United States Society on Dams

Monitoring Levees

May 2016

USSD Committee on Levees
and
USSD Committee on Monitoring of Dams and Their Foundations

U.S. Society on Dams

Vision

A world class organization dedicated to advancing the role of dam and levee systems and building the community of practice.

Mission

USSD, as the United States member of the International Commission on Large Dams, is dedicated to:

ADVOCATE: Champion the role of dam and levee systems in society.

EDUCATE: Be the premier source for technical information about dam and levee systems.

COLLABORATE: Build networks and relationships to strengthen the community of practice.

CULTIVATE: Nurture the growth of the community of practice.

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FOREWORD

The importance of monitoring programs for dams is widely accepted. There are many historical cases of dam failures where early warning signs of performance anomalies might have been detected if a good dam safety monitoring program had been in place, such that dam failure, and the catastrophic consequences associated with dam failure, could have been prevented. Historically, monitoring of levees has received less attention than monitoring of dams, except during intensive visual inspection efforts made during flood events ("flood fights"), when great efforts are made to locate and address levee problems before they become levee failures. The reasons for this lesser attention might include their generally have lower structural heights, when compared to dams, and their daunting lengths. However, the consequences of levee failures can be just as catastrophic as dam failures, so monitoring issues and discussions for levees should not be put off or avoided, just because the long lengths of levees can make the topic vexing. This White Paper addresses monitoring issues for levees, in an effort to provide information and perspective regarding this topic to professionals working in the fields of levees and levee performance monitoring.

This White Paper was prepared as a collaborative effort between the United States Society on Dams (USSD) Committee on Levees and the Committee on Monitoring of Dams and Their Foundations, and can be viewed as part of a series of White Papers by the USSD Committee on Monitoring of Dams and Their Foundations:

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

While the above series of White Papers focuses on the monitoring of dams, many of the topics and issues discussed relate as well to the monitoring of levees. This series of White Papers primarily addresses the programmatic aspects of instrumentation for dam safety monitoring, rather than technological advances in instruments. These papers provide professionals working in the area of levee monitoring with some basic information to consider with respect to levee safety monitoring programs.

The Lead Author for this White Paper was Jay N. Stateler (Bureau of Reclamation, Denver, Colorado) of the Committee on Monitoring of Dams and Their Foundations. Co-authors from the Committee on Monitoring of Dams and Their Foundations were Pierre Choquet (RST Instruments, Coquitlam, British Columbia), John Lemke (Geodaq, Sacramento, California), Barry K. Myers (Engineered Monitoring Solutions, Newberg, Oregon), and Steven Z. Meyerholtz (Army Corps of Engineers, Seattle, Washington). Co-authors from the Committee on Levees were George L. Sills (Consultant, Vicksburg, Mississippi), Stephen L. McCaskie (Hanson Professional Services, St. Louis, Missouri),

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The Publication Review Committee (PRC) for this paper was headed by USSD Board Member Alex Grenoble (HDR, Inc.), with Committee members William Empson (Army Corps of Engineers), Andrew Verity (Terracon), Paul Booth (Arcadis), and Brett Cochran (Denver Water). The work of all these individuals, as well as the other members of the Committee on Levees and the Committee on Monitoring of Dams and Their Foundations who provided input regarding this paper, is acknowledged and appreciated.

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INTRODUCTION

Levees are an important component of the civil infrastructure of the United States. They provide for the safe conveyance of water and reduce damage caused by floodwaters, so as to protect property and guard against potential loss of life. Due to the tremendous length of levee structures, totaling many thousands of miles, proper operation and maintenance of levees can be challenging. Events like Hurricane Katrina in 2005 have shown that levee failures can be catastrophic, and very costly. Historically, levees have been used to protect and/or reclaim land used for agricultural purposes. However, levees are increasingly providing protection for vast amounts of commercial and residential property as well. If levees fail, there is a potential for significant property damage, and in some cases, loss of life, as was experienced in New Orleans in 2005 relative to Hurricane Katrina. Because of this, levees need to be appropriately maintained and actively monitored so that they can be safely operated.

The failure of a number of dams in the 1970s, most prominently Teton Dam in 1976, led to a substantial and appropriate increase in the attention paid to dam safety and monitoring of dam performance, to look for early indications of developments that could conceivably result in dam failure. The 2005 levee failures in New Orleans led to a similar substantial and appropriate increase in the attention paid to levee safety, and the monitoring of levee performance, by the engineering profession. This White Paper is intended to support those efforts in the area of levee monitoring.

The goal of this White Paper is to provide an overview of the current state-of-the-practice in monitoring levees. This monitoring includes the use of visual observations and instrumentation for both regular, on-going monitoring work, as well as during flood events when “flood fighting” is taking place.

This White Paper begins with some sections that provide background discussion and information regarding topics that relate to the monitoring of levees:

- Types of levees, including some other types of long, linear structures that are similar to levees, such as flood walls and canals.
- Similarities and differences with respect to monitoring dams and monitoring levees, so that appropriate perspective allows proper use of pertinent methods and equipment used more commonly for dams
- Potential failure modes for levees, since understanding the potential failure modes is the first step in defining an appropriate monitoring program for a levee
- Risk considerations regarding levees and levee monitoring, since the fundamental purpose of levee monitoring is risk reduction
- Types of instruments that may be relevant to levee monitoring efforts
- Data collection, reduction, and storage relative to instrumentation used at levees, including the use of data acquisition systems

With this background in place, the discussion then moves to two central topics for this White Paper:

- Types of monitoring activities for levees, including methods employed
- Conclusions with respect to monitoring of levees

A separate section in this White Paper is devoted to each of the eight bulleted topics listed above, in the order indicated.

An appendix is included at the end of this White Paper that features a listing of publications that are relevant to the topics of levee monitoring and instrumentation, which will allow the reader to pursue topics raised and discussed in this White Paper in greater depth, as desired.

Note that common parlance used in this paper includes terminology such as "flood protection," and "flood damage prevention." This is mostly for convenience in simplifying the semantics used herein. While man-made structures have provided substantial benefits relative to mitigating potential damage due to naturally occurring flooding, it needs to be recognized that levees cannot protect against all possible levels of flooding. The impacts of man-made structural systems can have benefits in flood risk reduction, but other non-structural approaches can also be beneficial, and depending on the circumstances, may be more appropriate. When communicating with the general public, it is important to use care in selecting the words and phrases used, and make clear the distinction between "flood damage prevention/protection" (a virtually unachievable goal) and "flood risk reduction" (a desirable and achievable goal).

TYPES OF LEVEES

Levees are generally long, linear, raised structures, commonly earth embankments, that are located and constructed to prevent the flooding of adjoining and other protected property. They can also be comprised of flood walls, particularly where land and right-of-way is confined, and closure structures, which are used to fill gaps where roadways, railways, etc. cross a levee.

The area protected by levees can range from undeveloped countryside, where the cost of levee failure would be relatively low, to densely developed urban areas, where the cost of levee failure could be very high. The nature of the protected property can be used as rationale or justification for allocating limited resources (construction funding and monitoring funding) to protect areas of greatest societal concern.

Levees typically have numerous penetrations for underground utilities, and may also have penetrations associated with storm discharge pipes, which may need to be equipped with gates, valves, etc. to allow closure to prevent backflow during flooding events. Levees often also include other features, such as pump stations that are used to remove landside storm water during flooding events, when the gravity drainage stormwater pipes are closed off to prevent backflow. Levees can also include seepage barriers (cutoffs) and relief wells/trenches. Levee designs and levee monitoring programs need to appropriately consider all these various factors and components, and the potential vulnerabilities that they may present, especially those that constitute a discontinuity in foundation soils and/or embankment materials.

Levees can be classified according to two distinguishing characteristics:

- The resources they protect – typically broadly classified as "rural" or "urban" levees
- Their geomorphic setting – typically classified as coastal and riverine. (However, at transitions between river and coastal environments, they are often also classified as estuarine.)

From an overall risk perspective, considerations regarding the first bullet above greatly impact the consequences of levee failure, and considerations regarding the second bullet impact the potential loads on the levee (that could impact the risks of levee failure).

Levees are a subset of a more general category of long, linear structures that also includes:

- Road and railroad embankments
- Flood walls (normally concrete or sheet pile, I-wall or T-wall)
- Canals (frequently concrete-lined)

The focus of this White Paper is on levees, but discussions in this White Paper also would apply to road and railroad embankments when they serve the same purpose as levees in a flood event (protecting property from floodwaters), since their earthfill composition and role during the flood event are the same. Flood protection levees often tie into road and railroad embankments instead of natural high ground. Also, they often intersect abutments for bridges that pass over the river that the levee provides protection against.

Flood walls are specifically constructed to reduce the risk of flooding, differing from levees only in terms of the composition of the structures themselves. Canals are a means of transporting and delivering water to farmlands and municipal users, and differ from levees in that they regularly operate to their normal capacity, while levees at some locations are more intermittently loaded, with potentially long periods of time between loading conditions that approach their design capacity.

For the purposes of this White Paper, much of the discussion will be devoted to monitoring of "intermittently" loaded levees, as opposed to "frequently" loaded levees. There are levees in certain environments, such as deltaic environments, which are loaded frequently or continuously at, or near, their design capacity. In these cases, the levees are essentially acting as a low-height dam, in which monitoring techniques recommended for dams would be largely applicable.

Note that some embankments are referred to as levees simply because they were constructed years ago and named "levees," when in reality such embankments are functioning as dams. This may be the case in certain reaches of an embankment, such as at a stream crossing where the surrounding landform is lower when compared to elsewhere along the embankment.

Natural Levees

In a riverine environment, the formation of a natural levee is caused by depositional and erosional processes, where sediment deposits eventually constrain the limits of "typically occurring" flood events. Natural escarpments develop at the margins of the "typically flooded area." If the river bed elevation increases, the natural levees on either side of the channel also naturally increase in height. Sediments picked up by the river in the flood event get deposited at the river bank areas, where flow velocities are lower, and therefore the water's sediment carrying capacity is less than in areas away from the river banks.

In a coastal environment, natural dunes may be present as well as ancillary offshore structures such as jetties and breakwaters, which mitigate wave impacts and encourage deposition of natural deposits. Man-made dunes are often used as coastal flood protection. Dunes (both artificial and man-made) are typically considered "sacrificial" features that are expected to degrade over time due to flood loading, wind, and other loads, and must be appropriately replenished through diligent management practices.

Artificial Levees

Artificial levees are intentionally constructed to protect adjacent property from flooding. Often times, artificial levees may have been built upon or may tie into natural levees. Artificial levees are located in many different environments, and for many different purposes, including the following:

- Along rivers (riverine)
- In deltas (coastal/estuarine)
- On lake shores (coastal), including structures that extend or supplement dunes along ocean shores or the shores of large bodies of water (coastal)
- Polders (water-impounding structures where there is no natural outflow)

Artificial levees can consist of permanent structures, or may be temporary, emergency structures that may be constructed using sandbags or rapidly placed earthfill.

Riverine Levees

The most common type of artificial levee is the riverine levee that is constructed along and typically parallel to a river channel. Riverine levees are the primary focus of this White Paper. However the topics addressed are, for the most part, readily adaptable to other types of levee systems.

The U. S. Army Corps of Engineers (USACE) has categorized riverine levees into five principal types:

- Mainline and Tributary Levees: Generally parallel to the main channel and/or its tributaries.
- Ring Levees: Completely encircle or "ring" the perimeter of a protected area.
- Setback Levees: Generally built as a backup to an existing levee that has become "endangered" due to such actions as river migration.
- Sublevees: Constructed for the purpose of underseepage control. Sublevees encircle areas landward of the main levee that are flooded, generally by capturing seepage water, during high-water stages, thus counterbalancing the hydrostatic pressures beneath the top soil stratum on the landward side.
- Spur Levees: Project from the main levee and provide protection to the levee by directing erosive river currents riverward.

(The information above is taken from the Memphis District website at http://www.mvm.usace.army.mil/Missions/FloodRiskManagement/Levees.aspx.)

Levee Types Based on Ownership and Maintenance Responsibilities

The National Committee on Levee Safety defines several levee categories, based on levee ownership and maintenance responsibilities:

- Owned by USACE, maintained by a local sponsor
- Owned and maintained by USACE
- Federally owned, but USACE is not the owner
- Not Federally owned (obtaining USACE assistance under Public Law 84-99 may be accomplished, as discussed below)

Levee Owned by USACE and Maintained by a Local Sponsor. The majority of the levees owned by the USACE fall into this category, where the local sponsor is required to perform essentially all operations and maintenance work. The sponsor furnishes assurances that it will maintain and operate the flood control works in accordance with regulations prescribed by the Secretary of the Army (i.e., USACE). The local sponsor is responsible for performing annual inspections of the levee, which are generally carried out immediately prior to the beginning of flood season.

Levee Owned by USACE and Maintained by USACE. A small portion of the levees owned by the USACE fall into this category. The local responsible agency is only required to perform minor maintenance work, such as cutting grass and repairing small erosion problems, and major maintenance work is the responsibility of USACE. Again, the local sponsor is responsible for performing annual inspections of the levee, which are generally carried out immediately prior to the beginning of flood season.

Federally-Owned Levee and USACE is Not the Owner. While the USACE owns a large portion of the federal levees, there are also other federal owners. For these levees, the bureau or agency that owns the levee would have full responsibility for all operations and maintenance regarding the levee, though assistance from the USACE could be requested through an interagency agreement, or services could be contracted for.

Levee that is Not Federally-Owned. The levee owner could be a state or local governmental entity, or a private entity. Again, the owner would have full responsibility for all operation and maintenance regarding the levee, though assistance from the USACE (or others) could be received via contract. Assistance can also be received from the USACE relative to flood situations under Public Law 84-99, as discussed below.

Public Law 84-99. When flood conditions exceed, or are predicted to exceed the response capability of levee and drainage districts, and local or state governments, the USACE has the authority under Public Law 84-99 (PL 84-99) to provide emergency flood response assistance, in the following categories (without further specific authorization of Congress):

- Emergency operations and "flood fight" assistance
- Rehabilitation of damaged "Flood Damage Reduction Projects"
- Advance measures

The assistance is intended to be supplemental to (and not a replacement for) local interests' self-help and requires a Cooperation Agreement with USACE.

In the "advance measures" category, direct assistance or technical assistance can be provided. Direct assistance can take the form of supplies, equipment, and/or contracting for the construction of temporary and/or permanent flood control projects. Examples of technical assistance include having the USACE help with: (1) the performance of hydraulic, hydrologic, and/or geotechnical analysis efforts, (2) personnel to inspect levees to identify potential problems (and solutions to them), (3) evaluation work to determine the requirements for additional flood control protection, (4) recommendations regarding construction methods, and (5) the preparation of "flood fight" plans. Advance measures are designed with respect to a specific (impending) threat, and are to be temporary in nature, unless specifically excepted from this requirement.

The distinctions for the responsibility of a levee (ownership and maintenance) are important since it will likely define the type and frequency of inspections and other monitoring activities that occur, as well as other pertinent information, such as defined in Operation and Maintenance (O&M) manuals and other documents.

SIMILARITIES AND DIFFERENCES — DAMS AND LEVEES

From a performance monitoring perspective, a great deal of information and many valuable references are available relative to instrumentation and monitoring of dams. Among these are:

- Guidelines for Instrumentation and Measurements for Monitoring Dam Performance (ASCE, 2000)

- Conference proceedings, publications, and White Papers from USSD
- Conference proceedings and guidance information from the Association of State Dam Safety Officials (ASDSO)
- Publications and guidance information from the Bureau of Reclamation (Reclamation) and the U. S. Army Corps of Engineers (USACE)

With respect to monitoring levees, the volume of available information is more limited, but rapidly growing. Some of the most recent innovative instrumentation applications (e.g., fiber optic sensors) were developed as a direct result of attempts to overcome one of the greatest challenges associated with levees, which is their substantial lengths (compared to dams). In addition, since the primary function of a dam and of a levee – to hold back water – is essentially the same, there are many similarities between the methods and equipment used for dams and what would be appropriate for levees, so information that is available regarding dam monitoring can have applicability regarding levees. Given this situation, it is useful to note the similarities and differences between monitoring dams and monitoring levees so that proper use of information regarding dams is made.

Similarities

Use of Potential Failure Modes Analysis (PFMA). An important similarity is that the PFMA method can and should be used to understand the risks and define the monitoring programs for both levees and dams. Additionally, where specific failure mechanisms/concerns are identified, monitoring (and evaluation) methods can be the same for dams and levees.

Some of the common potential failure modes for levees are the same as those for embankment dams:

1. Overtopping failure in a flood
2. Seepage erosion failure in a flood (through the embankment, through the foundation, and/or involving transportation of embankment materials into and through the foundation). Particular vulnerabilities exist where there are penetrations, which are often much more numerous for levees.
3. Slope instability in a flood, leading to overtopping failure
4. Slope instability in a flood, leading to embankment cracking and seepage-related failure
5. Blowout at the downstream toe in a flood, leading to one of the three previous potential failure modes
6. Slope instability leading to overtopping failure, due to coincident earthquake and flood loads
7. Slope instability leading to seepage-related failure, due to coincident earthquake and flood loads

Embankment dams can (and typically do) have additional potential failure modes, such as those associated with spillway performance, as well as others associated with normal (non-flood) operating conditions. However, in general, the potential failure modes that apply to levees align well with those that are applicable to dams.

Infrequently Wetted. Some flood-control dams are not frequently wetted, or may generally have low reservoir levels, except during flood situations. Such flood-control dams would be very similar to levees in terms of the potential failure modes that would be developed for them in the PFMA process. Considerations of the length of time a water load would be acting on the embankment, and how the embankment might respond, would be similar for flood control embankment dams and intermittently-loaded levees.

Ownership and Level of Regulation. Ownership issues and variations in the level of regulation is another area of similarity between dams and levees. Many times, entities responsible for levees do not have a source of revenue that is directly tied to levee operation and maintenance work, so funds available for this work may be very limited. Dam owners whose facilities do not generate much revenue, such as irrigation districts whose farmers do not make much profit on their cash crop, may be similarly strapped for funds for needed maintenance work. Regulatory oversight of levees may be limited or minimal in some instances. Similarly, when it comes to dams, state regulators are almost universally stretched very thin to oversee the large number of non-federal, non-FERC-regulated dams in their state.

Differences

Aerial Extent. The most obvious difference between dams and levees is that for dams, the area of concern is generally relatively limited in aerial extent. This makes studying and evaluating a damsite a more straightforward proposition than comparable efforts performed for levees. Consequently, the result can be a more manageable and implementable monitoring program. Visual inspections at dams can encompass the whole site on a relatively frequent schedule. For levees, their length creates many practical problems, including characterization for design and construction, and complications regarding operations, maintenance, and performance monitoring due to the length of levees.

Characterization of the Structure. Foundation geology unknowns and unknown variations in embankment composition and construction are much more likely to be present at a levee that at a dam, since a long levee structure cannot be explored as intensively as a damsite. For dams, site exploration work that produces a reasonable understanding of the characteristics of the site and structure can lead to a monitoring program that is fairly confidently defined. For levees, site and structure characterization is important, but it is not feasible for this characterization to be as complete as at dams. Foundation conditions for a levee can vary greatly since the levees are commonly constructed on fluvially deposited sediments, which can be complex and heterogeneous. Relic streambeds can incise the foundation below levees, perhaps at multiple locations. Effectively identifying all important geologic anomalies in levee foundations, either through direct subsurface exploration, geophysical methods, or review of historical data is highly desirable, but long levee lengths may make this challenging (at a minimum), or not realistically possible, in some cases. Another consideration is that the embankment materials used in a levee may vary greatly, since local materials are typically used and the local geologic environments can vary greatly along the length of a levee.

In light of this situation, paying attention to anomalous performance of a levee under load is often an important way to learn where to have special concerns and employ more intensive monitoring techniques. Even without high water loads, lush vegetation in an area can point to seepage concerns, which can lead to the area being a special attention area in a flood event. These considerations apply to dams as well, but given the special circumstances associated with levees, these considerations often take on even greater importance. Reaction to performance plays a greater role in the definition of the monitoring program at levees, than at dams, though the basic principle applies in both instances.

Additional Potential Failure Mode Consideration for Levees. As previously discussed, dams and levees share many similar potential failure modes, such as seepage and backward erosion of material due to piping. However, erosive forces occurring on the waterside of the levee can induce rapid loss of soil during a flood event. Such a condition is intrinsic to levees, where the flow of water is generally parallel (or sub-parallel) to the embankment, and high flow velocities are a regular occurrence during flood stages. A loss of waterside foundation or levee soil may exacerbate many of the common potential failure modes, in that waterside levee slopes may be destabilized, seepage paths through or beneath the levee may be shortened, and landside levee slopes may be destabilized due to higher pore pressures. For dams, while it is possible that similar erosion situations could develop near the inlet structures for spillways and/or outlet works, this situation is not nearly as prevalent.

Complicated Consequence Evaluations. For risk evaluation work, special considerations often exist for levees, not just relative to the potential failure modes, but for the potential consequences as well. It may be necessary to consider the impacts associated with failure of various system components. This may be more involved and complicated than comparable work performed for dams.

Heterogeneous Components. Levees are linear systems, often comprised of segments of heterogeneous components, including earth embankments, flood walls (of various types), and closure structures. There are often numerous major transitions along a levee's length, whereas a dam typically only has a limited number of major transition areas. Transition areas are particularly vulnerable to problem development due to the change in materials and configuration, and require special attention during design and construction, and subsequent monitoring.

Subsurface Penetrations. An acute vulnerability for dams and levees is subsurface penetrations. While dams and levees typically both have penetrations, levees frequently have a greater number and variety of them.

Practical Realities in Defining a Monitoring Program. For dams, there can be debates about the extent of the monitoring program, and the frequency that monitoring needs to be performed, but these debates may pale in comparison to the complexity of these debates regarding levees, where the area to be covered can be tremendously greater. Partitioning of levees, with respect to monitoring efforts, may be a necessity so that limited resources for monitoring efforts can be deployed as wisely and efficiently as possible. For example:

- **Special Attention Area** – Significant concerns exist. Monitoring program definition and execution can be much like that of a dam. Note that in some special attention areas associated with seepage, the vegetation may become so thick that the ability to effectively visually inspect the area is severely compromised, making the ability to quantitatively monitor actual seepage flow(s) in the area (if they exist) very valuable and beneficial.

- **Questionable Area** – Some elevated level of concern exists such that performance monitoring needs to be performed to an appropriate degree. However, if a significant amount of the structure is viewed to be in this category, then practical realities can limit, and perhaps severely limit, the monitoring effort that can realistically be carried out. Therefore, a challenging situation exists regarding the definition of questionable areas. Too much area designated as questionable means that the monitoring intensity may be diluted. However, too little area designated as questionable means that some areas may receive less monitoring than they should, and perhaps much less.

- **Seemingly Satisfactory Area** – Intensive monitoring efforts do not seem to be required, so the resources available for monitoring efforts are not deployed significantly in this area, but instead are diverted to areas of seemingly greater need. However, is enough really known about these areas to significantly scale back on monitoring efforts? Maybe so, but maybe not. Previously unknown problems may exist, or new problems may develop (e.g., new burrowing animal activity). What to do from a monitoring standpoint about long distances of seemingly satisfactory levees, particularly during a flood event, can be a difficult issue.

At dams, appropriate monitoring attention can be provided in most situations because of the much more limited aerial extent of the dam. It is often more evident for dams where special attention should be focused based on: (1) the location of the stream or river valley they are constructed across, (2) the location of certain geologic features that required special treatment, and (3) areas where critical loadings are present (e.g., the maximum section of the dam).

Magnitude of Water Pressure Loads. Another key difference is the magnitude of the water pressure loads on the structure. Dams and their foundations are typically subjected to significantly greater reservoir water pressures than levees. Therefore a flaw or weakness at a levee may not develop into a seepage incident, whereas at a dam, the same circumstance could develop into seepage-related failure of the structure.

Transitory Loading Condition. Some dams are operated with sustained high water level conditions, which is a more severe test regarding a seepage-related failure mode than transitory loading conditions associated with floods, which are more the norm for levees.

Length of Seepage Path. The length of the seepage paths at levees is typically significantly shorter than at dams. Therefore, any shortening of seepage paths due to animal burrowing activity, roots of vegetation, etc. may be more significant and consequential at levees than at dams.

POTENTIAL FAILURE MODES FOR LEVEES

In one form or another, the concept of delineating potential failure modes for dams has been around for a number of years. The "Federal Guidelines for Dam Safety: Glossary of Terms (FEMA 148)," defines a potential failure mode as:

> "[a] physically plausible process for dam failure resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir." (FEMA, 2003).

It is believed that in the 1990s, the U. S. Bureau of Reclamation (Reclamation) was the first organization to make the concept of defining potential failure modes a fundamental element of their dam safety evaluation efforts. In 2002, the Federal Energy Regulatory Commission (FERC) initiated efforts that led to the development of the Potential Failure Modes Analysis (PFMA) program that was extended to all FERC-regulated dams within the following few years. Due to this, performing failure mode analyses for dams rapidly moved from "a new idea" to becoming more and more prevalent throughout the dam safety community.

The benefits of performing a PFMA include:

1. Identification of the most significant potential failure modes (threats) for the structure
2. Assessment, at least in a qualitative sense, of the level of risk associated with the various potential failure modes identified
3. Identification of actions that can be taken to reduce risks
4. Identification of immediate actions that can be taken in the event of intolerably high risks
5. Development of an appropriate monitoring program to address the various potential failure modes identified

While the PFMA process was developed for dams, clearly the same process can be carried out for levees, achieving the same benefits as noted above.

Steps associated with performing a PFMA for a levee include:

1. Gather the available records for the levee
    a. Geologic information
    b. Design information
    c. Construction information
    d. Historical aerial photographs
    e. Performance history, based on instrumentation data and visual observations
    f. Current design earthquake and flood loadings
    g. Analysis/evaluation work performed to date

2. Gather the people that have knowledge about the structure and/or have technical expertise to be drawn upon with respect to a discussion of potential failure modes, including:

    a. Facility operating and maintenance personnel
    b. Facility management personnel
    c. Geologist
    d. Geotechnical engineer
    e. Flood loading specialist
    f. Earthquake loading specialist, when appropriate
    g. People who have written performance reports, inspection reports, evaluation reports, etc. for the structure
    h. Other technical disciplines/personnel that have experience/information to share

3. Conduct a focused brainstorming session involving the above personnel to share information and experience about the structure so as to develop:

    a. Potential failure modes for the structure, and an understanding of the degree of threat they pose
    b. Actions that can be taken to reduce risks
    c. Additional information gathering, exploration work, etc. that might be appropriate in light of the unknowns encountered during the discussion
    d. An appropriate future monitoring program to address the potential failure modes identified

Synergy during the brainstorming session can lead to results superior to those that might otherwise be achieved.

The potential failure mode evaluation is site specific. The process searches for potential failure modes that are physically possible (or cannot reasonably be ruled out) given the information available. The potential failure mechanisms need to be described as precisely and specifically as possible, so that the remainder of the PFMA process can be effectively carried out. The most probable location(s) for development of each potential failure mode needs to be specifically identified, along with the manner in which the potential failure mode would likely initiate, progress, and eventually result in structure failure.

The identified potential failure modes are typically presented in order of apparent threat or likelihood (qualitative ranking), to help establish which modes deserve the most energy, effort, and attention in the monitoring efforts. (Quantitative risk analysis work, if subsequently performed, can refine this initial ranking effort.) It is important to understand that the identification of potential failure modes does not necessarily mean they are likely to occur. If the likelihood is viewed to be more probable than "fairly remote," then a "deficiency" may exist that most likely should be addressed in some manner. The concept of a potential failure mode being "physically possible, but of low likelihood" may be difficult to deal with in some instances, but the fundamental reality is that there is inherent risk associated with every levee, no matter how apparently well-designed and "safe" it may appear, and it is that reality that is typically being addressed by continued vigilant monitoring activities and periodic evaluation activities.

For dams, potential failure modes typically are developed for three loading categories: (1) normal operations, (2) flood loading conditions, and (3) earthquake loading conditions. Since levees are designed to address high water levels in flood events, and under normal conditions levees may have little or no water against them, the predominant potential failure mode category of interest for levees relates to flood loading conditions. Since it is very unlikely to have a major seismic event occur coincident with a major flood, often earthquake loading conditions end up being considered, but set aside, due to a low probability of coincident major earthquake and flood events. However, in highly seismic areas, consideration of this possibility may be appropriate.

For areas that are not highly seismic, the potential failure modes may include some or all of the following under flood loading conditions:

1. Overtopping, erosion of levee embankment materials due to overtopping flow, and failure by breaching.
2. Seepage-related failure due to backward erosion through the foundation, through the levee embankment, or through the foundation and then through the levee embankment, leading to failure by collapse of the overlying embankment and subsequent breaching. Penetrations through a levee, such as a conduit or pipeline, are particularly vulnerable locations for this potential failure mode, since compaction of materials against the penetrating structure may not have achieved densities comparable to other areas. Also, arching effects associated with the penetrating structure can provide "roof" support for a developing "pipe," and seepage flows can concentrate at the embankment/structure contact.
3. Slope instability, leading to embankment cracking and seepage-related failure.
4. Slope instability, leading to item 1 above.

5. Progressive slope failure, eventually leading to overtopping and failure by breaching, due to saturation and destabilization of the landside slope of the levee, followed by slope failure, repeated a number of times.
6. Blowout at the landside toe area, or further away from the levee, due to high pressures caused by underseepage beneath a confining layer, leading to items 2, 3, or 4 above.

For areas that are highly seismic, the potential failure modes may also include some or all of the following under coincident flood and earthquake loading conditions:

1. Overtopping, erosion due to overtopping, and failure by breaching, due to slumping that resulted from seismic shaking
2. Slope stability failure, leading to overtopping, erosion due to overtopping, and failure by breaching, due to liquefaction of foundation and/or levee embankment materials
3. Seepage-related failure due to flow though a seismic-induced crack or gap in the levee embankment that results in erosion of material and eventual failure by breaching

The above lists of potential failure modes for levees are by no means exhaustive and complete. Rather they are intended to give a sense of some of the more common potential failure modes for levees. PFMA work is site-specific, and many times some potential failure modes are developed that are unique for a particular structure. Participation by everyone associated with the levee, especially local operating personnel, is very important in the brainstorming discussions to uncover important information and develop potential failure modes unique to the particular circumstances of the levee being studied.

RISK CONSIDERATIONS FOR LEVEES

Risk considerations in the context of levee monitoring and instrumentation include those factors that could reduce the risk to the protected areas. The factors to consider are:

- Potential risk reduction
- Residual risk to protected areas
- Benefit to Cost Ratio
- Instrumentation risk

Potential Risk Reduction

The primary purpose of levee monitoring is to reduce the risk of levee failure and the associated consequences. Levee monitoring includes the possible use of instrumentation, so levee monitoring should be thought of as visual inspections, augmented by instrumented monitoring where appropriate.

Conventional levee monitoring programs rely primarily on observation of the levee system to identify potential problems that could lead to levee failure. Operation and monitoring plans include periodic inspections by trained personnel utilizing checklists and forms, or more sophisticated tablet tools, to identify areas of potential weakness that may require repair prior to flood season. Instrumentation is used to augment and enhance the visual monitoring efforts, particularly in areas where special concerns exist.

The strategy for monitoring levees with instrumentation, as opposed to visual monitoring, is different in that physical sensors are placed on, in, or below the levee and/or landside area to provide data regarding the actual performance of a levee at the point of measurement, which is compared to the expected performance of the levee for a specific loading condition. The reduction in risk based on the data from the instrumentation may be experienced by:

- Identifying levee components requiring repair due to instrumentation data that indicate that levee failure may occur when the day comes that the design loading conditions are experienced, or
- Reducing residual risk by removing people and moveable property from protected areas in anticipation of a levee failure, based on instrumentation data of concern.

Residual Risk to Protected Areas

The residual risk to protected areas has two components:

- Known risk - Levees only provide protection up to their design flood level (often the 100-year flood), so flood events exceeding the design flood level would be expected to overtop and fail the levee, and flood the protected area.
- Unknown risk – The potential for levee failure during a flood event less than the design flood event and for conditions not exceeding the design criteria.

Note that often the residual risk for different portions of a levee system may be quite different. For example, the approach of providing 3 feet of freeboard without evaluating the uncertainty associated with various flood events probably will not result in a uniform level of risk.

Managing the known risk is accomplished by communicating to the public in the protected areas what flood events the levee is designed to provide protection for and what flood events will fail the levee, and then working together on how to address this risk (e.g., additional flood protection measures, evacuation plans, etc.).

Managing the unknown risk is accomplished through monitoring activities, remediation efforts to address identified problems, and efforts to deal with emergency situations during a flood to prevent levee failure.

Benefit to Cost Ratio

There are insufficient funds to perform all the monitoring activities that would be desirable for all levees, and this situation is most prevalent and recognizable with respect to instrumenting levees. Given this situation, it is necessary to develop a strategy to allocate funds to those levee systems where the greatest benefit will occur. This is normally expressed as a benefit to cost ratio. Higher ratios are normally associated with urban areas. Since urban areas have a relatively high residual risk in the event of levee failure, it may be worthwhile to consider instrumenting these levee systems if it can be done at a reasonable cost and if it can be shown that the instrumentation: (a) can actually reduce the risk of failure, and/or (b) identify levee sections that may have a significant likelihood of failure in the event of a major flood event.

Instrumentation Risk

There is a risk associated with the instruments themselves that could affect the instrument reliability. Instrument risk can include:

- Instruments may not have a satisfactory performance history
- Instruments may fail unexpectedly and unknowingly, which is particularly problematic if they are heavily relied upon for detecting early signs of distress
- Required maintenance of the instruments may not occur

Instrumentation may be incorporated in the original design and construction of a levee, but it is more likely that it will be provided at an existing levee. Unacceptably large disturbance of the existing levee may be associated with installation of some types of instrumentation (e.g., installing settlement cells in the foundation soil) which basically precludes their practical use.

One drawback to instrumentation programs is associated with the general funding mechanisms that are typically associated with both dams and levees. Instruments may be designed and installed as part of a capital improvement program; however, the operation and maintenance of the instruments will likely be the responsibility of the local sponsor. Local sponsors are generally funded through local assessments. Their budgets are generally small and operating and maintaining the instrumentation system may be an unsupportable burden. Even for a USACE levee, O&M funding will come from the "routine operations" budget, which must often be used for many different important and competing needs.

If reliance is placed on instrumentation for reduction of residual risk, and the instruments fail to provide data, the money has been wasted. However, a bigger concern is if the instrumentation is faulty and does not provide accurate data. In this case, it is possible that a real problem goes unrecognized, and instead the situation is viewed to be satisfactory, when in fact it is not. Potentially, a levee failure could occur in an area where the available instrumentation data says everything is satisfactory, which obviously would be a very bad situation. The other possibility is that the inaccurate instrumentation data indicates a problem where none truly exists. A lot of resources could potentially be misdirected to addressing this "non-problem" situation, which obviously would be another bad situation. Resources are scarce and need to achieve real benefits. Finally, if an instrument is installed incorrectly, the instrument installation work could compromise the integrity of the levee, increasing the risk of failure. If instrumentation installation work is improperly executed, a variety of problems could result. However, instrument installation work done in accordance with the current state-of-the-practice poses very little risk regarding collection of invalid data or damage to the levee. Nonetheless, as is the case with dams, each piece of instrumentation must have a specific purpose, as well as being installed using appropriate means and methods, because some limited risk (at least) does exist relative to each instrument installation.

TYPES OF INSTRUMENTS FOR USE AT LEVEES

A number of different instruments and technologies can be used for levee monitoring. Some of them are the same as those used for monitoring embankment dams and for that reason they may provide an indication of conditions that are representative of a relatively small volume of the levee, while others may be more specific for levee monitoring in the sense that they attempt to provide an understanding of the condition of the levee on a broader scale. Instrumentation can broadly be classified according to the parameter it is used to detect and measure, which generally falls into one of the following three main categories:

- Hydraulic head (pore water pressure)
- Seepage
- Displacements (vertical and lateral)

The first consideration in selecting the type of instrumentation to be used is deciding what specific objective the instrumentation is to achieve (e.g., monitor pore water pressure in the foundation at the landward levee toe area). Specific monitoring locations and specific instrumentation types can then be chosen based on where and how the parameter is best measured, with consideration given to how the readings are to be taken, stored, and transmitted. Information from a risk-based evaluation of the potential failure modes to be addressed by the monitoring effort can be helpful relative to designing the instrumented monitoring program, which should supplement and augment visual monitoring efforts at the levee.

Observation Wells and Piezometers for Water Pressure Monitoring

Observation wells are the simplest device for measuring water pressures in soils. Under unconfined conditions, the elevation of the water table can be determined. Observation wells generally consist of a slotted plastic pipe surrounded by sand in a borehole with an impervious bentonite seal provided at the top of the borehole to prevent impacts on the collected data from precipitation, snowmelt, surface runoff, etc. The elevation of the water table can be determined manually by inserting a water level indicator into the standpipe, or the readings can be automated by installing a pressure transducer (typically a vibrating-wire pressure transducer) in the standpipe.

Piezometers are used to measure the pore pressures (head) in levees and their foundations under both unconfined and confined conditions. Open-standpipe piezometers generally consist of a plastic standpipe that is installed in a borehole which has a porous element (typically plastic and having very small openings) attached at the bottom of the standpipe. Sand surrounds the porous element and a bentonite layer is used above the sand (and potentially below the sand as well) to isolate the "influence zone" for the instrument. The elevation of the water in the standpipe can be determined manually using a water level indicator, or the readings can be automated by installing a pressure transducer (typically a vibrating-wire pressure transducer) in the standpipe. More than one piezometer can be installed in a borehole (i.e., a "nested piezometer installation" with piezometers at different elevations) to measure the hydraulic gradient present. Alternatively, vibrating-wire piezometers can be installed directly in a borehole by placing them at the desired depths and backfilling around the instruments with sand and bentonite layers to isolate the desired "influence zones," or by backfilling the borehole with a specially designed grout for the full height of the borehole. Other types of piezometers include twin-tube hydraulic piezometers and pneumatic piezometers, but their use in levees is very rare.

One consideration when installing water pressure monitoring instruments is the "lag time" or delay in instrument response associated with a change in pore pressure in the soil. In the case of an observation well or open-standpipe piezometer, a rapid change in soil pore pressure may not be immediately reflected in the water level in the standpipe. A sufficient volume of water must flow into the standpipe to achieve equilibrium with the pore water pressure of the surrounding soil. If the hydraulic conductivity of the soil is very low, it could take days, weeks, or months for this to occur. Where this is an important consideration, vibrating-wire piezometers should be installed directly in the borehole, as discussed above (eliminating the plastic standpipe).

Water pressure data are useful for understanding how the hydraulic head is dissipated as seepage water travels through and under the levee to the landside of the levee system. Anomalous seepage paths, high pressures in the landside foundation that could cause blowout, water pressures that could create instability, etc. can be identified and better understood. Baseline data can be collected and used to predict water pressures that might develop during a flood event, which then allows better assessment and evaluation of potential instability and seepage-related potential failure modes. Baseline data can be compared to data collected during a flood event to understand and better assess levee performance under flood loading conditions, and to calibrate and assess the validity of seepage models that have been used. Frequent readings often are desirable during flood events, which may point to the need for automation of instrument readings, and potentially real-time data transmittal as well.

Seepage Flow

Direct measurement of seepage through a levee or its foundation can be a challenge if the seepage path is not known or if the seepage water cannot be collected and directed to a measurement location. When the opportunity exists to channel seepage water into a ditch or channel, weirs or flumes installed in the ditch or channel can be used to quantify the seepage flow. Small flows can be measured by timing how long it takes to fill a container of known volume (i.e., using the bucket and stopwatch method). In some instances, a velocity meter might be employed to develop the flow rate where the area of the flow is known and constant, such as a pipe that is flowing full. Water levels at weirs or flumes can be read visually using staff gages or using instruments. The instruments could be pressure transducers submerged in the flow, strain measurements associated with buoyancy changes of partially submerged weights, or non-contact type instruments such as ultrasonic or radar level sensors that sense the distance from a reference point to the water surface. The depth of water at the weir or flume is used to calculate the water flow rate using formulas that incorporate the weir or flume geometry.

Soil Moisture Sensors

A change in moisture or water content in the levee embankment or foundation soils can be indicative of a change in the phreatic surface or ground water level, and rising pore pressures. Consequently, it is thought that this information could prove useful in monitoring relative to seepage-related issues.

Soil moisture content can be measured using soil moisture sensors or using suitable geophysical methods such as electromagnetic surveys which determine the electrical resistivity of soils along a continuous profile. Soil moisture sensors measure the dielectric properties of the soil-water system and provide an estimate of volumetric water content. Most commercial soil moisture sensors work on the principle of time domain reflectometry, frequency domain reflectometry, or capacitance, offering the possibility to be read with either portable readouts or automated data acquisition systems.

Soil moisture sensors measure volumetric water content immediately around the sensor. Measuring the soil water content along a continuous profile and being able to automate the measurements is interesting, but commercial products or methods currently available for this are not mainstream. Research work is ongoing. Alternatively, automated electrical resistivity arrays using geophysical equipment could also be considered as a method for continuously monitoring soil moisture content along a profile.

Surface Settlement and Vertical Displacements

Areas of significant settlement are obviously important with respect to possible levee overtopping in a flood event. Settlement is a naturally occurring phenomenon, due to the consolidation of the levee embankment material and its foundation over time, but anomalous or excessive settlement may be an indication of internal erosion due to seepage taking place in the levee embankment or foundation.

A number of methods and types of instrumentation are available to measure settlement and vertical displacements. The methods vary depending on what type of displacement is to be measured, and what sort of measurement methods is feasible. The simplest form of displacement measurement (apart from just a qualitative visual observation) is the total displacement at the ground surface of a fixed location or marker, determined by surveying. This method provides the total vertical displacement, compared to an initial

baseline reading. Obviously lateral displacements can also be monitored coincident with this effort.
Other “traditional” methods can be used to provide the relative displacement of a location compared to a specific reference point, but these methods generally require installation of instrumentation within the body of the levee. Examples include “Borros” anchors, spiral or fixed-foot anchors, settlement cells, and extensometers. These might be appropriate during construction of a new levee, or major reconstruction of an existing levee, but their use at existing levees typically is very limited.

In addition to “traditional” surveying methods, newer technologies, including Light Detection and Ranging (LiDAR) and Interferometric Synthetic Aperture Radar (InSAR), have become available which can be very cost-effective when used regarding long levee systems. These are discussed below.

Interferometric Synthetic Aperture Radar (InSAR). InSAR is a radar technique used for remote sensing. It can be ground-based, low-level airborne (airplanes or helicopters), or satellite-based, with commercially available sources for each. The technique uses two or more synthetic aperture radar (SAR) images of the ground surface to generate maps of surface deformations by using the difference in phase of the radar waves returning to the emitting source. InSAR holds the potential to provide centimeter-scale accuracy over timespans of days to years. Some ground-based InSAR systems even claim millimeter-scale resolution.

SAR systems that are under development include multi-frequency radar that allows fine resolution of surface features as well as penetration into the ground to detect buried anomalies.

Light Detection and Ranging (LiDAR). LiDAR is also a radar technique. It has been commercially available for a longer time than InSAR. LiDAR measures the distance to a target by robotically rotating a laser and measuring the time delay between the emitted and reflected signal. Ground based LiDAR is also called Terrestrial Laser Scanning or 3D Laser Scanning. Airborne and satellite LiDAR are also available.

Lateral Displacements

Besides surveying monuments to determine lateral displacements, inclinometers are the primary method to monitor for lateral displacements at levees. Inclinometers can monitor for lateral displacements or offsets (perhaps associated with a slide plane) within the body of a levee embankment and/or within its foundation. Measurements are taken on two orthogonal planes along the alignment of inclinometer casing that is installed in a borehole. Displacement surveys are typically conducted using an inclinometer probe which is pulled through the inclinometer casing at 2-foot intervals to develop a complete alignment profile of the casing at that point in time. The profile can then be compared to previous profiles to look for offsets and changes. The inclinometer casing usually is installed vertically in a borehole to monitor horizontal displacements. However, it is also possible to install the casing horizontally to measure vertical displacements (settlements) along the alignment of the casing. An alternative to using a portable readout unit to develop a complete profile of the inclinometer casing is to use one or more in-place inclinometers in the casing. Each in-place inclinometer consists of a rod which can vary from one foot to 10 feet or more in length. The rod has a tilt sensor, can freely rotate at each end, spans a section of the casing of interest with respect to possible casing movement, and is left in place in the inclinometer casing. These in-place installations can be either read periodically using portable readout units, or automated, in order to provide continuous, real-time monitoring of changes in tilt sensor inclination.

For structures such as flood walls, inclinometer casings can be installed in the backfill adjacent to the structure, or within the concrete flood wall itself. Also, tiltmeters can be installed on flood walls to infer the lateral displacement from rotation of the face (assuming the flood wall is a rigid structure).

In some instances, it may be preferable to use shear strips or employ time-domain reflectometry (TDR) in lieu of installing inclinometer casing in a borehole. These instruments can be installed at less cost and can be rapidly read, but a full deflection profile is not obtained (which can be obtained when inclinometer casing is used). Rather, indications that shearing movements are occurring, and approximately where they are occurring, is the only information that is obtained. Often, this is all the information that is really needed. If desired, the reading and transmittal of data from shear strips can be automated, if desired.

Temperature Sensors

Temperature measurements within the body of a levee, the foundation of a levee, or along the landside toe of a levee may help identify locations of concentrated seepage flows or locations of changed seepage flow (increased or decrease flow). The underlying principle is that if there is seepage, the seepage will cause a change of temperature along and near the seepage path. For example, relatively low temperatures may indicate the presence of significant seepage flow in an area if the water in the river is colder than the temperature in the levee embankment or foundation.

Temperature sensors, such as thermistors, resistance temperature detectors (RTDs), or thermocouples can be installed in boreholes or trenches in the levee soil or its foundation. Temperature sensors measure temperature locally (immediately around the sensor). Measuring temperatures along a line (perhaps at the landside toe of a levee) can be done using strings of temperature sensors, often called thermistor strings, where the spacing of sensors along an electrical cable linking the sensors can be as close as every 12 inches. Readings of thermistor strings or other strings of temperature sensosrs are often automated using data acquisition systems. Another way of obtaining a continuous temperature profile (perhaps along the landside toe of a levee) is to embed a suitable fiber-optic cable in the levee or in its foundation soil, as discussed in the section below.

Distributed Temperature and Strain Sensing Using Fiber Optics

Fiber optic cables can be used for distributed sensing of temperature and strain. The fiber optic cable is the sensor, and temperature and/or strain can be measured along its full length using an optoelectronic readout apparatus. Most commercially available systems currently measure only temperature and are based on Raman scattering, which is a wavelength shift in the light that is sent through the fiber-optic cable using a laser. Typically, Distributed Temperature Sensing (DTS) systems can locate the temperature to a spatial resolution of 1 meter, with an accuracy to within ±1°C at a resolution of 0.01°C. Measurement distances can reach approximately 30 kilometers, and some specialized systems can provide even tighter spatial resolutions.

Other types of fiber optic monitoring systems, called Distributed Temperature and Strain Sensing (DTSS), analyze scattering in the injected light using the Brillouin approach, which has much less intensity than the Raman scattering and is based on the change in refractive qualities of the light carrier. DTSS systems are more expensive and less common than DTS systems. Their temperature measurement specifications are similar to the DTS systems and their strain measurement specifications are typically in the range of an accuracy of 10 microstrains and a resolution of 1 microstrain, with measurement distances that can be several kilometers to tens of kilometers. Specifications vary with the length of fiber optic cable that is monitored.

For both types of systems, the fiber optic cable needs to be strong enough to be embedded permanently in levee embankment or foundation materials, and must also be able to accommodate stretching. This is achieved by using custom-manufactured fiber optic cables which have a thicker protective jacket than the standard PVC jacket used for typical indoor fiber optic cables. For reference, some manufacturers of geosynthetic materials have incorporated fiber optic cable in these materials, so if they are incorporated in levee construction or modification work, a fiber optic monitoring capability would be built into the installed geosynthetic material.

Microelectromechanical Systems (MEMS)

MEMS is a general descriptor used for a class of discrete multi-sensor systems that can be deployed in various types of arrays and patterns to improve spatial monitoring coverage. These devices take advantage of advances in miniaturization and reduced costs with new technological advances to produce sensors that can measure multiple types of responses (e.g., temperature, tilt, pressure, and strain). These devices often include on-board circuitry to process data directly into a digital format with no need for traditional analog to digital conversion.

Conclusions Regarding Instrument Types Used for Monitoring Levees

Traditional instruments used at dams have one primary drawback that is particularly problematic when it comes to levees. They only measure a single type of response at a single instrument location (at a discrete point, or in the case of an inclinometer, along a discrete axis). New sensors are being developed that can measure multiple types of responses. New technologies (such as fiber optics) are being adapted to help overcome the challenges of instrumenting levees, but their adoption is likely to be slow due to the fact that the costs currently are relatively high and installation without significant disturbance is relatively difficult. At this time, this basically precludes their use for anything but new levees or major levee modification work. Geophysical methods, such as resistivity surveys, can provide information regarding levee seepage performance over fairly large areas, but typically such methods are used in studies being conducted for a limited period of time, as opposed to be part of a long-term monitoring program for a levee.

Caution. Care should be used when drilling and installing instrumentation within levee embankments. The use of a drilling fluid (water or air), which is circulated under pressure, might result in hydraulic fracturing of the levee embankment. Consequently, the current state-of-the-art is that drilling fluids should not be allowed to come in contact with levee embankment material (for the same reason it is not allowed regarding embankment dams). Hollow-stem augers, sonic drilling, or other forms of “dry” drilling should be used to advance the boring through the levee embankment. Then, if the use of drilling methods using drilling fluids is desired in the levee foundation, casing can be installed through the embankment, so that the drilling fluid does not contact the levee embankment material.

DATA COLLECTION, REDUCTION AND STORAGE

Manual collection of data from instruments at levees is common. Typically, data are recorded in a field book for later entry into a computer to “reduce” the data to the desired engineering units, and to store the data. Printouts and plots of the data can then be produced. Plots can be prepared that are a function of time (e.g., water pressures at an instrument over time) or that compare the data from independent and dependent variables (e.g., water pressures at an instrument versus river level).

During a flood event, resources may be stretched thin and manually collecting the desired frequent readings from instruments may not be realistically possible. Automated means for collection and transmittal of instrumentation data may be highly desirable in this situation, which could then allow essentially real-time evaluation of levee instrumented performance. The automation system software could be written so that more frequent readings are obtained during flood events, compared to non-flood monitoring.

Automated data acquisition systems relevant to levee monitoring typically include battery-powered electronic hardware capable of collecting, storing, and transmitting digital readings from multiple sensors and multiple sensor types deployed at levee systems. The data acquisition system software conditions the raw sensor signal by applying anti-aliasing filters, offsets, and signal gain before converting the signal to digital values. The basic components of the levee data acquisition system include: sensors, signal conditioning circuitry, analog-to-digital conversion circuitry, data storage hardware, data communication hardware, and a power source. The power source for a

remote data acquisition system typically includes a rechargeable battery with solar panels and charge controllers. For remote applications like levee monitoring, the data communications hardware usually includes some form of wireless transmission (cellular, radio, or satellite) to a PC computer or web-server computer.
The data acquisition system typically collects readings from a large number of sensors, and this can be accomplished using a multiplexer approach or a digital network approach. The multiplexer method typically includes connection of each sensor cable to a central data acquisition system, and sensor readings are collected by switching input channels one by one. Alternatively, multiple sensor cables can be replaced by digital network nodes. Each network node digitizes the sensor signal as close as possible to the sensor and transmits the result digitally to a central data acquisition system via a single network cable or a wireless transceiver. All sensors can be sampled simultaneously in a network system.

Automated instrumentation systems used at levees have challenges that include: (a) the costs associated with the hardware, sensors, and installation work covering significant distances, (b) the costs of ongoing maintenance of the automated systems, which can be considerable, (c) survivability of sensors and data collection equipment exposed to harsh environmental conditions, including lightning strikes that can destroy even installations that employ state-of-the-art lightning protection, (d) potential vandalism or disturbance of equipment, sensors, or survey targets located in rural or populated areas with no security, and (e) exposure to damage from rodent or animal activity. Although challenges exist, equipment exists that can be successfully used, and efforts are always underway in the instrumentation community to come up with improved equipment that better addresses the challenges noted. It is generally wise to focus automation efforts on the key instruments and areas of concern, rather than simply embarking upon a program that tries to automate every instrument.

TYPES OF MONITORING ACTIVITIES

Many types and levels of monitoring activities can be relevant to levees:

- Investigations to determine levee areas where performance concerns are greatest
- Comprehensive evaluations
- Routine visual monitoring
- Routine instrumented monitoring
- Monitoring during a flood event

The above five activities will be discussed below.

Investigations to Determine Levee Areas Where Performance Concerns Are Greatest

Considerations regarding monitoring of dams and monitoring of levees are significantly different with respect to this activity. Sorting out where more intensive monitoring is needed for levees is a major issue that greatly impacts instrumentation and monitoring plans. Providing instrumentation at a significant density along all portions of a levee is typically inefficient, uneconomical, and unrealistic. Providing extra visual monitoring for the most potentially troublesome areas during a flood event is very important. Investigation work needs to be carried out to identify areas that appear to warrant special monitoring efforts. As previously noted, levees can be categorized as follows (though obviously other categorization methods can also be used):

- Special Attention Area
- Questionable Area
- Seemingly Satisfactory Area

This categorization then allows instrumentation and monitoring efforts to be appropriately scaled to the circumstances that exist along different sections of the levee. In performing site characterization work, consideration of the potential failure modes of concern can guide the information and data gathering activities.

Site characterization almost always includes initial visual reconnaissance efforts and topographic mapping of levee geometry using optical surveying methods, Global Positioning System (GPS) surveying methods, and/or airborne topographic surveys using LiDAR or other methods. Early site characterization work may also include the use of one or more of the following geophysical approaches to broadly look for areas where seepage issues may be especially prevalent and to look for structures passing through the levee which may create preferential seepage paths:

- Electromagnetic surveys to assess electric conductivity/resistivity (ground-based or airborne)
- Ground-penetrating radar (ground-based or airborne)
- Self-potential surveys

Subsequent phases of the work may focus in on questionable or potentially troublesome areas of the levee system, and may involve sampled soil borings, cone penetration tests (CPTs), additional geophysical work, and other information gathering.

For seepage-related potential failure modes, indications of anomalously high amounts of water or moisture in an area are important and would be relevant. These observations would generally be apparent when there is sufficient river stage such that seepage through and/or under the levee would be occurring at the time the information and data are being gathered. Otherwise, potentially misleading information and data may be collected. Therefore the timing of these seepage-related data gathering efforts is important. Evidence of potentially seepage-related sinkholes, depressions, etc. also would be of interest. This evidence, along with indications of low spots on the crest that could lead to overtopping, and indications of slope instability (longitudinal cracks, scarps, bulges at the toe of a slope, etc.), can be observed at any time the levee can be effectively viewed and inspected. Typically visual inspections and topographic surveys are used in combination to gather this evidence and information.

The time when these investigations are being carried out, and information about the levee and its foundation is becoming available, represents an appropriate time to carefully evaluate instrumentation needs for the levee. Instruments can help define and better understand "Questionable Areas," and monitoring of some of these instruments may potentially only be needed for a limited time (until the uncertainties are better understood). Instruments can be installed for more permanent, long-term usage in areas viewed to be "Special Attention Areas." Drill holes performed during exploration efforts can be completed with instrument installations (piezometers, inclinometers, etc.) at relatively low cost. Ideally, at the same time the iterative site investigation efforts are being carried out, the PFMA would be iteratively updated, and efforts to determine (and provide) appropriate instrumentation for the levee would take place, also iteratively updated as new information and data become available.

Comprehensive Evaluations

The USACE requires comprehensive levee inspections, termed Periodic Inspections by the USACE, every five years for their levees. This is viewed to be an appropriate activity for all levees, federal and non-federal.

The USACE Periodic Inspection is conducted by a multidisciplinary team led by a professional engineer. Components of the Periodic Inspection include evaluating routine inspection items; verifying proper operation and maintenance; evaluating operational adequacy, structural stability, and safety of the system; and comparing current design and construction criteria with those in place when the levee was built. Local sponsors participate on the inspection teams and all final inspection results are provided to the local sponsor and FEMA.

The USACE has been performing periodic levee inspections for many years. The currently used USACE Periodic Levee Inspection Program was created in 2006 and the first set of inspections was completed in 2010.

If visual inspections are performed when water levels are low, the ability to effectively evaluate the potential adverse effects of seepage may be compromised. Having performance records during flood events, that can be studied and evaluated, is clearly very important.

It would be desirable that a PFMA effort would take place as part of a comprehensive evaluation, with the effort appropriately scaled to the issues and concerns associated with the levee. Portions of the levee viewed to be "Special Attention Areas" should receive PFMA evaluations comparable to those of dams. The PFMA approach should also be applied to "Questionable Areas" and "Seemingly Satisfactory Areas," with effort levels appropriate to those situations. An important product of the PFMA work would be a Surveillance and Monitoring Plan for the levee that is developed in light of the location-specific potential failure modes identified as concerns, and the perceived risks associated with them.

Routine Visual Monitoring

Routine visual inspections of levees are typically performed at least annually, and are generally performed prior to the flood season. The USACE refers to these inspections as "Routine Inspections." These walking inspections are performed to ensure: (1) the levee systems are being properly operated and maintained, (2) that no new encroachments on the levee have occurred, and (3) that no new structures, facilities, pipelines, roads, etc. have been constructed that pass over, under, or through the levee. These inspections verify maintenance work is being carried out that: (1) promotes the growth of a good sod cover for all levee surfaces not otherwise protected, (2) exterminates burrowing animals, (3) appropriately addresses the growth of undesirable vegetation on levee surface, and (4) provides routine mowing of grasses so visual inspections of all levee surfaces can be effectively performed.

These inspections are to be performed by trained personnel, under the guidance and leadership of experienced geotechnical engineers, utilizing checklists and forms, or more sophisticated tablet tools (discussed below), to identify areas of potential weakness that may require repair prior to flood season. Problems and concerns revealed by the visual inspections need to be promptly and appropriately addressed. Recent technological advances that involve handheld tablet devices that (1) take photographs, (2) allow the location and view direction of the photographs to be automatically recorded, and (3) allow notes to be tagged with the photographs, are very beneficial in speeding up inspection efforts, allowing precise documentation of inspection efforts and promoting straightforward storing and future retrieval of the collected information in computerized databases. The USACE developed the automated Levee Inspection System (LIS) tool as part of the National Levee Database (NLD). It is a Geographic Information Systems (GIS)/Global Positioning System (GPS)-based inspection tool that incorporates the levee inspection checklist and links directly with the NLD. This technology and these devices are also valuable with respect to visual inspections performed as part of a periodic comprehensive evaluation, and monitoring work performed during a flood event.

It bears mention that the development of the capabilities and use of unmanned aircraft (drones) undoubtedly will lead to their increased use to aid and supplement routine visual monitoring efforts at levees, most particularly during major flood events when resources are stretched thin.

Routine Instrumented Monitoring

Instrumented monitoring activities generally involve instruments, sensors, and other systems that are installed on a permanent basis within, on, or beneath levees. These instruments or sensors are read at various times, either manually using portable readout units, or by automated means.

More commonly used instruments for levee monitoring include observation wells, piezometers, inclinometers, surveyed monuments, and seepage monitoring installations (weirs, flumes, etc.). Other types of instrumentation can be incorporated into levee monitoring systems, including temperature sensors, fiber optic cables (measuring temperatures and possibly strains as well), soil moisture sensors, and remote sensing methods such as InSAR and LiDAR, to identify changes in the levee geometry over time. Instrumentation and monitoring considerations for some of the most prevalent potential failure modes for levees are discussed below.

Seepage Erosion-Related Potential Failure Modes. The only direct evidence of initiation or progression of a seepage-related potential failure mode is evidence of sediment transport by seepage flow. However, since sediment transport almost invariably is episodic, rather than continuous, "moment-in-time" monitoring of the suspended solids concentration in a seepage flow (using a portable turbidity monitoring unit, for instance, or chemically analyzing a flow sample) is not beneficial, and can be very misleading. (Permanent installation of turbidity monitoring units has been found to monitor the deposition of "film" on optical surfaces, as opposed to the clarity of the water, rendering this alternate approach ineffective as well.) Routinely inspecting sediment trap locations along a seepage flow path permits detection of sediment transport, regardless of when it occurred, and therefore provides the desired "continuous" monitoring. Weir boxes and stilling pools in front of weirs are examples of effective sediment trap locations that can be routinely checked for evidence of sediment transport. Sediment traps should be provided along all seepage flow paths so that "continuous" monitoring for evidence of sediment transport is provided. Care must to be taken to prevent wind-blown soils, soils carried by surface runoff, etc. from depositing in sediment trap locations and creating uncertainty about whether sediment transport by seepage flow is occurring. High walls, covers, or other means may need to be employed, as appropriate for the situation.

An indirect method of monitoring for evidence of sediment transport is to look for indications of higher seepage flow rates over time, correcting for changing river water levels. Seepage paths that are expanding in size, due to erosion of material along the seepage path "walls" (i.e., the flow is eroding and transporting sediments) will show increasing flow rates with time. It is often easier to detect seepage problems in this manner, since flow rates can be accurately measured, as opposed to looking for visual evidence of sediment transport. However, looking for visual evidence of sediment transport should always be done, regardless of how effectively flow rates are being monitored. There can be other reasons that seepage flows might be increasing with time, that are not related to initiation/progression of a seepage-related potential failure mode, such as deterioration over time of an engineered seepage barrier, dissolution of foundation limestone by seepage flow, etc. However, any evidence of increasing flows with time should be promptly investigated since there is a real and significant possibility that it could be related to initiation/progression of a seepage-related potential failure mode. Typical instruments used for monitoring seepage flow rates include weirs, flumes, and velocity meters. A bucket and stopwatch approach can also be used for small flows. A seepage monitoring installation that can both measure flow rates and trap sediments carried by the flow, such as a weir and weir box, or a weir along a flow path, is the best choice, when practical.

In addition to instrumented monitoring, routine visual monitoring is important relative to seepage-related potential failure modes. This monitoring includes looking for:

- New seepage areas and wet areas (and evidence of sediment transport at these areas),
- Transverse cracks that could provide open seepage paths when the river water level is high,
- Open joints, cracks, etc. in conduits and walls in contact with levee embankment materials that could provide seepage paths,
- Animal burrows and roots of vegetation that could present open seepage paths, and
- Sinkholes, depressions, etc. that could be indications of subsurface removal of material by seepage flow.

Piezometers typically are not particularly useful for detecting the initiation/progression of a seepage-related potential failure mode since it is unlikely that the location of “point” measurements will be coincident with the developing seepage path. However, these instruments can provide information to allow a better understanding of general seepage patterns in an area of a levee, allowing potential seepage-related potential failure modes to be appropriately defined and better understood. A note of caution is appropriate here. Sometimes in the past it has been viewed that low hydraulic gradients (developed from piezometer data, along with headwater and tailwater data) mean that a potential seepage path has no prospect of developing into a failure mode. However, experimental testing as well as case history performance of dams has shown that sediment transport and seepage-related potential failure modes can develop with gradients even less than 0.1.

If significant concerns exist about the possibility of concentrated seepage flow developing in an area, that might lead to seepage-related levee failure, a dense network of soil moisture sensors or temperature sensors could be installed in the area to provide an alert of developing adverse conditions. Real-time (automated) monitoring of these sensors probably would be appropriate in this situation. Seepage detection could be accomplished by placing a line of instruments near the area of concern, which would commonly be the at the landside toe of the levee, or vulnerable areas offset from the toe (ditches, low spots, etc.). One approach for carrying out this instrumented monitoring would be to install a fiber optic cable along the landside toe of the levee, which could monitor for temperature anomalies every meter along the length of the cable, in the area of concern, as has been noted previously.

<u>Blowout at the Downstream Toe due to High Water Pressures from Underseepage</u>. Piezometers can be used to gather information about water pressures associated with underseepage beneath a confining layer, and about water pressure gradients, to determine if an apparent problem exists. Preemptive remedial actions can be taken before the flood season to appropriately address concerns about this potential failure mode. If the situation is less certain, then water pressure monitoring during flood events, perhaps using automation equipment, can provide additional data to better assess the situation.

Calculations can be made to determine water pressures that could lead to instability, and then the automation systems could provide alarms if those pressures are exceeded.

In general, the discussion included in the "Seepage Erosion-Related Potential Failure Modes" subsection above also applies regarding this potential failure mode. Additionally, discussion included in the "Slope Stability Failure" subsection below may also apply, if the failure mechanism that will breach the levee potentially could be slope instability caused by the increased foundation pore pressures.

Overtopping in a Flood Event. It is important that levees be periodically surveyed to observe for any anomalously low areas where overtopping in a flood could occur, as well as to determine the basic level of flood protection provided (i.e., actual levee crest elevation present). Visual inspections may be able to identify suspicious areas, where follow-up using optical or GPS-based surveying methods could be used to investigate the situation. For periodic surveys of the entire length of longer stretches of levees, remote sensing approaches such as LiDAR and SAR imagery can be used. LiDAR surveys can be performed using either a ground or aerial platform and SAR would most likely be performed from an aerial platform (airplane, helicopter, or satellite). It is conceivable that in the next few years, drones may be used to routinely conduct these surveys.

Slope Stability Failure. In the typical situation, where elevated instability concerns do not exist, monitoring efforts typically consist of visual inspections, looking for bulging at the landside toe area, longitudinal cracking at the levee crest or at the slopes of the levee, or evidence of scarps, sloughs, slides, depressions, etc. on the slopes of the levee. Periodic surveying of monuments on the levee embankment, looking for unusual settlements or deformations, also can be a component of the monitoring program, where this is viewed to be appropriate and warranted.

If elevated instability concerns exist, instruments that could be deployed include one or more of the following: inclinometer casing read with a portable probe, in-place inclinometer, shear strip, time-domain reflectometry (TDR), and surveyed monuments on the levee slope. If the concerns are high, then real-time data collection may be warranted, along with real-time data transmittal and evaluation.

Monitoring During a Flood Event

Phenomena related to all potential failure modes must be carefully monitored during a flood event. Structures are best monitored by visual inspection. Walking or using all-terrain vehicles, and traveling along the landside toe of the levee during high water events is recommended, as a minimum. Levee failures during floods are frequently associated with overtopping flows, through-seepage, underseepage, or blowout. Recently, more seepage-related failures and incidents are being documented associated with animal burrowing. Instruments need to be read at an appropriate frequency during the flood event to collect the needed information.

During flood events and immediately following each major high water period, levees need to be inspected to look for unusual settlements, sloughing, caving on either the landside or waterside, seepage, and sand boils. Immediate steps must be taken to correct any dangerous conditions disclosed by such inspections.

Flood fighting is an art, but it certainly benefits from routine monitoring efforts, evaluation work, and planning work done prior to the flood. Comprehensive evaluations, and routine visual and instrumented monitoring need to be regularly performed so that key baseline information is available at the time of the flood event. Appropriate routine maintenance needs to be performed so the levee is in suitable condition at the time of the flood. Before every flood season, preparation and training to respond to a potential flood should be performed. Following each flood event, levees should be closely inspected and the performance of the levee during the flood should be documented. This documentation should include, as a minimum, photos, accurate locations and degrees of seepage, and information about any other poor performance issues which may have occurred during the event. As future flood events approach, this documentation should be studied to help identify potential problem areas. Also, this documentation should be reviewed to determine necessary remedial work that should be performed prior to the next flood season.

CONCLUSIONS

Visual Inspections Are Central to Monitoring Efforts

Routine visual inspections of levees are the central element of levee monitoring programs. These inspections should be performed: (1) at least annually, preferably just before the start of the flood season, (2) at a frequency during a flood event appropriate to the level of concern and risk about each section of the levee (i.e., different sections can have different, risk-based, inspection frequencies), and (3) as a part of more comprehensive levee evaluations that are performed approximately once every five years. Problems and concerns revealed by the visual inspections need to be promptly addressed and rectified as appropriate. Recent technological advances that involve handheld devices that (1) take photographs, (2) allow the location and view direction of the photographs to be automatically recorded, and (3) allow notes to be tagged with the photographs are very beneficial in speeding up inspection efforts, allowing precise documentation of inspection efforts, and promoting straightforward storing and future retrieval of the collected information in computerized databases. Increased capabilities and use of drones undoubtably will lead to their increased use to aid and supplement routine visual monitoring efforts at levees, most particularly during major flood events when resources are stretched thin. Personnel that perform visual inspections should be trained with respect to the critical nature of the work, and the potential consequences associated with failure of a levee.

Definition of Areas Warranting Close Attention is Important

Defining sections of levees that need more monitoring attention is an important activity regarding monitoring efforts. Levees are often long structures, and efforts to focus monitoring efforts in the areas where close monitoring is most needed provides effective and efficient monitoring, using the limited available resources to the best advantage. A three-category system (Special Attention Area, Questionable Area, and Seemingly Satisfactory Area) is noted herein, as an example of how the levee system could be categorized. Categorization can occur (1) by performing investigations to determine levee areas where performance concerns are greatest, (2) as part of comprehensive levee evaluations that are performed approximately every five years, and/or (3) as a result of actual levee performance experienced, particularly during major flood events. Phased approaches may be appropriate for investigations, where rapid, lower-cost methods can be used initially to cover all areas (e.g LiDAR surveys, electromagnetic surveys, etc.), and subsequent phases can collect more detailed information regarding areas that are apparently or potentially troublesome (potentially including drill holes where instrumentation might be installed). Good data and records collected during flood events about problem areas are valuable in defining areas warranting close attention in future floods, as well as identifying areas where remedial construction work would be appropriate.

Instrumentation Can Be Beneficial In Areas Warranting Special Attention

With a good understanding of the potential failure modes and the performance history of a levee, instrumentation systems can be designed to appropriately supplement visual monitoring efforts. The instrumentation may be temporary in nature, to gather more data about a specific concern in a specific area. Alternatively, the instrumentation may be for long-term use, when heightened concerns exist in an area. Automated data collection and transmittal may be appropriate where the instrumentation is intended to give a real-time warning of anomalous, unexpected, or undesirable performance.

APPENDIX A

PUBLICATIONS RELATING TO LEVEE MONITORING AND INSTRUMENTATION

No national standards, guidelines, or minimum criteria have been established for levee monitoring and instrumentation. Various federal, state and local agencies have adopted or put forth design requirements and standards, guidelines, and/or minimum criteria for the design, construction, operation, and maintenance of levees. In turn these indirectly influence levee monitoring and instrumentation. Many of these design, construction, operation, and maintenance requirements are necessary for levee recognition under the National Flood Insurance Program, participation under the Flood Control and Coastal Emergency Act (PL 84-99), and USACE Inspections under the Levee Safety Program.

The International Levee Handbook was published 2013 by the Construction Industry Research and Information Association (CIRIA) and represents the result of a collaborative effort involving the United States, France, and the United Kingdom, with support from Ireland, the Netherlands, and Germany. This handbook is intended to be a compendium of good practice, offering comprehensive guidance on the design, construction, maintenance and improvement of levees. Three pages of this 1,350-page handbook discuss the topic of "instrumentation and monitoring for levees."

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