United States Society on Dams

Operation and Maintenance of an Instrumentation Program

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Prepared by the USSD Committee on Monitoring of Dams
and Their Foundations

U.S. Society on Dams

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FOREWORD

The importance of monitoring programs for dam safety is widely accepted. There are many historical cases of dam failures where early warning signs of failure might have been detected if an effective dam safety monitoring program had been in place. A monitoring program can provide information that is needed for a solid understanding of the on-going performance of a dam. Monitoring programs, including instrumentation and visual inspection, provide dam owners with knowledge that a dam is performing as expected, and the ability to detect a change in performance. This knowledge and ability is critical because the dam owner is directly responsible for the consequences of a dam failure. Therefore, an effective dam safety monitoring program should be a key part of every dam owner's risk management program.

This paper is part of a series of White Papers by the USSD Committee on Monitoring of Dams and Their Foundations to address important topics with respect to the development and successful implementation of dam safety monitoring programs:

- Why Include Instrumentation in Dam Monitoring Programs?
- Development of an Instrumentation Program
- Instrumentation Data Collection, Management and Analysis
- Operation and Maintenance (O&M) of an Instrumentation Program
- Routine Instrumented and Visual Monitoring of Dams Based on Potential Failure Modes Analysis

While each of the above White Papers addresses its topic in a "stand-alone" manner, there are interrelationships between these papers. Readers of this paper may find it beneficial to refer to one or more of the other White Papers for a broader understanding and perspective with respect to dam safety monitoring programs.

This series of White Papers primarily addresses the programmatic aspects of instrumentation for dam safety monitoring rather than technological advances in instruments. These papers should provide dam owners, large and small, with basic information needed to evaluate or implement an adequate dam safety monitoring program. These programs become more and more critical as our nation's dams, and other infrastructure, reach and extend beyond their design lives.

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1.0 INTRODUCTION

1.1 Overview

A well-maintained, properly-operated dam instrumentation monitoring program combined with an adequate visual inspection program (often termed a 'surveillance and monitoring program') can detect adverse dam performance in a timely fashion, and allow appropriate actions to be taken to avoid potential dam failure. Instrumentation provides a window into dam performance that may indicate developing adverse conditions that are not readily visible. However, proper and regular operation and maintenance of an instrumentation system are required for effectiveness and are vital to the safe operation of a dam.

Quality instrumentation data provide an important historical record for each project feature. The historical record can help to reduce risks if the instrumentation program is implemented and managed appropriately. As such, it is important that all aspects of the monitoring program are performed with care, beginning with design of the program and installation of the instrumentation and continuing through operation and maintenance of the monitoring system over the life of the project.

To provide reliable information, the dam safety instrumentation program must be properly planned, installed, monitored, and maintained, and the instrumentation data must be collected, validated, evaluated, and documented on a regular schedule by qualified individuals.

Once data have been collected, the data must be evaluated and reviewed promptly by those who understand the implications of the results. Data evaluation results should be shared with all staff responsible for the dam including management, engineering, operations, and construction staff, as applicable. If data are not evaluated promptly, then the opportunity to proactively manage a potential dam safety situation is lost.

The same rigor and diligence used in design and construction is needed during operation and maintenance to continuously evaluate project performance. Individuals responsible for the safe operation of a project cannot afford to become complacent. If the data show a potential problem, the amount of time available to appropriately investigate the problem could be limited. For example, a developing storm may accelerate the need for further investigation rather than allowing investigation to be done at a later, more convenient time.

This paper provides guidance to dam owners for operating and maintaining their instrumentation program and developing a project-specific dam safety instrumentation Operations and Maintenance (O&M) Manual.

1.2 Documentation

While it may be possible to operate and maintain a modest instrumentation program with little documentation and information about the program passed along through on-the-job training, formal documentation of the program in an Operations and Maintenance (O&M) Manual helps provide the individuals responsible for managing and implementing the program the information needed to understand their roles and responsibilities and apply the program as intended. Accurate and up-to-date documentation is particularly critical during staff transitions and can be a crucial reference during dam safety-related incidents. For simple programs, the O&M Manual may be no more than a few pages. However, note that length is not a key indicator of a successful document; the goal of such a document is to collect, organize, present, and maintain up to date key information in a format that is easily understood and usable by all involved with the operation and maintenance of a Project.

In the United States, federally owned and FERC-regulated dams are generally required to have four documents that link a Project's surveillance and monitoring program to Project-specific dam safety concerns. The names, organization, and content of these documents differ somewhat depending on the agency involved, but their collective intent is the same. These four documents include the Instrumentation Program O&M Manual, the Potential Failure Modes Analysis (PFMA) , the Surveillance and Monitoring Plan (SMP), and the Emergency Action Plan (EAP). The Instrumentation O&M Manual is described in more detail in this white paper. The PFMA documents the credible potential failure modes that form the basis for design and implementation of the surveillance and monitoring program and for evaluating anomalous results from visual or instrumented monitoring programs. The SMP describes the link between the most important identified potential failure modes and the associated surveillance and monitoring that are used to monitor these potential failure modes and that can help to identify initiation and development of the identified potential failure modes. The EAP describes the steps to be carried out in the event a failure mode is developing, to prevent or delay failure, reduce public safety risks, and mitigate damage from uncontrolled release of water. The EAP defines actions taken by the Owner including coordination with various levels of emergency management officials. Table 1 provides suggested references that can be used as guidance for development of these documents. Depending on the location and purpose of the project, some state-regulated dam owners may be required to develop and maintain these documents. For those instances where no specific guidance exists, Table 1 provides guidance to dam owners to help evaluate what documents may be needed for a given project. The documents listed in Table 1 are readily available sources of information which form the basis for many state dam safety programs as well as programs implemented by other federal entities including the National Park Service (NPS), U.S. Fish and Wildlife Service (USFWS), Bureau of Indian Affairs (BIA), Tennessee Valley Authority (TVA), and others including private owners, that own and operate dams.

Table 1: References to Develop Dam Operations Documents

Type of Document	Suggested References
Potential Failure Modes Analysis (PFMA)	• FERC[1], Engineering Guidelines for Evaluation of Hydropower Projects, Chapter 14 • USBR[2] Best Practices in Dam Safety (https://www.usbr.gov/ssle/damsafety/risk/methodology.html) • USACE[3] 1110-2-1156, Dam Safety Program (https://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1110-2-1156.pdf) • CDA[4] Dam Safety Guidelines • British Columbia: Operations/Inspection & Maintenance Guidelines (https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/drought-flooding-dikes-dams/dam-safety/technical-resources)
Surveillance and Monitoring Plan (SMP)	• FERC[1], Engineering Guidelines for Evaluation of Hydropower Projects, Chapter 14 • USBR[2] Best Practices in Dam Safety (https://www.usbr.gov/ssle/damsafety/risk/methodology.html) • USACE[3] 1110-2-1156, Dam Safety Program (https://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1110-2-1156.pdf) • CDA[4] Dam Safety Guidelines • BIA[5], Safety of Dams Program Handbook (https://www.bia.gov/sites/bia.gov/files/assets/public/raca/handbook/pdf/idc1-027631_1.pdf) • British Columbia: Operations/Inspection & Maintenance Guidelines (https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/drought-flooding-dikes-dams/dam-safety/technical-resources) • State Examples: Indiana (https://www.in.gov/dnr/water/files/Part-2-Dam_Safety_Manual.pdf)

Type of Document	Suggested References
Emergency Action Plan	• Federal Guidelines for Emergency Action Planning for Dams, FEMA Publication P-64 • FERC[1], Engineering Guidelines for Evaluation of Hydropower Projects, Chapter 6 • BIA[5], Safety of Dams Program Handbook (https://www.bia.gov/sites/bia.gov/files/assets/public/raca/handbook/pdf/idc1-027631_1.pdf) • British Columbia: Dam Emergency Planning Guidelines (https://www2.gov.bc.ca/gov/content/environment/air-land-water/water/drought-flooding-dikes-dams/dam-safety/technical-resources) • State Examples: Washington and Indiana (https://fortress.wa.gov/ecy/publications/documents/9222.pdf) (https://www.in.gov/dnr/water/files/Part-4-Dam_Safety_Manual.pdf).
Operation and Maintenance Manual	• State Examples: Washington and North Carolina (https://fortress.wa.gov/ecy/publications/documents/9255c.pdf), (https://files.nc.gov/ncdeq/Energy%20Mineral%20and%20Land%20Resources/Land%20Quality/Dam%20Safety/Dam_Operation_Maintenance_and_Inspection_Manual_rev_2006.pdf)

Notes:
[1] FERC = Federal Energy Regulatory Commission, [2] USBR = United States Bureau of Reclamation, [3] USACE = United Stated Corps of Engineers, [4] CDA = Canadian Dam Association, [5] BIA – Bureau of Indian Affairs

Instrumentation programs should be consciously designed based on the results of a Potential Failure Modes Analysis (PFMA) or other similar evaluation, and the design intent of the facility. The program design should include provisions for collection, storage, transmission and analysis of data, data review by qualified personnel, and an action plan to address readings/observations that exceed acceptable limits. The program design, including the process for establishing acceptable limits (termed by some agencies as action levels or threshold values, upper and lower limits, etc.), the associated actions when readings reach and/or exceed those acceptable limits, as well as the acceptable limits themselves, should be documented in a Surveillance and Monitoring Plan.

1.3 Personnel

The personnel responsible for operation of the instrumentation program should be qualified to do the work. Any person who will be reading instrumentation should be familiar with the project features and its instrumentation systems, each instrument's purpose and relationship to credible potential failure modes, reading, documentation, and evaluation procedures, and the use and importance of the data.

Where possible, these tasks should be assigned to permanent employees to improve reading consistency and lessen the need for repeating introductory training. Consistency also allows those persons to become familiar with the instruments and their typical reading range or response. Personnel reading instruments at a dam should be alert, observant and trained to note damage to the instruments or anomalous readings and to recognize visual clues to potential adverse dam safety conditions when they are at the dam site collecting instrumentation data and during general surveillance.

Personnel collecting data need to understand the significance of their work in terms of the overall project performance, and the importance of proper readings and evaluation. This may require formal training in:

1) How the dam and reservoir system works – what is retaining the water, where are stability concerns, how and why similar structures have failed, what seepage control measures have been constructed, what is the function, condition, and use of the outlet works and spillway(s), etc.
2) Purpose of the measurement system—why was it installed, and how is the data used.
3) The criticality of the data.
4) The system components.
5) How the instruments work.
6) How the instruments could fail or provide misleading data.
7) How the recording and transmission systems work.
8) How to collect and document the data.
9) What to do in the event of anomalous data.
10) How to store and transmit the data.
11) How to troubleshoot the systems.

This training is particularly important given that collection of data is usually performed by personnel who are not trained as dam engineers. Decisions that may be made based on the data collected from the instruments have the potential to impact life safety and property. Decisions protecting these interests can only be as certain as the data used to evaluate alternatives, and the data are only as good as the systems, equipment, and procedures used to collect it.

Personnel maintaining instruments should be properly trained in the maintenance of the instruments and the importance of their data. Maintenance tasks should be assigned to permanent employees, who may be the same personnel who collect the data, or may be more specialized electrical or electronic technicians, depending on the instrument(s). If possible, maintenance and data collection staff should report to the individual responsible for making decisions about dam safety.

Regular training of staff responsible for surveillance monitoring should be performed on a periodic basis to re-emphasize the importance of dam monitoring, re-confirm the proper procedures, address concerns that develop, and identify means of system and program improvement.

2.0 OPERATION

Operation of a dam monitoring system includes inspecting the instruments to look for damage, reading the instruments (manually or electronically), storing the data, transmitting the data to a central facility, interpreting the data, and taking appropriate actions. It is vital for personnel responsible for overall management of an instrumentation program to provide adequate resources for these activities. Failure to adequately perform any of these activities may result in failure of the monitoring system function.

2.1 Data Collection

Dam safety instruments are read either manually (e.g. by visual observation of a scale or gage or using a portable electrical readout unit) or using an automatic data acquisition system (ADAS). Instrument manufacturers provide detailed information regarding the proper reading methods to be used. This section includes general discussion regarding specific additional O&M manual content regarding data collection for both manually read instruments and instruments read using an ADAS. In all cases, the O&M manual should be prepared under the responsible charge of the individual(s) responsible for interpreting the data and making decisions based on the data.

2.1.1 *Manually Collected Data*

The O&M manual would typically include:

1) Roles and responsibilities for data collection, troubleshooting, and evaluation.

2) Frequency of readings for reporting/observation, including triggers for increasing the reading frequency during high water events, after an earthquake, or other unusual loading events.
3) Equipment required to read the instrument, how to access it, and how to use it.
4) Calibration/recalibration requirements for the instruments and readout unit(s).
5) A site plan and cross sections showing the instrument locations.
6) Instrument reading procedures.
7) Process to be used to identify abnormal data at the time readings are taken (i.e., take repeat readings; compare the new reading with instrument performance limits, established project performance limits, and the previous reading, etc.).
8) Proper response in the event of abnormal data (i.e., follow a chain of events to verify the reading, report the abnormal reading, increase the monitoring frequency of the instrument and other relevant instruments, and/or take other actions).
9) Procedures for how the reading is to be recorded, evaluated, and transmitted to others.

2.1.2 *Data Collected using an Automated Data Acquisition System (ADAS)*

The O&M manual would typically include:

1) Roles and responsibilities for data collection, troubleshooting, and evaluation.
2) Frequency of readings for reporting/observation, including triggers for increase of reading frequency during high water events, after an earthquake, or other unusual loading events.
3) Description of process used to determine recording frequency, setting alarms, and automatic or semi-automatic recording of data.
4) Documentation of the programming of the data logging equipment components.
5) How to collect/download data.
6) How to collect data manually as a backup to the automated system.
7) Documentation of custom-developed computer programs and explanation of program function.
8) Equations and other data used by software to convert raw instrument readings to meaningful engineering data.

9) Process to be used to identify abnormal data at the time readings are downloaded (i.e., compare readings with instrument performance limits, established project performance limits, and historic readings, etc.).
10) Proper response in the event of abnormal data (i.e., follow a chain of events to verify the reading, report the abnormal reading, increase the monitoring frequency of the instrument and other relevant instruments, and/or take other actions).
11) Procedures for how the reading is to be evaluated and transmitted to others.

The O&M manual should include a specific schedule for data collection, analysis, checking, and reporting. See the USSD White Paper titled *"Instrumentation Data Management and Analysis"* for more discussion regarding this topic.

2.1.3 *Mechanical Instruments: Special Considerations*

Some mechanical (manual) data collection methods are simple such as using a ruler to measure the distance between points on either side of a crack, or measuring flow rate using a calibrated container and stopwatch. Others require the use of manually-read mechanical instruments such as a staff gage for a weir, a vernier scale for a crackmeter, or an optical coordinoscope for a plumbline. These reading methods are generally reliable, but data quality may be impacted by mishandling or shocks incurred by the equipment. A short turn-around time between the time of reading and initial evaluation of the reading is highly recommended.

Comparison, at the time readings are obtained, with recent readings and established acceptable limits, is strongly recommended so that unusual variations can be detected immediately, and a second reading can be made to confirm the initial potentially anomalous reading. Including prior readings as well as established limits on the data collection form for easy reference and immediate comparison is a best practice that makes on-the-spot evaluation/assessment of newly obtained readings simple and straightforward. If a valid abnormal reading is indicated, investigation and evaluation can begin immediately per the procedures established for the Project. This can easily be accomplished by incorporating best practices, such as formatting paper records to incorporate the relevant data, and automatically by programming thresholds and comparisons into the software used to store, evaluate, and plot the data.

2.1.4 *Electrical Instruments: Special Considerations*

Electrical instruments are read using either portable electrical readout units or an ADAS. For electrical readout units, a short turn-around time for initial data evaluation, similar to manually-read instruments, is recommended. Best practices similar to those recommended for manually-read instruments can be systemized and incorporated into software or manual procedures to increase the likelihood that this happens.

For instruments read using an ADAS with real-time data transmittal, the turn-around time between the time of reading and the initial evaluation and notification can be almost immediate if acceptable performance limits and associated automatic notifications are established. If the ADAS unit stores data locally and the unit is connected only periodically to the database to download its memory, then the turn-around time will be defined by the frequency of data download, which should be established in accordance with the purpose of the monitoring.

Data collection frequencies should be set as a function of the criticality of the data to making decisions for safe and reliable operation of the facility as determined by the purpose of each instrument and its relation to monitoring for initiation and development a potential failure mode. Generally, leaving stand-alone dataloggers in the field to collect data for months without transferring stored data to a central database is not recommended, as malfunctions or vandalism of instruments could occur, and the opportunity for timely identification of anomalous readings may be missed. If the data are functionally important, data transfer technologies such as satellite transmission, cellular modem transmission, or even radio telemetry make most facilities and systems accessible year-round. Critical to projects with ADAS is to maintain regularly scheduled field surveillance activities. Regular surveillance programs should include observation to identify damage to instruments, ADAS system components, or possible damage to structures.

2.2 Abnormal Readings

Abnormal readings may be erroneous readings, accurate readings that fall outside of the typical range for the instrument, or readings that exceed some established threshold (tolerance) value. Distinguishing between an erroneous reading or a potentially serious situation where a threshold value has been exceeded may be difficult without proper training and experience. To maintain project safety, the O&M manual should identify a plan of action to be followed when abnormal readings are found. This may be as simple as notifying the dam safety manager for additional review, or as detailed as a specific operational plan of action including repeat readings, reanalysis, field reconnaissance, exploration, or other actions depending on the severity of the reading as compared with its purpose.

Data outside of typical expected limits should be treated as valid until proven otherwise. Decisions to disregard such data should be based on engineering judgment resulting from evaluation of the reading, field conditions, and visual observation of the area of concern. This evaluation should be subject to review and acceptance by the dam safety officer responsible for making decisions based on the data. Such decisions should also be fully documented. The decision to reject data should never be taken lightly and should never be delegated to or assumed by those without responsibility for or understanding of the safety of the structure.

2.2.1 *Troubleshooting*

A variety of skills may be required to troubleshoot an abnormal reading. The person troubleshooting the reading may be different from the person assigned to take the readings. The skills required will depend on the instrument type, location, reading method, and other factors. The following are some general principles/best practices that can help to define a problem and troubleshoot abnormal readings.

1) Repeat the measurement several times, where possible; how do these readings compare to the initial reading or to historic readings?
2) If the measurement is still out of range, visually observe the instrument installation. Is there an obvious problem (broken wire, loose connector, leak, visible change to the structure where the instrument is located, etc.) that could explain the reading?
3) Research the instrument history. Are the instrument installation and maintenance records correct and up to date? When was the last maintenance performed? When was the instrument last calibrated? Has the same instrument given suspicious readings previously?
4) Is the abnormal data consistent with or contradicted by other information that is available from nearby instruments or changes in field conditions such as reservoir or tailwater elevations or ambient temperature?
5) Are construction or other atypical project operations a potential factor?

For electrical instruments, troubleshooting can be done on the output signal of instruments to assess the quality of measurements and evaluate the need for repair or maintenance. Some observed measurement noise (e.g. scatter in readings) may be normal, but it may also be beyond what should normally be expected from the instrument. Manufacturer's literature, including user's manuals, are a good source of information on instrument troubleshooting and the working principles of the instruments.

If there are multiple instruments in the vicinity of the instrument with the questionable readings, the other instruments can either lend credibility to the questionable readings if they are reading similarly or could suggest erroneous data if they do not present a similar response.

For ADAS systems, a means of manually reading the instrument should be available so that abnormal readings caused by the ADAS can be independently checked. These supplemental reading procedures should be documented in the O&M manual.

As with manual instruments, electronic sensors should be validated by trained personnel who understand the operational theory of the sensors. For example, when checking a pressure transducer in an open-standpipe piezometer, removing the sensor from the standpipe and measuring depth to water with a water level indicator does not provide an accurate check because the water level in the standpipe will decrease when the sensor is removed (due to the water normally displaced by the sensor and cable). Nonetheless, such a check can be useful to evaluate whether a sensor is working, even though it is not an acceptable substitute for calibration. An acceptable method for validating sensor readings that accounts for these sorts of issues should be documented in the O&M manual for the affected sensors.

It is important that abnormal readings not be dismissed simply because they are abnormal. This would defeat the purpose of the monitoring activity. A timely, thoughtful response to abnormalities or apparent abnormalities is essential. Data collected should be examined on the schedule identified in the design and refined per the SMP. Ideally, this will include an initial review of manually collected data before the individual collecting the readings leaves the site. This is most easily accomplished by comparing current readings with prior readings and/or threshold values, but in some cases may require further evaluation including statistical evaluations and plotting results to confirm that data are consistent with expected performance trends.

2.2.2 *Thresholds*

Manually collected readings can be readily compared in the field with threshold levels provided on the data collection form. Some software packages and most ADAS hardware incorporate the option of setting alarm thresholds that trigger emails, text messages, or other notification features. This allows automatic highlighting of measurements that are abnormal or deviate from expectations. However, the selection of appropriate threshold values requires a solid knowledge of the purpose of the instrument and expected/design performance. Thresholds should be developed by and reviewed periodically by an experienced engineer with knowledge of the project. Review of graphical plots by personnel familiar with dam safety and instrumentation is needed to identify sometimes subtle trends even when computer alarms are present, as problems may arise without exceeding a threshold limit or triggering an alarm. The review needs to consider the basis for the threshold value, which may include historical instrument data values, parameter values used in stability analyses, normal operating conditions versus flood operating conditions, and other factors.

The dam owner, in coordination with the project engineer or geologist, may establish upper (maximum) and lower (minimum) bound threshold values depending on the criticality of such information and dependent on the type of instrument and its purpose. Thresholds may be modified with time if needed, but modification of historical-data-based thresholds is rarely appropriate simply because the readings are showing a gradual increasing or decreasing trend. The process used in determining the threshold values should be documented and be readily available to those responsible for collecting, reviewing, and evaluating instrumentation data.

If a project has an Emergency Action Plan (EAP), and the EAP and the O&M manual are separate documents, they should be coordinated and consistent with each other. The EAP will identify the process to be followed to evaluate and respond to a potential dam safety emergency, including actions to protect the safety of operating personnel and the general public (both at the dam and downstream). The EAP may identify the steps to take in the event of abnormal instrument readings that (1) appear to represent valid data based on the initial troubleshooting efforts, and (2) appear to have dam safety implications, or it may refer the reader to the SMP for that information. If the situation allows, steps should be taken to differentiate instrument error from a dam safety concern prior to commencing disruptive and potentially hazardous mitigation measures such as recommending evacuations.

Depending on which documents are developed for a certain project, the O&M Manual should be written in a way that clearly identifies whether a separate EAP governs regarding project personnel and public safety. As appropriate, the O&M Manual should discuss data evaluation and refer the reader to the EAP if a condition representing a significant dam safety concern is believed to exist.

2.3 Data Management, Presentation, and Analysis

Guidance regarding data management, presentation, and analysis is provided in the USSD White Paper titled *"Instrumentation Data Management and Analysis"*.

3.0 MAINTENANCE

Obtaining reliable data requires appropriate attention to the maintenance requirements of the physical components of the system, including the instruments and the means to collect, record, process, and store the collected data.

Cooperation among the dam safety manager, field technicians, operators, and all staff involved in the surveillance and monitoring of the project to preserve the reliability of the components and the method of acquiring readings (manual or automated) is crucial to an effective and efficient maintenance program. Instrument manufacturers typically provide detailed information regarding proper maintenance, including guidelines on suggested recalibration (as appropriate) over the life of the instrument and equipment that can easily be incorporated into O&M procedures.

Maintenance requirements can vary greatly and require different levels of knowledge for different systems. Thus, appropriate documentation and associated training on maintenance procedures is critical for all staff. To maintain the quality of the measurements, maintenance procedures have to be well-defined, appropriate tools have to be available, and appropriate checks and balances need to be in place such that scheduled and unscheduled maintenance are performed as required.

Future maintenance needs should be carefully considered when an instrumentation program is being designed such that the short-term and long-term requirements are included in the cost and labor budgets. A sophisticated electronic monitoring system may be appropriate in a portfolio where the expertise is available to maintain such a system and data needs are extensive. A manual measurement array may be more appropriate where resources are limited or data needs are smaller as it requires less maintenance and specialized technical knowledge, but possibly more effort to collect the data, depending on the size of the system. For some projects, an automated system may not be suitable or applicable.

3.1 Maintaining Instrumentation System Reliability

The purpose of instrumentation system maintenance is to maintain the reliability and quality of instrumentation data used for monitoring project performance.

Reliability and quality of data start with a system design that is simple and practical while still meeting project needs. Further guidance on instrumentation system planning, design and specification can be found in the USSD White Paper *"Development of a Dam Safety Instrumentation Program"*.

Considerations for reliability start with the system design and extend through abandonment or replacement and include the specified components and their purpose, installation locations, necessary protections, operational and maintenance requirements, reading procedures, safe access, calibration, repairs, and overall life.

When specifying components for measurement systems, reliability of critical components under conditions anticipated at the site should be thoroughly evaluated. Component considerations include:

1) Instrumentation hardware (e.g., types of instruments, dataloggers, portable readout units, etc.).
2) Supporting installations (e.g., enclosures, platforms, power sources, etc.).
3) Data collection and transfer methods (e.g., manual methods, such as hand-written notes by dam inspectors, or fully automated methods, such as data telemetry between the dam site and a regional office or headquarters).
4) Data storage and evaluation methods (e.g. database software, graphing software).
5) Other attributes of the system (e.g. access to instruments, vandalism potential, etc.).

Reliability and data quality from instruments are influenced by their working principle, their function, data collection methods, quality of materials and construction used in building the instrument, and details of their installation at a specific project. The location of an instrument – whether exposed on the surface, protected in a borehole, or in a gallery, can impact long-term reliability.

In general, repeatability over time is the main attribute which is expected from a reliable dam monitoring instrument. The instrument must provide a similar reading under similar conditions when measurements are repeated over time. The inability of an instrument to meet this criterion is termed drift, and if instrument readings are drifting, it may be impossible to compare readings over long time periods. Drift can be mitigated with regular re-calibration, or by using technologies that are less subject to drift. The conditions being monitored may have changed over time and judgment is often required to evaluate whether the measured change is due to changing conditions or changes in the instrument itself that require maintenance.
It is generally desirable to use as simple an instrument and instrumentation system as possible. Manual instruments are not typically susceptible to drift but may not be suitable in all project scenarios. Among electrical instruments, vibrating-wire instruments have earned a reputation for reliability in the geotechnical and dam instrumentation community, while strain gage-based instruments and other types are more typical in other industries.

Reliability is based on several factors. Instrument construction quality is important. Some instruments may be affected by water ingress or aging. Waterproofing quality and resistance to corrosion in general are essential for long-term reliability and performance. Table 2 presents some considerations for dam owners regarding reliability of dam monitoring components.

Table 2: Considerations for monitoring system reliability

Component Type	Condition and Consideration	Possible ways to address
Data Collection Electronics, usually in enclosures on dam surface, gallery	Burrowing gnawing animals, e.g. gophers, damaging buried cables	Enclose all external wires and cables in plastic or steel conduit.
	Temperatures > acceptable for electronics	More than one nested enclosure, the outside one is ventilated. Shading enclosures from direct sun can reduce temperatures to near ambient.
	Low temperatures which can greatly reduce battery output	Larger batteries, insulated enclosures, choose battery chemistry that is less sensitive to cold, have data acquisition equipment go to a "low power" mode during severe cold.

Component Type	Condition and Consideration	Possible ways to address
	Water condensing on electronics	Dessicant packets in the enclosure with the electronics reduce humidity and likelihood of condensation, but require regular replacement.
Submerged Instruments, e.g. pressure sensors for piezometers	Corrosion	Select appropriate materials. For the relatively benign water usually found around dams, stainless steel usually suffices, but titanium and plastic housings are available and are more resistant to corrosion in aggressive ground chemistry.
	Water intrusion	Care in assembly, proper fit of o-rings and other sealing elements.
Data collection devices	Power reliability	AC power in remote locations can be difficult, near-surface buried cables can act as antennae and are susceptible to voltage spikes during lightning storms. Buried cables, if needed, should include spark/transient protection between cable and data collector. Equipment should be grounded, but installing an effective ground can be difficult, especially in a rock fill dam.
		Battery power is often used, with solar panels to recharge batteries. Lead-acid batteries are prone to sulfation if allowed to deep-discharge. Larger batteries can help slow the rate of discharge, while larger solar panels can help with rapid recharging.

3.2 Other Maintenance Considerations

Maintaining access roads and trails used by field personnel to access instrument locations should be considered part of the project's maintenance activities and included in the O&M Manual. Regular maintenance of roads and trails, including clearing vegetation, clearing snow, repairing fences, handrails, stairways and lighting, replacing damaged signage, and replacing damaged or faded labels on instrument installations will improve the effectiveness of a monitoring program.

Many instruments will be warranted for a period of time by the manufacturer if the instrument is installed in accordance with instrument manufacturer instructions. Whether covered by warranty or not, the need to replace malfunctioning instruments that are deemed critical to the dam safety should be regularly evaluated. If instruments are not replaced, the SMP should be updated to acknowledge the abandonment of the instrument and its potential impact on the monitoring program effectiveness.

The dam owner should be aware of the potential need for instrument replacement over the life of the dam and this should be reflected in the facility's operating budgets. While it is hard to predict when problems will occur, and to what extent, a suggested rule of thumb is approximately 10% of the original cost of the instrumentation system as an annual budget for replacement and upgrades. The O&M manual should address recommended repair methods for each type of instrument installed at the project. Proper maintenance can greatly improve the longevity of an instrument. Preserving an instrument is generally much more helpful for continuity of monitoring and may be more cost effective than replacement, though the dam owner should perform an evaluation of each instrument and its continued contribution to the overall monitoring prior to replacement.

3.2.1 *Transients*

Electrical instruments are susceptible to damage due to nearby lightning strikes that can cause high transient voltages to be induced in wires, especially in near-surface buried cables. Such high transients can travel over long distances and damage instruments. The general advice for protection against lightning damage is to keep horizontal cable runs between instruments and junction boxes or data acquisition systems as short as possible. Transients are actually generated by the difference in potential between the ends of cable runs, and the longer the distance between these ends, the higher the transients that can be generated. Lightning protection needs to be built into the instruments (spark gap), and also is needed at the closest accessible point to the instrument along the cable run. Another increasingly common approach is to use radio links to electrically isolate installations by grouping sensors on smaller loggers to limit strike damage to smaller nodes and reduce the chance of a single strike taking an entire monitoring system off line.

3.2.2 *Power Reliability*

For all telemetry methods, one important aspect is the availability of power under anticipated conditions. Many telemetry failures occur due to lack of power, which may be caused by insufficient maintenance. Systems with telemetry often include monitoring stations in remote locations, where the only available power source is solar energy. These remote monitoring stations harness solar energy using a solar panel, charge controller and rechargeable battery. These components constitute a small power system, and they require maintenance and/or replacement on a regular schedule. The health of the solar power system can be monitored by programming thresholds on the ADAS that monitor minimum and maximum voltage and report alarms to maintenance personnel. The battery manufacturer's manual should provide guidance to help develop minimum and maximum voltage to use for these alarms.

3.2.3 *Instrument Fragility*

Certain instruments may also be subject to specific issues affecting their reliability. For instance, pressure sensors with a low full-scale measurement range, typically 25 psi or less, can be affected by light or moderate shocks that may cause a shift in the zero reading of the instrument. This may happen when piezometers are lifted periodically from the standpipes of open-standpipe piezometer installations. If a transducer is dropped or otherwise mistreated during this operation, a zero shift can occur.

4.0 REASSESSMENT FOR LONG-TERM MONITORING

From time to time, the instrumentation program should be reassessed and refined as the needs and performance of the project evolve. This may include modification of the number and/or type of instruments; location of instruments; or changes to the monitoring schedule. Periodic reviews of the overall program will confirm that the project and its performance are monitored efficiently and successfully. This review should follow the Potential Failure Modes Assessment (PFMA) process. Refer to the White Paper titled, *"Routine Instrumented and Visual Monitoring of Dams Based on Potential Failure Mode Analysis"* for more information on this topic. A PFMA or simplified review of the impacts of the modification to the monitoring program on the overall existing PFMs or the possible development of new PFMs should be the essential first step in considering modifications to a monitoring program.

Over the lifetime of a dam, evidence of new issues that need to be monitored may arise requiring new instruments to be installed or requiring changes in monitoring methods or schedules. What was once standard design practice may later be considered a design flaw (e.g. inclusion of seepage collars along an outlet works conduit) requiring extra monitoring. As dams age, their monitoring needs should be reassessed in light of considerations of deterioration of materials, new regulatory and performance requirements, evolving industry experience, and extensions of design life.

During the life of the instrumentation and the project, technology improvements in the individual components may need to be addressed to respond to new information or new requirements. These improvements are typically a result of lessons learned by designers, regulators, service providers, manufacturers, and dam owners. Other drivers may include improvements in installation, sensor, software, or electronic technologies, or economic factors. Incorporation of changes and technical advancements should be evaluated to determine the need for their application and/or incorporation as compared with the additional cost of new equipment.

Review of the program may also indicate the appropriateness of abandonment of malfunctioning or unnecessarily redundant instruments, or instruments whose data are no longer required. In these instances, it may be prudent to maintain redundant instruments in place, but to cease readings such that readings could be resumed if necessary.

The possibility of creating a potential failure path due to removal/abandonment of an instrument should be evaluated prior to such activity. Inoperable components of the instrumentation program require proper abandonment and possibly replacement. This is especially true for components that are physically inaccessible, such as instruments where the elevation and depth of embedment make it impossible to retrieve the inoperable device.

Notably, changes to the overall program and system should be reflected in updates to the project's documents and applicable training to the staff responsible for operation, monitoring, and maintenance of the Project should also be imparted as soon as possible, preferably prior to implementation of the program modifications.

5.0 O&M MANUAL

The above sections describe the importance of various features of a Project's surveillance and monitoring program and identified the need to include these steps in an O&M manual. Thus, it is critical that each dam have a comprehensive dam safety instrumentation operations and maintenance (O&M) manual. The O&M manual should include step-by-step procedures to:

- collect and document data (manual and automated);
- process and evaluate data;
- address abnormal data;
- prepare appropriate reports regarding the data;.
- troubleshoot malfunctioning instruments; and
- repair and maintain instruments.

These step-by-step procedures may have different titles in different organizations (Standard Operating Procedures (SOPs), Guidelines, Operating Instructions, Surveillance, etc.). The O&M manual should highlight the responsibilities of all team members so all are aware of the chain of responsibility. Written procedures are critical for continuity when staff changes occur, and as part of the overall succession plan.

In the event that no O&M manual or similar documentation exists for a facility, the first effort that should be made is the development of an instrumentation O&M Manual. Appendix A presents a sample outline for an Instrumentation and Monitoring O&M Manual for reference and consideration. Each organization has its own program, hierarchy, and procedures, therefore, the Appendix A sample outline is provided primarily to show items and topics that should be considered for inclusion in a project-specific O&M manual. The organization and content of a project-specific O&M manual should be customized to meet the specific needs of each individual organization and situation.

Key items that should be documented in an O&M Manual include:

1) Chain of responsibility for dam-related items with current contact information for each individual in the chain.
2) Reasoning used to develop the surveillance and monitoring system—why was it installed, what is its connection to dam safety.
3) System operation
    a. How the instruments work
    b. Data recording process (manual, ADAS (fully or semi-automated))
    c. The criticality of the data and how it is used
    d. How to collect the data
    e. How to store and transmit the data
    f. How to troubleshoot the systems
4) Instrumentation system components—design and installation documentation.
5) Maintenance and calibration procedures including manufacturer's instructions.
6) Operating and reading checklists.
7) Reporting forms and examples.

The O&M manual for a given facility should include specific instructions for operation and maintenance of each instrument type. Information from instrument manufacturers should be included.

5.1 Operation

5.1.1 *Readings*

Each instrument type has a unique reading method. Consistency in both procedure and schedule for collecting data is essential so that readings can be compared over time. Each instrument must be read in the same manner each time so that current data can be effectively compared to previous and historic data. Lack of consistency will reduce confidence in the data, and may lead to overlooking an important change in performance of the structure, unnecessary remedial action, or abandonment of a functioning instrument or system as a result of inconsistencies in data collection.

Specific actions that can be taken to promote consistency in data collection include training on proper reading techniques and implementation of procedures for timely verification and reporting of abnormal readings.

Ideally, the same person would always read each instrument in the same way, using the same equipment, and under the same conditions. Since this is not realistic, the use of an appropriate procedure and a checklist, coupled with training, will increase the likelihood that the data are collected appropriately and in a way that gives those responsible for making dam safety decisions the data needed. Prior to personnel reading instruments for the first time, it is advisable that they be trained on the overall purpose of the instruments and the reading and documentation procedures. Ideally, a new staff member should be accompanied by an experienced individual for at least the first set of readings.

Once verified, data should be forwarded promptly to the qualified individual who is responsible for evaluating the data and identifying and trends that require further review and investigation.

5.1.2 *Equipment Installation*

The O&M Manual should address new equipment installation as part of the project's overall operation and maintenance procedures, because equipment can fail or need to be replaced. When a new piece of equipment is being used, calibration prior to first use is critical. Calibration procedures for newly installed instruments will be available from manufacturers and suppliers. In addition, O&M manuals may incorporate best management practices to capture site or segment specific best practices. For example, if a piece of equipment used to read an instrument is being replaced, it is a best practice to read the instrument with both the new and old equipment to document differences between the readings.

5.1.3 *Manual Readings*

For manually read systems, checklists and record sheets should include field conditions that may be relevant to the instrument readings, such as upper and lower pool levels, temperature, precipitation, spillway and/or powerhouse discharge, etc., as part of the data set. This will allow evaluation of the data related to dam performance and field conditions. The relevant parameters should be outlined and collection procedures defined under the responsible charge of the person tasked with interpreting the data.

The manager of the dam safety/instrumentation program must confirm that the O&M manual is kept up-to-date and provides the most current and accurate information available for the project. This individual should also be responsible for conducting regular, periodic training of staff involved in the surveillance and monitoring of the project.

5.2 Maintenance

This section includes general discussion regarding O&M manual content regarding maintenance considerations. The framework for most of these requirements is available from the instrument manufacturers and should be tailored as part of the O&M manual development process. A system maintenance plan should typically incorporate the following maintenance items:

1. SCHEDULE: Establish the operation (or reading) schedule and the maintenance schedule (monthly, annual, biennial, etc.) for all system components; including general maintenance, repairs, calibration, adjustments, replacement, and abandonment.

2. RESPONSIBILITY: Designate who is responsible for carrying out required maintenance work and qualifications for those persons including training requirements.

3. RECORDS: Establish the requirements for maintaining a log to document the completion of maintenance work.

4. ACCESSORY INFRASTRUCTURE: Establish methods and frequency of repairs to access roads, fences, computer systems, and other aspects peripherally related to the instrumentation monitoring program.

Some best practices for instrumentation maintenance include:

1. CALIBRATION: Define recalibration intervals for expected performance limits as well as for readout equipment and sensors.

2. PERIODIC MAINTENANCE: Some instruments, for example twin-tube hydraulic piezometer installations, require special maintenance attention, including flushing the tubing and obtaining master gauge readings annually.

3. EXPERIENCE: Experienced instrumentation technicians and engineers should be consulted in developing O&M processes for existing structures to supplement existing staff observations.

With portable electrical readout units and ADAS, concerns may exist about possible drift of readings due to the electronics. Both types of systems now incorporate electronic controllers in which self-calibrating procedures are activated each time the unit is turned on, so that the need for re-calibration is reduced but it is still necessary to verify and document the operation of the systems. Manufacturers generally provide recommendations on suitable intervals between re-calibration of readout units and ADAS equipment.

Data collection and transfer methods can vary considerably, from simple field notes manually transferred to a database, to automatic transfer using data acquisition systems and telemetry. Where non-manual methods are employed, data transfer reliability must be verified through proper testing and maintenance. Similar to the readout devices, the data transfer hardware will require maintenance on schedules that will vary with their type. These intervals should be incorporated into the O&M manual processes.

6.0 SUMMARY

Instrumentation monitoring systems provide insights into the performance of a dam and its appurtenant features. Instrumentation allows monitoring for adverse conditions, and can provide the advance warning needed to address those conditions in a timely fashion. In order to maintain the reliability and repeatability of instrumentation systems, diligence with respect to operations and maintenance of instruments and their related components is needed. A well operated and maintained system, documented in a project-specific Operations and Maintenance (O&M) Manual greatly aids the successful performance of the overall program, investigation of abnormal readings, and improves confidence in acting upon the information from the instruments.

7.0 REFERENCES

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Appendix A

Sample Comprehensive Outline for an Instrumentation and Monitoring O&M Manual

NOTE: This is a sample outline, and must be customized for a particular project.

Suggested Introduction

Table of Contents
Glossary
Acronyms and Abbreviations

Suggested Section 1 – Overview

Introduction
Purpose of Instrumentation
Basis for Design
- Relationship to Potential Failure Modes Analysis (PFMA)

Related Documents
- PFMA Report
- Emergency Action Plan (EAP)
- Others (e.g. current Surveillance and Monitoring Plan (SMP), current Comprehensive Review (CR) report, etc.)
- Project Design Documents, As-Built Drawings

Brief Overview of O&M Manual Content and Organization

Suggested Section 2 – Instrumentation System Description

Instrumentation System Overview
Detailed Description of Each Instrument – manufacturer, model number, etc.
Installation Details for Each Instrument
Testing/Commissioning Information for Each Instrument
Description of How Each Instrument is Read
Data Acquisition System Description (if applicable)

Suggested Section 3 – Instrumentation System Operations Information

Organization/Structure
- Staffing
- Contracted Services (e.g. surveying)

- Roles and Responsibilities

Qualifications and Training
Data Collection and Validation
Data Review and Evaluation
Resolution of Anomalous Data
Data Reporting
Data Management and Storage
Periodic System Adequacy Review and Update

- PFMA Changes
- Inspection Recommendations and Regulatory Requirements
- Technology Advances

Suggested Section 4 – Instrumentation System Maintenance

Routine Preventative Maintenance
Calibration Procedures
Troubleshooting and Repairs
Replacement of ageing or outdated equipment

Suggested Section 5 – References

Suggested Appendices

System Drawings

- Instrumentation Layout
- Installation Details

Installation Records

- Logs
- Testing/commissioning records
- Calibration records

Manufacturer's Information

- O&M Manuals
- Product Data Sheets
- Support Services Contact Information
- Safety Data Sheets
- Instrument Drawings

Dam Safety Organization Chart
Data Collection Forms
Data Collection/Review/Evaluation Procedures
Instrumentation Supply and Installation Subcontractor Contact Information

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