United States Society on Dams

Instrumentation Data Collection, Management and Analysis

March 2013

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

U.S. Society on Dams

Vision

To be the nation's leading organization of professionals dedicated to advancing the role of dams for the benefit of society.

Mission — USSD is dedicated to:

- Advancing the knowledge of dam engineering, construction, planning, operation, performance, rehabilitation, decommissioning, maintenance, security and safety;
- Fostering dam technology for socially, environmentally and financially sustainable water resources systems;
- Providing public awareness of the role of dams in the management of the nation's water resources;
- Enhancing practices to meet current and future challenges on dams; and
- Representing the United States as an active member of the International Commission on Large Dams (ICOLD).

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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 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.

The Lead Author for this White Paper was Christopher Hill of the Metropolitan Water District of Southern California, and the co-author was Manoshree Sundaram of MWH. The Lead Reviewer was Barry Myers of HDR, and the Independent Reviewer was David D. Moore (Grant County Public Utility District, Ephrata, Washington) of the USSD Committee on Dam Safety and Dam Security. The work of all these individuals, as well as the other members of the USSD Committee on Monitoring of Dams and Their Foundations who provided input regarding this paper, is acknowledged and appreciated.

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1.0 INTRODUCTION

The purpose of a dam instrumentation and monitoring program is to monitor the ongoing performance of the project so that conditions of concern can be quickly identified and properly addressed. These conditions of concern may indicate the need for maintenance, remedial action, or an imminent threat to the downstream population. Proper data collection, management, and analysis are vital for identifying and responding to these conditions so that the project can be operated safely.

Providing for proper data collection, management, and analysis begins with the design of the performance monitoring program. The design includes developing a good understanding of the purpose of the instrumentation and monitoring program. This topic is addressed in a separate white paper titled "Development of an Instrumentation Program." The data collection, management, and analysis tools should also be designed to meet the specific needs of the personnel who are responsible for monitoring the project. Depending on the size of the project, this may consist of one person or a team of people. Their technical backgrounds may also vary significantly from operations personnel who need a simple presentation of the data that is easy to interpret, to engineers and scientists who may require detailed information and analysis tools to evaluate the current condition of the project. Regardless of the size of the team, project or owner, the purpose of the monitoring must be understood and the system must be designed to provide the information needed to make informed decisions.

The goal of this paper is to provide a general overview of the data collection, management, and analysis that is needed to support an effective dam safety surveillance and monitoring program.

For reference, and for additional background information on instrumentation and surveillance monitoring programs, the following white papers are also available on the USSD website (www.ussdams.org):

- Why Include Instrumentation in Dam Monitoring Programs
- Development of an Instrumentation Program
- Operation and Maintenance of an Instrumentation System
- Routine Instrumented and Visual Monitoring of Dams Based on Potential Failure Modes Analysis

2.0 DATA COLLECTION

The purpose of a dam safety instrumentation and monitoring program is to obtain data that can be used with visual observations and other information to evaluate the performance of the dam. However, the data is useful only if it provides information relevant to the safe performance of the dam, and the data are evaluated by knowledgeable individuals in a timely manner. For this reason, it is important to regularly review the purpose and function of the monitoring instrumentation and to determine if the data are being provided in a format useful for making decisions.

Additional guidance for defining monitoring needs can be found in the other USSD white papers. In addition to the fundamental requirement of collecting data for performance monitoring, specific data collection and reporting requirements as prescribed by a state or federal regulatory agency may also exist. The Association of State Dam Safety Organization (ASDSO) web site at http://www.damsafety.org provides information pertaining to specific state requirements.

Instrumentation can be installed to monitor physical parameters such as water pressures, seepage quantity and turbidity, leakage, movement, strain and temperature. Visual observations are also very important and include the documentation of current conditions and new developments that may be of concern. For both instrumentation and visual observations, complementary data must be collected and documented such as the date and time of the reading, reservoir/river and tailwater information, and climatic conditions including precipitation and air temperature. These complementary data are needed to understand observed changes in the instrumentation data.

Various methods and formats of data collection are used by project owners and operators. Most importantly, the data collected must be what is required to meet the monitoring objectives. This means both selecting the correct parameters to monitor and defining the frequency of data collection needed. For example, if the parameter that is being monitored can change rapidly, then very frequent readings and possibly real-time notification of a change may be needed. On the other hand, collecting frequent data for a parameter that is expected to change slowly may result in unnecessary data which can become a distraction. Data can be collected using manual measurements that are made by project personnel. Alternatively, data can be collected using electronic equipment that stores the data until it is downloaded or automatically transmits the data to a remote location using radio, telephone, satellite, or an internet connection. The best method for data collection will depend on many factors including types and quantity of data to be collected, the reading schedule and frequency, site access limitations, availability of electrical power, availability and qualifications of monitoring personnel, and other factors. The following is a brief discussion of the three general types of data collection currently used for collecting dam safety monitoring data.

2.1 Manual Data Collection

As data is collected manually in the field, it may be entered into a field survey book, paper forms, a handheld device, or a tablet PC. Data must be entered correctly and complementary data such as date and time of the reading, reservoir/river and tailwater levels, ambient temperature, precipitation, and other relevant site conditions should be noted. Manual collection methods can include the use of weighted tapes, scales, calipers, survey rods, and other measurement devices which may be read manually. The measurements might also be made using electronic sensors with readout devices. These readout devices sometimes allow for digital storage of the readings which can be later downloaded to a computer in the office. Digital photographs are collected to assist in documenting the current conditions. Once the data have been collected and transported into the office, the data may be graphed or tabulated for analysis by hand or entered into a computer for analysis and presentation. In addition, visual observations made during the data collection must be stored in a manner that allows for future reference and retrieval. The data collection process should include procedures to verify that the reading has been performed correctly, and should also include a comparison with previous readings or limits to verify that the recorded readings are within the expected historical range of the instruments. If readings do not fall within the expected performance range, procedures should be in place to address the apparently anomalous readings promptly; this may include re-reading the instrument to verify the accuracy of the anomalous data, checking the calibration of any electrical or mechanical readout devices or sensors, increasing the frequency of readings, and other measures judged to be appropriate.

A key advantage of including a handheld device or computer in the data collection is that previous readings and threshold limits can be displayed to provide immediate feedback to the operator that the instrument reading is suspect or of concern. Downloading the data electronically from these devices into database or other analysis tools also reduces data entry errors. Log books can provide a means to refer to historical data as readings are documented manually to the log book or data collection form. In these instances, the log books and data collection forms should be formatted to include the threshold limits and previous or typical readings.

2.2 Stand Alone Dataloggers

Sometimes, readings are required to be collected at short time intervals, e.g. every 15 minutes, hourly or daily to meet monitoring objectives. These readings can be very helpful in developing an understanding of how the dam responds to changing loading conditions such as reservoir level, rainfall, and air temperature, for example. Readings from multiple instruments can be collected simultaneously so that different parameters can be directly compared. This can also be accomplished with manual readings, but depending on the size of the project, number of instruments, location of instruments, and frequency of readings, it is generally too labor intensive if readings are needed at an interval of more than once a day. When frequent readings are required, stand alone dataloggers can be an effective data collection method. Stand alone dataloggers can also be used to capture data when an event of interest occurs. For example, the datalogger can be configured to monitor a water level or flow rate sensor and collect data at short time intervals if the reading exceeds a threshold value. Dataloggers may also be a good alternative to manual readings for remote sites or for areas of difficult access, such as a dam gallery.

There are many different types of standalone dataloggers and a number of manufacturers make units that are battery- or solar-powered and environmentally hardened for direct field deployment. These units can be configured using a computer or handheld device and then left in the field for unattended data collection. The data is then retrieved using the computer or handheld device by personnel who periodically visit the site. Visual observations and manual readings on other less frequently read instruments are typically performed during these periodic site visits. Site visits for downloading data should be performed frequently because data could be lost if a datalogger malfunctions. Also, regular visual observations should continue to be performed even if data is being collected frequently, as visual observations can often identify developing problems before an instrument registers a response.

Dataloggers can be configured to read single instruments or they can be used to read a number of sensors. Once data has been downloaded from the datalogger, the data then must be uploaded to a computer for evaluation. This should be done promptly following collection of the data. Similar to the manual readings, a verification procedure should be in place to make sure that accurate readings are recorded. For example, if irregular readings are noted upon uploading the data, these should be immediately investigated, explained, and/or corrected. Also, periodic manual readings should be taken to verify the digital readings.

2.3 Real-time Monitoring Networks

If both frequent unattended data collection and real-time display or notifications are required, then an automated data acquisition system (ADAS) may be the best option. Automated systems can also save labor and reduce the time for data evaluation by providing automated data retrieval from a remote location. The data is typically retrieved from the site periodically and automatically loaded into a database for presentation to the end user. Using programmable ADAS equipment, data can be processed into engineering units, evaluated for alarm conditions, and displayed in real-time to operations and dam safety personnel. These displays can be customized to present the monitoring results in the format needed to make decisions. For operations personnel this may mean simple displays that show normal or alarm conditions. The interface for the dam safety personnel usually warrants a more comprehensive presentation for evaluation of short term trends, correlation relationships, alarm thresholds, statistical parameters, and geographic relationships. Although ADAS provides remote monitoring of the project, regular site visits are still required to perform the scheduled visual observations and system maintenance tasks. Many projects that utilize an ADAS for some instruments also have other instruments that require less frequent readings and are read manually.

There are two general system architectures that are used to automate the collection of performance monitoring data on dams: host-driven systems, and node-driven systems. The host-driven architecture consists of a central intelligent host (master) device and remote units (slaves) that are polled by the master unit to collect the instrument readings. Because the intelligence is primarily in the host device, the system performance relies heavily on maintaining stable uninterrupted communications. Examples of host architectures are supervisory control and data acquisition (SCADA) systems and PC-based systems.

The node-driven architecture, in contrast, puts the intelligence at each node in the network. A node would be a location on the dam site that monitors a single instrument or a group of instruments, but is physically separated from the other nodes. Each node is capable of standalone operation and can be programmed to collect data and make alarm notification decisions on its own. The nodes may be configured to allow for two-way communications with each other so that information can be readily shared between the units. This information may be measured with parameters used in calculations such as a barometric pressure correction, or it may be instructions to increase the rate of data logging based on a certain reservoir level condition or the occurrence of strong shaking from an earthquake.

Communications between the nodes can be accomplished by a wide variety of wireless and hardwire methods. The best method will depend on site conditions, communication services available, and the real-time monitoring and notification needs of the project. The node-driven architecture is more commonly used for dam safety monitoring because the instrumentation tends to be widely distributed around the project site and in locations where power is not readily available. Low power operation is possible with the node-driven systems because communication activity can be minimized while still maintaining the real-time functionality of the system. If a node detects an alarm condition, it can immediately communicate with the other nodes, but under normal conditions, communications are kept to a minimum. A properly designed node-driven system can also provide improved reliability. In the event of the loss of communications or equipment damage in the network, the other nodes will continue to function independently. For critical systems, it is also desirable to have multiple communication paths that can be utilized.

The primary advantage of an ADAS is to allow for the near real-time collection and reduction of the instrumentation data so that dam operators and dam safety personnel can rapidly evaluate the conditions at the dam. A properly designed ADAS provides real-time remote notification of a significant change in the performance or conditions at the dam 24 hours a day, 7 days a week.

2.4 Advantages and Disadvantages

Table 1 summarizes some of the advantages and disadvantages of the three data collection methods described above. The objective in designing a monitoring program is to use the best tools for the intended purpose. Many dam projects use a combination of the data collection methods depending upon the monitoring needs for the parameters that are being measured.

Table 1. Summary of Data Collection Methods, Advantages and Disadvantages

Data Collection Method	**Advantages**	**Disadvantages**
Manual Readings	• Generally simple to perform and do not require high level of expertise • Personnel are already on site for regular visual observations • Data quality can be evaluated as it is collected	• Labor intensive for data collection and reduction • Not practical to collect frequent data • Potential for errors in transposing data from field sheets into data management/ presentation tools • May be impractical for remote sites where personnel are not frequently on site
Stand alone Dataloggers	• Frequent and event-driven data collection • Consistent data collection and electronic data handling • Equipment is fairly inexpensive and simple to set up	• Requires some expertise to configure dataloggers • Data quality cannot be evaluated until it is collected from the field • Potential for lightning strikes • Power source needs to be considered
Real-time Monitoring Networks	• Frequent and event-driven data collection • Consistent data collection and electronic data handling • Real-time display and notification (24/7) • Reduces labor effort for data collection and processing • Can remotely change the monitoring frequencies and data collection configurations as needed • Allows for rapid evaluation of monitoring results	• Automation may encourage complacency if overall monitoring program is not well defined or understood • Requires a higher level of expertise to install and maintain • Higher cost of installation and periodic maintenance • The importance of frequent routine visual inspections may be overlooked or discounted somewhat due to the real-time presentation of automated instrument readings • Potential for lightning strikes • Power source needs to be considered

3.0 DATA MANAGEMENT AND PRESENTATION

Collecting good data is very important, but the data must also be carefully managed and evaluated in a timely manner to effectively monitor the project performance. Data collected but not processed or evaluated right away does not serve the owner, but only provides fodder for the lawyers, auditors, investigators, etc. who may become involved if a problem with dam safety or operation arises. Quick and effective analysis of the data is crucial to maintaining the safety of the project.

Many dam owners maintain the analyzed, documented data at a central office with copies at the project site, whereas many others maintain the data only at the project site. Successful management of collected instrumentation and monitoring data to measure the performance involves the following:

- Collection of data in an effective manner suitable for the project and intent of the monitoring program;
- Validation of data readings and resolution of apparent anomalies;
- Processing and reduction of the data to convert raw readings to useful engineering units; and
- Maintenance of historical data in a usable and easy to evaluate format, including suitable backup and archiving procedures.

3.1 Data Management

Electronic Formats

ASCII: Data that are uploaded to a computer or handheld readout device may be in a generic "ASCII" (American Standard Code for Information Interchange) format, or may be stored in a more specialized format such as a proprietary spreadsheet or database form. If the data is stored as ASCII it can readily be imported into a spreadsheet program for further processing, but it may be inconvenient to utilize the data in its original form.

Spreadsheet: Many project owners store and evaluate data using spreadsheet programs. This accommodates typical calculations for converting field data into engineering units. Also, the data is ready to plot in various formats for evaluation. However, care must be taken in developing plots to ensure that data plotted as time-histories are plotted to time-scales and in a means that is useful to evaluate project performance. Time-history plots, as well as other plots showing instrument performance versus reservoir levels, precipitation, temperature, etc., which are also effective means of evaluation, can be created automatically when data is input into the spreadsheet.

Database: Spreadsheets are a good tool for reducing and plotting the data, but they do not store the data in an easy-to-manage format. Using a relational database tool allows the data to be stored so that it can be readily queried and compared to other data in the database. For dam safety monitoring, the data are typically stored with a relationship to the date and time collected. The data can then be queried for the desired time interval and readily compared to other instrument data over the same time period.

Most database software applications also have tools designed to make the tasks of maintaining data quality and archiving the data easier. For these reasons, database systems are commonly used on large projects with an extensive instrumentation and monitoring program and for those with an extensive history of instrumentation data. Some databases have their own plotting tools and most can be configured for compatibility with a spreadsheet program to develop graphs.

A reliable procedure for backing up data regularly is essential, whether the data is managed using a database or stored in spreadsheet files. The general “rule of thumb” is to back up the data as often as you can afford to lose it.

<u>Intranet and Internet Access to the Data:</u> Web sites may also be utilized to access and evaluate the data that is stored in databases and spreadsheets. The advantage of utilizing a company’s intranet (internal computer network) or the public internet is to allow access to the data for various users at different remote locations. Using database software, multiple users may simultaneously access the data for evaluation while new data is being added. Regular backup of these systems is a good practice.

3.2 Data Processing

Once instrumentation data has been collected, evaluation of the information collected is required. Calibration information, baseline information, and instrument locations are all necessary in order to process data. Data can be processed manually and/or with the aid of computer software. For instance, vertical movement readings such as crest settlement data must be processed by evaluating the relative change in vertical elevation between consecutive surveys as well as the change from initial surveys. Additional processing of vertical movement readings can include developing plots of the data to evaluate trends over time or with respect to other references.

Likewise, readings from piezometers must be processed to determine the elevation of the water in the instrument using the raw reading of the depth to water measured and the surveyed ground and top of piezometer elevations. Other reference information such as the installed location of instruments, materials in which the instruments are installed, etc. are important for interpreting the data and evaluating how the dam is performing.

Some of the processing can be automated depending on the method of data collection and management used. Spreadsheets can be developed to automatically process raw data as the information is entered. Likewise, databases and other available software can be programmed to automatically process data as raw data is input and/or uploaded. As with manual processing, automatic processing of data relies upon well-documented reference information, calibration data, and instrumentation details. Therefore, managing and archiving the reference information is equally as important as the management and archiving of raw data.

3.3 Data Maintenance

An important activity of a dam safety program is the maintenance of data; it is vital for personnel managing an instrumentation program to provide adequate resources for this activity. Not only is the maintenance of data important to current evaluations, but also for emergency or adverse performance of the dam. For dams managed by federal agencies, instrumentation data is required to be maintained for the life of the dam: "**A complete record** or history of the investigation, design, construction, operation, maintenance, **surveillance**, periodic inspection, modifications, repair, and remedial work **should be established and maintained so that relevant data relating to the dam is preserved and readily available for reference**. This documentation should commence with the initial site investigation for the dam **and continue through the life of the structure**." (FEMA, 1979, emphasis added)

Typical records essential to maintain for an instrumentation program include design memoranda, instrumentation data, installation and maintenance records for instrumentation, significant event records, reports of significant remediation to the dam, and data evaluation reports. Of critical importance is the maintenance of historic information which, as staff and responsibilities change, must be maintained and included as part of regular training of incoming or rotating staff. Information that should be maintained includes:

- General information such as drawings; date(s) of installation; initial measurements and testing; manufacturer's calibration data; borehole logs; model number and manufacturer; wiring schematics, etc.

- Instrument maintenance records including routine maintenance activities; calibrations of instruments; cleaning of foundation drains; replaced readouts; removal of vegetation; cleaning of approach channels of weirs; outages, reservoir drawdowns, major maintenance; installation of drains, flushing of pieozmeters, and redirecting flow, etc. These are often sources of changes in recorded data. Maintenance records also provide documentation of schedules, reasons for repair (such as damage from vandalism or construction), and information for future maintenance and may also provide support to explain abrupt changes in readings.

- Significant project event records such as records of floods, earthquakes, major construction, and remediation must be maintained. These will provide information on the performance of the project under these loads and can provide critical empirical information to help with calibration of dam safety analyses that are intended to evaluate and prepare for future extreme events.

- Data evaluation reports, or performance reports, are the tangible product of instrumentation programs. As such, managers must ensure their maintenance and availability to all personnel responsible for some aspect of the dam safety and performance of the project.

<u>Archival Procedures:</u> How long should data be retained in its original form? The practice of surveyors, for example, is to maintain the original field record as "truth" and any errors in the data as originally collected are thus preserved, and the trail by which any such errors are corrected should likewise be preserved.

Management of paper data is equally as important as the management of electronic data. For those projects where data is simply documented and evaluated on paper, data sheets should be filed chronologically to allow easy access for routine evaluation and historic comparisons, and for use in evaluation during times when potential threats to the safety of the dam/project are apparent. For those projects where the data is entered into an electronic data management system, the data sheets should be similarly filed in an easily accessible format.

Although, theoretically, the data sheets are not needed once data is entered into the data management system, the sheets should be filed in some form of permanent storage, e.g. paper or electronically scanned, to facilitate review and re-creation of data in the event the electronic data management system is corrupted, or to check suspected data entry errors. This will also facilitate review of data during a power outage, for instance, if questions arise, or to verify if any supplemental reference information was also documented on the data sheets but not entered into the electronic system. If a secure backup of the electronic data is created and if all information contained on the physical data sheets is confirmed to be entered in the database, the project owner can elect to discard the paper sheets. Project owners should also consider that dam safety-related events might occur during a power outage; for that reason, paper printouts of critical instrument plots should be updated and filed regularly and maintained on site and at other critical locations.

Figure 1 shows an example of a simple spreadsheet used to manage and evaluate piezometer readings.

Well reference information

Enter raw reading here

Spreadsheet calculates elevation using well reference information

Complementary information useful for evaluation of data

READINGS													
WELL INSTALLED	PZ-1		PZ-1A		PZ-2		PZ-3		PZ-4		HW	TW	COMMENTS
WELL TOP	1042.05		1039.38		1039.26		1032.12		1041.54		---------	---------	Top of Wells Surveyed:
WELL BOTTOM	1021.95		1008.78		1019.16		1011.92		1013.54		---------	---------	May 2004
DATE	ACTUAL READING	ELEVATION OF WATER	ACTUAL READING	ELEVATION OF WATER	ACTUAL READING	ELEVATION OF WATER	ACTUAL READING	ELEVATION OF WATER	ACTUAL READING	ELEVATION OF WATER	ELEVATION OF WATER	ELEVATION OF WATER	
4/9/1996	10.00	1032.05	18.00	1021.38	12.67	1026.59	7.90	1024.22	18.00	1023.54	1035.00		
8/7/1996	10.00	1032.05	17.90	1021.48	12.80	1026.46	8.00	1024.12	18.00	1023.54	1035.00		
4/14/1997	10.00	1032.05	17.80	1021.58	12.50	1026.76	8.00	1024.12	18.00	1023.54	1034.90		
7/17/1997	10.00	1032.05	17.80	1021.58	12.40	1026.86	7.90	1024.22	18.00	1023.54	1035.00		
4/20/1998	10.10	1031.95	17.80	1021.58	12.50	1026.76	8.00	1024.12	18.20	1023.34	1035.00		
8/3/1998	10.00	1032.05	17.70	1021.68	12.40	1026.86	7.90	1024.22	18.00	1023.54	1035.00		
5/3/1999	10.00	1032.05	17.70	1021.68	12.40	1026.86	7.80	1024.32	18.00	1023.54	1035.00		
10/4/1999	10.10	1031.95	17.80	1021.58	12.50	1026.76	7.80	1024.32	18.00	1023.54	1034.90		
4/13/2000	10.00	1032.05	17.80	1021.58	12.50	1026.76	7.80	1024.32	18.10	1023.44	1034.90		
8/15/2000	10.00	1032.05	17.70	1021.68	12.40	1026.86	7.80	1024.32	18.00	1023.54	1034.90		
5/8/2001	10.00	1032.05	17.80	1021.58	12.40	1026.86	7.80	1024.32	18.00	1023.54	1034.90	1005.10	
8/23/2001	10.00	1032.05	17.80	1021.58	12.50	1026.76	7.90	1024.22	18.20	1023.34	1034.90	1004.50	
5/24/2002	10.00	1032.05	17.70	1021.68	12.40	1026.86	7.80	1024.32	18.00	1023.54	1035.00	1005.00	
9/5/2002	10.00	1032.05	17.70	1021.68	12.50	1026.76	7.80	1024.32	18.20	1023.34	1035.00	1005.10	
10/29/2002									18.20	1023.34	1035.00	1005.00	
5/13/2003	10.00	1032.05	17.70	1021.68	12.40	1026.86	7.80	1024.32	18.00	1023.54	1035.00	1005.10	
5/5/2004	10.10	1031.95	17.70	1021.68	12.50	1026.76	7.90	1024.22	17.90	1023.64	1035.00	1005.00	
9/8/2004	10.00	1032.05	18.00	1021.38	12.30	1026.96	7.90	1024.22	17.90	1023.64	1034.90	1005.40	2.5" rain on 9/05/04
5/9/2005	10.00	1032.05	17.90	1021.48	12.30	1026.96	7.80	1024.32	17.90	1023.64	1034.90	1004.80	
8/12/2005	10.00	1032.05	17.80	1021.58	12.40	1026.86	7.90	1024.22	18.00	1023.54	1035.00	1004.20	
4/11/2006	10.10	1031.95	18.00	1021.38	12.50	1026.76	8.20	1023.92	17.90	1023.64	1035.00	1004.20	
HI	10.00	1032.05	17.70	1021.68	12.30	1026.96	7.80	1024.32	17.90	1023.64	1035.00		
MEAN	10.02	1032.03	17.80	1021.58	12.46	1026.80	7.88	1024.24	18.02	1023.52	1034.96		
LOW	10.10	1031.95	18.00	1021.38	12.80	1026.46	8.20	1023.92	18.20	1023.34	1034.90		

Calculate maximum, minimum and average readings for reference and to easily identify outliers

Figure 1. Example of spreadsheet used to manage and evaluate instrumentation data.

3.4 Data Presentation

Tabular

Tabular presentation of data either in text or column/row format is compact and, for small numbers of values or certain types of data, can be easily read, understood, and evaluated. Some types of survey data are best presented in tabular format. Also data which is collected at a relatively low frequency can often be misleading when simply plotted and therefore should be supplemented with tabular presentation of data.

Graphical

As the total number of collected readings increases, plots of the data may provide the best method of data evaluation. In addition, identification of trends and cyclic responses can be difficult using tabular data. Data managed in an electronic system (spreadsheet or database) can easily be plotted for evaluation. Some spreadsheet programs can be formatted to allow a dynamic environment where plots are instantaneously updated as data is entered. Plots are usually preconfigured with database tools so that the most up-to-date data can be viewed and compared instantaneously with other parameters to rapidly identify changes in performance.

Whether plots are generated dynamically or updated manually, care must be taken to develop effective plots that accurately represent project performance. Collected data can be plotted in a time-history format which will help illustrate gradual changes over time and responses to various project conditions. Care must be taken in developing plots to ensure that time-history plots are plotted in a means that is useful to evaluate project performance. In addition, multiple plots developed for each instrument type should be prepared at the same scale for ease in comparison.

Additional plots, other than time-history, illustrating relationships of parameters (for example, reservoir levels versus seepage quantities, instrument performance versus reservoir levels, etc.) should also be generated to provide alternate methods to evaluate project performance and to identify different project performance relationships. Appropriate instruments should be grouped together to provide an accurate picture of the project's condition.

Plots should include appropriate complementary data such as reservoir and tailwater levels, precipitation, etc. Time-history plots should be developed to observe the project response since the inception of the monitoring program; more detailed plots of data from a shorter time period, *e.g.,* the last year or five years should also be developed to aid in evaluating trends or small changes in readings that may not otherwise be easily identified.

An appropriate and realistic scale should be selected for the plots to provide an accurate representation of the of the project performance. For example, plots of settlement data at a concrete structure plotted at a large scale may not show much change; however a plot of the same data at a scale similar to the limits of accuracy of the monitoring equipment may provide an exaggerated representation of cyclic variation which on first glance may appear troubling. For this reason, it is essential that data be evaluated by someone who understands the purpose of the monitoring system and is familiar with the project and its performance.

Cross-Sections

Plots of data along a cross-section through the dam or feature provide an additional means of evaluating project performance and provide an alternative interpretation of readings. For example, a cross-section plot showing piezometric elevations from the upstream face through the embankment and downstream face can aid in evaluating variations in phreatic surface under differing headwater and tailwater conditions over time, and can present the normal response of the phreatic surface to changing reservoir conditions. Similarly, plots of settlement data along the perimeter of a cofferdam or through a cross-section of a dam can provide a better overall sense of project performance.

3.5 Photos and Diagrams

Photographs and diagrams may be inserted onto plots of data or provided as reference documentation. This may enhance the understanding and interpretation of the data by illustrating the location, instrument, installation, or spatial relationships. This type of presentation may significantly aid those who are not intimately familiar with the instrument.

Figure 2 presents examples of a time-history plot as well as important complementary data and a plot of two different parameters other than time. Figure 3 shows an example of a cross-sectional plot. Note in Figure 3 that the vertical and horizontal scales are different – this can be done to improve presentation of the data while still facilitating clear evaluation of the data.

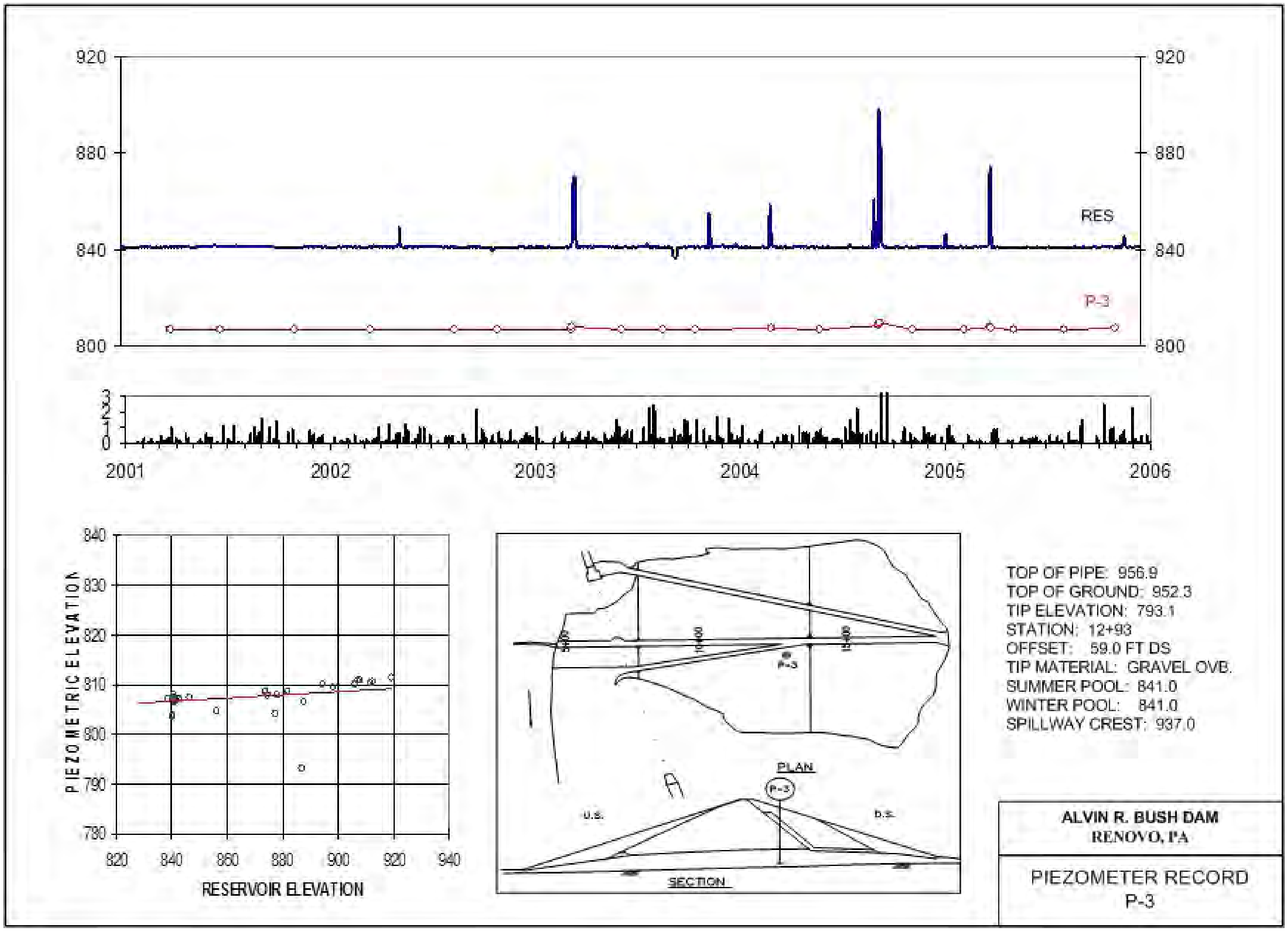

Figure 2. Example of a time-history plot with location and correlation data

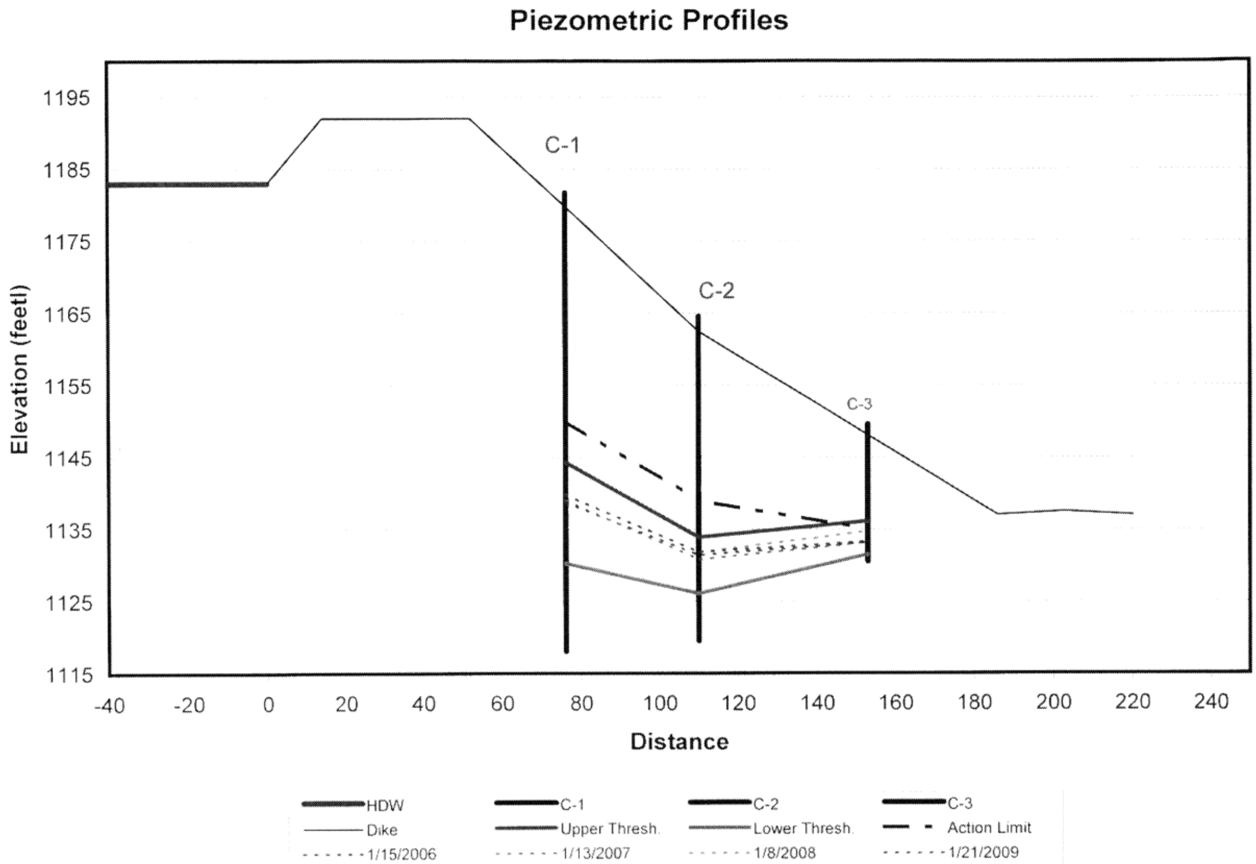

Figure 3. Example of a cross-section plot

4.0 DATA ANALYSIS

Those responsible for collection and evaluation of the data should have an expectation for how an instrument will behave, and some knowledge and familiarity of what it means if the instrument reading is outside the "expected" range. Many instruments are installed in dams to confirm design assumptions, others are installed to monitor construction, and others are installed to provide long-term monitoring or monitoring of potential failure modes. The purpose of the instrument, its individual function, and its function as part of the entire monitoring system as a whole must be understood before an evaluation of the data can be used to make effective decisions.

Analysis of the data includes evaluation of trends such as levels increasing or decreasing with time; response to changing headwater and/or tailwater levels; cyclic responses to project reservoir levels; responses to changes in temperature; effects of precipitation on project response; effects of construction activities; effects of changes in project operations, etc. These represent a few of the potential responses of a project as portrayed through the surveillance and instrumentation data. The data should be evaluated in terms of detecting a developing failure mode or potentially unsafe condition, and the general health of the project. Monitoring with respect to potential failure modes is further explored in the white paper entitled "Routine Instrumented and Visual Monitoring of Dams Based on Potential Failure Modes Analysis".

During the process of developing the instrumentation system and during periodic re-evaluations, it can be helpful to maintain historic maximum and minimum readings or other statistical parameters, to help identify if the current readings are within the expected range. Also, a list of steps to follow if the reading falls outside the expected range should be developed.

Review of data must be performed in a timely manner by a person familiar with the project so that an adverse condition will be quickly identified and decisions can then be made to effectively address the problem. Initial reviews may be done by the individual responsible for collection of the information. Knowledge and familiarity with the typical performance of the instrument will help to immediately determine if a reading is within the expected range. Procedures should be in place to address those readings which, upon verification, exceed the typical response. This may include contacting supervisory engineers, performing more frequent visual inspections, increasing the frequency of instrument readings, performing engineering analyses, obtaining additional support from engineering consultants, contacting regulatory agencies, and possibly activating the project emergency action plan.

A second level of review should also be performed on a regular basis by an individual familiar with the project design and the objectives of the monitoring program. This review should include observation of the data for changes in performance; identification of anomalous data; and the determination if additional engineering analyses such as slope stability, seepage, shear-friction sliding stability, overturning stability, or structural strength analyses are needed. An organizational requirement of the turnaround time from data collection to evaluation should be established and maintained.

The dam owner should establish a protocol to distribute or to notify the appropriate individuals of updated instrumentation data. As data is received, it should be either distributed to the appropriate individuals for processing, evaluation, and analysis or it should be easily accessible for the same purpose.

Additional guidance on developing effective surveillance and monitoring programs, and on working with instrumentation, data collection systems, and data management and evaluation tools can be found in the documents listed in the references section below.

5.0 SUMMARY

Dams are high maintenance structures by nature, and there is no such thing as passive dam safety. A program of inspection, maintenance, data collection, data management and analysis are key elements needed for safe dam operation.

The goal of this paper is to provide a general overview of the data collection, management, and analysis that is needed to support an effective dam safety program.

Effective data collection methods discussed herein include:

- Manual data collection
- Stand alone dataloggers
- Real-time monitoring networks

Management of the collected data depends on the size of the project and the magnitude of data collected, as well as the purpose of the data collected. Means for effective data management, processing and maintenance include:

- ASCII files or spreadsheets
- Databases
- Intranet or Internet sites

Evaluation of the data requires presentation in a manner that is meaningful to the project's performance as well as to those involved in reviewing the information. Effective means of data presentation include:

- Tabular Presentation
- Graphical Presentation
- Cross-Sections
- Photos and Diagrams

Analysis of the collected and presented data must be done very soon following collection of the data, especially to be able to identify potential problems as they occur or to monitoring potential dam safety issues.

The information provided herein is intended to provide a guideline to help understand the importance of effective data collection, management, presentation, and analysis. The references listed below provide additional detail on all of these topics.

6.0 REFERENCES

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