evolved into Comprehensive Reviews (CRs).

In the early 2000s, the Federal Energy Regulatory Commission (FERC) adopted the Performance Parameters approach for the facilities they regulate, and called the process “Potential Failure Mode Analysis (PFMA),” which became the commonly used name for the process. For reference, as part of a PFMA, a “Surveillance and Monitoring Plan (SMP)” is developed for the FERC-regulated dam under study.

The PFMA activity is discussed further in Section 11.8, “Development of a Monitoring Program.” However, it is so fundamental to dam safety monitoring efforts and activities that it warrants some discussion at the start of this document. Two other comments regarding PFMA work:

- The PFMA process ties monitoring activities to specific failure modes. However, some appropriate monitoring can fall in the category of “General Health Monitoring,” that is not tied to a specific failure mode. Such monitoring almost always is “high value, low cost.” Determining what does and does not represent appropriate “General Health Monitoring” is a continuing challenge with respect to defining dam safety monitoring programs because clear-cut answers are not available, and opinions change with time.

- Many key monitoring parameters relate to visual monitoring efforts, as opposed to situations that can be effectively monitored using instruments. Hence, this document is called “Instrumentation and Monitoring,” as opposed to its previous title of “Instrumentation.” The next section provides more discussion regarding this topic.

11.2.2 Importance of Visual Monitoring

A review of the historical record of embankment dam failures reveals that seepage-related internal erosion failure modes account for roughly one-half of the failures. Key monitoring issues associated with internal erosion potential failure modes include:

- Is there evidence of material transport by seepage flow?
- Are seepage flow rates increasing with time?
- Are there any new seepage areas or wet areas?
- Are there any existing wet areas or downstream ponds that are increasing in size or depth over time?
- Are there any new areas of lush vegetation, or changes in existing vegetation appearance, that could be due to new or changing seepage conditions?
- Is there any woody vegetation on the embankment with roots that could create paths for concentrated seepage flow?
- Is there animal burrow activity that could give rise to shortened seepage paths and concentrated seepage flows?
- Are there any sinkholes or depressions?
- Are there any transverse cracks through the dam embankment?

A number of the items listed above cannot realistically be effectively addressed using instruments. Instead, routine visual monitoring is required, in addition to instrumented monitoring. The need for both instrumented and visual monitoring would exist for many other potential failure modes as well. While water pressure data and deformation data (such as inclinometer data and/or surveyed monuments) would be important for a potentially unstable slope, visual inspections for cracking, bulging at the toe area, etc., would also be important. Adverse deformations of a spillway structure that could give rise to structure failure during a flood event could be detected by surveyed monuments on the walls and floors, and instrumented monitoring of joints for offsets. However, a combination of both instrumented and visual monitoring is most commonly used to look for deformations and deflections of concern.

A knowledgeable inspector is able to examine all visible aspects of a dam, its dam site, and its appurtenant structures, and potentially can find evidence relating to a potential failure mode that has not been previously identified for the dam. However there are two main drawbacks to relying solely on visual inspections for routine dam safety monitoring:

- Visual examinations may not be able to detect subtle changes at the site.

- Parameters of the performance or functioning of a dam that are within the dam, foundation, or abutments would not be detected by a visual inspection.

A routine program of collecting and evaluating instrumentation data can address the two issues noted above.

a. **Lack of hard data.** Instruments provide hard data to an accuracy and sensitivity controlled during the instrumentation design. Changes that would not be visually noticeable can be detected.

b. **Limited to only surface observations.** Instruments can be installed within the dam, foundation, abutments, and/or appurtenant structures to give information about performance parameters that are not available from inspection of visible surfaces.

The routine dam safety monitoring program for a dam should normally include both instrumented and visual monitoring. While much of this document focuses on instruments, the routine visual monitoring program for a dam normally has at least the same level of importance as the instrumented monitoring program.

11.2.3 Role of Instrumentation at Various Stages in the Life of a Dam

11.2.3.1 Original Dam Design

Exploration drill holes may be completed as observation wells or piezometers to gather groundwater information, or subsurface water pressure information, for one or more of the following reasons:

- For use in the design and/or the development of the construction specifications.

- For baseline information, so that when the dam is completed and the reservoir is filled, changes in water levels at the site and in the vicinity can be determined for engineering and/or legal reasons.

11.2.3.2 Original Dam Construction

The instrumentation (and monitoring) needs can fall into three categories:

- Verification of design assumptions and analyses during the construction process

- Controlling construction activities

- Maximizing worker safety at the construction site

Examples regarding each of these categories are provided below.

a. **Verification of design assumptions and analyses.** Perhaps concerns exist about the magnitude of foundation settlement/compression that may take place due to the weight of the embankment to be constructed. Collecting settlement data at the embankment/foundation contact during construction could allow the estimated behavior to be checked. If the actual performance during the course of the construction varies significantly from the design assumptions and analyses, adjustments to the dam design can be developed and implemented with respect to the partially constructed embankment to address the observed behavior.

b. **Controlling construction activities.** A classic example would be monitoring embankment pore pressures to ensure that construction-induced excess pore pressures do not develop to a degree that would allow slope instability to occur. High pore pressures may require a slowdown or temporary halt in embankment construction, to let the excess pore water pressures dissipate to some degree, so that a costly slide in the embankment does not occur.

c. **Maximizing worker safety.** It may be that temporarily exposed excavated slopes in a cutoff trench, at an abutment, etc., may be quite steep (to limit excavation costs). Because construction workers may be endangered if a slope failure occurs, real-time slope monitoring may be performed so that initial indications of instability can be detected and actions can be taken to prevent workers from being endangered by a slide.

11.2.3.3 Dam Modification

If the dam will undergo a significant dam modification, the concepts discussed above regarding original design and construction generally apply during the modification work, but with a couple of noteworthy differences:

- The modification design effort will have the benefit of the instrumentation data collected for the dam and dam site during its years of operation. This is a very different data situation than existed during the original design process for the dam.

- Because some amount of water most likely will be present in the reservoir during the dam modification construction work (and perhaps a lot of water will be present), appropriate monitoring needs to be performed to limit the risks of dam failure and uncontrolled release of reservoir water during construction.

11.2.3.4 First Reservoir Filling

This information applies to a new dam or a dam that has undergone significant modification work. However, it can also apply in a similar way to a dam that has potentially been damaged by seismic shaking, or a dam with a reservoir that has been low for an extended period of time. No record of historic performance is available for the current state of the embankment and its appurtenances. Therefore, significant performance uncertainties can exist when reservoir levels rise in the future because the new, modified, or potentially damaged dam embankment will be tested with reservoir water at a time when its condition is not confidently known. Consequently, these typically are the times in the life of the dam when the most intensive monitoring takes place. Reclamation typically requires an "around-the-clock" presence of experienced inspectors at the dam site, and nighttime lighting of the downstream slope and toe area, so that visual inspections (and instrument readings) can be carried out multiple times each day. Adverse seepage performance is typically the principal concern, although possible slope instability could also be a noteworthy concern. If potentially significant settlement of the dam and/or its foundation upon wetting is a major concern, then settlement and deflection data for the embankment would be of great interest, along with visual inspection information regarding possible embankment cracking, depressed areas, etc.

11.2.3.5 Long-Term Performance Monitoring

The instrumentation (and monitoring) needs can fall into three categories:

a. Monitoring of specific concerns or issues identified during the design process

b. Monitoring of specific concerns or issues identified during PFMA work at the dam

c. General, long-term monitoring ("General Health Monitoring") to look for adverse or anomalous performance that could lead to failure or other adverse consequences if not detected

These three topics will be discussed in Section 11.8, "Development of a Monitoring Program."

11.2.3.6 Response to Adverse or Anomalous Performance

Detection of adverse or anomalous performance can require additional monitoring efforts relative to two issues:

a. Increased monitoring may be needed to ensure early detection and recognition of conditions that could indicate progression toward dam failure

b. Gathering additional data may be needed to support evaluation and analysis work to better understand what is taking place at the dam site

Relative to item a, “around-the-clock” monitoring may be required. Presumably, Response Level 1 or 2 would have been declared in accordance with the Emergency Action Plan (EAP), and prepositioning of equipment and materials may be appropriate so that a capability to arrest worsening conditions is available. In the event of a new seepage flow, for example, channeling and/or use of sandbags may be necessary to collect the new flow and send it over a newly installed weir, or into a pipe through a sandbag “wall,” so that it can be quantitatively monitored. The stilling pool behind the sandbag wall or in front of the weir would allow sediments carried by the new seepage flow to settle out, so that sediment transport by the new seepage could be recognized if it is occurring.

Relative to item b, new instruments could be promptly installed to better understand and evaluate what is taking place. Surveyed monuments, inclinometers, shear strips, piezometers, etc., could be installed in the event of a slope instability situation. For a seepage-related internal erosion situation, piezometers could be installed so that flow paths and gradients could be better understood. Two important considerations for dealing with an internal erosion situation include:

- New piezometers will be unable to provide information about pre-event conditions, so they will not be able to answer questions about “What has changed that has caused or led to this situation?” This is where issues about providing piezometers for “General Health Monitoring” come into play because such instruments could provide pre-event information (if one or more pre-event piezometers happened to be located in key locations).

- Dye testing and/or geophysical methods are commonly employed quickly after the development of a seepage-related incident to better understand seepage flow paths and the flow velocity along the seepage path (from the point of dye injection to the dye exit point).

11.2.3.7 Dam Decommissioning

Typically, instrumentation does not play a large role during the decommissioning of a dam. However, there may be a need to gather groundwater information or subsurface water pressure information for baseline information so that when the reservoir is no longer present, the change in water levels in the vicinity of the former dam and reservoir is known. Perhaps adjacent landowners will be adversely impacted by changed groundwater levels due to reservoir removal.

11.2.4 Benefits Associated With Instrumented Monitoring

11.2.4.1 Basic Understanding of the Behavior of the Dam and Dam Site

Instrumentation can provide hard data regarding important performance characteristics of a dam, such as: (1) settlements and deflections; (2) the dissipation of reservoir water pressures as seepage water moves downstream through the core of the dam, or through the foundation or abutments of the dam; (3) water pressure drops upstream and downstream of grout curtains, cutoff walls, etc.; and (4) seepage quantities through the dam, foundation, abutments, etc. Such information provides actual performance data about the dam and dam site that can be compared to the design expectations.

11.2.4.2 Detection of Anomalous Performance

This is the category of benefits most closely linked to the basic goals of the routine dam safety monitoring program. For an instrumentation and monitoring program to be effective in warning of a potential problem, appropriate parameters must be monitored, and a change in the parameters must be noted and conveyed to dam safety engineers and decisionmakers in a timely fashion.

The PFMA process fosters the development of a customized monitoring program for each dam, tailored to the dam's current dam safety concerns and threats (the potential failure modes). There is also provision for "General Health Monitoring" that meets the "high value, low cost" test that allows for prudent monitoring activities that are not related to the currently identified potential failure modes.

The timeliness of getting instrumentation information from the installations to the data evaluators and decision-makers is a very important factor in the effectiveness of the instrumentation program relative to providing warning about the initiation and/or progression of potential failure modes. It would be no consolation that a failure could have been prevented (i.e. the information existed that could have been acted on) if, in fact, no action was taken because the data had not been reviewed and evaluated. Timeliness involves the frequency of reading the instruments, the time required for the data to reach the data evaluators and decisionmakers, and the time required for decisionmakers to process and act on the information. These are all important factors to consider in the design of an effective instrumentation monitoring program. *Reclamation Manual* FAC 01-08, "Dam Safety Performance Monitoring for High- and Significant-Hazard Dams," dated April 12, 1999, indicates the following default timeframes for reporting and reviewing monitoring data and information:

- "Frequencies for transmission of data and visual observations. (Unless otherwise defined, this time period will be 2 weeks for "infrequently read instruments," which are instruments read no more frequently than annually, and 3 working days for all other instruments and visual observations.)

- Time period within which data and observations received at the central database by dam safety performance monitoring specialists must be reviewed and findings reported. (Unless otherwise defined, this time period will be 2 weeks for "infrequently read instruments," which are instruments read no more frequently than annually, and 3 working days for all other instruments and visual observations.)

For each Reclamation dam, the above default timeframes can be superseded by customized timeframes established for the dam's particular dam safety situation, threats, and consequences of failure, as noted above. This superseding of default timeframes typically occurs as part of a CR.

11.2.4.3 Investigation of Anomalous Performance

In the event of anomalous performance, or suspected anomalous performance, instrumentation can be used to learn more about the situation so that it can be better understood and evaluated. Information about the cause, nature, and/or extent of the situation can be gathered. When a rapid reservoir drawdown in 1981 led to a slide at the upstream slope of B.F. Sisk Dam, piezometers, inclinometers, and measurement points were used to help define the failure surface and to help determine the reason for the slide (slopewash material that lost strength upon wetting and had low residual strength). With this information, the remediation work could be appropriately designed, including remediation of two other areas of the dam that had not experienced an upstream slide but were also revealed to have low factors of safety due to the presence of slopewash material beneath the upstream slope.

11.2.4.4 Verify that Performance is Satisfactory

When difficult situations are encountered and/or when great uncertainty exists, it is valuable to have hard data that provide insight regarding the performance of the dam. By carefully selecting the parameters to be monitored, and properly carrying out the monitoring program, the instrumentation program can help engineers deal with difficult situations and/or uncertainty in a cost-effective manner. Lacking such information, it is possible that choices might be made that are excessively conservative and costly, or they may involve unnecessary risks. During the first reservoir filling of Ririe Dam, which was the first Reclamation-operated dam to undergo first reservoir filling following the Teton Dam failure, seepage appeared in the right groin area. However, additional instrumentation was installed at Ririe Dam and vicinity after the Teton Dam failure (due to recommendations resulting from that failure). From this instrumentation, it could be determined that the source of the seepage was not the reservoir, but the irrigated farmlands at the right abutment of Ririe Dam. Consequently, filling of Ririe Dam's reservoir was allowed to proceed (and was completed without incident).

11.2.4.5 Feedback Regarding Remedial Measure Effectiveness

Instrumentation can allow remedial work at a dam to be effectively evaluated. This is particularly important with geotechnical engineering issues, where some level of information may be available about a situation, but substantial knowledge gaps may be filled, to the degree possible, by educated and well-reasoned hypotheses. In these circumstances, instrumentation installations can play a vital role in allowing engineers to understand the effect of remedial measures on important performance parameters. In this way, the engineers can reliably determine when a problem has been satisfactorily resolved, or when a problem has not been resolved and further work is still needed. Reclamation's experience at Helena Valley Dam in the 1960s is an example of this situation. High water pressures were present at the downstream toe area, and reservoir blanketing and grouting were employed in an attempt to address the situation. Piezometers allowed immediate feedback relative to remediation effort effectiveness.

11.2.4.6 Research

Installing instruments for research purposes is rarely well-received by owners, who may not benefit from the information gained. The data collected do not affect the design or function of their structure. The data can only benefit future design efforts for other structures. Instrumentation programs for research issues need to be carefully thought through and designed to provide complete information about the situation under study, so that valid and useful data on all the relevant parameters are obtained.

Another aspect of "research" is to pull together instrumentation data from large numbers of dams to analyze the data for general patterns of dam performance. Again, access to all relevant parameters needs to be obtained to understand the complete performance picture. However, when possible, this approach to "research" can provide very valuable information.

11.2.4.7 Legal

This topic was previously discussed in Sections 11.2.3.1 and 11.2.3.7 above. There may be a need to gather groundwater information, or subsurface water pressure information, for baseline information, so that when reservoir levels change, the change in water levels in the vicinity of the dam and reservoir is known for legal reasons. Perhaps adjacent landowners will be adversely impacted by changed groundwater levels at their property.

11.2.5 General Considerations for Selecting the Appropriate Instrument Type for Use

Sections 11.3 through 11.6 provide information about various instrument types. Before embarking on these discussions, it is useful to present some general considerations that may impact which instrument type is selected as most appropriate in a particular situation:

- Long-term reliability
- As simple as possible
- Vandal resistant
- Low maintenance
- Compatible with construction techniques to be employed
- Low cost

11.2.5.1 Long-Term Reliability

Long-term reliability is a very important consideration for instruments used at dams, particularly those embedded within dams that cannot realistically be retrieved and replaced in the event of instrument problems/malfunction. A lot of geotechnical instrumentation that is sold for use at structures other than dams is used for relatively short durations during construction, such as monitoring the stability of temporary construction bracing, monitoring the effectiveness of dewatering systems, etc. Long-term reliability is not a central consideration in these situations. Therefore, it is important to recognize that instrument longevity issues are different for dams, with their long design lives, and some available instrumentation is not appropriate for use at dams. Having the “latest and greatest” is always tempting, but a solid track record of reliable long-term performance is clearly preferable when considering instruments to be used at dams.

11.2.5.2 As Simple as Possible

Seeking as simple an instrument or instrumentation system as possible to provide the required information directly relates to the issue of long-term reliability. With complexity comes greater opportunity for something to go wrong. When anomalous data suddenly appear, instruments that are complex (and may seem like a “black box’ situation) may face data validity questions. What is the point of having instruments whose data are not believed when they indicate something out of line with expectations?

11.2.5.3 Vandal Resistant

Another factor to consider for long-term reliability is how instruments can be made resistant to vandals. Losing an instrument that cannot readily be replaced due to vandalism is obviously a bad situation. Lockable and stout protective enclosures for instruments are important. As an example, using a solar panel for power supply could create a vulnerable situation ripe for vandalism. Even though the solar panel can be replaced, data collection would stop when the backup battery power is exhausted, leading to gaps in the data. The need to frequently replace damaged solar panels would also be inconvenient and costly.

11.2.5.4 Low Maintenance

Instruments requiring little or no maintenance are intrinsically desirable from a cost and convenience standpoint and are preferable for long-term reliability as well. Failure to perform required maintenance could cause an instrument to stop functioning as it is supposed to. If no maintenance is required, then this particular risk to the instrument's longevity does not exist.

11.2.5.5 Compatible with Construction Techniques to be Employed

It is important that instrumentation installations be compatible with the construction activities that are occurring at the time they are being installed for two basic reasons:

- So that the instrument installations are successful and satisfactory
- So that the constructed dam is not adversely impacted by the installed instruments

The classic example of instrumentation that is incompatible with construction is when an attempt is made to install a large number of open-standpipe piezometers in or beneath the embankment of a dam under construction. The piezometer standpipes, and the associated protective mounds around them, need to extend vertically up to the top of the dam. Therefore, this situation presents numerous obstacles to the equipment placing and compacting the embankment material. To illustrate this situation, figure 11.2.5.5-1 shows protective mounds for instrument installations at a dam under construction.

Figure 11.2.5.5-1. Protective mounds around instrumentation installations at an embankment dam under construction.

Scrapers and compaction equipment present noteworthy risks for damage to equipment. The significant percentage of the dam embankment that is placed as specially compacted material to construct the protective mounds is detrimental to the dam embankment. Also, care must be taken to ensure that the embankment material placed adjacent to the protective mounds is well compacted. The sinkholes that developed at W.A.C. Bennett Dam in 1996, at specially compacted areas associated with instrumentation installations are a cautionary tale. Figure 11.2.5.5-2 shows a photograph of one of these sinkholes.

Figure 11.2.5.5-2. Sinkhole at W. A. C. Bennett Dam believed to be due to inadequate compaction of embankment materials near and around instrumentation installations.

11.2.5.6 Low Cost

Instrumentation installations that cost less are preferable to those that cost more, all other things being equal. However, cost savings achieved at the sacrifice of other considerations discussed in this section is unwise. Cost, while important, may be the least important consideration noted in this discussion.

11.2.6 Sources of Detailed Instrumentation Information

Instrumentation equipment and installation methods are always evolving. Consequently, detailed, specific information provided in this document may quickly become out-of-date. Therefore, this document discusses equipment types and installation methods in more general terms, providing key information and principles that are more enduring.

Only a limited number of pictures and schematics are provided in the sections below that discuss specific instrumentation equipment and methods for two reasons. Fundamentally, good references already exist that present this information (listed below). Also, from a practical standpoint, John Dunnicliff's book *titled "Geotechnical Instrumentation for Monitoring Field Performance*" (noted below), which is an excellent source of pictures and schematics, is over 500 pages long. A length of that magnitude is not appropriate for this document.

Section 11.14, References, includes a fairly lengthy compilation of information sources regarding the general area of instrumentation and monitoring of dams. Below, a few of the most useful sources of detailed information about instruments and instrumentation installations are listed below. Although any published book becomes dated almost immediately upon publication, the following sources contain a wealth of useful information:

- Dunnicliff, John, *Geotechnical Instrumentation for Monitoring Field Performance*, John Wiley & Sons, Inc., 1993. This book is generally considered to have the most comprehensive and detailed discussion of geotechnical instrumentation available.

- *Geotechnical News* (BiTech Publishers Ltd.). John Dunnicliff has indicated that he does not plan to update his 1993 book (listed above); however, he plans to regularly publish articles and information in this magazine, which address new ideas, developments, etc., in the field of geotechnical instrumentation.

- Bureau of Reclamation, *Embankment Dam Instrumentation Manual*, January 1987. This publication is dated in some areas, but it contains a lot of valuable information.

- Bureau of Reclamation, *Operations and Maintenance Guidelines for Hydraulic Piezometer Installations at Dams*, June 7, 2005. This publication contains basically current information on hydraulic piezometer installations.

- Bureau of Reclamation, *Water Measurement Manual*, 1997. A valuable source of information about weirs, flumes, and other water flow measuring approaches. It includes equations and tables for converting staff gauge readings to flow rates for a wide variety of weirs and flumes. Although it is a few years old, the information is considered current.

- American Society of Civil Engineers (ASCE), *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance*, prepared by ASCE Task Committee on Instrumentation and Monitoring Dam Performance, 2000. This publication contains information that has

> been compiled on a variety of subjects. A new ASCE Task Committee began work on updating this document in 2011.

The Web sites maintained by instrumentation equipment manufacturers present their current equipment offerings. In many instances, they also contain useful application and installation information. Additionally, the sales professionals that work for the equipment manufacturers typically have extensive practical experience they can share. These are great resources for current information, although independent verification of information provided may be appropriate.

11.2.7 Security Considerations

All information collected and disseminated from an instrumentation system of a dam is considered "Highly Sensitive" and "For Official Use Only." From the raw data to the data plots and reports that are based on the data, instrumentation information is to be shared only on a need-to-know basis. This includes details of any instrument, drawings of the instrumentation system(s), dimensional information of the dam, reservoir level data, operational data, site access information, and risk and consequences estimates. Publications and presentations using any such information need to be screened for security purposes. Access to instrumentation related information and data files should be granted on a very restricted basis.

11.3 Instrumentation Types – Seepage Monitoring

11.3.1 General

Flow rates should be routinely and accurately determined for all seepage, drain, and relief well flows at every embankment dam unless safety or access problems cannot be overcome, in which case visual flow rate estimates (at a minimum) should be regularly made. Monitoring of seepage and drain flows also must include awareness concerning possible transport of materials occurring in conjunction with the flow, with materials potentially carried in suspension being the primary concern.

Providing sediment trap locations along seepage flow paths (weir boxes, stilling pools in front of weirs, stilling pools in inspection wells, designed sediment trapping installations, etc.) enables continuous monitoring of possible sediment transported by the flow and the collection of sediments for later observation. This continuous monitoring capability is very important because sediment transport by seepage flow typically is an episodic process, rather than a steady process. Consequently, monitored sediment trap locations should be provided along all seepage flow paths to the extent possible. In addition, sediment trap locations should be painted white, when possible, so that any collected sediments are readily observable. Where providing sediment traps is not feasible, close visual monitoring for evidence of sediment transport by seepage flow should be diligently performed instead.

Turbidity monitoring units that are available for use may seem like a perfect means to monitor possible transport of materials by seepage flows. However, in practice, these devices have not proven to provide useful information (as discussed in Section 11.3.3.7, “Turbidity Meters,” below).

The permeability of embankment and foundation materials is difficult to estimate in advance of actual performance data. Estimates that are accurate to within one order of magnitude are about all that is realistically possible in many situations. Consequently, flow monitoring installations should be capable of accurately monitoring a wide range of potential flows. Using a concrete headwall to which a weir plate (V-notch, rectangular, etc.) is bolted provides valuable flexibility. For example, if a V-notch weir plate is in place, and flows exceed its capability, the weir plate can be changed out to a rectangular weir plate. Trapezoidal flumes can accurately monitor a wide range of flows but lack the essential sediment-trapping stilling pool that exists in front of weirs. Consequently, weirs are preferred over flumes, unless appropriate sediment traps are provided somewhere along the seepage flow path when a flume is used.

Reclamation’s *Water Measurement Manual* is a valuable source of information about weirs, flumes, and other water flow measuring approaches. It includes equations and tables for converting staff gauge readings to flow rates for a wide variety of weirs and flumes.

11.3.2 Applications

11.3.2.1 Specific Issues Related to Potential Failure Modes

Seepage-related internal erosion failure modes have historically accounted for roughly 50 percent of dam failures; hence, the importance of closely and accurately monitoring all seepage, drain, and relief well flows for changes in historical flow rate performance, and for evidence of material transport by the flows. Material transport by seepage flow may represent direct evidence of initiation/progression of an internal erosion failure mode. Therefore, it should be taken as such until a technical evaluation indicates otherwise. Similarly, a pattern of increasing seepage flows (corrected for varying reservoir levels) may represent a flow path that is getting more open with time due to progression of an internal erosion failure mode. This should also be taken as such until a technical evaluation indicates otherwise. New seepage areas or wet areas indicate changes in the seepage performance of the dam, its foundation, and/or its abutments. This also should be promptly investigated to determine if initiation or progression of an internal erosion failure mode is taking place.

Close monitoring of seepage flows for changes from historical flow rate performance, and for evidence of material transport, should occur even for flow paths where appropriately designed filter protection has been provided because actual field conditions may vary from what was designed and is shown on drawings (even drawings noted as being “as built”). Closed-circuit television inspections of a number of toe drain pipes have revealed instances of split or damaged pipe where the designed filter protection may be breached due to loss of filter material into the toe drain pipe.

11.3.2.2 General Performance Issues

Relief wells, horizontal drain systems, and other drainage systems may have declining performance over time due to chemical, mineral, or organic deposits. Monitoring of flows at these installations and/or water pressures in the vicinity of them can indicate when flushing or other rejuvenation efforts may be needed to restore the performance to desired levels.

Monitoring programs may be set up to try to establish general patterns of subsurface seepage flows, particularly if anomalous seepage performance has developed. Self-potential surveys and resistivity testing are methods that can be used to help determine general seepage patterns over broad areas.

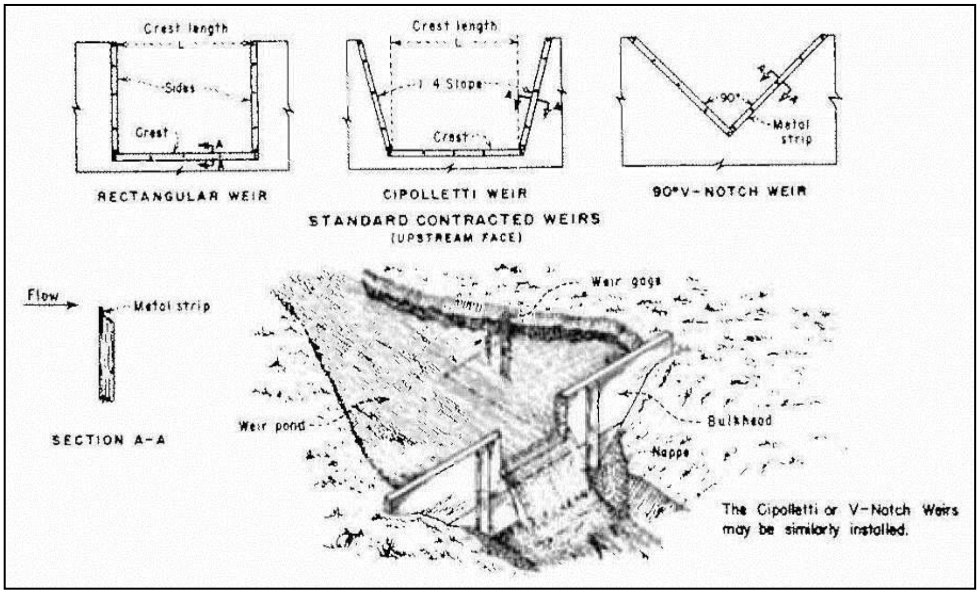
11.3.3 Instrument Types

11.3.3.1 Bucket and Stopwatch Monitoring

The simplest approach to obtaining a seepage flow rate is to measure the time needed to fill a container of known volume. To be successful, this approach requires a relatively low flow, a flow that has been concentrated to a specific outfall location (typically a pipe or V-notch weir), and a situation that permits all of the flow to be readily captured by the container (i.e., enough room exists to get the container under the flow stream). Unless a very large container is used, this method is effective only for flows up to roughly 25 to 30 gallons per minute.

11.3.3.2 Weirs

Weirs back up flowing water into a stilling pool behind the weir and create controlled release of the water over the weir. Major types of weirs include V-notch, Cipolletti, rectangular contracted, and rectangular suppressed weirs, which differ only in the geometry of the controlled release conditions of the weir. The elevation of the water surface of the stilling pool above the crest of the weir is measured at a point suitably upstream of the weir (to avoid drawdown effects near the weir). Then, established correlations presented in Reclamation’s *Water Measurement Manual* are used to convert the elevation difference to a flow rate. The correlations assume that the standard conditions at the weir, as defined in the *Water Measurement Manual*, are met. All Reclamation weir installations should be designed and constructed to meet the applicable requirements presented in the *Water Measurement Manual*; otherwise, the correlations presented in the manual are not valid. Figure 11.3.3.2-1 illustrates several different types of weirs.



The Cipolletti or V-Notch Weirs may be similarly installed.

Figure 11.3.3.2-1. Illustration of several different types of weirs.

The flow surface of the weir needs to be kept free of debris and clean so that the water “springs” off the weir blade. Full flow contraction must exist at the weir, both at the sides (except for suppressed weirs) and at the bottom, and the flow must fall freely for a vertical distance of not less than 0.2 foot below the weir crest elevation. Weir installations provide a sediment trapping capability in front of the weir that is vital for monitoring of internal erosion potential failure modes. Whenever flow rate data are collected, a check should be made for trapped sediments, and any indication of trapped sediments should be immediately reported.

11.3.3.3   Flumes

The principles for flumes are the same as for weirs, except that the controlled release of the water does not involve springing from a weir crest. Instead, it passes through a standardized, narrow channel section that has angled transition sections both upstream and downstream. Trapezoidal flumes have sloping sidewalls, while Parshall flumes have vertical sidewalls. Trapezoidal flumes are often preferable to Parshall flumes because they can accurately monitor a wider range of flows due to their sloping sidewall configuration.

Where the tailwater at the flume is high (the exact height depends on the specific flume used), the elevation of the tailwater needs to be determined, as well as the upstream pool elevation, to properly determine the flow rate using established correlations. As with weirs, it is important that the standard flow conditions defined in Reclamation’s *Water Measurement Manual* are present at the flume installation so that the flow tables and correlations presented in the *Water Measurement Manual* can be used to develop accurate flow rate data.

11.3.3.4 Velocity Meters

Velocity meters can, in many instances, be used to determine flow volumes if the flow is taking place in a conduit of known geometry or in a conduit where established correlations between velocities and flow volumes have been determined. Simple velocity meters use turbine-like propeller devices in the flow that rotate about an axis parallel to the flow in proportion to the flow velocity. Knowing the rotational speed of the device and its characteristics enables the flow velocity to be calculated. More sophisticated velocity meters use the electromagnetic principle that a conductor (the water) moving through a magnetic field (created by the probe) will have a voltage induced that is proportional to the velocity of movement of the conductor (the water). By reading voltage differentials across points on the probe and having known correlations, the water velocity can be determined.

To work properly, these sophisticated meters need care and attention, and they must frequently be calibrated. Depositions on the sensor points affect the collected data. Experience at Virginia Smith Dam, using velocity meters of both types, ultimately led to the exclusive use of the propeller-type device because of its relative simplicity and the consistency of the data it provided. The electromagnetic velocity meter produced more erratic data, which is presumed to be due to depositions on the sensor points. Where greater velocities and discharges are to be monitored, the electromagnetic velocity meter is believed to produce more stable and reliable data because depositions at the sensors should not be significant.

11.3.3.5 Water Quality Analyses

To monitor seepage flows for material transport, water samples can be obtained and analyzed for the concentrations of total dissolved solids and total suspended solids, for the concentrations of common cations and anions, for pH, and for other parameters. Water quality monitoring programs represent “moment-in-time” monitoring that is not effective when sediment transport occurs in “spurts,” rather than continuously. Typically, sediment transport cannot be assumed continuous, so this method should not be routinely used for sediment transport monitoring in seepage flows.

Water quality data developed from samples collected at several locations at a site can allow information to be obtained regarding patterns of dissolution of materials at the site. If such data are collected on more than one date, changes in dissolution of materials occurring at the site over time may be detected. This potentially can be useful if concerns exist about possible dissolution of gypsum or anhydrites by seepage flows. Leaching of the cementitious material in grout curtains may also be of concern. Typically these water quality monitoring programs have a duration of 1 or 2 years, at most, so that the dissolution or leaching questions can be answered. They are in addition to, and not part of, routine dam safety monitoring programs. Water quality monitoring programs need to be carefully planned and executed; even so, results sometimes are inconclusive.

11.3.3.6 Capturing Suspended Solids

A simple, but useful, approach to monitor for suspended solids that are being transported with flow from a drain is to put a “sock” over the drain that will trap particles greater in size than the mesh of the sock. By doing this over a specified period of time, any accumulation of particles can be recognized, and an approximate accumulation rate can be determined. Care must be taken, however, to ensure that the sock does not plug, and thereby obstruct, drainage (which could potentially be a very adverse situation).

Sediment traps can be created along flow paths where they otherwise do not exist (such as where flumes are being used to measure flow rates). Flows can be routed into and through pails, buckets, cans, etc., that preferably have white interiors to make collected sediments easily visible. The sediment trap arrangement needs to be checked to ensure that a pool of water having low velocity flow is successfully created that will allow any sediments to settle out and be retained in the installation.

11.3.3.7 Turbidity Meters

Turbidity meters are available that send known quantities of light through water and record the amount of light scattered while traveling the path from the emitting location to the receiving location. Increased scattering of light is related to increased amounts of suspended solids in the water. The optical performance of the emitting location, sensing location, and mirrors on the path must be maintained at a constant level of clarity for this approach to be valid, which has proven to be a problem. The use of permanently installed turbidity meters was discontinued at Virginia Smith Dam because of this problem. The steadily changing data reflected deposits on the optical and reflective surfaces, and obscured any information about possible changes in the water quality.

Portable turbidity meters are available for periodically checking water clarity. This prevents the deposition issue regarding the optical and reflective surfaces because the meter is placed in the flow for only a short period of time. However, periodic checks of turbidity represent “moment-in-time” monitoring that probably will not be effective (and may produce misleading results) because sediment transport can be episodic (occurring in “spurts”). Typically, sediment transport cannot be assumed continuous, so portable turbidity meters should not be used to monitor for possible sediment transport in seepage flows.

11.3.3.8 Thermal Monitoring Using Probes

Thermal monitoring can be used to obtain information about general seepage patterns in an area. The principle behind this approach is that in areas of the world where significant seasonal variations of air temperature take place, reservoir water (and, therefore, also seepage water) undergoes seasonal temperature variations as well. A network of temperature probes set at least 6 feet below the ground surface (to largely avoid temperature variations due to daily air temperature changes) is established in an area. The magnitude of seasonal temperature variations noted at each probe is related to probes in known "no flow" areas and correlated with the presence of seepage water in the area. Comparisons from probe to probe, as well as over time, provide information about potential changes in the subsurface seepage flows. This approach assumes relatively uniform thermal properties of earth materials in an area, which is not an unreasonable assumption in many cases. This approach was used at Virginia Smith Dam for a number of years. Eventually, it was judged that the costs and efforts associated with this program were out of balance with the dam safety monitoring benefits being realized, so the program was placed on standby status. The program could be reinstated if significant seepage concerns ever develop at the dam site.

Vibrating-wire piezometers typically have thermistors included as part of the sensing element of the instrument. In situations where a fairly dense array of these instruments is in place, efforts can be made to look for unusual variations in temperatures that might be attributed to large and/or relatively concentrated seepage flows in the area. While interesting in theory, it is uncertain if actual benefits have ever been achieved from efforts to perform this type of monitoring.

11.3.3.9 Thermal Monitoring Using Fiber-Optic Cables

Similarly to the use of probes for thermal monitoring, as discussed in the previous section, fiber-optic cables can be installed that provide temperature data at approximately 3-foot intervals along the cable to look for temperature anomalies that presumably are the result of seepage flow. This concept is illustrated in figure 11.3.3.9-1.

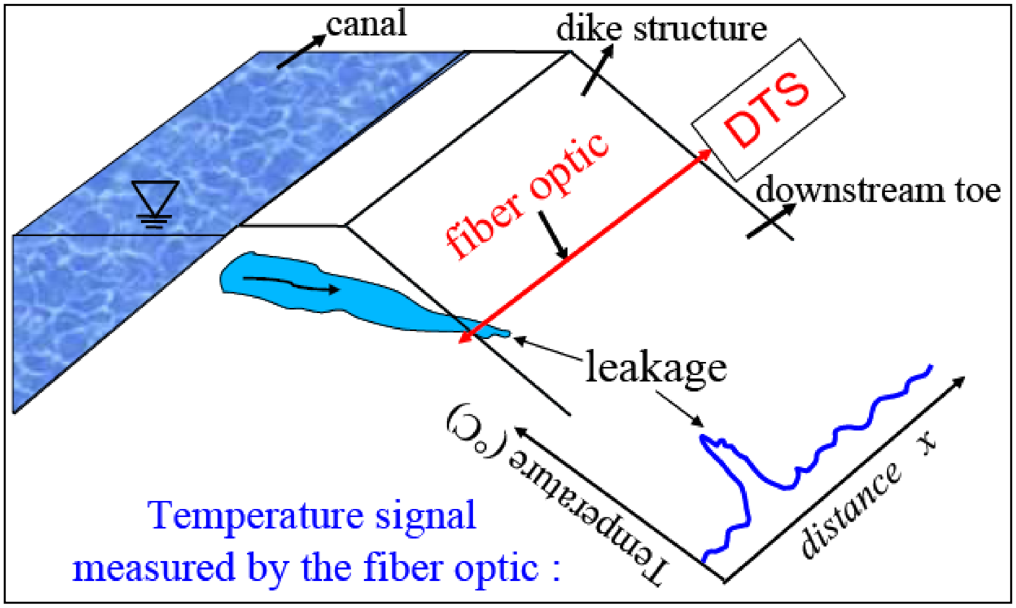


Figure 11.3.3.9-1. Illustration of thermal monitoring using a fiber-optic cable.

Another variation is to include a heating element in the cable, so that when a test for seepage flows is to be conducted, the cable is heated. Areas of seepage would locally depress the temperatures during the heating process, and when the heating was stopped, areas of seepage would cool faster than adjacent areas.

11.4 Instrumentation Types – Water Pressure Monitoring

11.4.1 General

Water pressure information may be desired to monitor a variety of situations, including the following: (1) groundwater levels in an area; (2) pore-water pressures in specified geologic units in the abutments, foundation, and/or downstream areas; (3) excess pore-water pressures in embankment or foundation materials due to dam embankment construction; (4) the effectiveness of grout curtains, cutoff walls, cutoff trenches, impervious embankment zones, or other seepage control features; (5) the performance and effectiveness of relief wells, toe drains, chimney drains, blanket drains, or other drainage features; and (6) the performance and effectiveness of construction dewatering efforts.

11.4.2 Applications

11.4.2.1 Specific Issues – Related to Potential Failure Modes

Water pressure data can be very valuable for identifying areas or situations of special concern when defining seepage-related internal erosion potential failure modes for a dam. An example of an area or situation of special concern would be an area where gradients exist from one zone or material to another zone or material, and where filter protection does not exist, which could allow material transport across the boundary of the zones or materials. Another example would be areas where high gradients exist that could initiate material transport by seepage flow along such a flow path. Importantly, water pressure instruments **are not** a good way to detect developing internal erosion failure modes at a dam site because these instruments provide data for a specific location. Therefore, it is unlikely that any of the instruments provided will happen to be right on the path of a developing internal erosion failure mode. It would be very unwise to assume such an unlikely occurrence, although elevated and erratic piezometer readings at Ochoco Dam were the first indications of seepage concerns that eventually resulted in dam safety modifications of the dam. Section 11.2.2, “Importance of Visual Monitoring,” lists key monitoring parameters associated with typical internal erosion potential failure modes. None of them relate to monitoring for water pressures. Instead, seepage flow monitoring and visual inspections are the key activities.

One category of potential failure modes in which water pressure data could provide pivotal information relates to uplift pressures at the downstream toe area of a dam. If high uplift pressures exist at the downstream toe area that potentially could cause blowout, or heaving that compromises filter protection, then uplift pressure monitoring could be very important, particularly relative to a flood event, when the uplift pressures could exceed their historic highs. Blowout in the downstream toe area could result in dam failure by causing: (1) progressive slope instability, resulting in dam overtopping; or (2) internal erosion failure due to suddenly large seepage flows at the blowout location, gross enlargement of the seepage path, and eventual dam breach. If blowout is a concern, water pressure data would need to be collected and evaluated so that potential uplift pressures during a flood event could be estimated. If the estimated flood-related uplift pressures could result in instability, remedial action would be necessary **before** the flood occurred. Recognizing a problem **during** the flood event would have essentially no benefit with respect to avoiding dam failure (and the only benefit would be from activation of the EAP to reduce the potential for downstream loss of life in the event of dam failure).

Another category of potential failure modes in which collection of water pressure data might be useful is when concerns exist about possible liquefaction of foundation or embankment materials. Water pressure monitoring instruments in potentially liquefiable materials could indicate when such liquefaction of materials occurred and how high the water pressures rose. Realistically, such monitoring could only provide useful dam safety/potential dam failure information if the instruments were automated, the automation equipment included a seismic trigger to activate the collection of very frequent readings upon seismic shaking, and the data could be telemetered real-time to personnel who could provide an immediate emergency response to indications of liquefaction at the dam site. Otherwise, such monitoring would have value only for research purposes.

11.4.2.2 General Performance Issues

Water pressure data could be beneficial for a wide range of performance issues, in addition to the items noted in Section 11.4.2.1, “Specific Issues – Related to Potential Failure Modes,” including the following:

a. Checking water pressures above and/or below horizontal blanket drains to ensure that they are free-draining and appear to have adequate capacity to pass the flows occurring within them.

b. Checking uplift pressures beneath concrete spillway and outlet works stilling basins to ensure that drainage at the basins is sufficient to prevent structure floatation issues.

c. Understanding the absolute and relative permeabilities of embankment and foundation materials by looking at absolute water pressure readings, as well as the responsiveness of the measured water pressures to changing reservoir water levels.

d. Understanding the gradients and water pressure relationships between different foundation members and embankment zones, and at embankment/foundation contacts.

e. Looking for construction-related excess pore-water pressures in embankment or foundation materials that could result in slope instability.

f. Checking the effectiveness of grout curtains, cutoff walls, cutoff trenches, impervious embankment zones, and/or other seepage control features.

g. Checking the performance and effectiveness of relief wells, toe drains, chimney drains, blanket drains, or other drainage features by seeing if water pressures adjacent to these features are in line with design expectations, and remain within design expectations over time. Elevated or rising water pressures could indicate declining performance of relief wells, which would indicate the need for well rejuvenation work. For other features, declining performance may necessitate feature replacement or other remediation work.

h. Close monitoring of the performance and effectiveness of construction dewatering systems and efforts such that action can be taken before work area flooding occurs, a slide into the work area occurs, etc.

As noted previously in section 11.4.2.1, it is important to remember that water pressure data correspond to the point where the instrument is installed. In contrast, seepage flow data correspond to an area of the dam site. Therefore, a system of seepage flow monitoring installations can effectively monitor the entire dam site for indications of the initiation/development of seepage-related internal erosion potential failure modes. Complete monitoring coverage of a dam site can never be achieved by water pressure monitoring instruments regardless of how many points are monitored.

11.4.3 Instrument Types

11.4.3.1 General Comments

Water pressure monitoring approaches fall into two general categories: open systems and closed systems. To some people, the phrase “open system” indicates that the monitored water is exposed to atmospheric conditions and, consequently, air in the system may escape. To other people, the phrase “open system” means that the monitored water at the sensing portion of the instrument is accessible and that, consequently, the water level can be checked in more than one way. Regardless of the definitional approach, observation wells and open-standpipe piezometers are "open system" instruments. Hydraulic piezometers, pneumatic piezometers, resistance strain gauge piezometers, vibrating-wire piezometers, and fiber-optic piezometers are "closed system" instruments that have their sensing units sealed off from atmospheric conditions, as well as human access, once they are installed. Closed system piezometers have a sensing unit and lines or cables that carry the pressure information from the sensing unit to a reading location, where pressure values are determined using gauges or other readout equipment.

11.4.3.2 Observation Wells

Observation wells are the simplest way to obtain water pressure information. Exploration drill holes are often completed as observation wells. Typically, they consist of slotted plastic pipe placed in a drill hole with the annulus backfilled with sand. The plastic pipe is typically extended above the ground surface and housed in a lockable protective casing. In a roadway, a small vandalproof manhole frame and cover flush with the road surface is used at the top of the installation. The installation is sealed at the top, typically using concrete, grout, and/or bentonite, to prevent water from entering the installation and affecting the water level data. A water level indicator is used to determine the depth to water in the plastic pipe from a surveyed reference elevation at the top of the installation (typically, either the top of the plastic pipe or a point on the protective casing). This approach is inexpensive, but it is suitable where only one unconfined aquifer is encountered in the drill hole. If more than one water-bearing geologic formation is encountered in the observation well installation, some uncertainty exists regarding what the water level data represents (i.e., which stratum or, possibly, neither stratum). In this situation, the water level data generally will approach the water pressure of the most pervious geologic formation encountered.

11.4.3.3 Open-Standpipe Piezometers

11.4.3.3.1 Slotted-Pipe Piezometers

Slotted-pipe piezometers are similar to observation wells, except that they are designed so that water may enter the plastic standpipe only in a discrete interval, the influence zone, which is in contact with only one geologic formation, or one zone within the dam embankment. The length of the influence zone of an open-standpipe piezometer typically is about 3 to 6 feet. Figure 11.4.3.3.1-1 schematically illustrates the difference between piezometers and observation wells.

At the influence zone, the plastic standpipe is slotted and surrounded by a graded sand that is more pervious than the foundation or embankment material it is in contact with, and meets filter criteria with the material. Elsewhere, the standpipe is not slotted. Normally, three rows of 0.01-inch-wide slots are cut on 120-degree centers around the pipe, although other slot widths and arrangements are commercially available. A layer of bentonite that is typically at least 5 feet in length surrounds the standpipe above the influence zone (and below it also, if applicable) to prevent vertical travel of water within the limits of the drill hole into the influence zone.

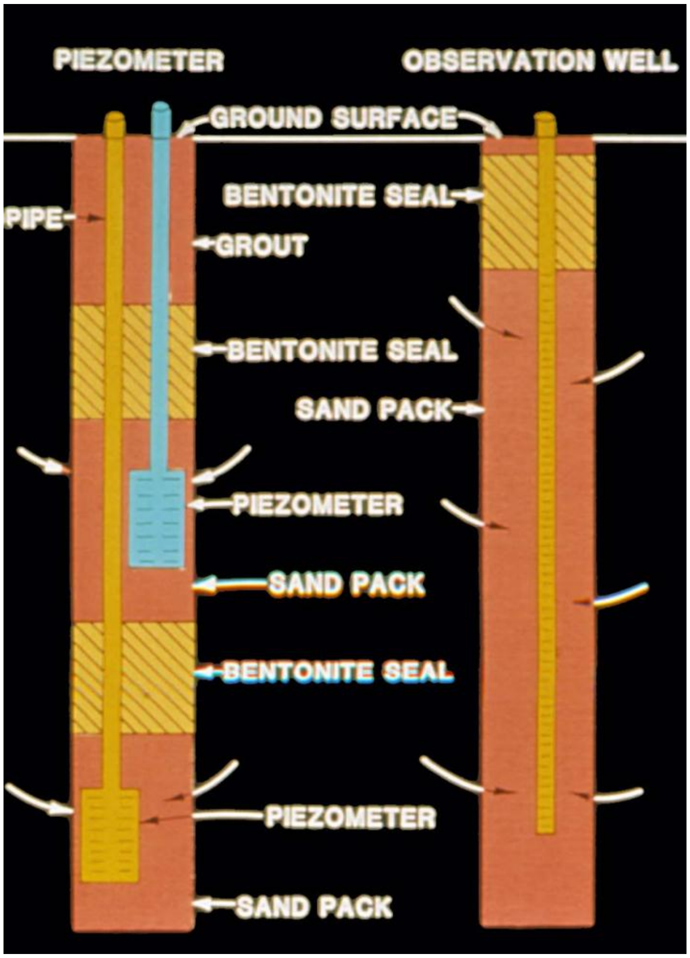


Figure 11.4.3.3.1-1. Schematic illustration of an open-standpipe piezometer and an observation well.

No more than two piezometers should be installed in one drill hole. Beyond two installations in one hole, chances become significant that defects will exist in the bentonite cutoff layers and invalid data may be obtained. If feasible, it is very desirable to have only piezometer installed in a drill hole, again out of concern for possibly compromised bentonite cutoff layers (and, therefore, possibly compromised data).

Slotted-pipe piezometers may also be installed in an embankment dam during construction. However, this causes substantial interference with embankment construction, which can lead to compromised construction or compaction in areas. In addition, it creates a risk that the installation will be damaged by construction-related deformations of the embankment. If this type of installation is carried out, a protective mound of specially compacted material is provided around the standpipe as it is brought up during dam construction.

11.4.3.3.2 Porous-Tube Piezometers

Porous-tube piezometers are identical to slotted-pipe piezometers, except that the slotted pipe at the influence zone is replaced by a short length (generally around 2 feet) of porous "stone," typically alundum or high-density polyethylene plastic, having effective opening sizes in the range of 1-100 microns. Porous-tube piezometers are used rather than slotted-pipe piezometers when the particle sizes of the in-situ material at the influence zone are such that the material might enter the plastic standpipe if the relatively coarse slots of a slotted pipe are used. The use of porous-tube piezometers is recommended in fine-grained soils.

11.4.3.4 Hydraulic Piezometers

Hydraulic piezometers are sometimes referred to as twin-tube piezometers because two water-filled lines transmit the pressure information from the sensing units to the termination location. The sensing unit has a porous "stone" (or two) similar to those used in porous-tube piezometers that protects a water-filled chamber from entry of soil particles. The water-filled chamber is connected to the twin tubes. Figure 11.4.3.4-1 shows a schematic illustration and an installation photograph associated with a hydraulic piezometer sensing unit used within dam embankment material.

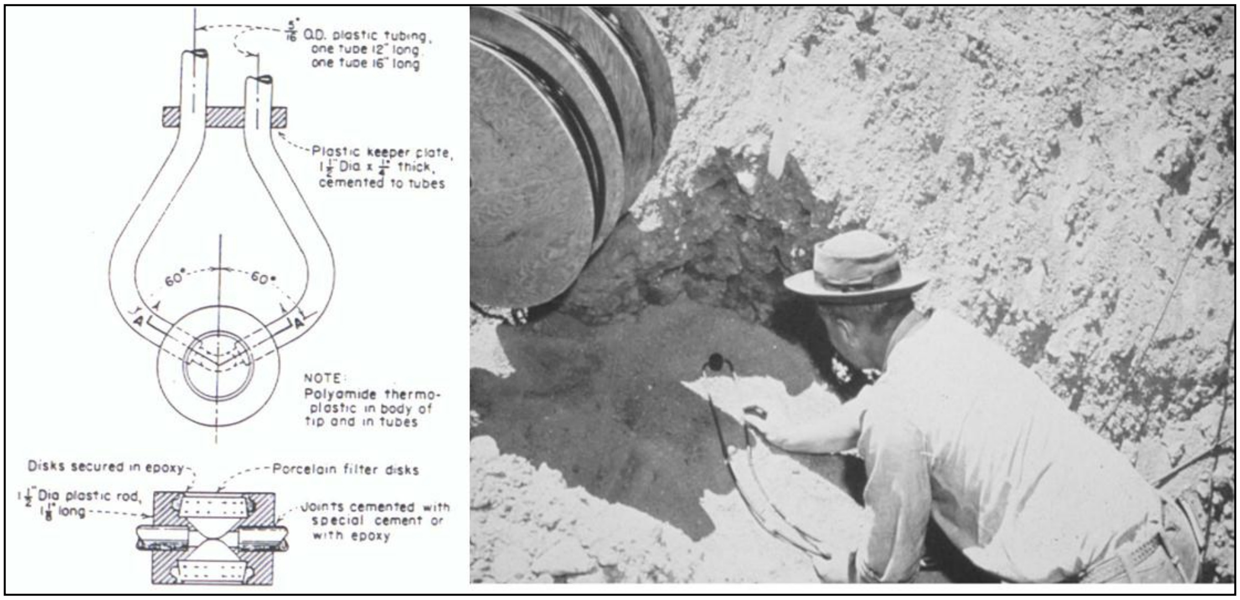


Figure 11.4.3.4-1. A hydraulic piezometer sensing unit used within dam embankment material.

At the termination location, each tube is connected to a Bourdon pressure gauge that directly presents the water pressure. After taking into account the elevation difference between the gauge and the sensing unit, the water pressure at the sensing unit can be determined. The termination structure must be appropriately located so that positive pressure is maintained in the lines. Pumps, water filters, and air traps reside in the terminal structure (or terminal well) so that the lines can be periodically purged of air (which leads to inaccurate data) and bacterial growth (which could lead to plugging off of the line and loss of the instrument). Figure 11.4.3.4-2 shows photographs taken within a hydraulic piezometer terminal well, while figure 11.4.3.4-3 schematically illustrates the equipment setup within a typical hydraulic piezometer terminal well.

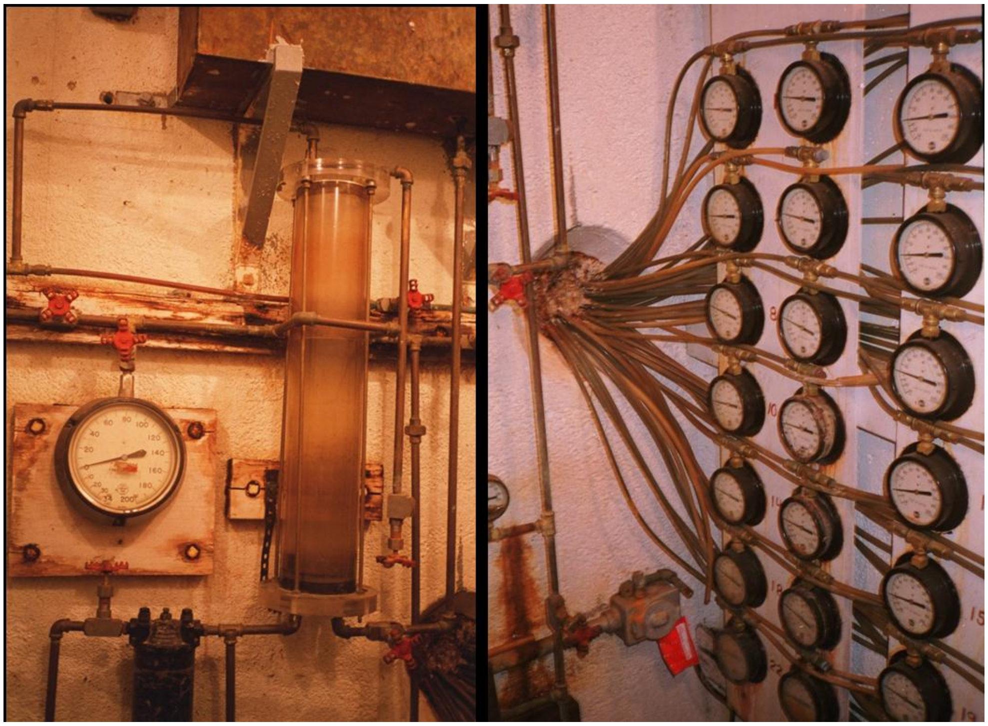


Figure 11.4.3.4-2. Photographs taken within a hydraulic piezometer terminal well. On the left, the master gauge, air trap, and filter unit can be seen. On the right are pairs of Bourdon pressure gauges; two of them are associated with each hydraulic piezometer.

Porous stones having effective opening sizes of around 1 micron are termed "high air entry" because air cannot "bubble" through the stone unless several atmospheres of pressure are applied. High-air-entry stones are useful for getting more immediate piezometer responses in situations where the permeability of the in situ material is low and the area is not always expected to be saturated. When this situation is not present, porous stones with larger effective opening sizes (roughly 100 microns) can be successfully used.

Because the operations and maintenance requirements for hydraulic piezometers are significant, Reclamation has prepared the document *Operations and Maintenance Guidelines for Hydraulic Piezometer Installations at Dams* (current version dated June 7, 2005) to provide complete and in-depth discussion of these requirements. The information in this document supersedes similar information presented in Reclamation's *Embankment Dam Instrumentation Manual* (dated 1987). Among the topics discussed in these documents are the following:

- Safe entry into hydraulic piezometer terminal wells
- Monitoring of conditions in hydraulic piezometer terminal wells
- Routine reading of hydraulic piezometers
- Annual maintenance of hydraulic piezometer installations
- Processing and evaluating hydraulic piezometer data
- Potential seepage-related internal erosion failure modes associated with hydraulic piezometer installations
- Abandonment of hydraulic piezometer installations

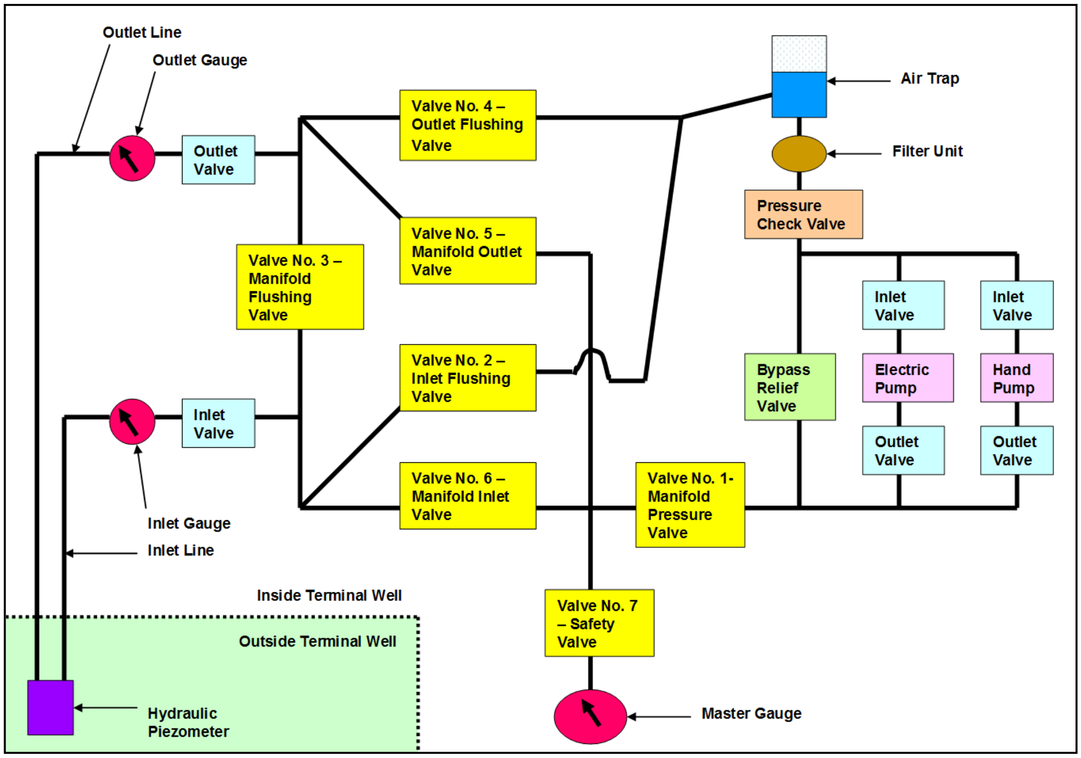


Figure 11.4.3.4-3. Schematic Illustration of the installations found in a typical hydraulic piezometer terminal well.

Hydraulic piezometer installations require significant ongoing maintenance, and hydraulic piezometer tubing suffers from deterioration with time, which often causes substantial loss of instruments after roughly 30 years. Therefore, these disadvantages have led Reclamation away from constructing new hydraulic piezometer installations since the 1980s. A number of older Reclamation hydraulic piezometer installations have been abandoned (in accordance with the document discussed above), but many other installations are still in use at Reclamation dams.

11.4.3.5 Pneumatic Piezometers

Pneumatic piezometers use gas, typically nitrogen, to transmit water pressure information from the sensing unit to the readout location. At the sensing unit, a porous stone, like that of a porous-tube piezometer, protects a water-filled chamber from entry of soil particles. The water in this chamber acts against one side of a nonmetallic flexible diaphragm. At the time readings are taken, gas pressure applied through a tube running from the termination structure builds up on the other side of the diaphragm until it slightly exceeds the water pressure in the chamber. At this point, the diaphragm moves slightly ("lifts") to permit return flow back through a second tube running back to the termination location. A continuous flow loop is now established between the sensing unit and the termination location, with the gas pressure on the supply side closely matching the water pressure at the sensing unit. With the flow rate cut back to a very slow flow (to minimize pressure differentials due to side wall friction in the tubes), the gas pressure is read at the termination location.

11.4.3.6 Resistance Strain Gauge Piezometers

Like pneumatic piezometers, the sensing units for resistance strain gauge piezometers have a porous stone that protects a water-filled chamber in which water pressure acts on a diaphragm. The diaphragm undergoes deflections related to the pressure acting against it, and these deflections lead to differences in the resistance to electrical current of electrical circuitry attached to, or associated with, the diaphragm in the sensing unit. Electrical circuits running back to the termination location allow resistance at the sensing unit to be determined, which means the water pressure can be determined through known calibration information for the unit. Because resistance levels of the electrical circuits can change based on factors other than changes in resistance at the sensing unit (e.g., splicing of cables during construction, and temperature-caused resistance changes in cables). Therefore, this electrically based approach is generally considered inferior to the electrically based, vibrating-wire piezometer.

11.4.3.7 Vibrating-Wire Piezometers

Similar to resistance strain gauge piezometers, the sensing units for vibrating-wire piezometers contain a porous stone that allows water to enter a chamber and press against a diaphragm that deflects to differing degrees, depending on the pressure imposed. In this case, the diaphragm is stainless steel, and a high-strength steel wire is fixed to the center of the diaphragm at one end and to a fixed "end block" at the other end. This wire is hermetically sealed within a stainless steel housing and is set to a predetermined tension during manufacture of the unit. Differing water pressures result in differing tension on the wire, which results in a differing resonant frequency of vibration for the wire. A coil/magnet assembly in the housing of the sensing unit allows remote readout equipment, tied to the sensing unit by an electrical circuit, to initiate vibration of the wire ("pluck" it) and, subsequently, to determine the wire's resonant frequency of vibration. The frequency values of the vibration can be related to water pressures through general equations and calibration constants that are unique to each sensing unit. Figure 11.4.3.7-1 is a schematic showing a vibrating-wire piezometer sensing unit, while figure 11.4.3.7-2 shows photographs of two terminal panel arrangements for vibrating-wire piezometers, along with a view of a readout unit used with these instruments.

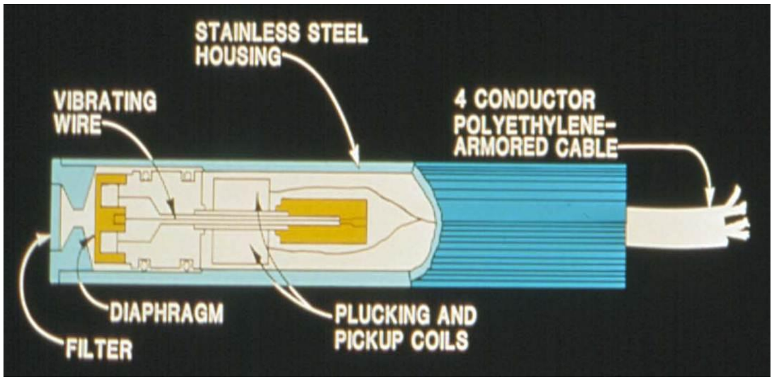


Figure 11.4.3.7-1. Schematic of a vibrating-wire piezometer sensing unit.

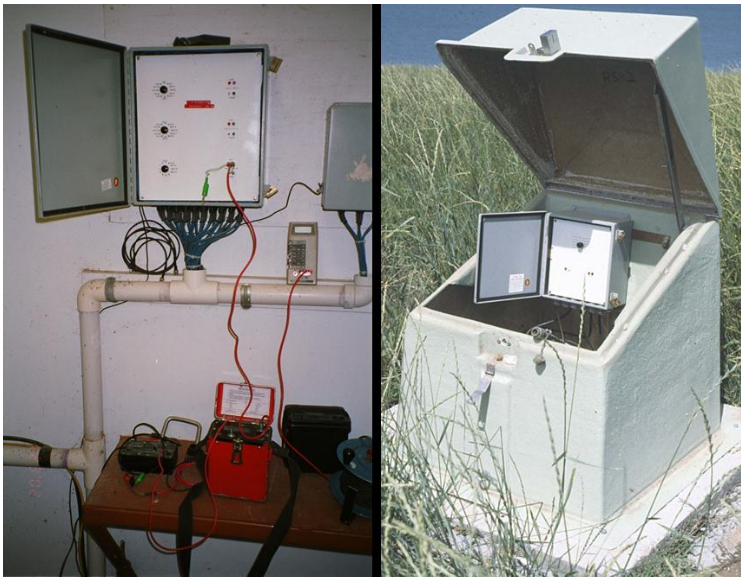


Figure 11.4.3.7-2. Indoor (left) and outdoor (right) terminal panels associated with vibrating-wire piezometer installations. Note the vibrating-wire piezometer readout unit visible in the left photograph and the locking protective enclosure in the right photograph.

11.4.3.8 Fiber-Optic Piezometers

Similar to vibrating-wire piezometers, the sensing units for fiber-optic piezometers contain a porous stone that allows water to enter a chamber and press against a stainless steel diaphragm that deflects to differing degrees, depending on the pressure imposed. The diaphragm represents one reflecting surface for a Fabry-Perot interferometer, and a reflecting surface at an optical fiber installed near the other side of the diaphragm serves as the other. The amount of deflection of the diaphragm over the Fabry-Perot cavity length can be accurately measured by the relative amount of interference – constructive (light wave forms in phase) or destructive (light wave forms out of phase) – seen in the light signal resulting from the multiple reflections of the wave light traveling between the two reflecting surfaces. Fiber-optic cable carries the light signal to a readout unit that can interpret the input and associate the diaphragm deflection with the water pressure acting on the diaphragm through equations and calibration constants that are unique to each sensing unit.

11.4.3.9 Bubbler Line

A bubbler line is a tube with one end underwater and the other end accessible so that a controlled air pressure can be applied into the tube through that end. When the air pressure in the tube matches or exceeds the water pressure at the end of the tube, air “bubbles” out of the tube until the air pressure matches the water pressure at the end of the tube. In this way, the water pressure at the end of the tube can be remotely monitored. This simple approach is most commonly used when a pressure transducer is installed in an observation well or open-standpipe piezometer (typically to automate the reading of it) so that manual check readings of the pressure transducer can be readily obtained. Figure 11.4.3.9-1 shows a schematic illustration and photograph of this method.

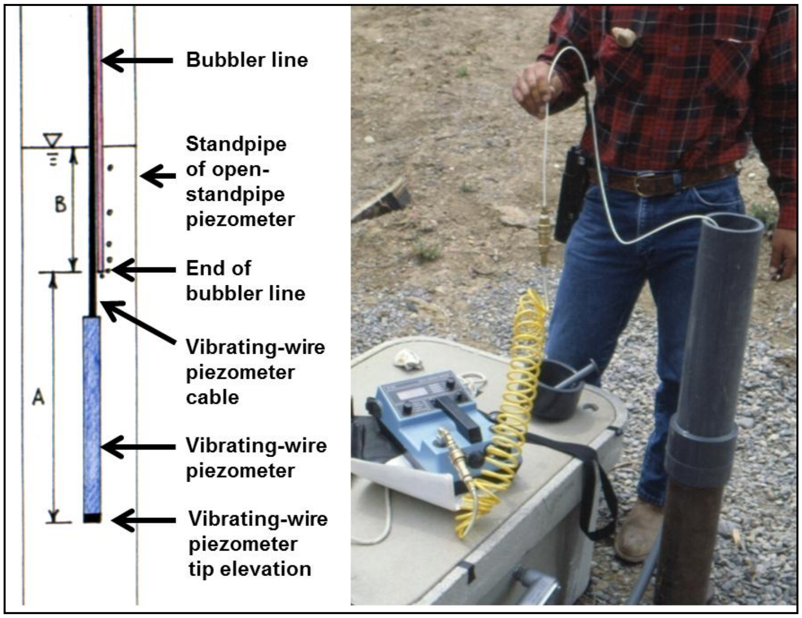


Figure 11.4.3.9-1. A bubbler line provides manual reading capability for an open-standpipe piezometer that has a vibrating-wire piezometer installed in it.

11.4.3.10 Comparison of the Commonly Used Major Piezometer Types

Table 11.4.3.10-1 provides a comparison of open-standpipe piezometers, hydraulic piezometers, pneumatic piezometers, vibrating-wire piezometers, and fiber-optic piezometers with a list of characteristics and parameters. This table reflects Reclamation's current view regarding the comparative advantages and disadvantages of each piezometer. Other individuals or organizations may view things differently.

Table 11.4.3.10-1. Comparison of Commonly Used Major Piezometer Types

Characteristic	Open-standpipe piezometers	Hydraulic piezometers	Pneumatic piezometers	Vibrating-wire piezometers	Fiber-optic piezometers
Length of time in use	Long	Long	Moderate	Moderate	Short
Precision of data	Moderate	Low	Low	High	High
Complexity of approach	Simple	Moderate	Moderate	Complex	Complex
Time lag in impervious soils	Long	Short	Very short	Very short	Very short
Interference in new dam construction	Substantial	Moderate	Moderate	Moderate	Moderate
Can have a central reading location?	No	Yes (at low elevation)	Yes	Yes	Yes
Approximate length from central reading location without problems	Not applicable	600 feet	600 feet	10,000 feet	10,000 feet
Time required for obtaining readings	Moderate	Short	Long	Short	Short
Complexity of reading process	Simple	Simple	Complicated	Very simple	Simple
Read negative pore pressures?	No	Yes	No	Yes	Yes
Maintenance requirements	Low	High	Usually low	Low	Low
Potential for future problems	Low	High	Moderate	Moderate	Moderate

Table 11.4.3.10-1. Comparison of Commonly Used Major Piezometer Types

Characteristic	Open-standpipe piezometers	Hydraulic piezometers	Pneumatic piezometers	Vibrating-wire piezometers	Fiber-optic piezometers
Other comments	Potential shearing or breakage of standpipes during construction of new dam due to embankment deformations. Bentonite seals in drill hole installations need to be watertight.	Without regular and conscientious maintenance, many problems will develop. Deterioration with time is likely.	Tubes vulnerable during construction. Must prevent moisture from entering tubes.	Black box nature not ideal. Lightning protection is important, but even with it, lightning damage can occur. Nearby electrical transmission lines or equipment can impact data. Potential for zero drift (loss of accurate calibration with time).	Black box nature not ideal. Readout information is cryptic. Expensive.

Reclamation currently views open-standpipe piezometers as the default choice, due to their simplicity. It is very desirable to have only one piezometer installed in a drill hole, where feasible, both for simplicity and to ensure high confidence in the validity of the data obtained. When construction realities, time lag considerations, automation considerations, etc., make open-standpipe piezometers an inappropriate choice, Reclamation views vibrating-wire piezometers as the best choice among the “closed-system” options. In the future, fiber-optic piezometers may become the preferred closed-system option because they are not vulnerable to lightning damage. However, their current expense, splicing complications, and general complexity make them a less desirable choice than vibrating-wire piezometers. Where lightning issues are a very prevalent concern, fiber-optic data transmission lines can be used in conjunction with vibrating-wire piezometers.

11.5 Instrumentation Types – Earth Pressure Monitoring

11.5.1 Applications

11.5.1.1 Specific Issues – Related to Potential Failure Modes

For seepage-related internal erosion potential failure modes, locations of special concern are at embankment/structure contacts, where structures run through the dam embankment in the upstream-downstream direction. The presence of the structure can result in a flow concentration at the embankment/structure contact, where the embankment material density may be inferior compared to other areas, due to arching effects and the use of special compaction methods. Earth pressure monitoring at the embankment/structure contact can provide an alert that a vulnerability to concentrated seepage flow exists or is apparently developing (though providing appropriate filter protection along the potential seepage would be the direct and preferred way to address this matter). The structure involved most commonly is an outlet works structure or a spillway structure, but can also be a penstock or the embankment/concrete contact of a composite dam.

Relative to concerns about the stability of abutment slopes, tendons or similar items may be used to reinforce a slope to prevent instability. Load cells can be included as part of these installations to monitor the tension in the tendons to indicate developing instability (a trend of rising tension noted) and/or the need for retensioning of a member (a trend of declining tension noted).

11.5.1.2 General Performance Issues

It may be tempting to try to measure earth pressures within the body of an embankment to identify low-pressure areas (perhaps due to arching effects) that could be vulnerable to developing into concentrated seepage flow paths. However, where it is necessary to specially place and compact earth materials in the vicinity of an earth pressure sensing device (using methods different than in adjacent areas), the representativeness of the data is very doubtful, making the monitoring effort pointless (or worse, if nonrepresentative data are taken to be valid).

Earth pressure cells may be used to assess the impact of arching effects on lateral pressures felt by conduits or other structures. This activity would not relate to dam safety performance monitoring; however, it would be a research endeavor that could benefit future design work.

11.5.2 Instrument Types

11.5.2.1 Total Pressure Cells or Earth Pressure Cells

Pneumatic total pressure cells and vibrating-wire pressure cells are both available. The sensing unit of a total pressure cell consists of two circular stainless steel plates welded together at their outer edges, with the narrow space between the plates filled with de-aired, lightweight oil. This oil is then connected to a device very similar to a pneumatic or vibrating-wire piezometer by a short length of small-diameter steel tubing. The piezometer-like devices allow remote determination of the fluid pressure of the oil in the same way that pneumatic and vibrating-wire piezometers function. The pressure of the oil matches the average pressure applied to the surface of the two circular plates that are welded together.

11.5.2.2 Load Cells

Load cells typically consist of steel cylinders having a cylindrical hole on the same axis that allows tensioned tendons, rods, wires, etc., to pass through the center of the load cell. With three or more strain-measuring devices placed axially around the circumference of the load cell, representative average strain values for the cell can be determined. Knowing the stress/strain characteristics of the load cell material, the stress on the cell can be determined, which would match the stress on the tensioned element passing through the cell and loading it. The strain measuring devices are commonly vibrating-wire strain gauges or resistance-based strain gauges. The principles behind these strain gauges are the same as for the piezometers using the same technology, but now, reading changes reflect movements between strain gauge end points, rather than of a piezometer diaphragm.

11.6 Instrumentation Types – Deformation Monitoring

11.6.1 Applications

11.6.1.1 Specific Issues – Related to Potential Failure Modes

Situations where deformation monitoring could provide information relating to a potential failure mode include the following:

a. Indications of slope instability at an embankment or abutment slope.

b. Unusual embankment settlements or depressions that could indicate internal erosion of material by seepage flow.

c. Differential embankment settlements that could lead to cracking of the dam embankment and the creation of paths for seepage flow.

d. Relative movements at a joint in an appurtenant structure (spillway, outlet work, etc.) that could give rise to flow surface irregularities that, in turn, could give rise to cavitation, high stagnation pressures, etc., that could result in a flow erosion failure of the structure.

e. Movements of an appurtenant structure that could indicate foundation issues, or internal erosion of material by seepage flow that could give rise to structure failure when it is subjected to flows during a flood event.

f. Unusual embankment settlements or depressions that could result in embankment overtopping in a flood event.

g. Earthquake-caused deformations that could result in embankment cracking and the creation of vulnerable seepage paths, or earthquake-caused deformations associated with slope instability.

11.6.1.2 General Performance Issues

Deformation information may be valuable with respect to a wide range and variety of situations, including the following:

a. General embankment surface settlement and/or deflection patterns.

b. Settlements occurring at the embankment/foundation contact.

c. Settlements/compression in foundation units.

d. Embankment compression.

e. Settlements and/or deflections of appurtenant structures (spillways, outlet works, etc.).

f. Possible movements of appurtenant structure stilling basins when underdrain grouting is occurring.

11.6.2 Instrument Types

11.6.2.1 Internal Vertical Movement Installations

Sometimes known as crossarm installations, the Internal Vertical Movement (IVM) consists of approximately 2-inch-diameter steel pipe that is installed vertically as embankment material is placed. At the measuring locations, a smaller diameter pipe is telescoped into the vertical pipe alignment (to allow unrestricted vertical movement of this smaller pipe), and a short length (for example, 2 feet) of steel channel section (a “crossarm”) is securely attached in a horizontal alignment to the smaller diameter pipe. As many crossarms can be installed at one installation as desired, although a 10-foot vertical spacing of crossarms is common. A probe is used to measure the elevation of the bottom of the smaller diameter pipe at each crossarm location to monitor vertical movements of the crossarms. Figure 11.6.2.1-1 shows a drawing cross section with two IVM installations. Figure 11.6.2.1-2 shows a schematic of the telescoping pipe and crossarm arrangement associated with IVM installations and an IVM measurement probe, as well as a photograph of an IVM measurement probe and the top of an IVM installation.

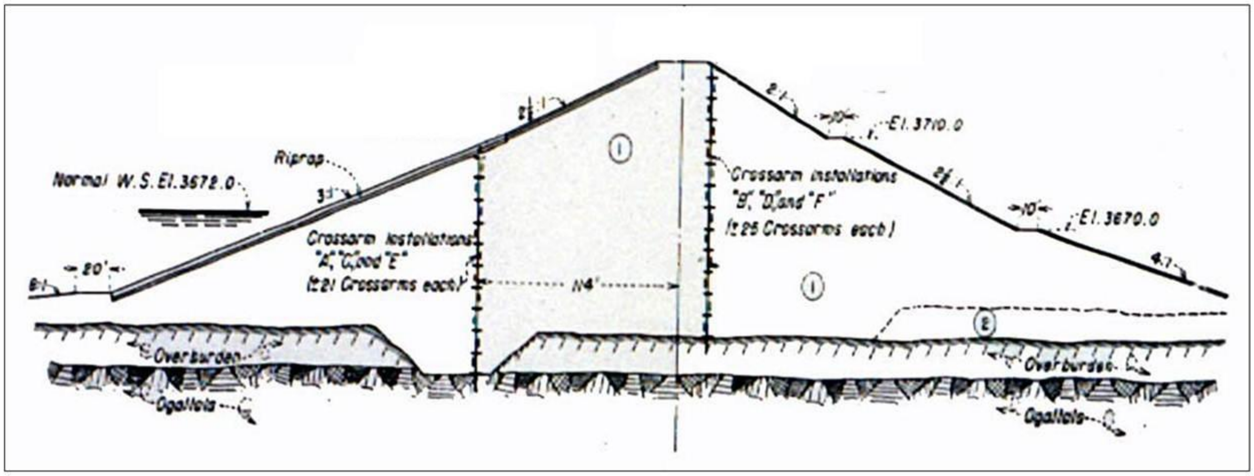


Figure 11.6.2.1-1. Drawing of two IVM installations at a cross section through an embankment dam. The bottom crossarm of the left IVM installation is on bedrock, while the bottom crossarm of the right IVM installation is on foundation soil.

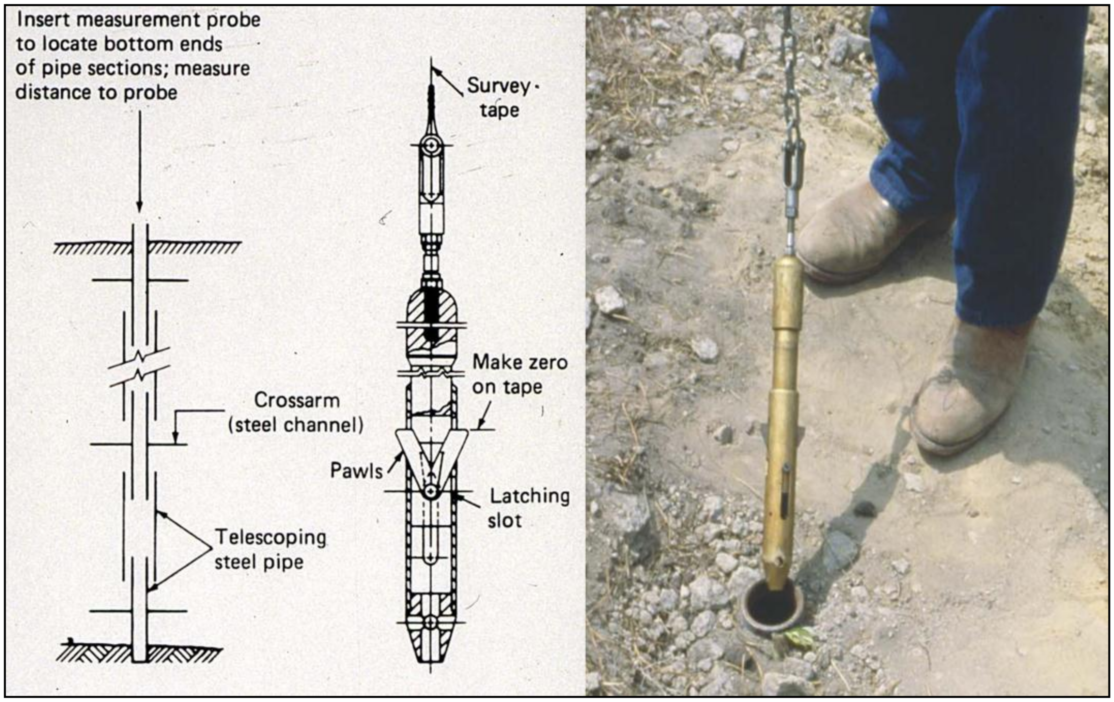


Figure 11.6.2.1-2. Left: schematic of the telescoping pipe and crossarm arrangement associated with IVM installations and an IVM measurement probe. Right: an IVM measurement probe and the top of an IVM installation.

11.6.2.2 Baseplates

A baseplate installation can be the same as an IVM installation, except only one crossarm is installed, typically at the foundation/embankment contact. Alternatively, a baseplate installation may be constructed by placing a square steel plate (for example, 2 feet by 2 feet) at the desired monitoring location, obtaining an initial surveyed elevation of the carefully leveled plate, placing embankment material above the plate until construction of the embankment is complete, and then drilling vertically to the plate from the top of the completed embankment. Small diameter pipe is placed in the drill hole to an elevation just above the plate, and a rod is placed inside the pipe that rests on the plate and extends to the ground surface. The pipe isolates the rod from drag due to embankment compression. Knowing the length of the rod, and surveying the elevation of the top of the rod, the elevation of the plate can be determined from that time forward (and compared to the initial surveyed elevation as well). Obviously, no settlement data are collected during the construction process, but if this is not an issue, then this installation avoids interference with dam embankment construction operations. Installations of this type were successfully carried out during the construction of Davis Creek Dam.

11.6.2.3   Inclinometers

11.6.2.3.1 General

An inclinometer installation involves inclinometer casing that usually is placed vertically, either in a drill hole or in embankment material as the material is being placed. The casing material is either anodized aluminum, epoxy-coated aluminum, or plastic, and it typically is about 3.5 inches in diameter. The casing has four vertical grooves (90 degrees apart) that are continuous across coupling locations that allow the spring-loaded wheels of the measuring probes to track down the hole in the same location every time readings are taken. It is good practice at coupling locations not to butt sections of casing against one another; instead, allow some room for telescoping movements to accommodate future compression of the surrounding material.

11.6.2.3.2 Inclination Probe

The inclination probe uses either force-balanced servo-accelerometers or Micro-Electro-Mechanical Sensor (MEMS) technology to measure angles of inclination from vertical. While some probes only monitor tilt in one plane, most probes monitor inclination from vertical in two planes (A and B) oriented at 90 degrees (orthogonal) to each other. The inclinations represent the tilt of the effective length of the probe (typically 2 feet), beginning at the axis of the upper pair of wheels and ending at the axis of the lower pair of wheels of the probe. Commonly used probes measure angles up to 30 degrees from vertical, although probes measuring up to 90 degrees from vertical are available. By taking readings at intervals matching the effective length of the probe (typically 2 feet), complete profiles of the alignment of the inclinometer casing can be developed. A heavy electrical cable connects the probe to the readout equipment, and this cable is marked to allow proper and consistent vertical positioning of the probe from one set of readings to the next. Several types of readout equipment are available, ranging from those that merely present the current probe inclination readings, to those that store the data for later data transfer. Figure 11.6.2.3.2-1 shows an inclination probe, inclinometer cable, an inclinometer readout unit, and the top of a typical installation as might be seen at a dam site. Figure 11.6.2.3.2-2 shows a schematic of an inclinometer installation being read with an inclination probe, along with example inclinometer data.

Figure 11.6.2.3.2.-1. Left: An inclination probe, inclinometer cable, and an inclinometer readout unit. Right: Top of a typical installation as might be seen at a dam site.

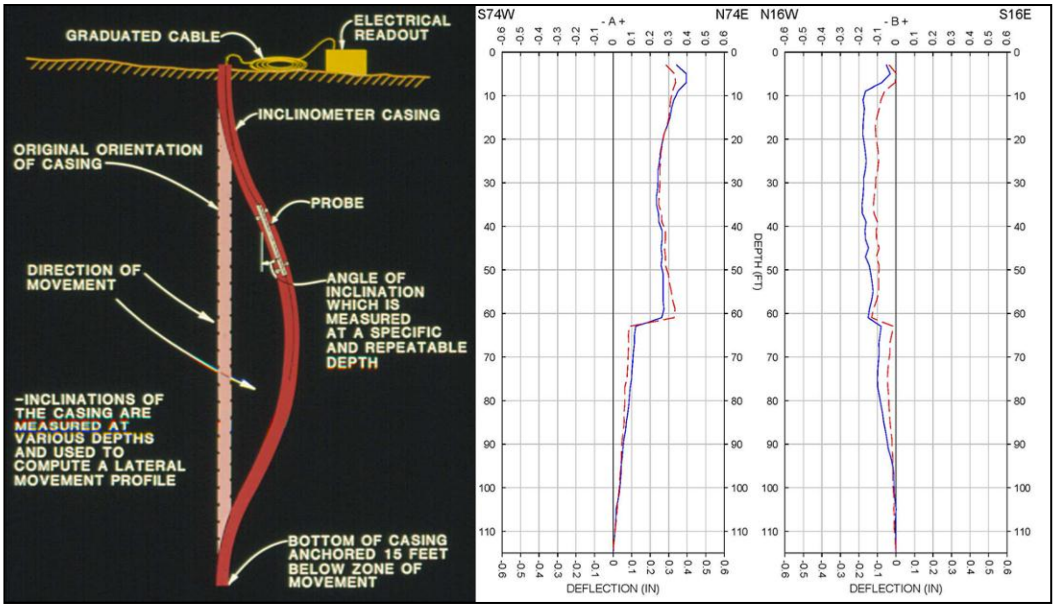


Figure 11.6.2.3.2.-2. Left: Schematic of an inclinometer installation being read by an inclination probe. Right: An example of inclinometer data, which are plotted as deflection change from the original casing alignment in two orthogonal planes. Note the indication of shearing at a depth of approximately 61 feet.

11.6.2.3.3 Fixed Position Inclinometer Installations

The sensing device of a fixed-position inclinometer installation is the same as described in section 11.6.2.3.2 above; however, now one or more are left in place in the inclinometer casing as part of a string of rods, pivot points, and fixed-position probes (although the string may be retracted as necessary). The monitored length is typically on the order of 10 feet, as opposed to the 2-foot length of the probe. A portable readout unit that simply displays the inclination angles of both orientations of the various sensors in a hole typically is used. Importantly, only tilt data over selected portions of the casing are recorded, as opposed to a complete profile of the installed casing that is available when the probe discussed in section 11.6.2.3.2 is used.

11.6.2.3.4 Settlement Probe

Where inclinometer casing is placed as an embankment is constructed, it is possible to tie the sections of casing to the embankment using “collars” on the outside of the casing and then monitor the elevation of casing sections over time to study compression of the embankment. Clearly, butted joints cannot be used to join lengths of casing in this situation. A special probe with spring-loaded wheels for tracking down the casing grooves is used to measure from the top of the casing to the bottom of the upper casing length at each telescoping coupling location. Aside from the wheels, the probe is comparable to the IVM probe. Figure 11.6.2.3.4-1 shows a schematic and photograph of the settlement probe.

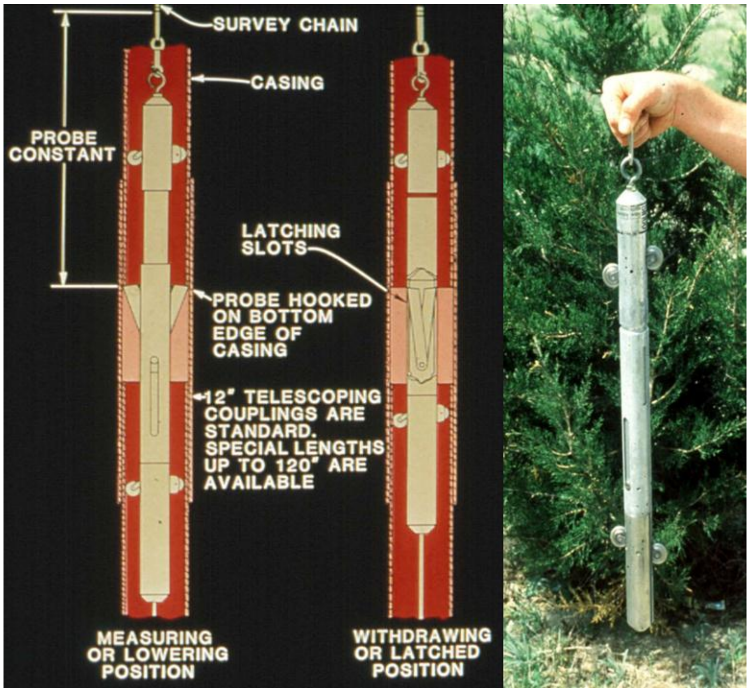


Figure 11.6.2.3.4-1. Left: Schematic of an inclinometer casing settlement probe being used to take a reading and being withdrawn. Right: example of the probe.

11.6.2.4 Tiltmeters

There are two basic types of tiltmeters. One type uses force-balanced servo-accelerometers, or MEMS technology, and it is essentially the same as an inclinometer inclination probe. The other type of tiltmeter uses a sensor consisting of a fluid-filled glass vial with three electrodes mounted inside the vial in contact with the conductive fluid. As with a common carpenter's level, a small air bubble inside the vial moves as tilt occurs, which creates an impedance change between electrodes that can be monitored and correlated with rotation. Both types of tiltmeters can be either permanently mounted or transported to special mating plates that are permanently mounted, which ensures consistent positioning of the sensing unit each time readings are obtained. Both types have readout units that are connected to the sensing units by electrical cable and display the rotation readings. Figure 11.6.2.4-1 shows a portable tiltmeter and the associated permanently mounted mating plate.

Figure 11.6.2.4-1. Portable tiltmeter and mating plate on the left, ready to collect data using the readout device on the right.

11.6.2.5 Shear Strips

A shear strip consists of an electrical circuit attached to a strip of brittle material. The electrical circuit consists of two parallel conductors running the length of the shear strip that are connected by as many as 100 resistors, which are placed at regular intervals a uniform, selected distance apart. The shear strips may be hundreds of feet in length and may be grouted into a borehole, attached to a structure, run in a trench at the crest of a dam, etc. Differential movement along the shear strip causes shearing failure of the shear strip, breaking the circuit. By knowing the initial location of the resistors along the circuit, and applying voltage across the two conductors, the approximate location of a break can be determined from the measured resistance of the broken circuit. The remote readout unit applies a voltage across the two conductors through an electrical cable. Typically, separate cables are run to each end of the shear strip. The readout unit may just report a resistance value, but generally, it directly presents the number of resistors detected in the circuit. Shear strips can be manufactured to break under differing amounts of shear or strain to meet the needs of various applications. Once the circuit is broken, new breaks further from the cable connection location than the existing break are not detectable by the instrument.

11.6.2.6 Fiber-Optic Cable Deformation Monitoring

Fiber-optic cables can be installed that provide strain data at 1-meter intervals along the cable. The cable and the readout equipment are both expensive, but the capability to provide sensitive strain information is available.

11.6.2.7 Time Domain Reflectometry

Time Domain Reflectometry (TDR) was originally developed to locate breaks in transmission cables but has been adapted to slope stability monitoring. The equipment used consists of a coaxial electrical cable grouted in a borehole, and a cable tester. The cable tester transmits an electrical pulse into the cable and monitors the return signal. Crimps, breaks, etc., in the cable can be identified in the return signal, and the distance to them can be roughly determined by measuring the elapsed time between transmission of the pulse and arrival of the reflected signal. The accuracy of the distance measurement can be improved by precrimping the cable at known locations that then serve as reference points when interpreting the return signal.

11.6.2.8 Settlement Sensors

Settlement sensors, like total pressure cells, are an adaptation of available piezometer technologies to other monitoring issues. Pneumatic and vibrating-wire settlement sensors are available and use the basic piezometer unit, along with a hydraulic line and hydraulic reservoir, to remotely monitor elevation changes at the sensing units. The hydraulic reservoir and the hydraulic lines that run from the instrument’s reservoir to the sensing unit are used to create water pressures in the settlement sensor that are read remotely (using the piezometer devices incorporated in the settlement sensor sensing units). By having the instrument’s hydraulic reservoir in an accessible location where the water surface can be read, the elevation of the sensing unit can be calculated. In practice, the accuracy of the data from these devices is often too coarse to be of much value, particularly for pneumatic systems.

11.6.2.9 Overflow Settlement Gauges

Similar to settlement sensors, overflow settlement gauges can be used to remotely determine the elevation of a point of interest in placed embankment, although for the overflow gauge, the readout location must be at the same elevation as the point of interest. The sensing unit has one end of a hydraulic tube that runs horizontally to the readout location. To take readings, water is introduced into the hydraulic tube at the readout location. When the hydraulic tube is filled, water will overflow out the end of the tube at the sensing unit and drain out of the sensing unit through a drain line. When this occurs, the elevation of the tube “lip” in the sensing unit matches the observed water surface elevation in the tube at the readout location. Thus, changes in the elevation of the tube “lip” can be monitored over time.

11.6.2.10 Simple Distance Measuring Devices

Relative movements between fixed points (such as across a joint or crack in a concrete structure) can be manually monitored in many ways, including using rulers, calipers, micrometers, Whittemore gauges, or other devices. The fixed measuring points may consist of virtually any kind of mark, mounted plate, or point set in the concrete, although it is common to use specially fabricated brass or stainless steel carriage bolts or cap screws set in concrete in conjunction with Whittemore gauge readings or other more precise approaches. The Whittemore gauge uses a dial gauge that can be read to a sensitivity of 0.001 inch to develop precise distance measurements between pairs of points typically set between 3 and 15 inches apart. For Whittemore gauge installations, two points are set on one side of the crack, joint, etc., and one point is set on the other side, so that both translation (shearing) and opening/closing movements can be monitored at the crack, joint, etc. Another approach is to mount two clear plastic “plates” on either side of a crack or joint, with one plate having a grid and the other a cross-hair. Relative movements of the cross-hair can then be tracked with time in reference to the grid.

11.6.2.11 Simple Extensometers

11.6.2.11.1 Tape Extensometer

A tape extensometer is a device designed to read the distance between points that are a significant distance apart (for example, 5 to 50 feet) using a steel survey tape stretched at a uniform tension and a dial gauge for interpolating between the tape markings. A spring and a tensioning adjustment permit control of the tension. Hooks at each end of the device are typically provided for measuring between eyebolts that might be in place in a conduit or tunnel. Tape extensometers may have application for monitoring points or monuments at a slide area.

11.6.2.11.2 Rod Extensometer

A rod extensometer has a similar purpose and design as a tape extensometer, with steel rods replacing the tape. Maintaining a uniform tension is no longer an issue. Interpolating between available gauge lengths is again accomplished using a dial gauge.

11.6.2.12 Multipoint Extensometers

Multipoint extensometers are designed to measure axial displacement of fixed points along their length and typically consist of multiple anchors installed at different depths in a drill hole. Rods inside hollow tubes extend from each anchor to a reference head at the collar of the hole where measurements of movement are made. As an anchor moves, the resulting movement of the rod attached to that anchor is measured relative to the reference head. Anchor movements may be measured either mechanically (using depth gauges) or electrically (typically using linear potentiometers or vibrating-wire distance sensors). Electrical readout equipment may be remotely located and connected to the head of the extensometer by electrical cable for installations read electrically. Various types of anchors are available, and hydraulic anchors, expanding wedge rockbolt anchors, and “snap-ring” anchors are common. Typically, no more than six anchors are used in one drill hole, and the hole is grouted when the anchors are set. Though extensometers are normally installed in uncased boreholes to monitor compression or extension movements, similar installations may be placed in an embankment during construction. Figure 11.6.2.12-1 shows a schematic of a multipoint extensometer and a photograph of an electrical readout device.

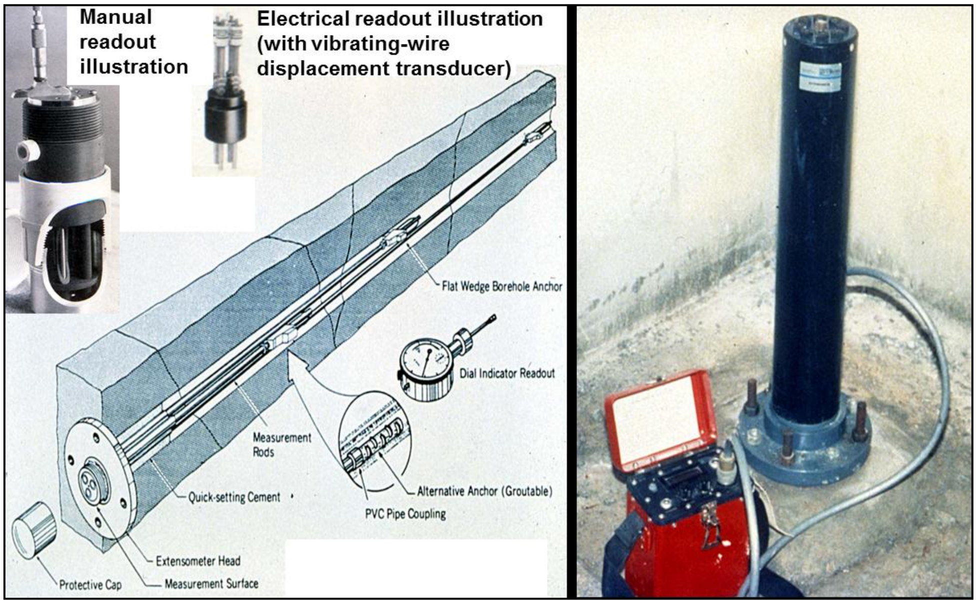


Figure 11.6.2.12-1. Left: Schematic of a multipoint extensometer. Right: Installation and electrical readout unit.

11.6.2.13 Probe-Type Extensometers

Along with multipoint extensometers, other approaches, involving probes moving through plastic pipes, exist for monitoring axial displacements of points along a line. A common method involves using steel rings around the pipe at locations where displacements are to be monitored. The readout probe employs an induction coil with a current output that rises when the probe is in the vicinity of a steel ring. Using a survey tape to record distances at which maximum current readings are obtained, it is possible to track axial displacements of the steel rings over time. If the pipe is not installed in a near-vertical orientation, it may be necessary to provide a cable and pulley system to move the probe through the pipe. A nearly horizontally installed pipe can also have its elevation profile monitored over time by using a probe working on the same principle as an overflow gauge or a manometer.

11.6.2.14 Joint Meters or Crack Meters

A vibrating-wire joint meter or crack meter spans between anchorage points on either side of a joint or crack. The tension on a high-strength steel wire that is hermetically sealed within stainless steel housing within the instrument changes in direct response to distance changes between the anchorage points. Changes in wire tension result in changes in the resonant frequency of vibration of the wire, and the correlation relating relative movements with resonant frequency changes is determined by the instrument manufacturer and is specific and unique for each instrument. A coil/magnet assembly in the housing of the instrument allows remote readout equipment, tied to the sensing unit by an electrical circuit, to initiate vibration of the wire ("pluck" it) and then determine the wire's resonant frequency of vibration. Relative movements between the anchorage points can then be determined.

Many variations using vibrating-wire distance measuring devices are possible, with range and sensitivity capabilities tailored to the particular situation being addressed.

11.6.2.15 Linear Variable Differential Transformer

A Linear Variable Differential Transformer (LVDT) is another electronic means of precisely determining distance changes between points. An LVDT consists of a movable magnetic core that passes though one primary and two secondary magnetic coils. An excitation voltage applied to the primary coil induces voltage in each secondary coil. The induced voltages are affected by the location of the magnetic core. Therefore, movements of the core (which are tied to the potentially moving point of interest) can be determined by the induced voltages of the secondary coils. LVDTs work best when the cable length to the readout unit is short because long cable lengths degrade the output signal. A continuous power supply is strongly recommended for LVDT installations.

11.6.2.16 Surveys

Monuments or measurement points installed on the surface of an embankment dam and/or its appurtenant structures can be monitored for settlements and/or deflections by using surveying techniques. Traditional optical surveying approaches can be used for performing elevation surveys and surveys of offsets of points (deflections) from established baselines. Alternatively, Global Positioning System (GPS) surveying methods can be used to determine changes in elevation and location coordinates. Monuments or measurement points at embankment dams typically consist of 1-inch-diameter rods embedded to a depth sufficient to protect them from frost heave and are anchored in place by concrete at their top, to a depth of about 4 feet and having a radius of about 8 inches. Measurement points on appurtenant concrete structures typically consist of small carriage bolts embedded in freshly placed concrete or epoxied into small holes drilled into existing concrete.

Total station surveying and/or Electronic Distance Measurement (EDM) equipment allow surveys to be performed for elevations and/or deflections by trilateration or triangulation methods using a network of survey piers established around the dam or structure. A least-squares approach is used to reduce the redundant data and provide a measure of the accuracy of the results. The surveyed points in this situation are reflectors that return the beam emitted by the survey equipment. These reflectors may be permanently mounted, or they may be portable reflectors that are placed on top of the monuments or points at the time of a survey.

11.6.2.17 Real-Time Monument Movement Monitoring

Real-time monitoring of the elevation and location of one or more points using GPS equipment can be performed if visibility to overhead satellites is available.

11.6.2.18 Interferometric Synthetic Aperture Radar

Interferometric Synthetic Aperture Radar (InSAR) is a means of monitoring settlements and/or deflections occurring over time, over fairly broad areas, using data collected either from aircraft or, most typically, from satellites regarding stationary objects on the earth’s surface. Synthetic Aperture Radar (SAR) systems take advantage of the long-range propagation characteristics of radar signals and the complex information processing capability of modern digital electronics to provide high resolution imagery. An antenna transmits radiation, which is reflected from stationary objects. Differences in the phase of the waves returning to the satellite or aircraft are used in computations to develop terrain models. InSAR uses two or more SAR images to generate maps of surface settlements or heaves. The technique is capable of accuracy to about 0.4 inch, although when looking at a time series of collected data, the effective accuracy improves. Reclamation has successfully used InSAR data to look for settlement patterns along the 15-mile-long Reach 11 Dikes in Arizona, which are located in an area that is undergoing significant absolute and differential settlement.

11.6.2.19 Advantages and Disadvantages Associated with Commonly Used Deformation Monitoring Instruments

Table 11.6.2.19-1 summarizes some of the principal advantages and disadvantages of a variety of commonly used deformation monitoring instruments.

Table 11.6.2.19-1. Advantages and Disadvantages Associated with Commonly Used Deformation Monitoring Instruments

Instrument	What is measured	Advantages	Disadvantages
IVM installation	Embankment compression	Simple. Satisfactory sensitivity.	Specially compacted protective mound interferes with embankment construction. Risk of probe getting stuck in telescoping pipe.
Baseplate – installed during embankment construction	Foundation settlement	Same as above.	Same as above.

Table 11.6.2.19-1. Advantages and Disadvantages Associated with Commonly Used Deformation Monitoring Instruments

Instrument	What is measured	Advantages	Disadvantages
Baseplate – drilled back to plate set before embankment construction	Foundation settlement	No interference with embankment construction. Simple. Satisfactory sensitivity.	No data collected during dam embankment construction. Concerns about drilling through dam embankment material must be appropriately addressed. May miss plate when drilling back.
Inclinometer – readout with portable probe	Lateral deformations of installed inclinometer casing	Full profile of casing obtained with each data set in two dimensions – movement occurring anywhere along the profile can be detected. Capable of great sensitivity.	Time consuming to read. Training needed for proper reading. Probe will not be at exactly the same spots every time readings are taken, so “noise” will exist in data.
In-place inclinometer	Rotational movement between sets of points along installed inclinometer casing	If location of potential sliding shear plane is well known, then this is an economical approach. Easy to read. “Fixed” position of tilt sensor means great sensitivity. Can be automated for real-time information.	Collected data is very limited – only rotational movement between sets of points. (Does not provide profile of casing.) Greater distance between points lowers sensitivity for detecting movements.
Inclinometer casing and portable distance probe	Embankment compression	Simple. Satisfactory sensitivity.	Specially compacted protective mound interferes with embankment construction. Risk of probe getting stuck in telescoping casing.
Tiltmeter	Rotational movement	Simple. Capable of great sensitivity. Can be automated for real-time information.	Collected data is very limited – only rotational movement at instrument location.

Table 11.6.2.19-1. Advantages and Disadvantages Associated with Commonly Used Deformation Monitoring Instruments

Instrument	What is measured	Advantages	Disadvantages
Shear strip	Shearing movement sufficient to break shear strip	Simple. Easy to read. Approximate location of shear can be determined. Can be automated for real-time information.	Cannot detect developing shearing situation – strip is either intact or broken. Collected information is very limited.
Fiber-optic cable	Distance change between points along the cable	One cable can run for a long distance – several miles.	Expensive – both readout unit and cable.
Time Domain Reflectometry (TDR	Locations of bends along installed cable	Commonly used technology. Satisfactory sensitivity.	Technology involved is not simple.
Settlement sensor	Settlement		Experience has shown it provides unsatisfactory sensitivity – not recommended for use.
Overflow settlement gauge	Settlement	Simple. Satisfactory sensitivity.	Some noteworthy construction interference in running lines horizontally to downstream slope.
Simple distance measuring device	Distance change between fixed points	Simple. Satisfactory sensitivity.	
Tape or rod extensometer	Distance change between fixed points	Simple. Satisfactory sensitivity.	
Multipoint extensometer	Distance change between fixed points	Simple. Satisfactory sensitivity. Can read remotely and be automated for real-time information.	
Probe-type extensometer	Distance change between fixed points	Simple.	Sensitivity in some instances has not been satisfactory.
Joint meter or crack meter	Distance change between fixed points	Capable of great sensitivity. Can read remotely and can be automated for real-time information.	Vibrating-wire technology is “black box” in nature, but is well proven and reliable at this point if known manufacturing standards are followed.
Linear Variable Differential Transformer (LVDT)	Distance change between fixed points	Capable of great sensitivity. Can be automated for real-time information.	Not applicable for remote installations because readout unit must be close to instrument.

Table 11.6.2.19-1. Advantages and Disadvantages Associated with Commonly Used Deformation Monitoring Instruments

Instrument	What is measured	Advantages	Disadvantages
Surveys of embankment measurement points	Settlements and lateral deflections of monuments	Simple. Easy to install at any time. Generally satisfactory sensitivity. Monitoring frequency can be appropriately adjusted to the circumstances.	Trained surveyors and appropriate survey equipment needed for successful monitoring. Performing surveys is expensive.
Real-time monument movement monitoring	Settlements and lateral deflections of monuments	Satisfactory sensitivity. Can monitor remote locations. Real-time information.	Location requires good openness/visibility (for viewing by multiple overhead satellites). Expensive.
Inteferometric Synthetic Aperture Radar (InSAR	Settlements	Cost-effective approach to view general settlement patterns over large areas.	Not appropriate for sudden or short-term movement issues.

11.7 Other Monitoring Approaches

Sections 11.3, 11.4, 11.5, and 11.6 above discuss only major instrument types and categories. Many others exist, and new instruments and instrument types are regularly added to the monitoring options available. The references noted in Section 11.2.6 can be consulted for additional instrument types and instruments. Manufacturers and their Web sites can be consulted for the latest information about available instruments.

Section 11.2.2 noted the importance of visual monitoring with respect to a routine dams safety monitoring program. Many key monitoring parameters can only realistically be detected via visual monitoring efforts (such as new seepage areas, new cracks, etc.). Several topics related to visual monitoring are noted below:

- **Mapping.** To document potentially changing conditions over time, mapping can be used to improve the effectiveness of visual monitoring efforts. Mapping of seepage areas and mapping of cracks in a concrete structure are common.

- **Marking.** If uncertainty exists as to whether a crack in a concrete structure is getting longer with time, the end of the crack can be marked with spray paint, along with the marking date. This will enable future visual inspections to effectively track whether the crack is lengthening

- **Staking.** If uncertainty exists as to whether an existing (nonflowing) wet area is growing larger, the limits of the wet area can be staked to allow comparisons to be made over time. The most useful assessments would occur when the reservoir level and time of year are comparable to when the stakes were placed. Staking at the time of "full" reservoir conditions for a typical year is usually the preferred approach.

- **Cameras**. Photographs taken from the same vantage point over time can aid in the detection of gradually changing situations. Also, cameras can be installed at a dam site and be remotely monitored. Such an arrangement may be very beneficial for remote structures that are not manned, particularly for a rapid check on conditions in the aftermath of a nearby earthquake.

11.8 Development of a Monitoring Program

11.8.1 Development of a Monitoring Program – For an Existing Dam

As noted previously in Section 11.2.1, "Use of Potential Failure Modes Analysis For Monitoring Program Design," to establish a rational, cost-effective dam safety instrumentation and visual monitoring program, it is first necessary to identify the potential dam safety threats (the potential failure modes) that the program should address. In Reclamation, a comprehensive dam evaluation is performed where the potential failure modes are collectively developed by all parties involved with dam safety activities for the dam, and then the risks associated with each potential failure mode are also estimated. Using this information, the Reclamation dam safety program can then establish an appropriate dam safety monitoring program for the dam:

- For each potential failure mode that presents nontrivial dam safety risks for the dam, the key monitoring parameters are determined that would indicate the initiation or progression of the potential failure mode or that conditions are present that make it more likely to occur.

- For each element of the monitoring program, the value of the data/information provided is assessed to determine whether it is direct or indirect evidence (direct evidence is better evidence), whether the precision of the data/information is adequate and appropriate, and whether the instrument reliability is satisfactory.

- For the monitoring program as a whole, an assessment is made to determine whether the instrumentation installations provide adequate coverage of the dam site and whether unnecessary redundancy exists in the monitoring program.

- For each element of the monitoring program, the range of expected performance (consistent with satisfactory dam performance) is determined.

Using the above process, it is possible that some existing monitoring schedules may require adjustment and/or that some new instrumentation installations are necessary at the dam site. Similarly, some actively monitored instruments may be determined unnecessary for the dam's <u>current</u> monitoring needs and issues. These instruments can be put on standby, if it is felt that they might potentially provide some benefits at some point in the future, or they can be abandoned. Abandonment may mean simply ignoring the instrument in the future, or it may involve some active effort to remove it, grout it, etc., depending on the instrument. The comprehensive dam evaluation should provide guidance if some active abandonment effort is appropriate.

The above process focuses on monitoring activities that are directly tied to specific potential failure modes. However, some appropriate dam safety monitoring can fall in the category of "General Health Monitoring," that is not tied to a specific failure mode. Such monitoring almost always is "high value, low cost." Surveying embankment measurement points on an embankment dam for settlements and deflections every 6 years is an example of appropriate monitoring that falls in the category of General Health Monitoring. It is a continuing challenge to determine whether a certain type of monitoring appropriately fits the category of General Health Monitoring. However, subjecting the monitoring to questions of direct versus indirect evidence, precision, reliability, coverage, and redundancy in the comprehensive dam evaluation process helps ensure that only appropriate General Health Monitoring is included.

The dam safety monitoring program developed in the comprehensive dam evaluation process, to be used in the future at the dam and dam site, is documented as follows:

- "Schedule for Periodic Monitoring (L-23)," which presents the components of the monitoring program, the specified monitoring frequency for each component, extra monitoring requirements in the event of unusually high reservoir elevations (i.e., a flood event), and in the aftermath of significant seismic shaking at the dam site, as well as other notes related to carrying out the monitoring program. Importantly, the L-23 also includes a statement that the program specified in it applies only for normal operating conditions and satisfactory dam performance, and that additional monitoring requirements may be required in the event of unusual circumstances or dam performance. The L-23 monitoring requirements typically evolve during the life of a dam, with the most intensive monitoring typically occurring during the period of first reservoir filling. However, very intensive monitoring may also occur in later years during floods or in the event of unexpected/undesirable dam performance. Appendix A includes an example of a "Schedule for Periodic Monitoring (L-23)."

- "Ongoing Visual Inspection Checklist (OVIC)," which defines the routine dam safety visual monitoring program to be carried out at the dam site. The OVIC is set up so that any question answered "Yes" indicates unexpected performance that typically requires some sort of investigation and/or followup. Therefore, completed OVICs that have one or more questions answered "Yes" need to include additional information, attached photographs, etc., that help define the unexpected performance that was noted. Appendix A includes an example of an "Ongoing Visual Inspection Checklist (OVIC)."

- Tables are developed that show ranges of expected performance.

- Responsibilities and required timeframes are specified for monitoring program data/information transmittal and review.

11.8.2 Development of a Monitoring Program – for a New or Modified Dam

Ideally, the process described in the previous section for developing a monitoring program for an existing dam would also be used for a new dam, or a dam that has been significantly modified. However, a new or significantly modified dam lacks performance history, which plays a significant part in defining a dam safety monitoring program for an existing dam. Consequently, engineering judgment regarding performance is required. When the reservoir is filled, and performance history is gained from a few years of instrumented and visual monitoring, then the estimates about dam performance can be replaced with information, and the (preferable, potential failure mode and risk-based) procedures described in the previous section can be used in their entirety. Until that time, the Instrumentation Engineer, the Principal Designer, and the design team members work together to establish a monitoring program that is intended to appropriately address the anticipated dam safety issues at the dam site.

When final designs for a new dam, or a significant modification to an existing dam, begin to take shape, the design team needs to discuss and agree on the instrumentation that should be included as part of the design drawings and specifications. Consideration of potential failure modes is an important part of these discussions. Some aspects of the instrumentation program will be fairly standard from dam to dam, such as: (1) flow monitoring installations and sediment trapping capabilities for all seepage and drain flows, (2) a network of embankment measurement points to appropriately monitor future embankment settlements and deformations, and (3) a network of structural measurement points that are provided, as appropriate, on all the appurtenant structures (intake structures, conduits, stilling basins, etc.). Water pressure monitoring installations will typically be provided to monitor the effectiveness of drains, seepage cutoff features, relief wells, etc. Instruments might be provided to monitor settlements that occur at the embankment/foundation contact, and/or embankment compression occurring during embankment construction and thereafter. Beyond that, decisions about instrumentation needs will be site-specific, considering unusual, unique, etc., aspects of the dam site geology and the embankment and appurtenant structure designs. If a good reason does not exist for installing an instrument, it should not be done.

A technical memorandum needs to be prepared that appropriately documents all aspects of the instrumentation design, including why the various instruments were included in the program and any unusual aspects regarding the design. Data expectations should also be presented as specifically as possible. The criticality of a dam design parameter is usually determined by a sensitivity analysis during the design process. By doing this, target levels of instrumented performance can be developed. For critical or sensitive design parameters, great effort is necessary to both establish the target levels and track the instrumented performance.

For first reservoir filling and initial operation of a new or significantly modified dam, Reclamation prepares a “first filling” document that prescribes monitoring activities that are to be performed. An L-23 and OVIC are included in the document, along with discussion about specific monitoring concerns and actions to take in the event of unusual or unexpected performance. Typically, this is the time in the life of the dam when monitoring requirements are the most stringent because of all the dam performance unknowns that exist. Lighting may be required on the dam so that visual monitoring can be conducted during both day and night. Instrument readings may be required more than once per day. After first reservoir filling has been completed (which, in some cases, may be many years after completion of construction), and after the first filling dam performance has been evaluated, it is typical that the L-23 and OVIC will be revised to less stringent requirements that are more in line with a program for long-term operations. Additional L-23 and OVIC adjustments may be made in the months and years thereafter, based on dam performance and design team input, until the first comprehensive evaluation of the new or modified dam is performed, as described in the previous section.

11.8.3 Risks and Disadvantages of Instrumentation Installations

In most instances, installing instruments within an embankment dam involves compromising the dam’s integrity, to some degree, so that the instruments can be installed. Examples include: (1) trenching in the core of the dam embankment, placing instruments and cables, and backfilling the trench with specially compacted material; and (2) bringing pipes vertically up in the dam embankment as it is constructed, which involves constructing specially compacted embankment around the pipes to protect them during construction. Not only are construction anomalies created within the dam embankment, but interference with construction can affect other aspects of construction of the dam. For example, pipes that extend up vertically through the embankment, and their associated protective mounds, essentially present an obstacle course for equipment placing and compacting the embankment material. Embankment material placed and compacted adjacent to protective mounds may end up being less dense. As previously noted in Section 11.2.5.5, "Compatible with Construction Techniques to be Employed," the sinkholes that developed at W.A.C. Bennett Dam in 1996 at specially compacted areas associated with instrumentation installations represent a cautionary tale. Consequently, the risks and disadvantages of instrumentation installations need to be appropriately considered during the design of a monitoring program for a new or existing dam.

Steps can be taken to limit construction interference and construction anomalies associated with instrumentation installations. Limiting the extent of the instrumentation within the core of the dam embankment to only that which has strong justification is an obvious step. Also, steps can be taken to minimize the impact of an instrument installation. For example, at Davis Creek Dam, the foundation consists of overburden materials that conceivably could exhibit substantial settlement in the years after completion of dam construction, including potentially substantial differential settlement that could be very detrimental to the dam embankment. Consequently, a need for settlement monitoring at the embankment/foundation contact was evident. A choice existed between using baseplates and settlement sensors. The poor track record for the settlement sensor data quality led to the elimination of settlement sensors as an option. It was decided that, instead of installing the baseplates at the foundation contact and then bringing the baseplate installation riser pipes up as the dam embankment was being constructed, metal plates would be installed at the foundation contact, surveyed, and then drilled back to after embankment construction was completed. This approach reduced construction interference and avoided specially compacted mounds in the dam's core, which could adversely impact the dam embankment's integrity. The disadvantages of this approach were that baseplate settlement data was not collected as the dam was being constructed, and post-construction drilling through the dam embankment would be required. The advantages were judged to outweigh the disadvantages, in part because the drilling could be done using a hollow-stem auger that would pose essentially no risk of hydraulic fracturing of the dam embankment. Therefore, the "drill-back" approach was selected and successfully accomplished. (Drilling through the core materials of an embankment dam is not desirable and should not be done without a thorough assessment of the risks and benefits associated with such drilling. Section 11.10.2.g, "Drilling in embankment dams," discusses this topic further.)

11.8.4 Minimum Instrumentation for Dams

Reclamation does not have any minimum instrumentation requirements for new or existing dams. The procedures presented in Sections 11.8.1, "Development of a Monitoring Program – For an Existing Dam," and 11.8.2, "Development of a Monitoring Program – for a New or Modified Dam," describe how monitoring programs are to be developed, and these procedures do not include any minimum instrumentation requirements.

11.9 Instrumentation Design Considerations

11.9.1 General

Section 11.2.5, "General Considerations for Selecting the Appropriate Instrument Type for Use," previously presented general considerations for selecting particular instruments to be used:

a. Long-term reliability
b. As simple as possible
c. Vandal resistant
d. Low maintenance
e. Compatible with construction techniques to be employed
f. Low cost

Rather than repeating the "equipment selection" discussion here, refer to Section 11.2.5, "General Considerations for Selecting the Appropriate Instrument Type for Use," for a discussion of these important topics. Topics discussed in the this section focus on the entirety of the instrumentation system and program design, as opposed to equipment selection, and include the following:

- General program design considerations
- Consideration of range, sensitivity, and accuracy
- Accommodation of deformations
- Protection of installations
- Lightning protection
- Limitation of negative impacts on the dam
- Standardization of installations
- Recognition that anomalous instrumentation data will be challenged

The design of an instrumentation system for a dam needs to be performed as a collaborative effort involving the design personnel for the various features of the dam, the geologist(s), and the operating personnel, in conjunction with one or more experienced Instrumentation Engineers. The design personnel have the principal role in identifying the data collection and monitoring needs. The

Instrumentation Engineer(s) then works with the team to develop the detailed plans and specifications for the system so that necessary data collection and monitoring can be effectively and efficiently accomplished using appropriate instruments and an appropriate data collection and transmittal system.

11.9.2 General Program Design Considerations

11.9.2.1 Instruments to Monitor Specific Issues or Concerns

For instruments installed to monitor specific issues or concerns, the instrument's basic purpose is typically fairly clear and obvious. It is necessary, however, to address the question of what the anticipated readings will be so that the range and sensitivity of the instruments are appropriate, and so that the layout of the instruments is appropriate for getting the desired information. The careful, thoughtful design of an instrumentation program is important because the instrumentation system can only answer questions that it has been designed to address. Recognizing shortcomings of the instrumentation program after the fact is never pleasant. The least expensive and most desirable time to install instruments is during construction of the dam. Some monitoring, such as for dam embankment compression, is not possible if the instruments are not installed during initial dam construction.

11.9.2.2 Instruments for "General Health Monitoring"

For instruments installed to provide general, long-term monitoring, the rationale for the program often becomes murky. This should not be the case. The purpose of these instruments needs to be just as clear as for other instrumentation needs. For seepage-related internal erosion concerns, this could be addressed as follows:

a. Monitor all drain and seepage flows for increasing flow rates with time (under comparable reservoir levels and circumstances). If possible, all flows should pass through locations that would trap sediments (weir stilling pools, inspection wells, etc.).

b. Establish a network of surveyed monuments to look for surface manifestations of subsurface material removal by seepage flow (internal erosion).

Having a network of surveyed monuments on a dam (i.e., embankment measurement points) is a good general practice that allows general patterns of embankment deformations to be monitored over time. This monitoring is relatively low cost, but it can be very valuable if anomalous deformations occur which are detected. Often, it is desirable to have at least one instrument installed within a dam's embankment during original construction that provides embankment compression data. Such data can be used with embankment measurement point surface settlement data to assess settlement contributions from foundation settlements versus embankment compression.

Water pressure data at key locations of a dam site can help clarify general seepage flow patterns at the site. Water pressure data also can allow detection of diminishing effectiveness of drains, relief wells, grout curtains, etc., over time.

With the goals of the monitoring well defined, an appropriate monitoring program can be designed. Installing a number of instruments in the name of "general, long-term monitoring" without a coherent rationale often ends up being a waste of time and money. It is difficult to usefully evaluate data without a good understanding as to why the data have been collected.

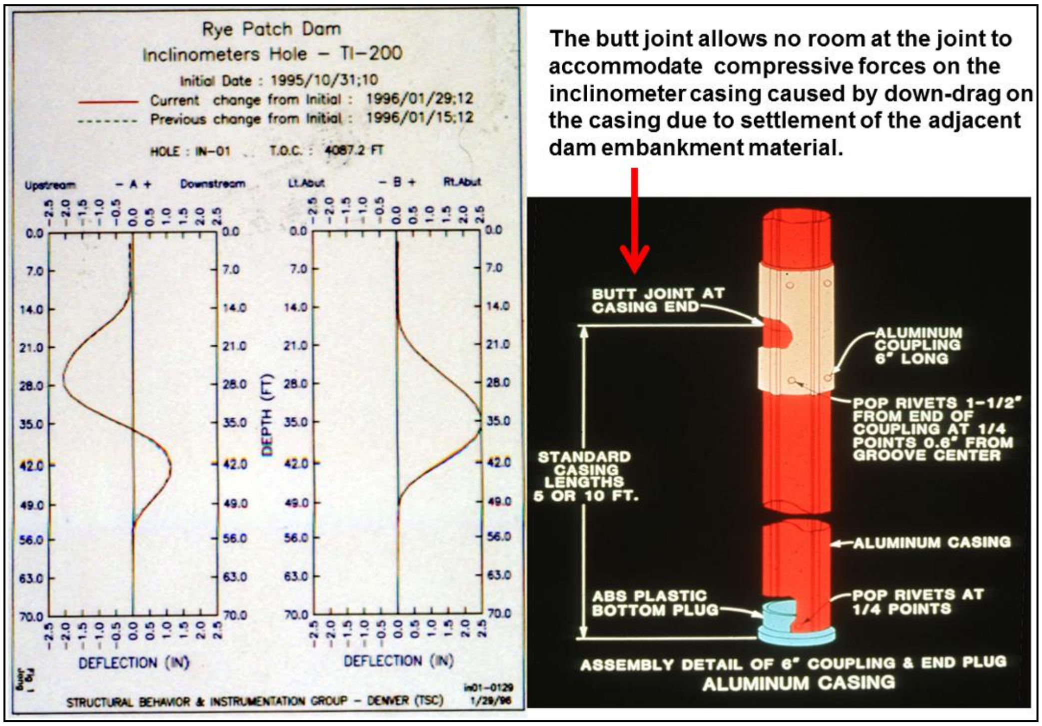
11.9.3 Consideration of Range, Sensitivity, and Accuracy

Instruments need to provide data of sufficient sensitivity and accuracy to answer the questions being addressed. For many instruments, there is a tradeoff between range and sensitivity. The most fundamental design issue is to avoid underestimating the needed range. If the instrument "pegs," it is unable to give data beyond a certain value, which could severely limit the benefits obtained from the instrument. Consequently, in the design process, a conservative range estimate needs to be developed. With the range appropriately established, sensitivity choices can then be explored. If 0.01 foot sensitivity is required, obviously 0.1 foot sensitivity is not acceptable. However, paying extra for 0.001 foot sensitivity does not make sense either. Regarding accuracy, in many cases, an extremely high degree of accuracy is not required as long as consistent data are provided that correctly reflect relative changes over time. For example, consistent seepage flow data over time may provide the answer to the question at hand, even if the seepage flow data are a bit inaccurate (5-10 percent high, 10 percent low, etc.). Water pressure data, earth pressure data, and deformation data needs may also fall into the same category in many situations, although this needs to be assessed for each particular situation.

11.9.4 Accommodation of Deformations

Embankment dams will deform during and after construction. Instrumentation installations involving components within the body of the dam need to be able to survive the forces imposed on them associated with the embankment deformations, without damage or failure. Some examples:

a. Butt joints should not be used for inclinometer casings. When embankment compression occurs, this creates a down-drag on the casing. If casing has telescoping joints, with some distance between the ends of the sections of casing being joined, then the embankment compression and down-drag on the casing can be accommodated. If not, the casing may fail by buckling like a column under axial loading. (This has been seen at an inclinometer casing at Rye Patch Dam, as shown in figure 11.9.4-1.)



The butt joint allows no room at the joint to accommodate compressive forces on the inclinometer casing caused by down-drag on the casing due to settlement of the adjacent dam embankment material.

Figure 11.9.4-1. On the left, a plot of inclinometer deflection data showing “columnar” buckling of an inclinometer casing, due to the use of butt joints in the casing, which is depicted in the schematic illustration on the right.

b. Embankment zones that settle or compress at different rates may impose large shearing forces on cables, tubes, etc., that cross their interface. A large number of instruments could be lost if a bundle of cables or tubes is sheared. Providing some slack in the cable and tubing that are placed in trenches in the body of the dam (by gently weaving the lines back and forth instead of installing them in straight and tight lines) allows accommodation for embankment deformations and can prevent shearing or failing in tension. Cables or tubes that exit a structure or pipe within the dam are of particular concern because the lines could get sheared at the structure interface or at the end of the pipe.

11.9.5 Protection of Installations

The designs for all instrumentation installations should ensure that they will be appropriately protected from potential future damage from human activities (either inadvertent or malicious) or from nature (weather, earthquakes, etc.). Section 11.2.5.3, “Vandal Resistant,” previously noted the need for installations to be vandal resistant. Operations and maintenance activities also can result in inadvertent damage to, or loss of, instruments if the installations are not appropriately marked and protected. Lockable and stout protective enclosures for instruments are important, as are appropriate barrier protection (fences, post, ballards, etc.) and appropriate marking of instrument locations (to prevent them from damage by mowing equipment or snowplows). Instrument readings during floods and immediately following earthquakes may be very valuable and important, so instrument installations must be designed to withstand potentially extreme loading conditions.

Moisture, dirt, dust, etc. entering enclosures housing instrumentation equipment can be very damaging to the equipment. Such enclosures should have a National Electrical Manufacturer's Association (NEMA) rating of 4. Cable entrances should be sealed and located at the bottom of the enclosure (to allow drainage if leakage occurs). It may be appropriate to include a desiccant in the enclosure that is periodically replaced to ensure effectiveness.

11.9.6 Lightning Protection

Over the years, many electrical instruments have been irreparably damaged due to lightning-induced electrical surges through instrument cables. Nothing can be done to prevent damage to an instrument caused by a direct lightning strike on the instrument. However, the risks can be reduced in the following ways:

a. Sacrificial lightning protection can be employed at the location closest to the instrument along its electrical cable that is accessible for future replacement (when it has performed its service). This lightning protection "absorbs" the surge and prevents it from travelling the rest of the way down the cable to the instrument. Currently, what is known as "Phase 3 Lightning Protection" is used. In time, this will probably be superseded when an improved and/or less costly method becomes available. After the lightning strike, reading of the instrument is not possible until this sacrificial lightning protection is replaced.

b. A "spark gap" is provided at the instrument that can address any remnant of the electrical surge that makes it past the sacrificial lightning protection discussed above.

A lightning strike that impacts the electrical cable "downstream" of the sacrificial lightning protection (between the sacrificial lightning protection and the instrument) will likely damage or ruin the instrument. However, with a properly designed system, the probability of this should be low.

Instruments that do not have electrical components have the ultimate lightning protection because they are not vulnerable to lightning strikes and the resulting electrical surges. Vibrating-wire instruments and resistance-based electrical instruments have vulnerabilities that are not shared by pneumatic, hydraulic, standpipe, and fiber-optic instruments. Obviously, this can influence the type of instrument that is selected for use at a dam site. Another option is to use fiber-optic "transmission" lines in conjunction with vibrating-wire or other electrical devices to limit potential instrument loss due to lightning-caused electrical surges.

11.9.7 Limitation of Negative Impacts on the Dam

Since the instrumentation is to be in service to the dam, and not vice versa, negative impacts to the dam embankment and appurtenance structures by instrumentation installations should be minimized to the extent possible. Aspects of this include the following:

a. **Minimize construction interference.** This topic was previously discussed in Sections 11.2.5.5, "Compatible with Construction Techniques to be Employed," and Section 11.8.3, "Risks and Disadvantages of Instrumentation Installations," Efforts to limit or prevent construction interference help to improve the quality of the constructed dam embankment. Vertical pipes being brought up with embankment dam construction, and the specially compacted protective mounds associated with them, are the most obvious examples of potentially detrimental instrument-caused construction interference.

b. **Minimize instrument trenches in the dam embankment, particularly those oriented in the upstream-downstream direction.** Even though bentonite plugs can be used along the trenches to address the potential for creation of preferential seepage paths by the trenches, having fewer trenches of shorter lengths is a better option for mitigating the seepage concern. Having no trenches is an even better approach. Current practice is to avoid instrument installations in the core of dam, to the extent feasible. At one time, installing a number of instruments in one or more sections through the core zones of embankment dams was standard practice so that the dissipation of reservoir-induced pressures in the core could be better understood. However, the current state of practice is generally opposed to such installations for two main reasons: (1) the value of the data is limited (given the understanding the profession has attained regarding data of this sort); and (2) these installations create construction interference, trenches, specially compacted areas, etc., that can be detrimental to the critical core zone of the dam embankment. For example, at Ridges Basin Dam, which was constructed from 2002 to 2008, no water pressure monitoring instruments were installed in the core of the dam. At Davis Creek Dam, constructed roughly two decades earlier, instrument cables were routed into the canal outlet works to limit the length of the instrument trenches in the core of the dam, and to avoid any trenches running continuously for a substantial width of the core of the dam.

11.9.8 Standardization of Installations

To the extent possible, using standardized installations is preferable, for the following reasons:

a. Standardized installations reflect collective experience developed over time, based on what has worked and what has not worked.

b. Specifications, drawings, and guidance provided to instrument installers for standardized installations typically will be better because they have actually been constructed as depicted many times.

c. Instrument installers become more proficient at installations over time when consistent approaches are used. This "experience" aspect is particularly relevant when the installation work is performed by Reclamation drill crews or other Reclamation personnel.

If standard installations are not appropriate to the specific application, they obviously should be altered and customized as necessary. However, unnecessary customization (that does not improve the installation in some way) should be avoided because no legitimate reason exists for departing from the "tried and true" methodology.

Drawings and specifications associated with standardized installations used by Reclamation can be obtained by contacting the Instrumentation and Inspections Group of the TSC.

11.9.9 Recognition that Anomalous Instrumentation Data Will Be Challenged

When instrumentation data are anomalous, the first assumption is usually that something is wrong with the instrument or the reading. That is not unreasonable, as often there is. However, if all anomalous data are viewed as erroneous and are discarded, leaving only the data that conforms to our expectations, then collecting the instrumentation data would be rather pointless. We have already decided that the performance of the dam conforms to our expectations, and any indications to the contrary are considered invalid.

Instrumentation designers must recognize that anomalous instrument data will be challenged, and be able to provide the needed assurance that the data can be relied upon. The assurance might involve one or more of the following:

a. The basic nature of the instrument (as simple a system as possible being desired)

b. An independent means of verification of the data

c. Appropriate levels of instrumentation redundancy

In dealing with water pressure data, providing strong support and assurance regarding anomalous open-standpipe piezometer data can be fairly straightforward. While the “density” of the network of instruments may not be sufficient to use the item c. approach above, the basic nature and simplicity of the instrument (item a.) clearly provide a strong argument. Also, independent ways to verify the data exist (item b.), including: (1) inserting a pressure transducer into the standpipe (and accounting for the water displacement issues); and (2) adding water to the standpipe and determining if the instrument “recovers” to the same anomalous reading. In dealing with anomalous data from a vibrating-wire piezometer within the body of a dam, items a. and b. are not applicable. Support would rest with redundancy (item c.), which may or may not be present, and with the basic reliability of the equipment provided by the equipment manufacturer (historical track record), which is important but probably will not resolve the data validity discussion.

During the first filling of Virginia Smith Dam, anomalously high water pressures quickly developed at several pneumatic piezometers in the downstream portion of the core. Support for the validity of the data came both from the inherently simple nature of the instrument (item a.) and the fact that multiple instruments exhibited the same behavior (item c.). However, design and construction personnel did not view the data as representative of actual field conditions. They pointed out the possibility that seepage was occurring along the upstream/downstream trenches that were used when the instruments were installed, leading to accurate but unrepresentative data. Bentonite plugs were to be periodically installed along the trenches to cut off any preferential seepage paths, but the challenge to the data was not successfully resolved, principally due to uncertainties about the construction of the plugs. In the end, some open-standpipe piezometers were installed in new drill holes in other areas along the dam alignment to get independent checks on the data (item b.), which verified that the pneumatic piezometer data was valid and representative. In this case, the lack of full confidence in the presence and effectiveness of the bentonite plugs along the trenches led to a need for additional verification of the anomalous data.

Instruments within the body of a dam that are resistance, vibrating-wire, or fiber-optic types will face data validity questions if they produce anomalous data, because items a. and b. cannot provide data integrity support. Only item c. (redundancy) is available to support the data; therefore, this must be considered when the monitoring program is designed. In general, support for seepage flow data and deformation data is more straightforward than it is for water and earth pressure data, partly because the data are usually collected at the ground surface, and are easily verified, as opposed to data collected below ground.

11.9.10 Automation of Instrumentation

The capabilities for automation of instrumentation facilities expand with each passing year. Many automation options and approaches exist.

The simplest level of automation is to use a datalogger to read and store data for one or more instruments in an area. The data are periodically manually retrieved by removing (changing out) the data storage canister and taking it to a computer, or by bringing a laptop computer to the datalogger. (In some instances, the datalogger itself is swapped out so as to retrieve the collected data.) These simple datalogger installations are fairly inexpensive and have low power requirements, which allow them to be fairly compact. This arrangement is appropriate when frequent readings of one or more instruments are desired, and real-time evaluation of the data is not required. As an example, this automated monitoring approach was used in 2008-2010 at Yellowtail Dam for a limited period of intensive water pressure data gathering at the left abutment.

The next level of sophistication in automation is to have data automatically read at one or more locations at a dam site, and then transmitted to a convenient central location at the site. The central computer typically is the main data storage location. Transmittal approaches from the remote units to the central computer may be by radio or by hard-wire, or by a combination of the two approaches. The amount of “intelligence” residing in the remote units may vary greatly, from “less sophisticated” units that just respond to “orders” from the central computer, to “more intelligent” units that independently decide when readings are to be taken and transmitted, perhaps depending on the characteristics of recent data. Of course, there is a tradeoff between less sophisticated units that tend to be more compact, less expensive, and less likely to malfunction, and the more intelligent units that have greater capabilities. Performance limits can be entered into the central computer (and remote units), enabling real-time data evaluation. Personnel at the central computer can see limit violations and system status information, and the central computer can also send out notifications regarding such information by text message, email, Web site posting, automated telephone call, etc. As an example, this “level” of automation has been employed at Glen Canyon Dam since 1989 to collect data from the numerous weirs and uplift water pressure monitoring installations at the dam.

The highest level of sophistication in automation is to not only have the data collected at a central location at the site, but also to make the data available to people at remote locations. Telephone communications allow a number of remote users to contact the central computer and download data, change reading frequencies, request that readings be taken at that time (if possible, based on the system configuration), etc. Telephone communication, although convenient, may be fairly expensive over time; may not be available during emergency situations, such as during a flood or post-earthquake, when readings may most be desired; and usually requires periodic initiation of contact by the remote users (i.e., it is not automatic). Another common communication alternative is to use satellites. Satellite communication is one-way communication (from the site to the remote users); therefore, no changes in reading frequencies, requests for instantaneous readings, or other two-way communications with the central computer are possible. However, routine transmittal of data to remote computer systems can be accomplished without operator involvement, inexpensively, and reliably. Data can then be posted to Web sites for broad access, if desired. It is a good idea to have both satellite and telephone communications because this provides a back-up communication source if problems occur. Again, performance limits can be entered into the system, allowing real-time data evaluation. Alarm notifications, system status information, etc., can be transmitted by text message, email, Web site posting, automated telephone call, etc. For example, automated readings of water pressure and seepage data have been made remotely accessible via telephone line communications at Navajo Dam since 1987 and via satellite communications from Ochoco Dam since 1995.

The design of an automation system needs to be appropriate to the circumstances of the situation. More sophisticated systems are not inherently “better.” They do have greater capabilities, but at a price of greater initial cost, greater maintenance cost and effort, and, often, less reliability. In general, the simplest system that will do the job effectively should be used. Some other design issues are discussed below:

a. **Power for remote equipment.** Where connection to the electric power grid is not feasible, batteries are needed for remote equipment. Recharging the batteries can be accomplished by periodically switching depleted batteries for recharged batteries (by having one or more extra batteries at the site). Solar panels can be used to recharge batteries (by “trickle charging”), although vandalism, storms, etc., may require the panels to be repaired on occasion. Thoughtful design of the automation system and equipment can reduce power requirements to very low levels, minimizing the difficulties encountered in providing power for remote equipment.

b. **Vandalism.** The topic of vandalism was discussed previously in section 11.2.5.3 and is a very important consideration with respect to instrumentation automation The economics and benefits of automation rapidly disappear if the system must frequently be repaired due to vandalism (or other causes). An assessment of the threats to the automation equipment needs to be made early in the design process, and appropriate solutions found. If solutions are not readily available, the decision to automate may need to be reconsidered. Protective housing and lock protection for the expensive automation equipment needs to be sufficient in light of the threats. To the extent that automation equipment can be located in galleries, powerplants, instrument houses, control structures, etc., the risks associated with vandalism are largely eliminated. Solar panels are almost invariably at risk of damage by vandals, so efforts to hide and/or provide protection for solar panels are typically worthwhile. Figure 11.9.10-1 shows an example of efforts made to protect a solar panel from potential vandalism.

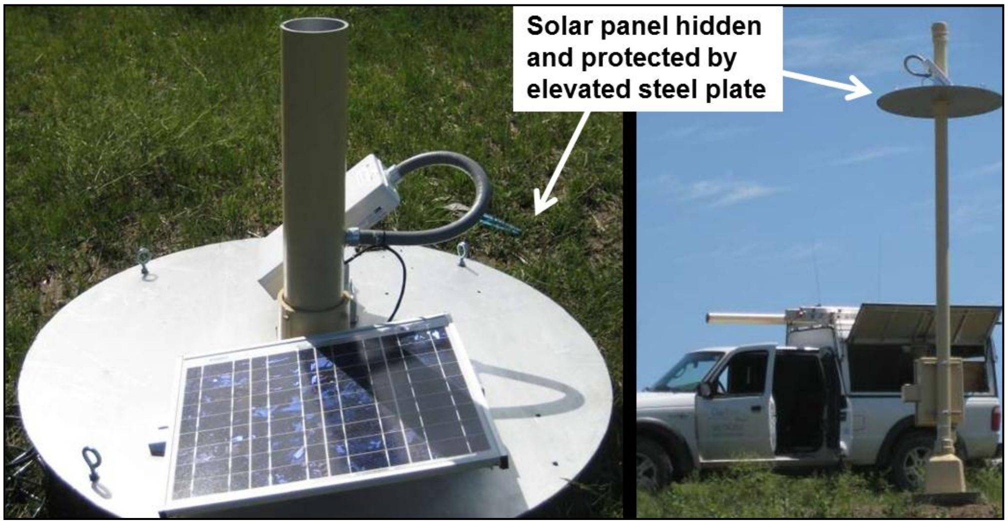


Figure 11.9.10-1. Photographs of a solar panel installation where efforts have been made to provide protection from potential vandalism.

c. **Lightning protection**. This topic was discussed previously in section 11.9.6 and is a very important consideration for instrumentation automation. Lightning is a very real threat to expensive automation equipment. Therefore, where feasible, automation equipment should be sheltered from direct lightning strikes. Where this is not possible, effective protective grounding can reduce the potential for damage. Long horizontal runs of electrical cable buried at shallow depths that often are a part of instrumentation automation efforts are at risk from large surges of current at either end of the run. Surge arrestors and protection at the ends of such runs are very important, along with measures taken in the placement of such cable in the trenches to minimize surges that may develop. Replacing buried cable runs with radio communication, to the extent feasible, can lessen the risks of lightning damage to automation systems.

d. **Notification protocols.** It is important to carefully think about who should be notified about anomalous data, system status, etc., how they will be notified, and under what circumstances such notification occurs. Frequent, relatively unimportant notifications run the risk of "numbing" those who receive the information and could lead to situations where important notifications are not noticed or identified as noticed amidst all the "noise."

Most types of electrical instruments can be fairly readily automated, including: vibrating-wire instruments (piezometers, total pressure cells, settlement sensors, strain meters, joint meters, readouts on extensometers, load cells, and strain gauges), resistance strain gauge piezometers, resistance strain gauge-based load cells, in-place inclinometers, tiltmeters, linear potentiometers on extensometers, shear strips, and thermistors. Pneumatic instruments can be automated, although this is fairly complicated because equipment must mimic the steps followed when manual readings are taken. Some other types of instruments that can be automated include those listed below:

- Pressure transducers placed down standpipes allow observation wells and open-standpipe piezometers to be automated. It should be noted that such an installation would have a long time lag in impervious soils (see Section 11.4.3.10, "Comparison of the Commonly Used Major Piezometer Types"), unless a seal is provided in the standpipe in the area above the transducer. Also note that including a bubbler line (see Section 11.4.3.9, "Bubbler Line,") as part of the installation provides a convenient way to obtain a manual reading, so that the automated pressure transducer data can be periodically checked for accuracy without removing the pressure transducer from the standpipe (which would alter the water level in the standpipe and therefore interfere with getting an accurate "check" reading).

- Pressure transducers can be integrated into the lines of hydraulic piezometer systems.

- Pressure transducers can be used with weirs and flumes to replace staff gauges.

- Vibrating-wire joint meters, strain gauges, or other electrical devices may be used to replace measuring between fixed points with calipers, micrometers, etc.

- In-place inclinometers can allow automation of existing inclinometer casing installations.

For earthquake-related issues, automation systems can include seismic triggers that detect earthquake-related shaking, and then institute special data collection protocols to collect post-earthquake transient performance, perhaps involving very frequent readings for a few minutes, hours, or days. Special data transmission protocols can also be designed to be triggered by the shaking, when appropriate.

Advantages associated with the automation of instruments include:

- Real-time data availability to a variety of end users can be provided, including via Web site (assuming Reclamation computer security requirements can be satisfied).
- Real-time data evaluation can be performed automatically, with customized notifications for anomalous instrumentation data.
- Data quality may be improved due to consistent reading methods and the elimination of human errors.
- Data can be obtained more frequently than is often possible with manual readings. In some instances, regardless of the costs, automating instruments may be the only way to adequately or safely monitor a situation.
- Costs may be reduced. The initial installation cost of the automation equipment, plus the system maintenance and repair costs, may be more than offset by the labor saved due to automating the reading of the instruments.

Disadvantages sometimes associated with automation:

- Costs may be increased. Lightning problems, vandalism, poor system design, poor system installation, poor or expensive system support, etc. can lead to automation costs that far exceed what is necessary simply to obtain the necessary readings manually. In most instances, it is not wise to choose automation simply because it is assumed that money will be saved, because experience typically shows this does not occur.
- Automation can lead to reduced human presence at the dam site, which may mean other adverse situations (which can only be detected by visual inspection) are less likely to be noticed in a timely fashion.
- When automation systems have problems, there are often not enough people available to obtain all the readings manually during the interim. Also, data files get polluted with bad data in significant amounts and on an ongoing basis until the problems are remedied.

- Manufacturers of automation systems may go out of business or discontinue certain products, making future repair and support of a system a problem.

- In some instances, the presence of an instrumentation automation system at a dam site, and all the maintenance and other activities required to keep it fully operational, can divert the attention of the dam operating personnel from the central task of looking after the health of the dam to the task of continually looking after the health of the automation system.

In conclusion, some things to look for in plans to automate instrumentation include:

- A realistic assessment of the costs and benefits of automation.

- A manual (backup) reading capability for all automated instruments, independent of the automation system, in the event problems occur with the automation system, and to provide a means to check anomalous automated data.

- A well-conceived design that addresses threats to the system. Lightning and vandalism are usually the biggest concerns, but all potential threats to the system must be adequately dealt with.

- Redundancy in communication links, using both telephone and satellite, where real-time remote data evaluation is desired.

- A system that is as simple as possible and consistent with the data needs.

- As scope for the automation project that is as limited as possible. Instruments should not be automated just because they can easily be tied into the system. Before long, a small, simple project can become a big, overly complex project.

- Careful assessment of the technical capabilities of automation system equipment suppliers.

- Careful consideration of the future support and maintenance needs of the automation system

Instrumentation automation systems have the potential to offer great benefits to dam safety monitoring efforts in the appropriate circumstances. However, the expected benefits of the systems are often not fully realized, and the costs in terms of time and money to operate the systems are often greater than anticipated. This track record must be considered when evaluating whether or not to embark on instrumentation automation efforts. Making a decision to automate instruments without careful consideration and analysis, perhaps to create the appearance of being a "state-of-the-art" operation, may be regretted.

11.9.11 Abandonment of Instrumentation Installations

In most instances, instruments can be left in place if they are no longer needed without increasing the dam safety risks. However, instrument installations that can be readily removed (for example, equipment at the head of a multi-point extensometer installation) typically are removed, so that they can be reused elsewhere and/or so that they are not in the way at the dam site. Instrument abandonment is a more significant matter in the following two situations:

- **Hydraulic piezometer installations.** The hydraulic piezometer tubing that runs in the upstream/downstream direction through the dam embankment can create some seepage paths of concern. In some instances, one or more highlighted potential failure modes for a dam may be associated with the tubing. Abandonment of hydraulic piezometer installations must be carried out appropriately. Reclamation's *Operations and Maintenance Guidelines for Hydraulic Piezometer Installations at Dams* document (current version dated June 7, 2005) provides specific guidance and information regarding the abandonment of hydraulic piezometer installations. It often is appropriate to routinely monitor the tube bundle entrance point in a hydraulic piezometer terminal well for possible seepage flow (and possible sediment transport by seepage flow) after abandonment of all the hydraulic piezometers associated with the well.

- **Drill holes.** Drill holes, and instrument installations installed in them (such as inclinometers, open-standpipe piezometers, etc.), may provide a pathway for seepage flow, transmitting high water pressures from one area to another, etc. Consequently, filling such pathways with impermeable, nonshrink grout may be important at the time of instrument abandonment.

11.10 Instrumentation Installation/ Construction Considerations

11.10.1 General

Installation/construction of instrumentation installations for Reclamation dams typically is done: (1) by Reclamation personnel, (2) under contract by a contractor, or (3) under contract by a subcontractor to a prime contractor. These situations will be discussed in this section, following discussion of some general instrumentation installation/construction considerations that apply to both situations.

Regardless of whether an instrumentation installation is to be performed by Reclamation personnel or under contract, the efficiency and effectiveness of the effort is enhanced by appropriate communication between the designers, those who will perform the installation work, and those who will oversee and/or inspect the installation work at the dam site. For major projects, Reclamation has found it beneficial to have a preconstruction meeting to improve understanding and communication regarding the planned work, and to discuss any issues, concerns, etc., that involved parties may have about it. In any event, Instrumentation Engineers in the Instrumentation and Inspections Group of the TSC (Code 85-836000) are available to provide support to field personnel relative to any aspect of the instrumentation installation work, and should be consulted whenever questions, concerns, problems, etc. arise.

It is important during all construction work at a dam site that all existing instrumentation installations be appropriately protected from damage. Signs, fences, flagging, barriers, etc., should be employed as necessary for the particular circumstances. Contract specifications should be written such that the contractor has ample incentive to take the steps necessary to avoid damage to existing instrumentation installations.

The basic elements of instrumentation installation/construction work are as follows:

a. Ensure that appropriate guidance has been provided concerning how the installation/construction work is to be carried out. For work performed under contract, this would include the contract drawings and specifications, and potentially could include a "construction considerations" document (that may be included in the specifications for the contract). For work to be performed by Reclamation personnel per a Field Exploration Request (FER), this would mean that the FER provides, or references, all needed installation/construction information.

b. Where submittals are required for materials and equipment, instrumentation installation/construction experience, etc., which commonly is the case for work done under contract, ensure that all required submittals are received and are appropriate. If not, promptly address all deficiencies.

c. Ensure that the correct materials and equipment have been delivered to the site and will be used in the installation/construction work. Any problems that are discovered must be dealt with immediately. Also, check to ensure that the materials and equipment are in good condition and have not been damaged, contaminated, etc., during delivery to the site or otherwise.

d. Perform functional testing of all equipment before installation to detect any nonfunctional equipment.

e. Perform calibration testing of equipment, where relevant, before installation to determine at the dam site the calibration constants for each instrument. Compare the calibration constants determined at the dam site with the ones provided by the equipment manufacturer to ensure consistency and accuracy, correcting as necessary for elevation differences.

f. Perform inspections of the installation work to ensure that it has been performed according to the drawings and specifications.

g. Immediately after the installation work for each instrument has been completed, perform a functional test of the instrument to ensure it is working properly, and has not been damaged during the installation work. An instrument malfunction discovered at this time can be successfully rectified without too much effort. An instrument malfunction discovered
h. only after a significant amount of embankment material has been constructed above it presents major issues relative to rectification of the situation.

i. Beginning immediately after the installation of each instrument, perform regular, frequent readings during the construction process. Not only does this allow potentially valuable instrumentation data to be collected during dam construction, but it also allows any instrument malfunctions to be promptly recognized, which increases the likelihood that the situation can be rectified. This also helps tie down the specific timing of any equipment malfunction, so that events that occurred at the dam site that might have caused the malfunction can be appropriately linked to the malfunction.

j. Fully document the instrumentation installation/construction work. Documentation requirements are discussed in Section 11.10.3, “Instrumentation Installation/Construction Considerations – For Construction Done by Contract,” and Section 11.10.4, “Instrumentation Installation/Construction Considerations – For Construction Done by Reclamation Personnel,” below. Full and accurate documentation is important so that: (1) the raw instrumentation data can be properly converted to the engineering units of most interest; (2) the instrumentation data can be properly evaluated because the instrument location, and areas and materials being monitored, are correctly identified and understood; and (3) the complete circumstances associated with any anomalous data are fully known and understood.

11.10.2 Instrumentation Installation/Construction Considerations – Specific Issues

Some specific comments pertaining to instrumentation installation/construction work are provided below:

a. **Weirs and flumes**. Flow that goes under or around, rather than through, these installations obviously would result in the collection of inaccurate data. It is important that both the design and installation efforts be alert to this issue and take appropriate steps to address it. It may be that concrete headwalls, sheetpiling, or similar seepage barriers need to be provided at the site to cut off flow around or under the installation. Erosion may occur after the installation work is completed that allows flow to occur around the installation, so this needs to be appropriately considered and addressed during the design and installation work, and regularly checked for when future readings are made at the installation.

b. **Flumes.** It is important to ensure that flumes are installed and maintained in a level condition. Otherwise, inaccurate data will be developed using the flume staff gauge readings. For reference, sediment traps should be provided somewhere along the flow path for seepage flows monitored by flumes so that possible sediment transport is monitored for the flow, as well as the flow rate.

c. **Labeling of cables and tubing**. Labels should be provided every 10 feet along all lengths of instrument cables and tubing to be installed. The labels should indicate which instrument the cable or tubing is associated with so that, if it gets severed, it is not necessary to dig back and expose too much material to determine which lines need to be spliced together.

d. **Splicing of cables and tubing.** Construction operations should be conducted to reduce, to the minimum possible, the potential for inadvertent severing of instrumentation cables and tubing. Severed hydraulic piezometer tubing is at risk for future leaks, which could potentially introduce high water pressures into embankment areas that otherwise would have low water pressures. Severed pneumatic instrument lines are at risk for water to enter them and interfere with obtaining instrument readings, which can require time-consuming, expensive desiccation efforts to be performed every so often. Severed fiber-optic lines require very costly and time-consuming splicing efforts. The only exception to this rule is vibrating-wire instruments. While splicing lines back together requires some time and effort, it is not a major concern because an adequate splice has no long-term detrimental impact on a vibrating-wire instrument or its data. Because of this, the construction process for vibrating-wire instruments sometimes involves a planned splice. Cable is run to the vicinity of the instrument installation location, and then a short length of cable that is attached to the piezometer is spliced to the cable and the piezometer is placed in the desired location. Such so-called “reverse” installations are beneficial because they do not require the piezometer element to be present at the construction site for a potentially long period of time, amidst potential bad weather, construction traffic that could damage it, etc.

e. **Protective mounds.** Protective mounds of specially compacted embankment material at least 3 feet in radius should be provided around all vertical riser pipes that are located in the midst of embankment construction to provide protection from inadvertent damage by construction equipment working on the embankment. The specially compacted embankment material should be closely inspected and tested to ensure that densities comparable to the surrounding material are achieved. Figure 11.2.5.5-1, which appeared in a previous section of this document, shows a photograph of protective mounds around instrumentation installations during construction of a dam embankment.

   Limiting or preventing the need for vertical riser pipes within the dam embankment during construction is preferred to eliminate or reduce, to the extent possible, the presence of specially compacted mounds and the construction interference they cause (see Section 11.2.5.5, “Compatible with Construction Techniques to be Employed”).

f. **Bentonite plugs in instrumentation trenches.** To avoid potential preferential seepage paths in instrumentation trenches, bentonite plugs that are at least 1 foot thick and extend 1 foot into the walls and below the bottom of all trenches should be provided in all instrumentation trenches. At least one bentonite plug should exist between every pair of water pressure monitoring instruments installed in each trench. Figure 11.10.2-1 is a photograph showing special compaction efforts taking place in an instrumentation cable trench. The difficulties associated with this work may necessitate the installation of bentonite plugs periodically along such trenches.

g. **Drilling in embankment dams**. Drilling through the core materials of an embankment dam is not desirable and should not be done without a thorough assessment of the risks and benefits associated with such drilling. Improperly done, such drilling could potentially cause hydraulic fracturing of the embankment, creating open seepage pathways through the core, which is intended to be a relatively impervious seepage barrier. Reclamation’s *Guidelines for Drilling and Sampling in Embankment Dams* presents detailed information relative to what is permissible with respect to drilling at Reclamation embankment dams.

Figure 11.10.2-1. Special compaction efforts taking place in an instrumentation cable trench.

h. **Naming of open-standpipe piezometers.** In all cases, the piezometer that has the lowest tip elevation in a double-piezometer drill hole installation should be given the "A" designation (e.g. PTP-10A), while the piezometer that has the higher tip elevation should be designated "B" (e.g., PTP-10B). Also, long and/or complex names for open-standpipe piezometers (e.g., PTP-10.06.2012-KG-21AAC) should be avoided because they are ungainly to use on a regular basis and could lead to transcription mistakes. The name may encode all kinds of information for the engineer or geologist who was involved in its installation/construction, but it represents a nuisance for those who read, enter, and review data from it on a regular basis.

i. **Bentonite seals for open-standpipe piezometers or observation wells.** The quality of the bentonite seals provided for standpipe water pressure monitoring installations is very important, since effective seals ensure that the water pressures that are read at an instrument truly reflect the water pressures acting on the instrument's influence zone. Ineffective seals can result in inaccurate, unrepresentative, misleading data, and a significant probability exists that the data may not be recognized as invalid. The water pressures that are read at an installation with one or more ineffective seals may be impacted by water pressures other than those at the instrument's influence zone.

It is important that the drill hole for the instrument installation does not inadvertently breach a low-permeability layer that separates more pervious layers above and below it by having pervious backfill placed in the drill hole, thereby connecting the two pervious layers. Where feasible, it is very desirable to locate a bentonite seal within the low-permeability layer. If this is not desirable or feasible, the permeability of the backfill material placed in the drill hole in contact with the low-permeability layer must be low enough to create an effective seepage barrier between the pervious layers. (It is illogical to have one influence zone in contact with both pervious layers above and below a low-permeability layer because it would not be known which pervious layer that recorded water pressure data corresponds with certainty to.)

Constructing an effective bentonite seal in a drill hole around an instrument standpipe in the hole presents a challenge. Constructing an effective bentonite seal where two standpipes are located in the hole is much more problematic; therefore, this situation should be avoided whenever possible due to the significant risk that a seal will be compromised, regardless of how carefully the work is carried out. If there are three or more standpipes located in a drill hole, construction of an effective bentonite seal is unlikely, so it should not be attempted. In a case like this, an additional drill hole (or two) for instrument installations would be appropriate. The length of the bentonite seal zone in an instrument installation should never be less than 5 feet, and should be longer when construction conditions are unfavorable (deep hole, constructing under water, constructing around two instrument standpipes, etc.). The use of specialized injection equipment for sand zones and bentonite zones should be considered when construction conditions are unfavorable or many installations are planned.

j. **Graded sand for piezometer or observation well installations.** The graded sand for backfill in the piezometer drill hole influence zones should be a washed sand with 95 percent of its total gradation falling between U.S. Standard sieve sizes No. 8 and 50. No more than 2 percent should pass a No. 200 screen, and no portion of the material should be retained on a No. 4 screen.

k. **Fully grouted piezometer installations.** Currently, some debate exists regarding a relatively new technique for installing vibrating-wire piezometers in drill holes. This new technique involves simply surrounding the piezometer with a special grout mixture without creating a clearly defined influence zone for the instrument (sensor surrounded by sand, with “impermeable” bentonite seals above and below). This installation approach is faster and less costly, and it is argued that the data are comparable to a “traditional” installation. At this time, Reclamation does not endorse the use of this approach because it is not clear <u>exactly</u>

what the data collected using the new approach represent. This would be a problem in complicated geologic setting, and a major problem in the event of anomalous data, regardless of the geologic setting.

Care is necessary in all instrumentation installation/construction work so that the data obtained from the installed instruments are representative of actual site conditions. The worst situation, from a monitoring standpoint, is the collection of credible, but inaccurate data that misrepresent the parameter being monitored. An instrument that provides no data is preferable to an instrument that provides unrepresentative data that are not recognized as such.

11.10.3 Instrumentation Installation/Construction Considerations – For Construction Done by Contract

It is important to recognize that the instrumentation work for all major construction contracts will typically be done by a subcontractor under contract to the prime construction contractor. The chief concern of the prime contractor is that the major elements of the contract work (dewatering work, excavation work, embankment construction work, outlet works construction work, spillway construction work, etc.) are moving forward efficiently and on schedule. The work of the instrumentation subcontractor, and efforts relative to instrumentation for the dam in general, sometimes are viewed by the prime contractor as an obstacle to efficient work accomplishment. The potential difficulties associated with properly accomplishing instrumentation work when a prime contractor-subcontractor situation exists (such as coordination of activities and timely, effective communication) must be recognized and planned for in advance.

Reclamation construction inspection personnel assigned to the instrumentation work may have limited experience in the instrumentation area and may require substantial assistance, at least initially. It is important that this assistance be sought from, and fully provided by, Instrumentation Engineers in the Instrumentation and Inspections Group (Code 85-836000), as necessary, so that all aspects of the inspection work can be properly accomplished.

On major construction projects, Reclamation construction inspection personnel typically will be responsible for completing monthly reports regarding the instrumentation installation/construction work. These reports should fully document important aspects of the work, should be promptly provided to 85-836000 (Instrumentation and Inspections Group, TSC) personnel, and should cover the following subjects:

a. Work status
b. Problems and/or abnormalities
c. As-built information

d. Pictures
e. Instrument readings

At the conclusion of the work, Reclamation construction inspection personnel are to prepare a final Technical Report of Construction that fully addresses the following topics regarding the instrumentation installations:

a. Materials and equipment actually installed
b. Records of preinstallation testing of equipment (functional testing and calibration testing)
c. Drill logs for instrument holes
d. Record test information
e. Problems and/or abnormalities
f. Deviations or modifications from specifications
g. Contractor claims
h. Pictures
i. As-built drawings and complete as-built information
j. Comments, criticisms, and suggestions for future work
k. All construction instrumentation readings

Information regarding the issues discussed above can be integrated into the main body of the Technical Report of Construction or prepared as a separate appendix to the report.

11.10.4 Instrumentation Installation/Construction Considerations – For Construction Done by Reclamation Personnel

11.10.4.1 Field Exploration Request

A Field Exploration Request (FER) is one mechanism for defining instrumentation installation/construction work to be performed by Reclamation personnel. Development of the FER is a team effort, which is led by the Principal Geologist for the dam. All members of the team, including the Instrumentation Engineer from the Instrumentation and Inspections Group (Code 85-836000) and the Principal Engineer for the dam, agree on and sign off on the completed FER before it is transmitted. The Principal Geologist and the Instrumentation Engineer work together to ensure that appropriate information is included in the FER so that the desired instrumentation installation/construction work can be accomplished as intended. In many instances, the FER includes some flexibility in the exact instrument locations, elevations, details, etc., so that information gathered during the actual exploration drilling can be considered in selecting the final plans for the instrument installations. The Principal Geologist works closely first with field personnel to obtain the necessary exploration information, and then with the Instrumentation Engineer to finalize the instrumentation design details.

Following completion of the FER, a report documenting the work needs to be prepared by the field office responsible for carrying out the work. Information comparable to a final Technical Report of Construction (discussed in the previous section) should be provided in the FER final report relative to the instrumentation installation/construction work.

11.10.4.2 Other

Reclamation personnel sometimes carry out instrumentation installation/ construction work in response to Safety of Dams (SOD) recommendations or Operations and Maintenance (O&M) recommendations, or for other reasons. In these situations, field personnel needs to communicate with the Instrumentation Engineer from the Instrumentation and Inspections Group (Code 85-836000) assigned to the dam so that appropriate installations are provided, and the Instrumentation Engineer needs to provide all necessary support to field personnel who carry out the work.

Following completion of the instrumentation installation/construction work, a report documenting the work is prepared by the field office responsible for carrying out the work. The report should provide information comparable to a final Technical Report of Construction (discussed in the previous section).

11.11 Instrumentation Maintenance Considerations

While most instruments do not require much or any maintenance, there are some noteworthy instrumentation maintenance issues:

a. **Hydraulic piezometer installations.** These installations require significant maintenance work on an annual basis, including flushing the lines and obtaining master gauge check readings for each of the separate gauges. This work is described in Reclamation's *Operations and Maintenance Guidelines for Hydraulic Piezometer Installations at Dams* (current version dated June 7, 2005).

b. **Weirs.** The flow surface of the weir needs to be kept clean and free of debris so that the water "springs" off the weir blade and accurate data can be collected.

c. **Weir boxes and stilling pools associated with weirs.** Evidence of sediment transport by seepage flow is direct evidence that a seepage-related internal erosion failure mode has initiated and is progressing. Therefore, it is very important to know that any collected sediments in a weir box, or a stilling pool associated with a weir, definitively came from the flowing water, as opposed to being carried in by surface runoff or wind. Weir box walls and other walls must be high enough to prevent surface runoff from flowing into weir stilling pools, and covers should be provided, when appropriate, to prevent significant quantities of windblown materials from being carried into weir stilling pools.

d. **Barriers and markers**. Barriers and markers should be provided, as appropriate, and maintained to protect instrumentation installations from damage.

e. **Vandalism protection.** Appropriate vandalism protection is needed at all instrumentation installations. For example, all open-standpipe piezometer installations and inclinometer installations should have lockable protective casings. All entrances (windows, where applicable, and doors) of instrument houses, terminal wells, inspection wells, etc., should be appropriately secured.

All instrumentation installations need to conform to *Reclamation Safety and Health Standards* and to all applicable Occupational Safety and Health Administration (OSHA) standards. It is important that confined space signage be provided and maintained where needed at hydraulic piezometer terminal wells, toe drain inspection wells, relief well inspection wells, etc., to appropriately warn people that they are entering a confined space, and that they need to take all the required safety measures associated with entering a confined space (including use of appropriate air monitoring equipment).

11.12 Monitoring Information – Data Collection and Transmittal

11.12.1 General

Instruments can be manually read, or automation equipment can be employed to automatically read the instruments.

For instruments that are manually read, the instrumentation data can be transmitted to the Instrumentation and Inspections Group (Code 85-836000) in several ways:

- Mail
- Fax
- Email

- Direct entry into the 85-836000 instrumentation computer system called DAMS (Data Acquisition and Management System)

For instruments that are read by automation equipment, the situation is more complicated and is discussed below in Section 11.12.3, "Automated Instrument Readings."

The following two sections provide discussion about options and issues associated with manual and automated instrumentation data collection and transmittal.

11.12.2 Manual Instrument Readings

The procedure for obtaining manual instrument readings is obvious and straightforward, with one exception. It is important that at the time the instrument reading is being made, the instrument reader has the ability to immediately determine if the reading is anomalous. This is particularly significant for instruments with data that are affected by the reservoir level (such as seepage flows and water pressure readings), where the instrument's performance limits are equations that are a function of the reservoir level. This capability is important for two reasons:

- If an error is made in the reading, and not immediately caught, there can be a lot of wasted time and effort associated with investigating the situation and correcting the problem.

- If an anomalous reading is, in fact, correct, there can be a lot of time wasted before the situation is recognized as a matter of concern that needs to be responded to.

It is very desirable for the instrument reader to be able to immediately check instrument readings to determine if they are unusual. Such data checks occur via computer at the time the data are entered into Reclamation's instrumentation computer system. However, a check at that time does not help the instrument reader while he is at the instrument collecting the data, ready to take a re-read if necessary, ready to check around the area for unusual conditions, etc. Several approaches are possible to address this need and allow immediate performance limit checks on instrument readings:

- **Graphs.** A plot of the expected performance limits for each instrument are presented on a graph, with reservoir level as the x-axis and the raw instrument reading as the y-axis. In practice, this approach is slow, clumsy, and not very user-friendly, but it can be used.

- **Spreadsheet-created data collection forms.** When data collection work is to be performed, first the reservoir level is determined and entered into the spreadsheet. Then a spreadsheet-created data collection form is printed that indicates the performance limits for each instrument in the raw reading units. When the instrument reader reads an instrument, the reading is written on the form between columns showing the upper and lower performance limits, so a quick check on the reading can be easily performed.

- **Handheld devices.** When data collection work is to be performed, first the reservoir level is determined and entered into the hand-held device. When the instrument reader reads an instrument, the reading is entered into the handheld device, which gives immediate feedback that allows the reader to know if the reading falls within the performance limits.

As noted previously, for instruments that are manually read, the instrumentation data can be transmitted to 85-836000 by mail, fax, email, or direct entry into DAMS. When the last option is used, the person entering the data can see if any readings are outside the instrument performance limits (but obviously not at the moment the instrument readings were made).

Some issues associated with manual readings of instruments:

a. **Perform a data check at the time the reading is taken.** The discussion above mentions methods that can be used to get an immediate check with respect to the instrument's performance limits. Without this level of checking, the instrument reader can at least use the previous reading for a check to identify clearly anomalous or erroneous data. Verified anomalous data warrant immediate phone communication to 85-836000 personnel.

b. **Be alert to other items, and report other relevant information.** The most obvious example of information that must be reported is evidence of material transport by seepage flow at the time a seepage reading is obtained, such as turbid water or sediment deposits in weir boxes, along flow paths, etc. Anything out of the ordinary is worth noting and reporting, such as a whistling sound coming from an instrument standpipe, an odd smell, a bent instrument standpipe, etc.

c. **Safety.** Proper procedures should be used when entering confined spaces, such as hydraulic piezometer terminal wells, toe drain inspection wells, relief well inspection wells, etc. Hazards associated with footing, rockfall areas, etc., should not be ignored and may warrant corrective measures or instrumentation automation, depending on the circumstances.

d. **Report dry open-standpipe piezometers and zero seepage readings.** These are readings. Knowing that the top of water level is somewhere below the piezometer's tip elevation is useful information that can be appropriately presented on an instrumentation data plot. For a seepage monitoring installation, a blank space on a data form gives the indication that no reading was taken, as opposed to indicating that zero flow was seen at the time a reading was obtained.

e. **Do not panic if a probe is stuck.** If an inclinometer probe, IVM probe, baseplate probe, etc., gets stuck in the pipe, the first reaction sometimes is to give the line a really forceful pull. However, if the line gets broken, the problem gets much worse. Calm problem-solving is the desired first reaction to a stuck probe, rather than a reflexive, brute force approach.

11.12.3 Automated Instrument Readings

Section 11.9.10, "Automation of Instrumentation," presents information about the design of automation systems for instrumentation. The discussion includes detailed information about how automation systems collect data, which will not be repeated here. The four most common arrangements for transmitting the collected data to the Instrumentation and Inspections Group (Code 85-836000) are:

- The data are transmitted by satellite to a Reclamation computer in the Pacific Northwest Regional Office in Boise, Idaho, and the data are subsequently transferred to the 85-836000 instrumentation computer system DAMS (Data Acquisition and Management System). This data transfer can be accomplished in several different ways: (1) personnel operating the Hydromet system in Boise attach one or more files to an email message that is sent to 85-836000 personnel, who then enter the data into DAMS; (2) 85-836000 personnel remotely retrieve the data from the Boise computer and enter the data into DAMS; or (3) an 85-836000 computer automatically retrieves the data at some prescribed frequency and emails it to 85-836000 personnel, who then enter the data into DAMS.

- The data are periodically downloaded by remote computer connection via telephone line with a datalogger, and the datafile is subsequently transferred into DAMS.

- The data are periodically downloaded by onsite temporary computer connection to a datalogger, and the datafile is subsequently emailed to 85-836000 for entry into DAMS.

- A data storage device or canister is periodically swapped out from a datalogger, and it is shipped to 85-836000, so that the data can be downloaded into DAMS. Alternatively, the datalogger itself can be swapped out for data retrieval.

For Reclamation dams, it is important to recognize that where an automation system is used to collect instrumentation data, DAMS does not currently provide real-time access to the data collected. The collected data needs to be periodically “manually” brought over (transferred) to DAMS. An automatic capability to bring the data from a receiving server into DAMS real-time could be developed, but this capability does not currently exist. While this might seem like a significant deficiency, actually it is not. It just means that the automation system at the dam site is the computer that needs to be programmed to do any desired real-time checking of the data against performance limits, and issuing of alarm messages by email, texting, fax, automated phone call, etc. DAMS is simply a repository for saving all the collected data for future analysis.

11.13 Monitoring Information – Review and Evaluation Process

11.13.1 General

The evaluation of instrumentation data typically falls into two general categories: (1) immediate reviews performed promptly after readings are obtained, and (2) periodic in-depth reviews. These are discussed in the following two sections, followed by more specific discussion of the evaluation of: (1) water pressure data; (2) earth pressure data; (3) deformation data; and (4) seepage and drain flow data.

11.13.2 Immediate Review of Data

The immediate review of monitoring data and information is necessarily somewhat cursory in nature because the basic goal is to pick up any noteworthy anomalies in a timely manner. Much data needs to be reviewed in a short timeframe. Using computer-generated plots, comparison sheets, etc., can greatly increase the efficiency and effectiveness of this work.

11.13.3 Periodic In-Depth Review of Data

Instrumentation data can be most usefully evaluated only if the reasons for installing the instruments are fully known and understood. At the time of design of an instrumentation system, the reasoning behind design decisions and the instrumentation program should be fully documented. Expected readings from the instruments should also be indicated, or at a minimum, thought through, as part of the design process. After first filling of the reservoir, the design expectations can be checked against actual performance, and any significant disparities can be studied and evaluated with respect to dam performance repercussions.

Engineering calculations and back analysis can be performed using collected instrumentation data to help assess when dam performance is acceptable or unacceptable. The back analysis is usually a deterministic analysis, but it can also be performed in a risk context. Sensitivity studies may be performed with respect to key parameters.

Periodic in-depth reviews should involve a careful, comprehensive review of the instrumentation program and data. These reviews should draw on all information that is available when evaluating and interpreting the data.

11.13.4 Evaluation of Water Pressure Data

In reviewing water pressure information obtained from observation wells, open-standpipe piezometers, hydraulic piezometers, pneumatic piezometers, vibrating-wire piezometers, fiber-optic piezometers, and/or other instruments, questions that might be relevant to evaluate include the following:

- How effective are the grout curtain and/or any other seepage control features?

- Do drainage features (e.g., blanket drains, relief wells, horizontal drains, etc.) appear to be free draining and effective?

- Are water pressure patterns at the dam site in line with expectations, both in terms of absolute pressure magnitudes and pressure gradients?

- Are changes in water pressures predictable and understandable?

- Are there any disturbing trends with time regarding the water pressure data, either increases or decreases?

- Is the instrument response to changes in reservoir elevation consistent with the absolute levels of water pressures recorded at the instrument? If not, is the lag in the response to reservoir level changes caused by the instrument due to embankment saturation/desaturation or both?

- Are there any (elevated) construction pore water pressures evident?

- Is the dissipation of construction pore water pressures in line with expectations?

It is generally useful to plot water pressures that are recorded at an instrument against the reservoir elevation to gain greater insight into the data. Doing so allows the correlation of the instrument's readings to changing reservoir levels to clearly be seen.

Where there are at least several instruments located at or close to a transverse section through the dam, it is often useful to present piezometric water surface elevation data on a cross-section drawing that also shows the site geology and embankment features and configuration associated with that section.

If there are concerns regarding slope stability (dam's slopes, abutment slopes, and/or slopes in the reservoir rim area), water pressure data can be used to help determine water pressures and effective stresses along potential failure surfaces.

Water pressure data are sometimes important relative to foundation and/or abutment materials having the potential to collapse upon saturation, or where uplift or potential blowout may be a concern.

For potential liquefaction concerns, water pressure information can be useful to determine if materials are saturated and, therefore, potentially susceptible to liquefaction. Water pressure data obtained immediately following an earthquake can also help determined whether liquefaction has apparently occurred and to what degree.

11.13.5 Evaluation of Earth Pressure Data

In reviewing earth pressure information obtained from pneumatic total pressure cells, vibrating-wire total pressure cells, and/or other instruments, questions that might be relevant to evaluate include the following:

- Are the pressures in line with expectations?
- Are the pressures changing with time, and if so, are the changes predictable and understandable?

11.13.6 Evaluation of Deformation Data

In reviewing deformation data obtained from surface measurement points, IVM (internal vertical movement) installations, baseplates, inclinometers, tiltmeters, shear strips, settlement sensors, surveys, multipoint extensometers, and/or other instruments, questions that might be relevant to evaluate include the following:

- Is design freeboard being maintained? (Do settlements exceed camber?)
- Are there any indications of slope instability regarding the embankment slopes, abutment slopes, or slopes along the rim of the reservoir?
- Are there differential movements that could cause internal cracking of the embankment?
- Are there absolute and/or differential movements that could affect the performance or integrity of any appurtenant structures?
- Are foundation settlements in line with expectations?
- Are patterns and magnitudes of embankment compression in line with expectations?
- Are rates of movement decreasing with time?
- Does the sum of the post-construction embankment compression and foundation settlement approximately equal settlements recorded at embankment measurement points?
- Are there anomalous deformations that could indicate subsurface erosion of material by seepage flow?

Regarding seismic issues, interest can center on potential liquefaction of embankment and/or foundation materials, and on the structure’s ability to withstand strong motion shaking without excessive displacements. Deformation data can be useful in assessing the effects and displacements that occurred at a structure due to a seismic event (whether or not liquefaction occurred).

11.13.7 Evaluation of Seepage and Drain Flow Data

In reviewing seepage and drain flow data obtained from bucket and stopwatch monitoring, weirs, flumes, water samples, geophysical methods, etc., questions that might be relevant to evaluate include the following:

- Is there any evidence of possible internal erosion or piping of materials by seepage flows (such as apparently discolored seepage flow, or sediment deposits in inspection wells, in front of weirs, in weir boxes, along flow paths, etc.)?

- How do the seepage and drain flow quantities compare with design estimates?
- Are seepage and drain flow quantities excessive for the conditions?
- Are seepage and drain flow quantities predictable and consistent for a given reservoir elevation (with other relevant parameters held constant as well)?
- Do any drainage features (e.g. relief wells, horizontal drains, etc.) appear to be losing efficiency or effectiveness?
- Are the patterns of subsurface seepage in line with expectations, and are they consistent over time?
- Is the size and appearance of any downstream wet areas predictable (considering the reservoir level, time of year, weather conditions, etc.) and basically consistent over time?

It is frequently useful to plot seepage flow rates against the reservoir elevation to gain greater insight into the data.

For potential liquefaction concerns, seepage information can be useful to address questions concerning whether liquefaction has apparently occurred. For instance, the observation of water emanating from the ground surface near the toe of a dam could be due to "excess water" exiting to relieve high subsurface water pressures created by liquefaction of materials.

11.14 References

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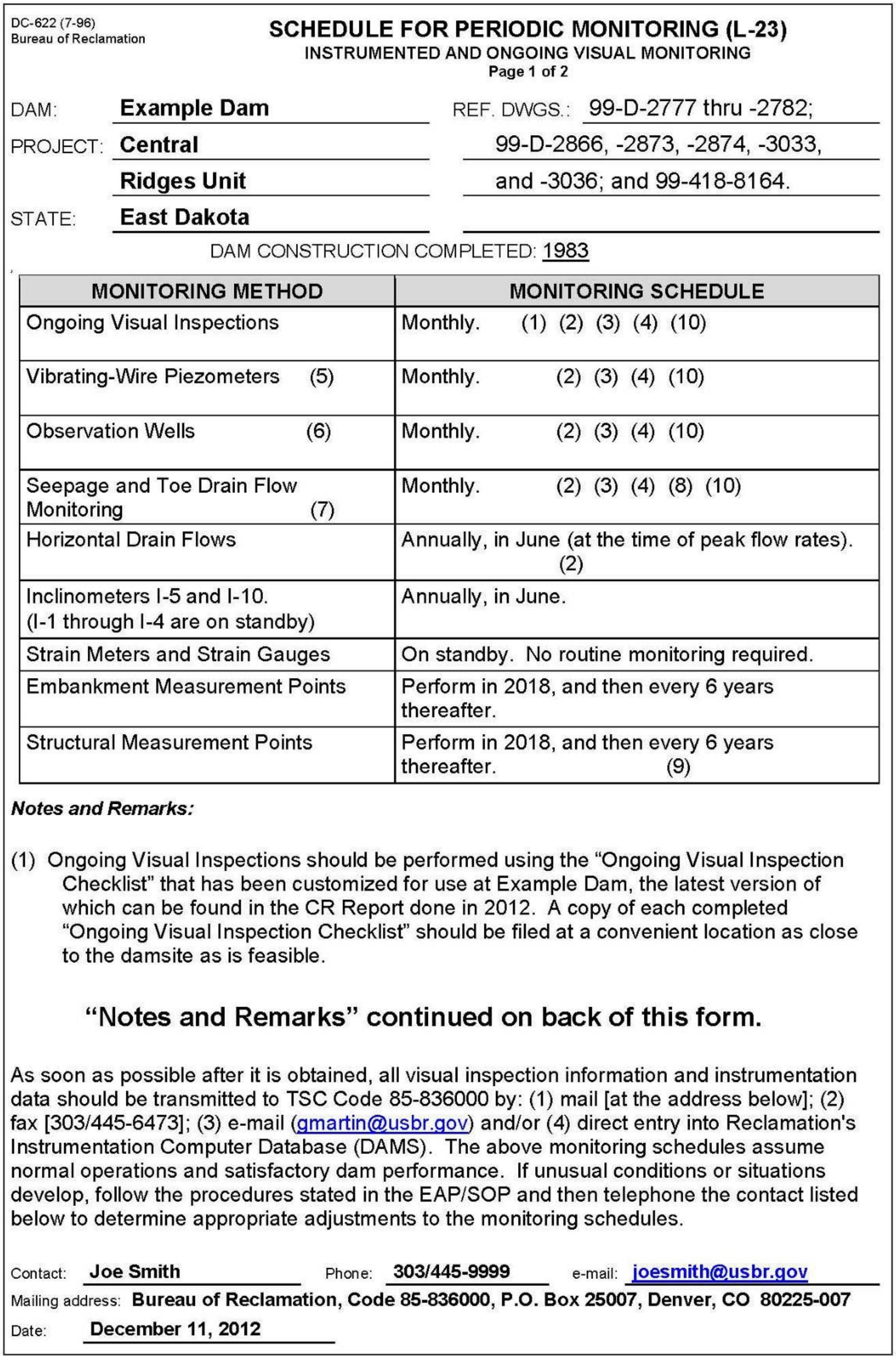
Appendix A

Example Forms

1. Schedule for Periodic Monitoring (L-23)

2. Ongoing Visual Inspection Checklist (OVIC)



DC-622 (7-96)
Bureau of Reclamation

SCHEDULE FOR PERIODIC MONITORING (L-23)

INSTRUMENTED AND ONGOING VISUAL MONITORING

Page 1 of 2

DAM: **Example Dam**
PROJECT: **Central Ridges Unit**
STATE: **East Dakota**
REF. DWGS.: 99-D-2777 thru -2782; 99-D-2866, -2873, -2874, -3033, and -3036; and 99-418-8164.

DAM CONSTRUCTION COMPLETED: 1983

MONITORING METHOD	MONITORING SCHEDULE
Ongoing Visual Inspections	Monthly. (1) (2) (3) (4) (10)
Vibrating-Wire Piezometers (5)	Monthly. (2) (3) (4) (10)
Observation Wells (6)	Monthly. (2) (3) (4) (10)
Seepage and Toe Drain Flow Monitoring (7)	Monthly. (2) (3) (4) (8) (10)
Horizontal Drain Flows	Annually, in June (at the time of peak flow rates). (2)
Inclinometers I-5 and I-10. (I-1 through I-4 are on standby)	Annually, in June.
Strain Meters and Strain Gauges	On standby. No routine monitoring required.
Embankment Measurement Points	Perform in 2018, and then every 6 years thereafter.
Structural Measurement Points	Perform in 2018, and then every 6 years thereafter. (9)

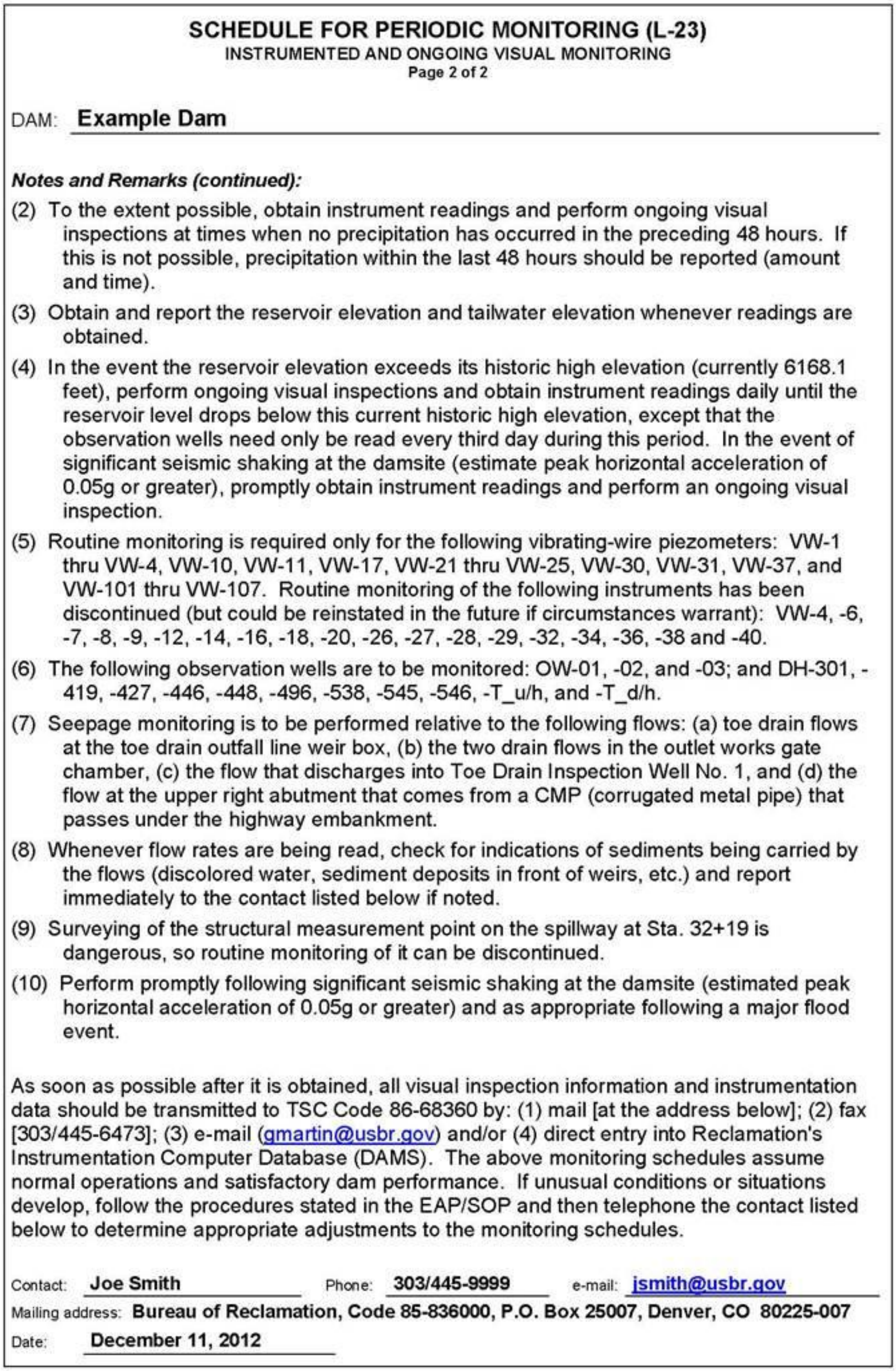
Notes and Remarks:

(1) Ongoing Visual Inspections should be performed using the “Ongoing Visual Inspection Checklist” that has been customized for use at Example Dam, the latest version of which can be found in the CR Report done in 2012. A copy of each completed “Ongoing Visual Inspection Checklist” should be filed at a convenient location as close to the damsite as is feasible.

“Notes and Remarks” continued on back of this form.

As soon as possible after it is obtained, all visual inspection information and instrumentation data should be transmitted to TSC Code 85-836000 by: (1) mail [at the address below]; (2) fax [303/445-6473]; (3) e-mail (gmartin@usbr.gov) and/or (4) direct entry into Reclamation's Instrumentation Computer Database (DAMS). The above monitoring schedules assume normal operations and satisfactory dam performance. If unusual conditions or situations develop, follow the procedures stated in the EAP/SOP and then telephone the contact listed below to determine appropriate adjustments to the monitoring schedules.

Contact: **Joe Smith** Phone: **303/445-9999** e-mail: **joesmith@usbr.gov**
Mailing address: **Bureau of Reclamation, Code 85-836000, P.O. Box 25007, Denver, CO 80225-007**
Date: **December 11, 2012**



SCHEDULE FOR PERIODIC MONITORING (L-23)

INSTRUMENTED AND ONGOING VISUAL MONITORING

Page 2 of 2

DAM: **Example Dam**

Notes and Remarks (continued):

(2) To the extent possible, obtain instrument readings and perform ongoing visual inspections at times when no precipitation has occurred in the preceding 48 hours. If this is not possible, precipitation within the last 48 hours should be reported (amount and time).

(3) Obtain and report the reservoir elevation and tailwater elevation whenever readings are obtained.

(4) In the event the reservoir elevation exceeds its historic high elevation (currently 6168.1 feet), perform ongoing visual inspections and obtain instrument readings daily until the reservoir level drops below this current historic high elevation, except that the observation wells need only be read every third day during this period. In the event of significant seismic shaking at the damsite (estimate peak horizontal acceleration of 0.05g or greater), promptly obtain instrument readings and perform an ongoing visual inspection.

(5) Routine monitoring is required only for the following vibrating-wire piezometers: VW-1 thru VW-4, VW-10, VW-11, VW-17, VW-21 thru VW-25, VW-30, VW-31, VW-37, and VW-101 thru VW-107. Routine monitoring of the following instruments has been discontinued (but could be reinstated in the future if circumstances warrant): VW-4, -6, -7, -8, -9, -12, -14, -16, -18, -20, -26, -27, -28, -29, -32, -34, -36, -38 and -40.

(6) The following observation wells are to be monitored: OW-01, -02, and -03; and DH-301, -419, -427, -446, -448, -496, -538, -545, -546, -T_u/h, and -T_d/h.

(7) Seepage monitoring is to be performed relative to the following flows: (a) toe drain flows at the toe drain outfall line weir box, (b) the two drain flows in the outlet works gate chamber, (c) the flow that discharges into Toe Drain Inspection Well No. 1, and (d) the flow at the upper right abutment that comes from a CMP (corrugated metal pipe) that passes under the highway embankment.

(8) Whenever flow rates are being read, check for indications of sediments being carried by the flows (discolored water, sediment deposits in front of weirs, etc.) and report immediately to the contact listed below if noted.

(9) Surveying of the structural measurement point on the spillway at Sta. 32+19 is dangerous, so routine monitoring of it can be discontinued.

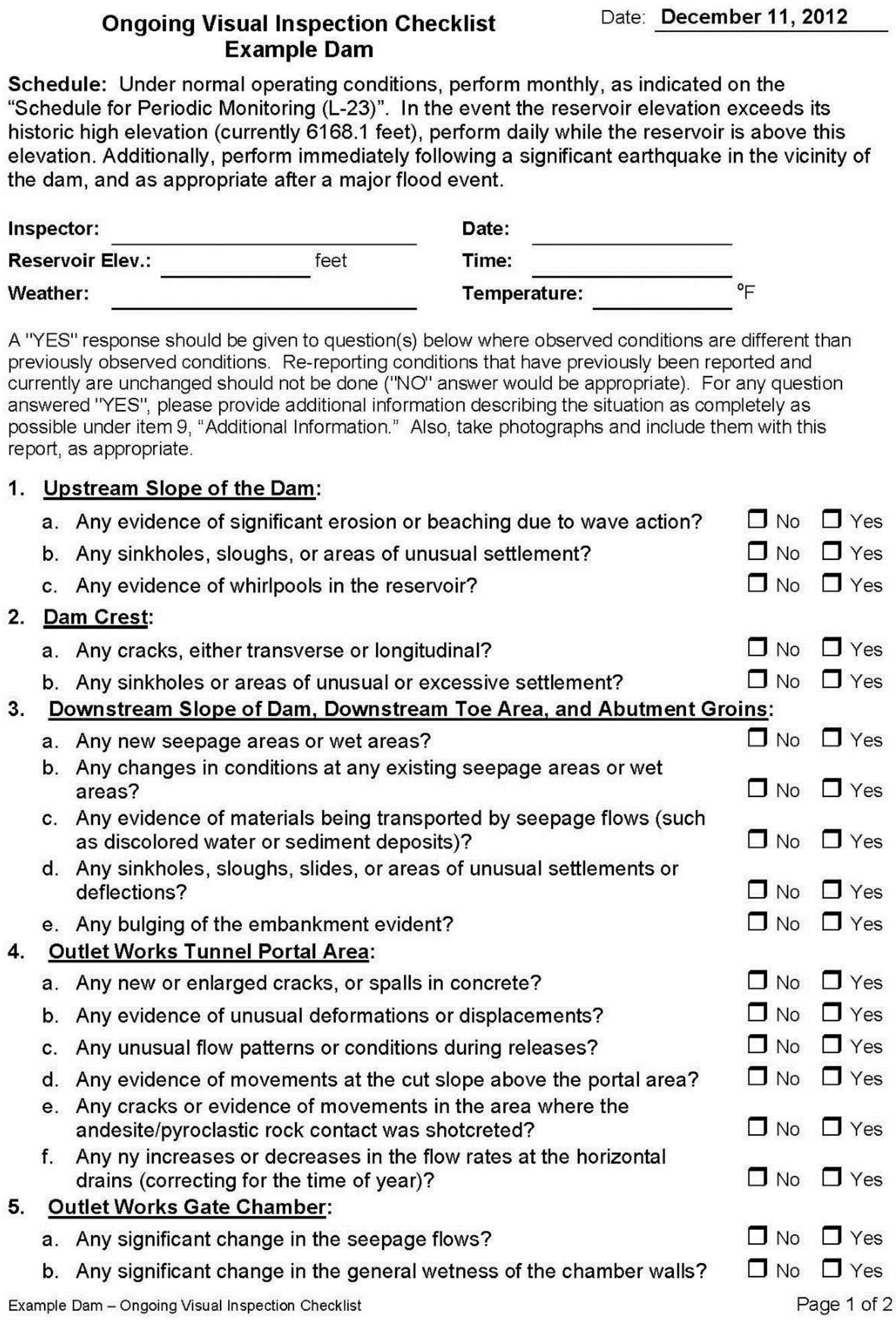
(10) Perform promptly following significant seismic shaking at the damsite (estimated peak horizontal acceleration of 0.05g or greater) and as appropriate following a major flood event.

As soon as possible after it is obtained, all visual inspection information and instrumentation data should be transmitted to TSC Code 86-68360 by: (1) mail [at the address below]; (2) fax [303/445-6473]; (3) e-mail (gmartin@usbr.gov) and/or (4) direct entry into Reclamation's Instrumentation Computer Database (DAMS). The above monitoring schedules assume normal operations and satisfactory dam performance. If unusual conditions or situations develop, follow the procedures stated in the EAP/SOP and then telephone the contact listed below to determine appropriate adjustments to the monitoring schedules.

Contact: **Joe Smith** Phone: **303/445-9999** e-mail: **jsmith@usbr.gov**

Mailing address: **Bureau of Reclamation, Code 85-836000, P.O. Box 25007, Denver, CO 80225-007**

Date: **December 11, 2012**



Ongoing Visual Inspection Checklist
Example Dam

Date: **December 11, 2012**

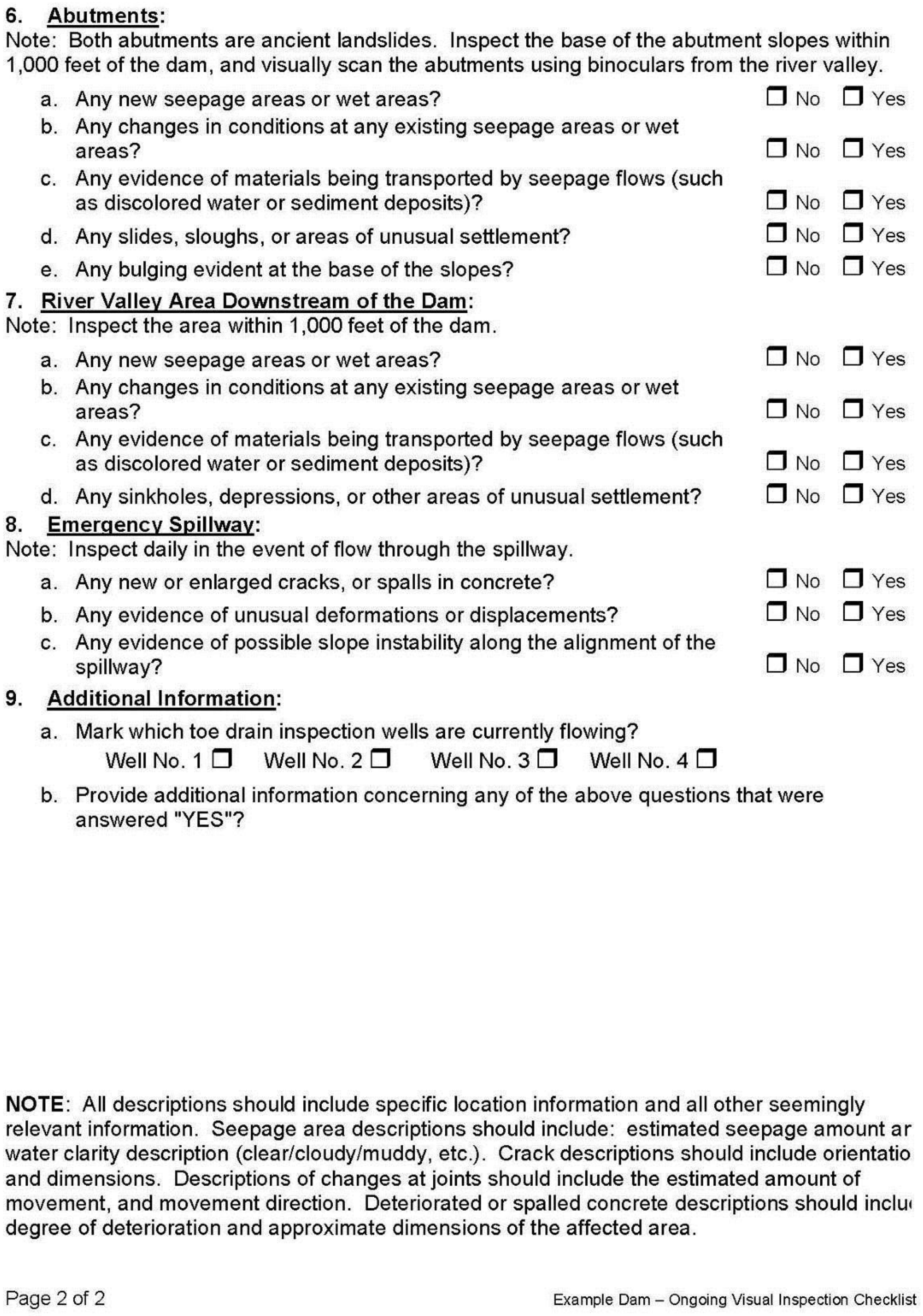
Schedule: Under normal operating conditions, perform monthly, as indicated on the "Schedule for Periodic Monitoring (L-23)". In the event the reservoir elevation exceeds its historic high elevation (currently 6168.1 feet), perform daily while the reservoir is above this elevation. Additionally, perform immediately following a significant earthquake in the vicinity of the dam, and as appropriate after a major flood event.

Inspector: ____________________ **Date:** ____________
Reservoir Elev.: __________ feet **Time:** ____________
Weather: ____________________ **Temperature:** __________ °F

A "YES" response should be given to question(s) below where observed conditions are different than previously observed conditions. Re-reporting conditions that have previously been reported and currently are unchanged should not be done ("NO" answer would be appropriate). For any question answered "YES", please provide additional information describing the situation as completely as possible under item 9, "Additional Information." Also, take photographs and include them with this report, as appropriate.

1. **Upstream Slope of the Dam**:
   - a. Any evidence of significant erosion or beaching due to wave action? ☐ No ☐ Yes
   - b. Any sinkholes, sloughs, or areas of unusual settlement? ☐ No ☐ Yes
   - c. Any evidence of whirlpools in the reservoir? ☐ No ☐ Yes
2. **Dam Crest**:
   - a. Any cracks, either transverse or longitudinal? ☐ No ☐ Yes
   - b. Any sinkholes or areas of unusual or excessive settlement? ☐ No ☐ Yes
3. **Downstream Slope of Dam, Downstream Toe Area, and Abutment Groins**:
   - a. Any new seepage areas or wet areas? ☐ No ☐ Yes
   - b. Any changes in conditions at any existing seepage areas or wet areas? ☐ No ☐ Yes
   - c. Any evidence of materials being transported by seepage flows (such as discolored water or sediment deposits)? ☐ No ☐ Yes
   - d. Any sinkholes, sloughs, slides, or areas of unusual settlements or deflections? ☐ No ☐ Yes
   - e. Any bulging of the embankment evident? ☐ No ☐ Yes
4. **Outlet Works Tunnel Portal Area**:
   - a. Any new or enlarged cracks, or spalls in concrete? ☐ No ☐ Yes
   - b. Any evidence of unusual deformations or displacements? ☐ No ☐ Yes
   - c. Any unusual flow patterns or conditions during releases? ☐ No ☐ Yes
   - d. Any evidence of movements at the cut slope above the portal area? ☐ No ☐ Yes
   - e. Any cracks or evidence of movements in the area where the andesite/pyroclastic rock contact was shotcreted? ☐ No ☐ Yes
   - f. Any ny increases or decreases in the flow rates at the horizontal drains (correcting for the time of year)? ☐ No ☐ Yes
5. **Outlet Works Gate Chamber**:
   - a. Any significant change in the seepage flows? ☐ No ☐ Yes
   - b. Any significant change in the general wetness of the chamber walls? ☐ No ☐ Yes

Example Dam – Ongoing Visual Inspection Checklist Page 1 of 2



6. Abutments:

Note: Both abutments are ancient landslides. Inspect the base of the abutment slopes within 1,000 feet of the dam, and visually scan the abutments using binoculars from the river valley.

a. Any new seepage areas or wet areas? ☐ No ☐ Yes

b. Any changes in conditions at any existing seepage areas or wet areas? ☐ No ☐ Yes

c. Any evidence of materials being transported by seepage flows (such as discolored water or sediment deposits)? ☐ No ☐ Yes

d. Any slides, sloughs, or areas of unusual settlement? ☐ No ☐ Yes

e. Any bulging evident at the base of the slopes? ☐ No ☐ Yes

7. River Valley Area Downstream of the Dam:

Note: Inspect the area within 1,000 feet of the dam.

a. Any new seepage areas or wet areas? ☐ No ☐ Yes

b. Any changes in conditions at any existing seepage areas or wet areas? ☐ No ☐ Yes

c. Any evidence of materials being transported by seepage flows (such as discolored water or sediment deposits)? ☐ No ☐ Yes

d. Any sinkholes, depressions, or other areas of unusual settlement? ☐ No ☐ Yes

8. Emergency Spillway:

Note: Inspect daily in the event of flow through the spillway.

a. Any new or enlarged cracks, or spalls in concrete? ☐ No ☐ Yes

b. Any evidence of unusual deformations or displacements? ☐ No ☐ Yes

c. Any evidence of possible slope instability along the alignment of the spillway? ☐ No ☐ Yes

9. Additional Information:

a. Mark which toe drain inspection wells are currently flowing?

Well No. 1 ☐ Well No. 2 ☐ Well No. 3 ☐ Well No. 4 ☐

b. Provide additional information concerning any of the above questions that were answered "YES"?

NOTE: All descriptions should include specific location information and all other seemingly relevant information. Seepage area descriptions should include: estimated seepage amount ar water clarity description (clear/cloudy/muddy, etc.). Crack descriptions should include orientatio and dimensions. Descriptions of changes at joints should include the estimated amount of movement, and movement direction. Deteriorated or spalled concrete descriptions should inclu degree of deterioration and approximate dimensions of the affected area.

Page 2 of 2 Example Dam – Ongoing Visual Inspection Checklist