Guidelines for Instrumentation of Large Dams

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DRIP
Dam Rehabilitation & Improvement Project

Central Water Commission
Ministry of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Front Cover Photograph: Idukki Dam across the Periyar River in Kerala.

Government of India
Central Water Commission
Central Dam Safety Organization

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The *Guidelines for Instrumentation of Large Dams* has been published for the first time in January 2018 under the Dam Rehabilitation and Improvement Project (DRIP)

Disclaimer

The *Guidelines for Instrumentation of Large Dams* in no way restricts the dam owner in digressing from it. The Central Dam Safety Organization or the Central Water Commission cannot be held responsible for the efficacy of the Instrumentation developed based on these guidelines. Appropriate discretion may be exercised while preparing and implementing an instrumentation program.

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MESSAGE

There are no simple rules or standards for determining the proper level of instrumentation and monitoring for dams. The size and hazard potential of the dam, complexity of the dam and foundation, known problems and concerns, and degree of conservatism used in the design criteria etc. all must be considered in deciding how much and what type of instrumentation, if any, is needed. With that understanding, the purposes of these guidelines are to consider factors affecting dam performance, means and methods of monitoring dam performance, planning and implantation of a monitoring program, data evaluation and reporting, as well as decision making.

Advances in technology will bring new and better means and methods for monitoring, but the broad principles outlined herein should have enduring value. These guidelines are intended to be educational, providing a handy source of information about instrumentation and measurements for monitoring dam performance. These guidelines are not intended to be prescriptive or to establish minimum standards for instrumentation. Each dam is unique, and deciding how to monitor its behaviour requires skill, and judgement beyond the scope of these guidelines.

Guidelines for Instrumentation of Large Dams are the first publication by Central Water Commission, conceived by a team of Central Project Management Unit of ongoing Dam Rehabilitation and Improvement Project (DRIP) comprises officials/experts of Dam Safety Organisation, and Engineering and Management Consultant. These Guidelines have been reviewed by a Review Committee having members from apex national organisations known to be expert in instrumentation area.

We know that risks associated with dams can not be eliminated completely. During planning and designing, majority of safety concern are addressed through sound engineering principles and practices. Some risks are taken care through reliable instrumentation, monitoring and evaluation program throughout the life of dam, and timely and appropriate maintenance program. Some unscheduled risks associated with uncertainties are minimised through emergency action plan as disaster mitigation protocols. Therefore, Instrumentation of a dam along with its monitoring, and evaluation program, is one of the important key element in addressing the safety as well as safety concern linked with a dam. Instruments cannot cure defective designs, nor can they indicate signs of impending deterioration or failure unless, fortuitously, they happen to be of the right type and in the right place.

I hope that this publication by Central Water Commission will help all dam owners, practising engineers as well as other stakeholders to properly plan, install, monitor and evaluate the dam safety performance of a given dam and address the dam safety issue, if any, accordingly.

(S Masood Husain)
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Central Water Commission

New Delhi
January, 2018

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FOREWORD

India has more than 5200 large dams, 80% of which are more than 25 years old. Their health and safety are of paramount importance for the sustainable use of these valuable national assets. The Central Water Commission (CWC) encourages and facilitates dam safety practices to reduce any risk to life and property from the consequences of potential dam failures.

Every instrument installed on a dam should be selected and placed to assist in answering a specific question. Following this simple rule, is the key to a successful Instrumentation Program for dam safety. Dam instrumentation plays a pivotal role providing an understanding of the foundation and structural behavior both during construction and operation of the dam. A monitoring program provides the information that is needed to develop a better understanding of the performance of the dam. Knowing that the dam is performing as expected, is reassuring to dam owner and other stakeholders including the general public. The ability to detect a change in this performance is critical for the dam owner who is directly responsible for any consequences. With operational performance knowledge, dam owners will have the ability to operate and maintain their dams in a safe manner.

Available measures to monitor unusual phenomena that may lead to a dam failure include a broad spectrum of instruments and procedures, ranging from simple to complex. Any program of dam safety instrumentation must be properly designed and consistent with other project components, both before and after the project is in operation only by professional having required domain expertise. Every instrument should have a specific purpose and expected design response and the dam owner possess the willingness and ownership to maintain the program.

The present *Guidelines for Instrumentation of Large Dams* describe all elements of instrumentation program for large dams and will hopefully be quite useful to dam engineers for planning, installation and data processing for ensuring the safety of dams. It is the first publication of its kind by Central Water Commission, a lot of efforts in terms of time and resources have been put through valuable suggestions of Review Committee Members.

I compliment all the individuals and organizations who have contributed to the development of these guidelines and hope that dam owners make use of these guidelines for instrumenting their new and existing dams. Central Water Commission acknowledges the guidance and support given by Dr Martin Wieland, Chairman ICOLD Committee on Seismic Aspects of Dam Design, Switzerland. I also put on record the support extended by World Bank in accomplishing these objectives and especially thank Mr. Jun Matsmuto, former Task Team Leader, DRIP as well as Dr. C Rajgopal Singh, present Task Team Leader, DRIP and their team for extending excellent support all the time.

(N K Mathur)
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PREFACE

Design, construction, operation, maintenance and inspection of dams are intended to minimize the risk of dam failures. Despite the technical and social adequacies of dam safety programs and their implementation, structural or operational situations may develop that may lead to dam failure. The Central Water Commission (CWC) encourages and promotes dam safety practices contributing to reducing risks to downstream lives and property.

Instrumentation plays a fundamental role in understanding the foundation and structural behavior both during construction and in operation of dams. A monitoring program provides the information that is necessary to develop a better understanding of the performance of the dam to reassure dam owners that the dam is performing well and to detect changes in the dam's performance. This is critical as the dam owner is directly responsible for any consequences of a dam failure. With this information, dam owners can maintain their ability to safely operate their dams.

The means and methods available to measure phenomena that can lead to dam failure include a broad spectrum of instruments and procedures, ranging from simple to complex. Any program of dam safety instrumentation must be properly designed and be consistent with all project components including prevailing geotechnical conditions at the dam and considering revised hydrologic and hydraulic factors present both before and after the project is in operation.

The extent and nature of the instrumentation depends not only on the complexity of the dam and the size of the reservoir but also on the potential for loss of life and property downstream. Beyond that, a dam owner needs to be willing to make a firm commitment to an ongoing monitoring program, or the installation of instruments will be of little use.

The guidelines cover overview of dam instrumentation, types & uses, system planning for embankment dams, concrete & masonry dams, seismic monitoring, instrumentation of existing dams, hydro-meteorological instrumentation, data collection & management, monitoring data organisation, analysis and automation. These Guidelines discuss examples of deficiencies in dams that may be discovered during inspections and the various types of instruments that could be used for monitoring these challenges. Increased knowledge of deficiencies acquired through a workable monitoring program is useful in figuring out both the cause of the deficiency and necessary remedies. Continued monitoring is essential to make sure that the selected remedy remains effective. Involvement of qualified personnel in the design, installation, monitoring, and evaluation of an instrumentation system is a pre-requisite to the success of the program.

These guidelines will help the dam owners in monitoring, evaluation and long-term health assessment of dams. It will also bring the uniformity and standardization of various health monitoring practices and will prove a great milestone in ensuring regulations in the field of dam instrumentation.

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LIST OF ACRONYMS

The following acronyms are used in this publication:	
ADAS	Automatic Data Acquisition System
ADC	Analogue to Digital Converter
ADCP	Automatic Data Collection Platform
ARG	Automatic Rain Gauge
ASTM	American Society for Testing and Materials
AWLR	Automatic Water Level Recorder
AWS	Automatic Weather Station
AWWA	American Water Works Association
BIS	Bureau of Indian Standards
CDSO	Central Dam Safety Organization
CWC	Central Water Commission
DDMS	Dam Deformation Monitoring System
DRIP	Dam Rehabilitation and Improvement Project
DTM	Digital Terrain Model
EPA	U.S. Environmental Protection Agency
GNSS	Global Navigational Satellite System
GPS	Global Positioning System
ICOLD	International Commission on Large Dams
IMD	India Metrological Department
LIDAR	Light Detection and Ranging
PGA	Peak Ground Acceleration
PGD	Peak Ground Displacement
PGV	Peak Ground Velocity
PTP	Precision Time Protocol
RCC	Roller Compacted Concrete
RTC	Real Time Clock
RTD	Resistance Temperature Detector
SDSO	State Dam Safety Organization

SMA	Strong Motion Accelerograph
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
WMO	World Meteorological Organization

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Chapter 1. OVERVIEW OF DAM INSTRUMENTATION

The primary purpose of a dam is to store water safely. However, the storage reservoir created by a dam presents a potential hazard to downstream inhabitants and property. The floodplain at risk in case of uncontrolled breaching of a dam may be extensive, densely populated, and of considerable economic importance. In such instances, a dam failure can result in many deaths and tremendous economic loss. A period of progressively increasing structural distress within a dam and its foundation normally precedes catastrophic failure of a dam from causes other than extreme floods or earthquakes.

Symptoms of dam distress can be detected by a *monitoring* scheme designed with the right *instrumentation*. Instrumentation consists of the various electrical and mechanical devices used to measure pressure, water flow, movement, stress, strain, and temperature at a dam and its appurtenant structures. Monitoring is the collection, reduction, presentation, and evaluation of the instrumentation data. An effective surveillance program then relates the identified symptoms to specific problems at an early stage of development by ongoing examination of the collected instrumentation data combined with a review of operation and maintenance records to decide if a dangerous trend is developing or appears likely to develop.

1.1 What Is Instrumentation?

Instrumentation is the use of special devices to obtain critical scientific measurements of engineered behaviour. A typical instrument arrangement consists of one or more of three basic elements:

- a sensor;
- a signal conducting media; and
- a readout/recorder.

Instruments may operate mechanically, optically, electrically, or via pneumatic or hydraulic principles. Some instruments are capable of instant response; others need a period to obtain readings. Some devices are designed for continuous operation, while others only produce readings periodically. Instruments may be mounted in one place or movable and may give readings at one point, on a line or axis, or over a particular area.

Some instruments are read remotely; others are read at or near their sensors. The signal may be transmitted by a rod, wire, a liquid column, an electrical/optical cable, light or laser beam, a line-of-sight, or a radio signal. The data recording may be done by hand, chart recorder, film recorder, digital printout, or magnetic recorder, and in some cases, may be transmitted directly to computer storage.

1.2 Purpose of Instrumentation

Dam safety monitoring is a common safety requirement. The long-term performance of a dam is a necessary factor in the evaluation of dam safety. Diurnal and seasonal effects, changes in hydrostatic pressure and related water seepage affect the health of dams. Wall deflection, settlement and heaving, the rate of water flow, seepage, temperature, vibration, stress, strain and other significant parameters require monitoring to detect changes in the performance of the dam.

The primary purpose of instrumentation is to supply data to aid in evaluating the safety of a structure by collecting quantitative data on its performance and by detecting problems at an early and preventable stage.

Catastrophic dam failure will threaten life and property downstream. The safe functioning of a dam is an important matter of economic benefit and public safety. A secondary purpose is to enable comparison of actual behavior with predicted behavior, which verifies design adequacy and helps gather useful information for refining the design of similar structures in the future.

1.2.1 Proving Behavior is as Expected

Instruments installed at a dam may infrequently (or never) show that an anomaly (abnormality) or problem exists. However, this information is valuable because it says that a certain aspect of the darn is performing as designed. These data serve to verify design assumptions. Also, although a problem may appear to exist or be developing, instrument readings may indicate that the deficiency (e.g., increased seepage) is normal (merely the result of a higher reservoir level), and was expected in the dam's design.

1.2.2 Warning of a Problem

Instrumentation data can detect unusual changes or trends (such as fluctuations in water pressure) that are not visible. In other cases, gradual progressive changes (e.g., slow seepage flow increases) that might go unnoticed visually can be detected by monitoring on a regular basis. This control can warn of the development of a serious problem.

1.2.3 Defining and Analyzing a Problem

Instrumentation data often help to identify and analyze the extent of a problem. For example, downstream movement of a dam because of high reservoir water pressure must be analyzed to figure out whether the movement is distributed uniformly along the dam, whether the movement is in the dam, the foundation, or both, and whether the movement is increasing, decreasing, or remaining constant. Such information then helps to develop proper corrective measures.

1.2.4 Evaluating Remedial Actions

Many dams, particularly old dams, are modified to allow for a change in purpose, for increased reservoir capacity, or to correct a deficiency. Instrument readings taken before and after the changes allow for analysis and evaluation of the performance of the modified structures.

1.3 Need for Instrumentation

Every structure creates certain risks, and dams are no exception. Most dam failures that have occurred could have been avoided if the structure's behavior had been inspected, monitored, and analyzed continuously, and proper corrective measures had been taken in a timely fashion.

Structural displacements, deformations, settlements, seepages, the piezometric pressure within the structure and its foundation are items that are the focus of a monitoring system. Seismic or microseismic vibrations from operation, maintenance work, and construction activity may cause damage such as cracking of the structure or liquefaction of the dam foundation

There are many reasons for installing instrumentation in both new and existing dams. Each dam is a unique situation and requires an individual solution for its instrumentation requirements. The fact that some existing dams have only minimal or no instrumentation at all is not an adequate reason for installing instrumentation. Nevertheless, effective instrumentation can play a vital role in the ongoing assessment of a dam's performance, can provide valuable information concerning the safety of the dam, and can help to improve dam design in the future.

1.4 Inspector's role

The instrumentation responsibilities assigned to inspectors vary from agency to agency. In some organizations, inspectors handle recording and interpreting instrumentation data. In other agencies, specialists record and interpret instrumentation data. However, all inspectors should summarize significant instrumentation data in their inspection reports and use the information to develop conclusions about the performance of the dam.

1.5 Frequency of Monitoring

Proper monitoring is imperative in evaluating the performance of a dam. The frequency of monitoring depends upon applicable regulatory requirements and other factors, including:

- the hazard to life and property that the dam presents;
- the height or size of the dam;
- the volume of water impounded by the dam;
- the seismic risk at the site;
- the age or condition of the dam;
- the frequency and amount of water level fluctuation in the reservoir; and
- the history of problems or abnormal behavior at the dam.

In general, as each of the above factors increases, the frequency of monitoring should also increase. For example, readings should be taken more often during and after higher than normal water levels and after significant storms and earthquakes. Specific reading schedules should be arranged by experienced dam inspectors and qualified engineers. These schedules will need instrumentation readings on a regular basis. In addition to the prescribed schedules, use the following general guidelines:

- Make visual observations during each visit to the dam, and preferably not less than once a month.
- Take frequent readings (daily or weekly) during the first reservoir filling because this is a critical time. The readings should be taken based on directions from the designer and on observed behavior as the filling progresses.
- Take readings during or after a flood or after an earthquake. Significant changes in seepage or movement also show a need for increased frequency of observations.
- Initial readings for a new problem, such as a new crack or seep, should be frequent until a trend becomes evident.

The following chapter will describe the actual mechanics involved in taking the various readings and will present specific frequency requirements and guidelines as they apply to instruments.

1.6 Calibration and Certification

Instrument calibration is one of the primary processes used to maintain instrument accuracy. Calibration is a comparison between a known measurement (the standard) and the measurement using the specific instrument. Typically, the accuracy of the standard should be ten times the accuracy of the measuring device being tested. However, accuracy ratio of 3:1 is acceptable by most standards organizations.

Calibration of measuring instruments has two objectives. It checks the accuracy of the instrument and it determines the traceability of the measurement. Calibration process shall differ from one instrument to other. In practice, calibration also includes repair of the device if it is out of calibration. A report is provided by the calibration expert, which shows the error in measurements with the measuring device before and after the calibration. Calibration chart is usually provided.

All measuring devices require calibration at regular intervals specified by manufacturer and also after an extreme event like floods or earthquake. The calibration services are provided by many government and private laboratories in India. Calibration kits may be provided for some special equipment by the manufacturer. Some specialized instruments may have to be sent to manufacturer or to some specialized agencies for calibration. All instruments used at the dam site should carry current calibration certificate which should be checked at every inspection. The date of next routine calibration should be invariably written in the calibration certificate.

1.7 Maintenance and Performance of Instrumentation

For instrumentation data to be of any value, the instruments must be calibrated and maintained properly. Proper care of the equipment is essential to ensure correct readings. Inaccurate readings are worse than no readings at all because they can mislead one about the performance of a dam and can allow serious problems to develop undetected. Proper care should be taken of all instrumentation and devices at the site as well as all related equipment taken to the site. Listed below are some general guidelines to help ensure the best operability and accuracy of instrumentation equipment:

- Make sure permanent survey points are fixed in place and have not been disturbed.
- Make sure all equipment is kept clean and operable.
- Follow all manufacturer's instructions and guidelines as given in the operating manuals, including instructions for proper care of the equipment.
- Replace all caps and covers after they have been removed or are found missing from the instruments.
- Exercise caution when driving or walking near instrumentation to prevent damage to the instrumentation.
- Ensure adequate protection from vandalism and other damage.
- Check onsite instrumentation on a regular basis for damage from weather, traffic, or vandalism.
- Make sure that exposed metallic components of instrumentation, especially those exposed to high humidity in galleries or maintenance holes, are clean and un-corroded, and that proper preservative treatments have been applied to avoid corrosion.
- Ensure that Instruments are not affected by high voltage power lines present in the vicinity.

1.8 Automated Instrumentation System

Automated instrumentation systems, which may include the remote acquisition of data or automated data processing, are a rapidly growing aspect of many dam instrumentation programs. These automated systems offer some advantages, including fewer labor requirements, better monitoring capabilities in physically or seasonally inaccessible areas, and frequent monitoring capabilities for critical problem areas. However, automated instrumentation systems are expensive, and site-specific cost-benefit analyses should be conducted to decide whether they are advisable.

Automated systems need frequent maintenance and repair by highly trained personnel. An important aspect to remember is that no matter how comprehensive or sophisticated an automated instrumentation system may be, it must never replace actual onsite monitoring and visual inspection.

1.9 Instrumentation System Planning

Instrumentation system planning should receive the same level of effort as other features of a dam. It should follow a logical, systematic process beginning with setting up the objectives and ending with predetermined action based on the data obtained. General considerations for the design of instrumentation systems are discussed by ICOLD (1969), USACE (1989a), and USCOLD (1986). Dunnicliff (1988, Appendix A) gives a checklist of steps for planning an instrumentation system.

1.10 Publication and Contact Information

This document is available on the CWC website

http://www.cwc.gov.in

and the Dam Rehabilitation and Improvement Project (DRIP) website

http://www.damsafety.in

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1.11 Acknowledgments

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- International Commission on Large Dams
- U.S. Army Corps of Engineers, USA
- U.S. Bureau of Reclamation, USA
- Federal Emergency Management Agency, U.S. Department of Homeland Security, USA
- Association of State Dam Safety Officials, USA
- Australian National Committee on Large Dams, Australia
- British Dam Society, U.K
- EN Euro codes,
- International Standards Organisation (ISO)
- Central Board of Irrigation and Power (CBIP), India

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Chapter 2. INSTRUMENT TYPES AND THEIR USES

This chapter discusses the several kinds of instruments that are available to measure physical parameters needed to evaluate dam safety and performance. Because every instrument is designed to measure specific physical properties, instruments are grouped by the parameters that they monitor.

The basic physical parameters that are most important in assessing the safety and performance of both embankment and concrete/masonry dams are as follows:

- water pressure,
- seepage and leakage,
- movement,
- reservoir water level and tail water elevations, and
- weather conditions.

  Other physical data that are important include:

- local seismic activity,
- stress and strain, and
- temperature.

A definition, purpose, and description, as well as specific instruction on reading the instrument and recording its data, are given for each instrument type. Onsite visual inspection of the instrument, data use and interpretation, and overall instrumentation assessment are also described.

This chapter covers a range of instruments. Some of the devices are simple; others are complex and specialized. The goal is to give an overview of the operation and use of the basic and more common instruments and to offer useful background information on the less common and more complex instruments.

2.1 Water Pressure

A certain amount of water seeps through, under, and around all dams. The water moves through the pores in the soil, and through the cracks and joints in the rock. The pressure of the water acts uniformly in all directions; it is termed *pore pressure*. The upward component of pore pressure, called *uplift pressure*, has the effect of reducing the effective downward weight of the dam and can decrease the stability of the structure. Devices used to measure pressure include several types of piezometers and total pressure cells.

Piezometers are devices used to measure the water pressure at specific locations in dam bodies, foundations, and abutments. The primary value of water pressure data is to warn of certain conditions or problems that may exist or may be developing. Unusual water pressure data may show that unanticipated movement or seepage is occurring.

The purpose of a piezometric measurement is to measure the water pressure at a specific point within a mass of earth, rock, or concrete. These measurements can be made directly or indirectly. Direct measurements are made to find the actual water level elevation at a specific point; these elevations can then be converted into water pressure equivalents at the point. Indirect measurements yield water pressure that can be converted into water level elevation values.

Piezometers, depending on their purpose, can have distinct designs. They all consist of three basic parts: (1) a *water inlet* with a filter, which protects the piezometer from penetration of deposit, (2) a *piezometer tube*; and (3) an upper section with protective devices. A further distinction is made between *open* and *closed* piezometers, which include a wide variety of types within each of the two categories.

There are two basic types of piezometers: (1) *hydraulic piezometers* in which the pressure is obtained directly by measuring the water level or the pressure into the tube; and (2) *electrical piezometers* in which the pressure is measured with electrical-acoustic or electric-resistant pressure gauges (manometers), or with pneumatic sensors.

2.1.1 Open-type Hydraulic Piezometers

Open-type hydraulic piezometers directly measure the water level elevation within a vertical tube. This elevation is the phreatic surface in the surrounding earth or rock.

2.1.1.1 Observation Wells

The simplest type of open-type piezometer is an *observation well.* Observation wells are usually vertical pipes with a slotted section at the bottom or a tube with a porous tip at the bottom (Figure 2-1). They are typically installed in boreholes with a seal at the surface to prevent surface water from entering the borehole. A vent is needed in the pipe cap so that water is free to flow through the well point. The depth to the water level is measured by lowering an electronic probe or weighted tape into the pipe.

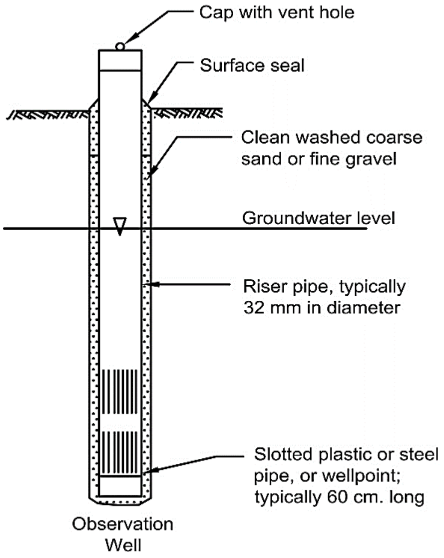


Figure 2-1. An observation well used to measure groundwater levels

Observation wells measure average water level elevations in different zones of materials, or over large areas in drill holes. Water passes through a slotted or perforated pipe, or rise through the bottom of an open pipe. The water that is measured may come from different underground zones and is not isolated by seals in the hole.

In a stratified material, a well creates a hydraulic connection between strata. Thus, the water level in the well is an ambiguous combination of the water pressure and permeability in all strata intersected by the borehole. Data from observation wells may lead to faulty conclusions regarding actual water pressures within the dam and foundation. For this reason, observation wells are suitable only in a uniform, permeable material.

2.1.1.2 Open Standpipe Piezometers

Open standpipe piezometers are observation wells with subsurface seals that isolate the strata to be measured (Figure 2-

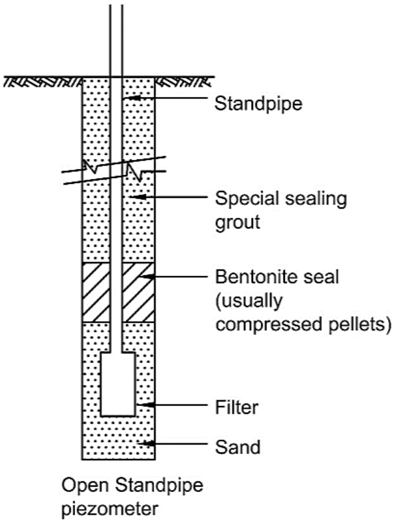


Figure 2-2. An open standpipe piezometer, also called a Casagrande-type piezometer, placed in a borehole

2). These devices are also known as *Casagrande-type* piezometers and, in concrete dams, as pore pressure cells. The seals are usually made of bentonite clay or cement grout and care must be taken during installation to develop a good seal. Riser pipe joints should be watertight to prevent leakage into or out of the pipe, which could change the water level in the pipe. The top of the standpipe should be vented, and the inside diameter should be greater than about 8 mm to be self-de-airing.

A common version of the open standpipe piezometer is a wellpoint, which is a prefabricated screened section and riser pipe that is pushed into place. If the screened section is not sealed, it will behave like an observation well rather than a piezometer. Dunnicliff (1988) discusses methods of sealing wellpoints.

The sensing zone (screened length or porous tip) of observation wells and open standpipe piezometers is susceptible to clogging, which can increase lag time or result in failure of the instrument. This susceptibility can be diminished by a properly designed filter pack that meets filter criteria with the surrounding soil and properly sized perforations that are compatible with the filter pack.

Open standpipe piezometers are used to measure pore pressure in soils with high permeability, such as sand, and is easily installed. These types of piezometers are the standard against which all other piezometers are judged. They are simple, reliable, inexpensive, and easy to check.

For fine-grained soils with low permeability, a Casagrande open piezometer is often installed in a borehole in the foundation or in the dam's embankment. The internal plastic piezometer tube emerges at the ground surface and, if the pressure of pore water in the tube is lower than the level of the embankment, the height of water in the piezometer (pore pressure) is measured using an ordinary electric probe. If the phreatic level is above the embankment surface, the tube is extended vertically above the ground level. This type of piezometer is readily installed in existing dams and is simple to use, reliable, and inexpensive. It is most suitable where the phreatic surface does not change much.

The main shortcoming of open standpipe piezometers is the need for a discharge of water to or from the tube for it to adapt to pore pressure changes. Because of this, there is a noticeable time lag in recording the pores pressure changes if they occur quickly.

2.1.2 Closed-type Hydraulic Piezometers

In *closed-type* hydraulic piezometers, the water surface is not exposed directly to the atmosphere, and water pressure usually is measured across a buried diaphragm, via

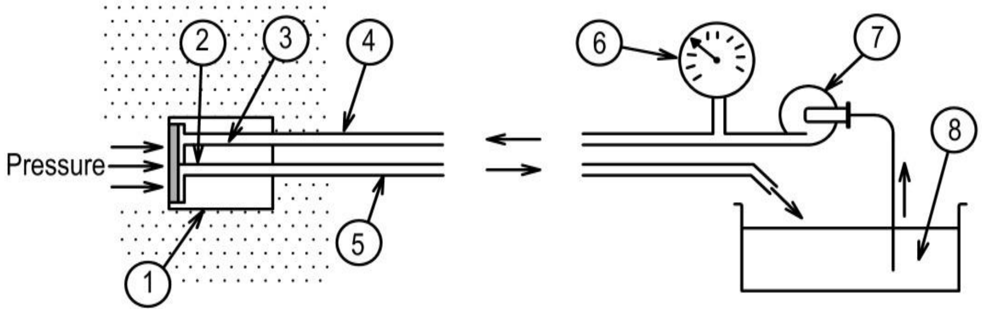


Figure 2-3. Diagram of the Glotzl-type closed hydraulic piezometer. (1) Plastic box, (2) porous ceramic tile, (3) elastic membrane, (4) supply tube, (5) offtake tube, (6) pressure gauge, (7) pump for circulating oil, (8) oil vessel

some mechanical or electrical means, or by gauges on a connecting water column.

2.1.2.1 Closed Standpipe Piezometers

Closed standpipe piezometers are identical to open standpipe piezometers, except that the water level being measured is higher than the top of the standpipe (artesian condition) and the pressure is measured with a pressure gauge (or pneumatic, or vibrating wire piezometer) fitted to the top of the pipe. In concrete dams, they are also known as pore pressure cells. Closed standpipe piezometers installed in concrete dams during construction usually have riser pipes that are not vertical but routed to a gallery for ease of monitoring. Provisions for venting gas trapped inside of the riser pipe are often made but are not needed for most common sizes of riser pipes.

One such piezometer is the Glotzl-type system shown in Figure 2-3. Referring to the figure; the device consists of a plastic box (1) holding a porous ceramic tile (2) through which the pore pressure acts upon an elastic membrane (3). The membrane, in turn, acts on a valve that separates the supply tube (4) from the offtake tube (5). A pressure gauge (6) is attached to the supply tube which is fed by a pump (7) that continuously draws oil from a holding vessel (8). When pore pressure acts on the membrane and closes the valve, the pressure in the supply tube increases and is balanced by pumping oil. The balanced pressure when oil just starts coming out from outlet is the pore pressure. This piezometer, with careful working, is precise and reliable. However, the entire installation is complex and sensitive, and the measurement takes a long time.

Another type of closed piezometer is the Bishop-type instrument shown in Figure 2-4. This device is best suited for use in low permeability soils and in non-saturated soils and thus can measure negative as well as positive pore pressures. Both hydraulic supplies are permanently filled with de-aerated and de-ionized water. The connecting leads can extend for considerable distances (more than 200 meters) to an instrument house where the pore pressure is measured by a transducer, or with a mercury manometer. De-aeration of the leads is needed at intervals to flush

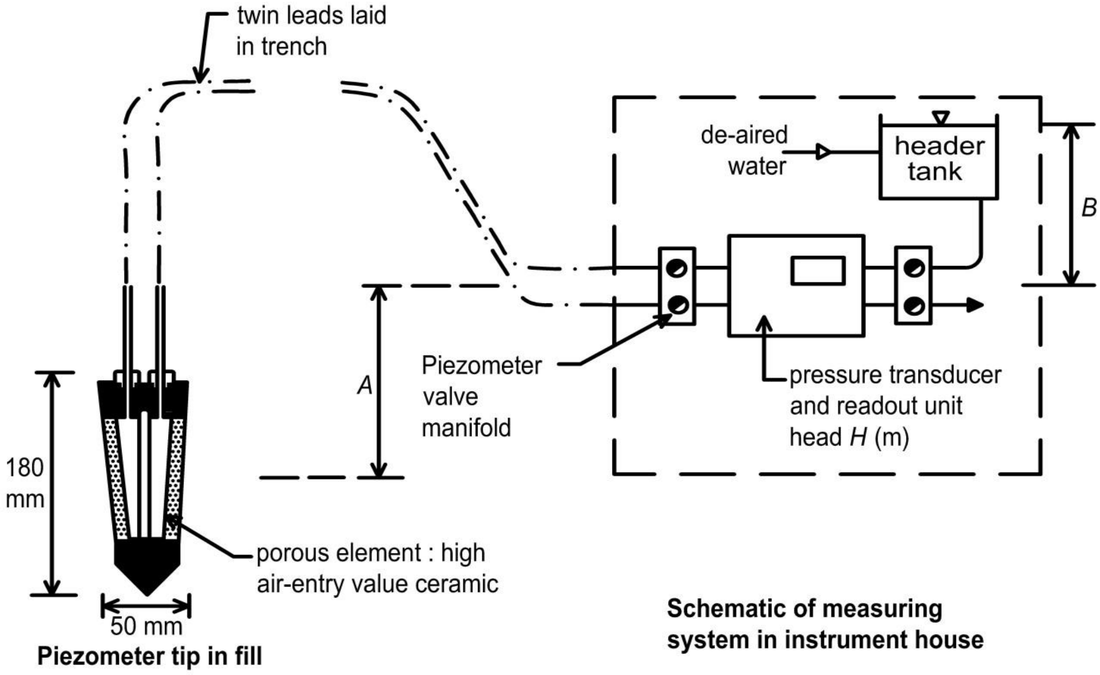


Figure 2-4. Bishop-type twin-tube hydraulic piezometer

out air or water-vapor obstructions. The frequency of de-aeration is reduced considerably if a fine-pored ceramic element is used at the inlet. The Bishop piezometer has proven to be precise and durable and is widely used and incorporated into embankments for measuring the pore pressure during construction (Penman et al. 1999, pages 128-131, Novak et al. 2007, page 297).

2.1.3 Electric Piezometers

Electric piezometers offer rapid response to a change in phreatic level but may prove to be expensive and less flexible in use than the hydraulic alternatives. They offer the advantage of needing only a small terminal measuring chamber, rather than the costly instrument house that is usually needed for twin-tube hydraulic instruments. Therefore, the device is well-suited to an isolated location that has only a few piezometers installed.

The illustration in Figure 2-5 shows the principle of an electrical piezometer with a pneumatic sensor. It functions by application of a known and controlled gas back-pressure to balance the pore water pressure exerted on the diaphragm. The pressure balance is shown by deflection of the diaphragm, allowing the gas to vent to a flow indicator and is confirmed at the closure of the diaphragm when the gas pressure is slowly reduced. (Novak et al. 2007, page 298).

Electrical piezometers can also measure pressure via resistance strain gauges bonded to a steel diaphragm or by use of a vibrating wire strain gauge. The tip of the vibrating wire piezometer holds a porous disk that allows water to enter and press against a stainless-steel diaphragm. A high-strength steel wire is fixed to the center of the diaphragm at one end, and to an "end-block" at the other end. This wire is sealed within a stainless-steel chamber and set to a predetermined tension during manufacture. Water pressure applied to the diaphragm causes it to deflect, thereby changing the tension and resonant frequency of the wire. A coil/magnet assembly is used with a readout device to "pluck" (vibrate) the wire and to measure the wire's vibration frequency. Calibration charts or tables are then used to calculate pore pressure values based on the frequency readings.

2.1.4 Monitoring Frequency

The frequency with which a dam's piezometers should be checked depends on several factors. The required frequency may be specified by the dam owner, or by regulatory requirements. Piezometers should be read at least every three months. Certain conditions may call for more frequent readings. Such conditions include:

- significant changes in reservoir elevation,
- new record reservoir levels,
- the first filling of the reservoir,
- the construction of any remedial seepage measures,
- the discovery of abnormal seepage or movement, and
- seismic activity.

2.2 Seepage and Leakage

The purpose of a dam is to store water effectively and safely and therefore,, its water-retention ability is of prime importance. *Seepage* from a reservoir is the interstitial movement of water through a dam, the foundation, or the abutments. It is different from *leakage*, which is the flow of water through holes or cracks. Seepage and leakage through a dam should not be large enough to erode material from inside the dam body. Such internal erosion can cause undermining or piping in embankment dams, and loss of material strength or density in concrete and masonry dams.

Seepage and leakage through, around, or beneath a dam is a significant factor in evaluating the condition and continuing level of performance of the dam. The level of water in the reservoir is the main factor affecting the quantity of water entering a seepage collection system. Any sudden change in the quantity of seepage collected without clear cause, such as a corresponding change in the reservoir level or a recent heavy rainfall, could be a sign of a severe problem. Similarly, whenever seepage water becomes cloudy (turbid) or discolored, has increased quantities of sediment, or changes radically in chemical content, a genuine problem may be developing. Seepage appearing at new or unplanned locations on the downstream slope, on the abutments, or in the area downstream from an embankment also may signify a problem.

A variety of instruments can measure seepage and leakage. The most common of these measuring devices include weirs, flowmeters, flumes, and calibrated containers Special circumstance may call for other types of flow measuring devices such as current meters. Geophysical surveys can map flow direction within embankments, foundations, and abutments. Bartholomew and Haverland (1987), Bartholomew et al. (1987), and USBR (2014) present more detailed discussions of seepage and leakage measuring devices.

The difference in water levels between the upstream and downstream sides of a dam is the primary cause of seepage and leakage. The factors influencing the amount of seepage and leakage are the same as those that affect pressure distribution. The amount of seepage or leakage is directly proportional to permeability and water pressure.

Most of the factors that control the amount of seepage or leakage do not change during the life of a project. Because reservoir level is the main influence, any change in seepage or leakage rates not related to reservoir level variation needs a prompt investigation. An increase in seepage or leakage may be a sign of internal erosion or piping.

A decrease in seepage may be an indicator of clogged drains. It may also be a sign that seepage is increasing elsewhere, perhaps through an internal erosion channel (piping),

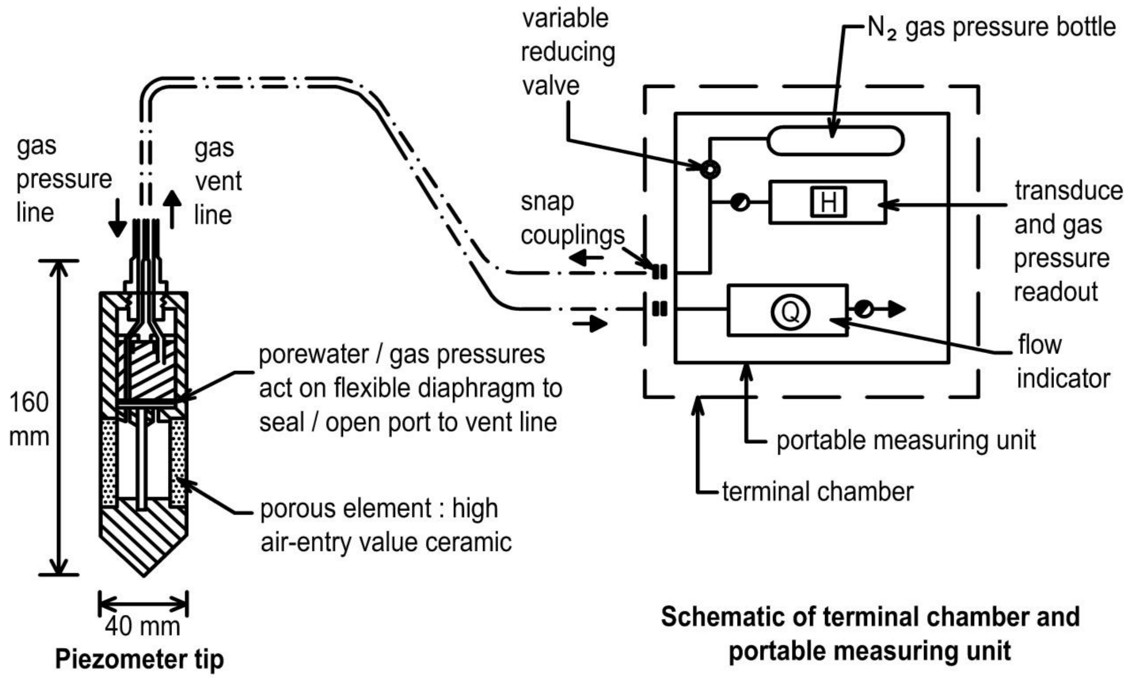


Figure 2-5. Illustration of an electric piezometer with a pneumatic sensor

thereby reducing flow at the measurement point. Cloudy or turbid seepage water may be a sign of piping. New seeps or leaks may also be related to developing problems, such as cracking or hydraulic fracturing.

Another variable that affects the amount of seepage or leakage is the development of the steady-state phreatic surface in a newly constructed project. The steady-state phreatic surface can take several years to be reached. During this period, seepage may increase gradually.

For dams on soluble rock foundations (e.g. gypsum or halite), seepage may increase with time because of dissolution of the rock. In these cases, a slow, steady increase in seepage may be a sign of developing problems.

Foundation drainage system is installed to reduce uplift pressure on the dam. These drainage systems are usually installed at the time of construction. Along with foundation drains, monolith/block joint drains and face drains are commonly installed to intercept seepage along block and lift joints. It is very important to maintain the drains in usable condition by cleaning regularly to maintain free flow conditions. Water flow from all the individual drains or groups of drains should be collected and measured at weir installations. The water should be checked for chemical and suspended content to aid in evaluation of solution or erosion that may be taking place. The elevation of the reservoir and tail water elevation should be recorded at the time measurement so that a relationship between these parameters can be developed.

2.2.1 Measurement Using Weirs

Weirs are one of the oldest, simplest, and most reliable devices used to measure water flow rates. The critical parts of weirs can be inspected easily, and improper operation can be straightforwardly detected and quickly corrected. The three types of thin-plate weirs normally used are (a) rectangular, (b) triangular (V-notch), and (c) trapezoidal (Cipolletti) (Figure 2-6). Discharge rates are found by measuring the vertical distance from the crest of the overflow portion of the weir to the water surface in the pool upstream from the crest. The discharge is then computed by formula or by reference to tables.

Weirs are usually flat plates of metal or plastic. They are installed in a ditch, gutter, pipe, or in maintenance holes in the relief-well collection system. Triangular notch weirs are right for flow rates less than about 0.05 m^3/s. Rectangular or trapezoidal weirs are best suited for larger flows. The crest of the weir should be thin enough that the nappe springs clear. Standard weir dimensions and calibrations are readily available (WMO 2010a and 2010b).

Weirs are simple, reliable, inexpensive, and require little maintenance. Limitations are the severe restriction of the flow channel,

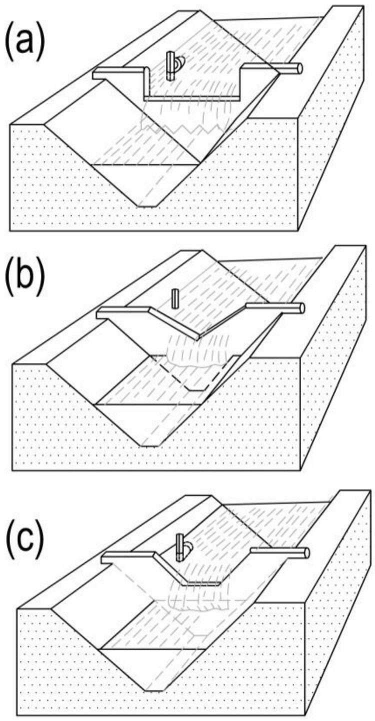


Figure 2-6. The three types of thin-plate weirs normally used to measure seepage flows: (a) rectangular, (b) triangular (V notch), and (c) trapezoidal (Cipolletti)

high head loss, and the need for enough elevation change to prevent the tail water from submerging the weir.

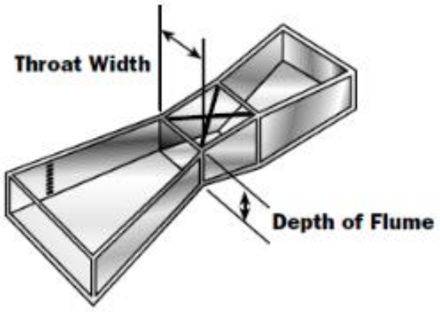


Figure 2-7. Parshall flume for measuring stream flow

2.2.2 Measurement Using Parshall Flumes

Parshall flumes are specially shaped open channel sections. They consist of a converging upstream section, a downward sloping throat, and an upward sloping and diverging downstream section (Figure 2-8). They are usually permanent installations made of reinforced concrete, metal, or prefabricated fiberglass and can be sized to measure a wide range of flows. Throat widths from 25 mm to 10 m are common. Standard flume dimensions are given in WMO (2010a). The quantity of water flowing through the throat is calculated by measuring the depth of water upstream and using the measurement in the proper hydraulic equation. Installation of Parshall flumes should be in a level channel section and, ideally, at a site free of downstream submergence.

Figure 2-8. USGS portable Parshall flume weighing about 5.4 kg.

Figure 2-9. Laser-Doppler velocity meter with ultrasonic depth sensor measuring discharge in a drainage collection channel

Parshall flumes are simple, reliable, and need little maintenance. They cause minimal restriction to the flow channel and low head loss. The primary limitation is the cost of installation which will be more than for most weirs.

The U.S. Geological Survey (USGS) portable Parshall flume (Kilpatrick and Schneider 1983) is a modification of the standard Parshall flume where the discharge section has been removed (Figure 2-9). The purpose of the modification is to reduce the weight of the flume and to make it easier to install, even on a temporary basis when making periodic measurements. With the discharge section removed, the flume should be used only where free-fall conditions from the throat of the flume will occur. As portability is of primary concern, the flume is constructed of 3.2 mm thick aluminum sheet. With a 7.6 cm throat width, the flume weighs about 5.4 kg.

2.2.3 Measurement Using Velocity Meters

Many types of velocity meters are available for measuring flow rates in open channels (WMO 2008). They include pitot type devices, propeller-type meters, acoustic flow meters and electromagnetic current meters. A standard propeller-type current meter is shown in Figure 2-10. Velocity meters using non-contact laser Doppler velocity technology and non-contact ultrasonic

Figure 2-10. Standard propeller-type velocity meter

water-level sensing have been introduced recently. The meter uses an ultrasonic level sensor to find the water level and calculates a sub-surface point in the discharge channel to measure velocity (Figure 2-10).

2.2.4 Measurement Using Calibrated Containers

Containers of known volume can be used to measure low flows that are concentrated and free-falling. The flow rate is computed as the volume of the container divided by the time required to fill the container.

Extremely low flow rates can be measured accurately. The largest flow rate is limited by the size of the container that can be maneuvered quickly into and out of the flow or into which flow can readily be diverted. Typically, calibrated containers are suitable for measuring flow rates less than about 3 liters per second.

Calibrated containers are reliable for low flows and are inexpensive. They have limited application because of the requirement for a free-falling flow, they are not accurate for large flows, and are labor intensive.

2.2.5 Detection by Visual Inspection

Visual inspection is particularly effective when checking on seepage. One item readily noted by a visual check is the turbidity of the seepage water. High turbidity is a dangerous sign because it can be caused by erosion of fine particles of cohesive material from within the dam body. Another item readily noted by visual inspections is the formation of springs, which often appear during the first filling of the reservoir as the result of seepage through the foundation.

Water quality measurements offer a way to evaluate the dissolution of the foundation rock, the source of seepage, or piping. Common water quality measurements include field measurements of pH, temperature, and conductivity, and laboratory measurements of total dissolved solids, total suspended solids, and a variety of minerals (e.g. sodium, potassium, carbonate, bicarbonate, sulfate, and chloride). Standard test methods are given by the American Society for Testing and Materials (ASTM), the American Water Works Association (AWWA), and the U.S. Environmental Protection Agency (EPA). Bartholomew and Haverland (1987) and Bartholomew et al. (1987) discuss the application of the standard test methods to evaluate seepage at dams.

2.2.6 Detection using Fiber-optic Cable

Using a fiber-optic cable as a sensor the temperature can be measured along the entire length of the cable. The technology offers the possibility of measuring temperature along cables of a few kilometers in length, continuously and with high accuracy. The method is based on the optical properties of the fiber which depend on the ambient temperature. A highly-developed measuring technique enables the analysis and evaluation of property changes resulting from a reliable temperature distribution along the fiber.

Fiber-optic cables have been installed inside dams, dykes and levees to measure seepage

(Hartog 2017, pages 303-305). The detection principle is the discovery of a change in temperature because of invading water arriving at a different temperature from that of the monitored structure. Using temperature measurements to detect seepage is quite challenging given the small temperature differences involved, the existence of seasonal and diurnal temperature variations as well as faster changes from exposure to the sun, the perturbative effect of rain and heterogeneities in the edifice caused either by the materials used in the construction or the presence of drainage channels.

In an embankment dam and its foundation, the internal temperature depends on the seepage flow field. Temperature gradients can exist in the form of permanent or seasonal differences, or in the form of significant variations at the probable source of seepage. If leakage is present, temperature anomalies will be transported into the structure by convection and will propagate throughout the earthen body, distorting the temperature field. Distributed fiber-optic temperature measurements find precisely the temperature anomaly and the area affected by excessive seepage or leakage.

Another approach to interpreting temperature measurements from fiber-optic cables is the active method or heat pulse method. This method is based on the thermal response of the surrounding cables to added heat and shows whether the cable is within a moist, a partially saturated, or a fully saturated medium, and whether seepage flow is present or not. By applying a voltage to the electric conductors integrated into a hybrid fiber-optic cable, the cable heats up. The temperature increase in the cable depends on the thermal capacity and conductivity of the surrounding soil material. If seepage water is present, the heat input from the cable dissipates faster. Consequently, the sections with seepage show distinct anomalies. Therefore, the analysis of the measurement data includes the evaluation of the temperature difference between the heated stage and a reference stage before heating. Tanchev (2014, pages 498-502) gives details of the fiber-optic temperature measurement method for seepage detection.

This technique of detecting seepage / leakage by fiber-optic cables has been applied behind the geo-membrane fixed in Kadamparai dam (Tamil Nadu) in India.

2.3 Movement

Various movements and deformations occur in all dams. Horizontal movement occurs in an upstream-downstream direction, but may also occur along the dam axis (usually toward the valley). It can involve the

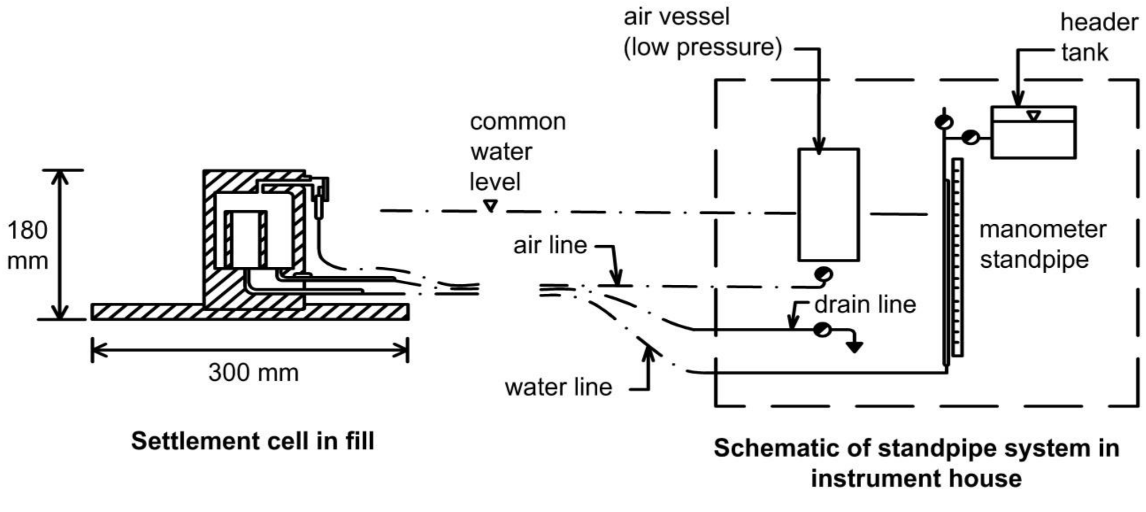


Figure 2-11. Hydraulic point-settlement cell

movement of an entire dam in relation to its abutments or foundation, or one part of a dam in relation to another. The downward vertical movement caused by the consolidation of the dam or of the foundation is called *settlement*. Vertical movement can also occur in an upward direction (particularly at the toe or heel of the dam), because of hydrostatic uplift pressures. Reservoir levels can have an important influence on movements.

When evaluating the performance and safety of a dam, it is essential that movements be carefully watched. This is especially true for concrete and masonry dams where even small shifts in position can lead to grave consequences. Measurement of movements in concrete dams is made with several different instruments including plumb lines, inclinometers, extensometers, strain meters, joint meters, and De Mac gauges. These devices can detect relative movements between parts of the dam or foundation blocks. Absolute movements can be surveyed to measure all aspects of the dam and its surroundings.

In embankment dams, the key movements to monitor include foundation and embankment settlement, and vertical and horizontal deformations within the embankment and its foundation. Embankment movement measuring instruments include settlement sensors, foundation baseplates, inclinometers, extensometers, surface points, and various survey instruments

2.3.1 Types of Movement

All structures move as the result of applied loads. Embankments settle and spread over time as the result of consolidation and secondary settlement of the dam and foundation from self-weight. Embankments also deform because of external loads produced by reservoir water, rapid drawdown, earthquakes, undermining, swelling clays, and piping. Concrete and masonry structures deform because of internal loads such as pore pressure, cooling, and alkali aggregate reaction of concrete; and from external loads caused by air and reservoir temperature, solar radiation, reservoir levels, uplift pressure, wind, earthquakes, undermining, ice, overflowing water, swelling clay, and foundation settlement.

Movements in response to such loads are normal and acceptable if they are within tolerable ranges and do not cause structural distress. Embankments are less brittle than concrete structures and can undergo larger movements without distress. Thus, measurements of surface movements of embankment dams are typically less precise than those for concrete structures. Sudden or unexpected direction change or acceleration of surface movement could be indications of developing problems.

Movement is divided into three types: *surface* movement, *internal* movement, and *joint or crack* movement. Because it can occur in any direction, measurements in three mutually perpendicular directions are needed to depict vector movement accurately. Measurements are typically made in vertical, transverse horizontal, and longitudinal horizontal directions. When movement in one or more of the three directions is found to be negligible, measurement in those directions can be dropped.

The following subsections describe instruments used to measure dam movement. ASCE (2000), Bartholomew and Haverland (1987), Bartholomew et al. (1987), ICOLD (1988, 1989, 1992, and 2000), USACE (1980 and 1995), USBR (2014), USSD (2002), ISO (2015 and 2016) and Indian Standards give more detailed information on the subject.

2.3.2 Surface Movement

Surface movement is the horizontal or vertical change in position of a point on the surface of a structure in relation to a fixed point away from the structure. It is usually found by some type of surveying. Modern equipment has increased the number and type of surveys that are available.

2.3.2.1 Level Surveys

Vertical surface movements are measured by conventional differential leveling surveys using theodolites, optical levels, and electronic distance meters. Optical leveling is the most common method of measuring settlement. Measurement of horizontal displacements is made using a theodolite or an electronic distance meter. On dams with a straight crest, horizontal displacements upstream and downstream can be spotted using a line of sight technique. Modern integrated total station survey equipment may be linked to a computer and can give readings to an accuracy of a few millimeters.

Measuring points are positioned on the crest or slopes of the dam. Embankment measuring points are usually steel bars embedded in concrete placed in the fill. Concrete dam measuring points are usually bronze markers set in the concrete.

Survey methods and equipment for measurement of embankments should be precise enough to discern a movement of at least 3 mm. A conventional level and rod are usually adequate. For concrete/masonry dams, survey methods and equipment need to have better measuring accuracy being able to discern a movement of at least 3 mm. Precision levels and rods equipped with micrometer targets are needed for concrete/masonry structures.

Level surveys are the simplest and most exact method for measuring the vertical movement of a dam. A limitation of level surveys is the labor cost, although modern surveying equipment has reduced the time needed to carry out a survey and process the data.

2.3.2.2 Alignment Surveys

Horizontal surface movements are usually measured as offset distances from a baseline. The same measuring points used for level surveys are often used for alignment surveys. The method and equipment employed depend on the type of dam and the desired accuracy.

For embankment dams, one or more lines of measuring points are set along the crest and on the slopes parallel to the crest. Instrument and target monuments are set up at the ends of the lines on the abutments beyond the dam. A theodolite is set up on the instrument monument on one abutment and sighted to the target monument on the opposite abutment to measure movement. Offset distances from the line-of-sight to each measuring point are found using a plumb bob and tape. Typically, survey methods and equipment should be sufficiently exact to discern a movement of 3 mm or less.

For concrete dams, a similar procedure is employed with refinements to increase the accuracy of the measurements. These measurements are also known as *collimation* surveys. Measuring points are set along straight lines on the crest and, in some cases, along the face of the dam. The measuring points are markers set in the dam concrete. Instrument and target monuments are set up outside the limits of the dam at the ends of the lines of measurement points. The monuments are usually 200 to 250 mm diameter concrete-filled pipes buried at least 3 m into the ground.

The top of the instrument monument is equipped with a threaded plate to which a theodolite is mounted. The target monument is also fitted with a threaded plate to which a target is attached. The line-of-sight is obtained using a high precision theodolite set on the instrument monument and sighted to the target placed on the target monument. Offsets from the baseline are measured with a micrometer attached to a moveable target leveled over each measuring point. Typically, survey methods and equipment should be sufficiently exact to discern movement about 3 mm.

Alignment surveys are the simplest and most exact method for measuring the horizontal movement in straight dams. Their application is limited for curved dams, irregularly shaped dams, or where the line-of-sight is limited because the number of measurement points along any one line is small. A limitation of alignment surveys is the labor cost, although modern surveying equipment has reduced the time needed to perform a survey and process the data

2.3.2.3 Triangulation

More data for displacements are obtained by triangulation measurements. For that purpose, a system of triangulation targets is placed on the surface of the dam (the crest and downstream face), as well as on the appurtenant structures (Figure 2-13). The system requires a network of instrument piers and a baseline downstream of the dam. The instrument piers should be positioned to enable collimation from each pier to as many measuring targets as possible. The number of piers is dictated by the nature and topography of the surrounding ground. Measurements must be carried out with precise instruments and methods, performed by well-trained, experienced and skilled surveyors. The results show deformations of the dam, in relation to the targets outside its body, and deformations of the canyon downstream of the dam, in the direction of the river flow and perpendicular to it.

Leveling measurements give the vertical displacements of points of the structure in relation to references that are positioned far enough away from the dam so as not to be affected by settlement created by the dam or impounded water. Leveling measurements also require the use of precise instruments and methods.

2.3.2.4 Triangulation and Trilateration

Triangulation and trilateration use trigonometric principles of triangles to measure the location of points on a dam. In triangulation surveys, angles to a measuring point on the dam are calculated from two locations on a baseline. Using the known distance between, and the elevation of baseline monuments, the triangle between the three points is solved trigonometrically to find the location (horizontal and vertical) of the measuring point. Angles are measured with precise theodolites.

In trilateration surveys, the distances between a fixed point on the dam and two locations on a baseline are measured. Using the known distance between, and the elevation of monuments on the baseline, the

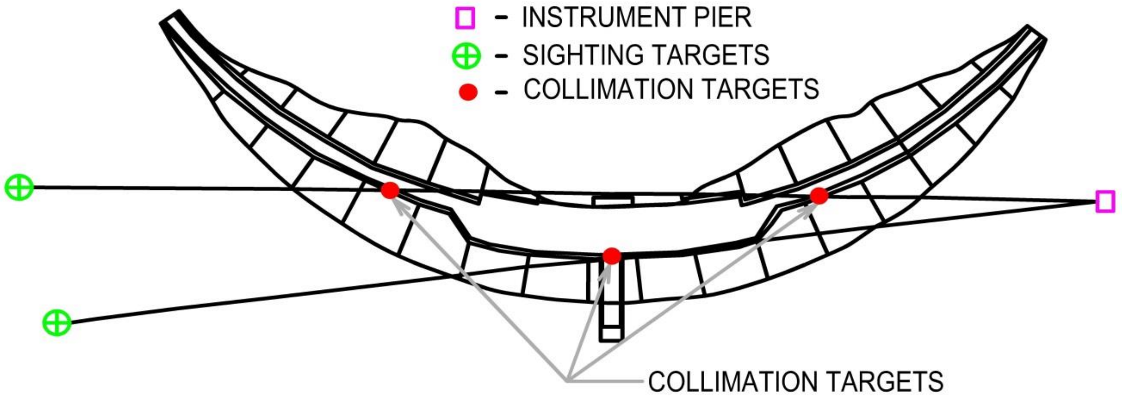


Figure 2-12. Layout for collimation measurements used for an arch dam

triangle between the three points is solved trigonometrically to determine the location (horizontal and vertical) of the measuring point. Because distances can be measured more precisely than angles, trilateration surveys are more precise than triangulation surveys.

Distances are measured with electronic distance measurement (EDM) equipment. EDMs calculate the distance by measuring the time it takes for light to travel from the source to a reflector and back and then multiplying by the speed of light. Extremely high accuracies can be obtained with this equipment. Measurements must be corrected for barometric pressure, temperature, and the curvature of the earth.

Baseline monuments are like instrument monuments used for alignment surveys of concrete dams. Triangulation and trilateration are useful when measuring points do not lie along a straight line or when lines of sight are obstructed. Vertical movements can be measured with both surveys if the baseline has a significant vertical component. The surveys are highly accurate but need an experienced crew. Disadvantages are the cost of the survey crew labor, the cost of setting up the baseline, the need for specialized equipment, and the complex calculations.

2.3.2.5 Collimation

Collimation, triangulation, and leveling are techniques used to measure the movement of points of the dam in relation to reference points outside the dam.

Collimation measurements are performed with a theodolite at measuring points at the dam's crest. At one of the abutments, a pier is constructed for the theodolite, which is set at a higher level than that of the crest, and a reference target pier is positioned at the opposite abutment, at the same level. These two points are situated so that the line of sight between them passes through locations on the dam's crest where measurements are to be made. More targets or piers are needed at arch dams because of the curvature of the crest (Golzé 1977). The deviation of the movable target from the line of sight yields the displacement of the point at the dam's crest. Three to four measuring points are usually installed, and the results are combined with plumbline readings.

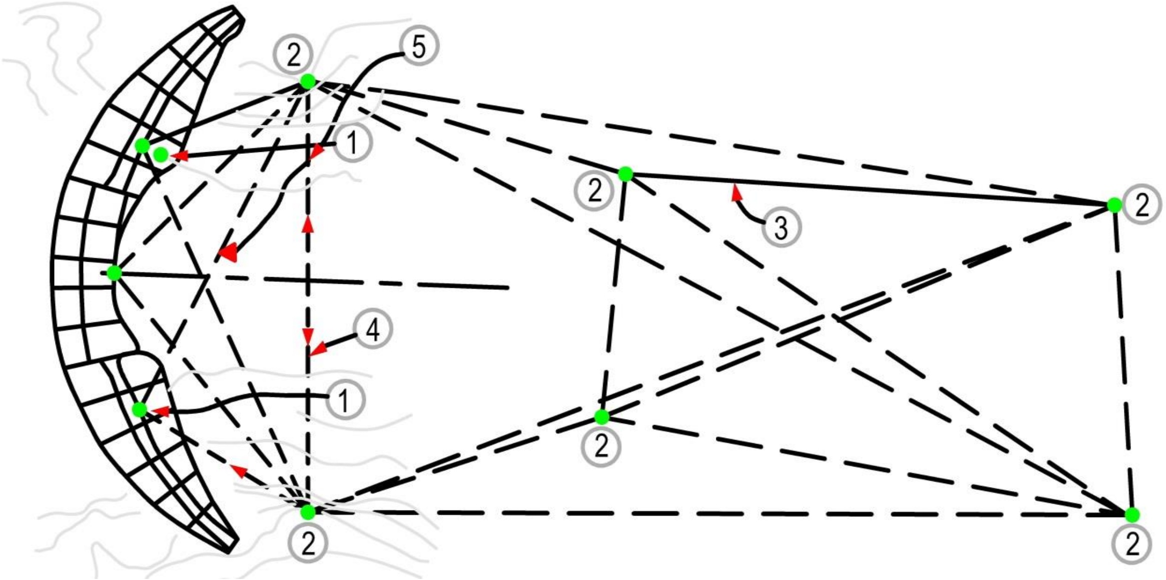


Figure 2-13. Layout for triangulation measurement: (1) Measuring targets on dam surface; (2) theodolite piers; (3) measured base line; (4) computed base line; (5) sight lines

Internal Movement

Internal movement is the horizontal or vertical change in position within the structure. Usually, the measurement is in relation to some point on the structure or in the foundation.

Internal settlement of an embankment or foundation can be measured with a variety of instruments including settlement plates, cross-arm devices, magnetic- or inductance-type probe extensometers, fluid leveling devices, pneumatic settlement sensors, vibrating-wire settlement sensors, and various other mechanical and electrical sounding devices. Internal horizontal and vertical movements of embankment dams are usually measured with inclinometers and extensometers. Internal movements of concrete and masonry structures are often measured with plumblines, tiltmeters, inclinometers, and extensometers.

Some common types of internal movement instruments are described in the following subsections. Measurements of internal movement at both embankment and concrete/masonry dams and their foundations should be detailed and precise. Measuring points should be installed so that they are not subject to movement from freeze-thaw action or traffic.

2.3.2.6 Plumblines

The plumbline is a suitable and comparatively uncomplicated device for measuring deformations caused by forces of water and temperature variations. The two types of plumblines in use are weighted plumblines and float-supported plumblines (Figure 2-14). A weighted plumbline is formed by a weight near the base of the dam suspended by a wire that drops down from the dam crest through a vertical well.

For the float-supported plumbline (also called an inverted plumbline), a float installed in a tank at the top of the dam connects by a wire to an anchor in near the

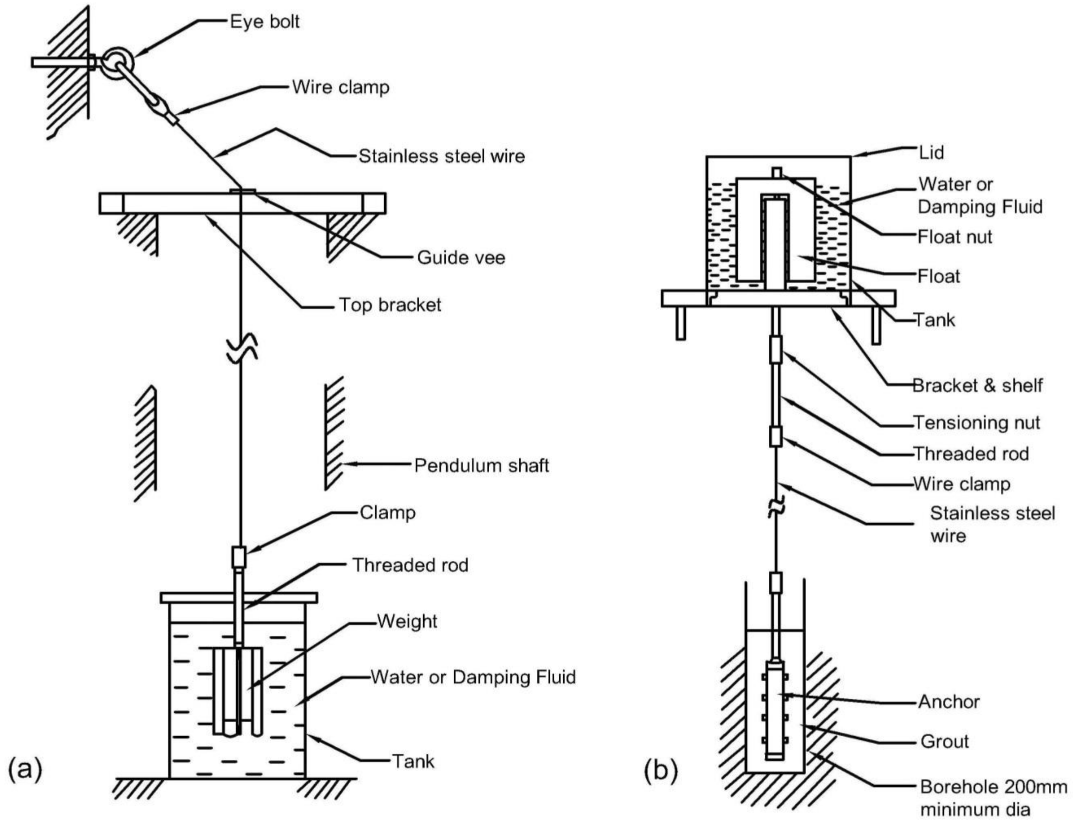


Figure 2-14. The two types of plumblines in use: (a) Weighted plumbline, and (b) float-supported plumblines (also called an inverted plumbline)

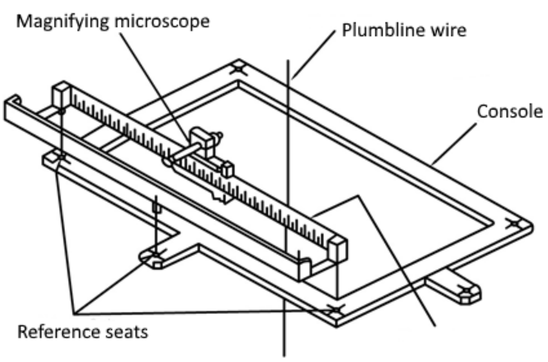


Figure 2-15. Mechanical measuring table for plumbline wire with removable microscope frame

base of the dam.

The measurements are taken at stations positioned in horizontal openings at various levels of the dam thereby recording deflections along its entire height. The measurements are made with a sliding micrometer equipped with either a peep sight or a microscope (Figure 2-15). The measured displacements show deformation of the structure with respect to the fixed end of the plumbline (USBR 1976 and 1977).

Gravity dams and arch dams often include plumblines. In the case of arch dams, particularly thin double-curvature arch dams, constructing a vertical well for a plumbline is usually not possible. And, with exactly this type of dam, the deflection of the crest in relation to the foundation is an important datum for an assessment of the dam's behavior. Inclinometers have been used to circumvent this problem. However, more recently, displacements have been measured directly in inclined shafts using a controlled monochrome light beam (a so-called laser plumbline).

The schematic diagram of a laser plumbline in Figure 2-16 illustrates its use in an inclined shaft inside an arch dam. A mounting fixture (2) at the top of the shaft holds a laser tube (3) which is attached to an element for directing and focusing the alignment (4). At the base of the shaft, above the measuring mark, there is a receiver (5) that measures the signal emitted from the laser tube. The emitter of the signal in the upper part of the dam, as well as the receiver at the base, i.e. the foundation, is watertight. Displacement measurements have an accuracy of ±0.2 mm (Tanchev 2014, pages 769-770).

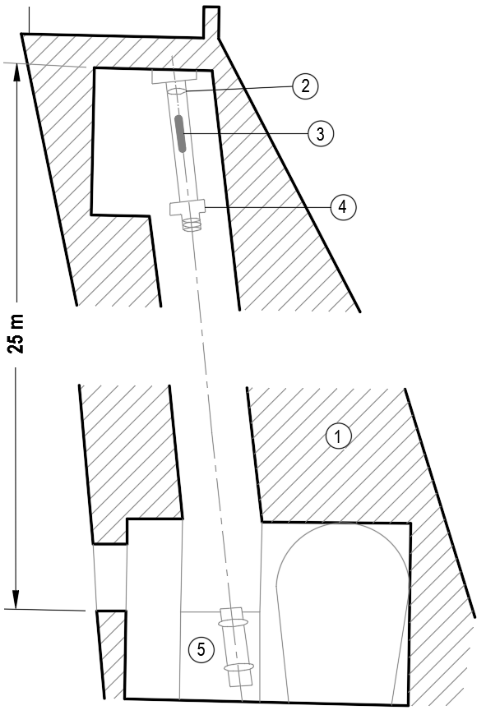


Figure 2-16. Schematic diagram of a laser plumbline installed in an arch dam: (1) Dam body (concrete); (2) mounting fixture; (3) laser tube; (4) modulating and focusing element; (5) receiver

2.3.2.7 Tiltmeters

Tiltmeters consist of a base plate, sensor, and readout device. The base plate is cemented or bolted to any horizontal or vertical surface and measure the vertical rotation of the surface. Instruments can be mounted permanently in one location to continuously record movement or moved from place to place to make intermittent measurements. When used as portable devices surveys are economical because only one tiltmeter is needed to make

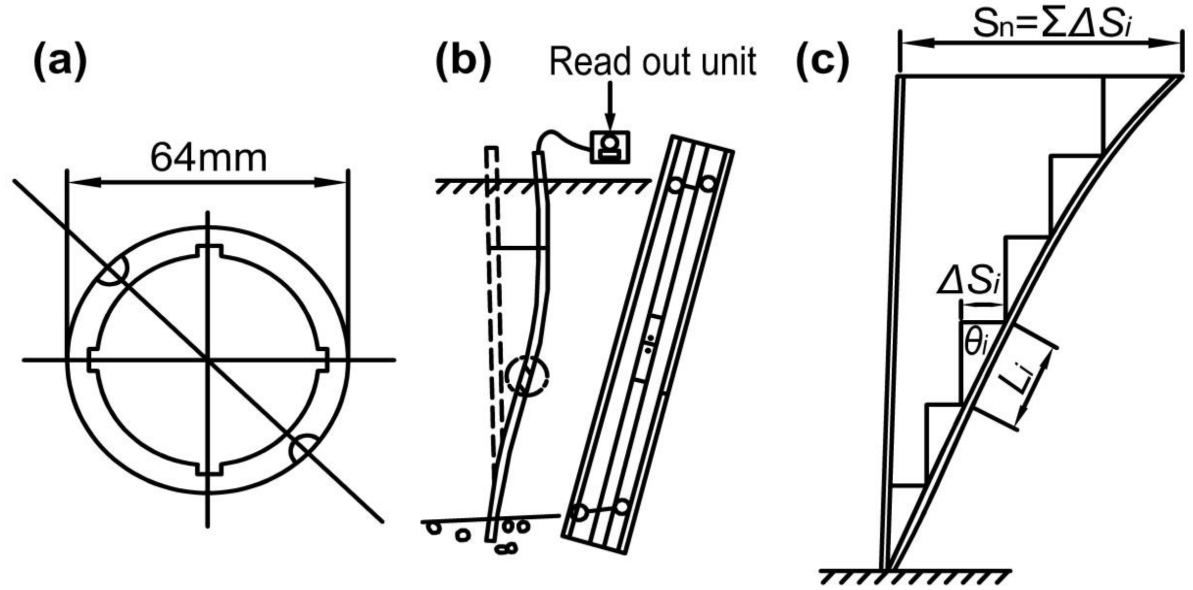


Figure 2-17: Schematic diagram of an inclinometer showing (a) cross section of the casing, (b) inclination of a single vertical increment of the borehole, and (c) final summation of incremental displacements

measurements at an unlimited number of locations.

The modern electronic tiltmeter, which is slowly replacing all other forms of tiltmeter, employs a simple bubble level principle, similar to the common carpenter level. An arrangement of electrodes senses the exact position of the bubble in the electrolytic solution, to a high degree of precision. Any minor changes in the level are recorded using a standard data logger. This arrangement is quite insensitive to temperature and can be fully compensated, using built-in thermal electronics.

2.3.2.8 Inclinometers

Inclinometers consist of a specially shaped plastic casing, a probe, and a readout device. They are installed in vertically drilled holes in dams, their foundations, and their abutments. The inclination of the casing is measured at regular intervals, and lateral movement with respect to the bottom of the casing is calculated (Figure 2-17).

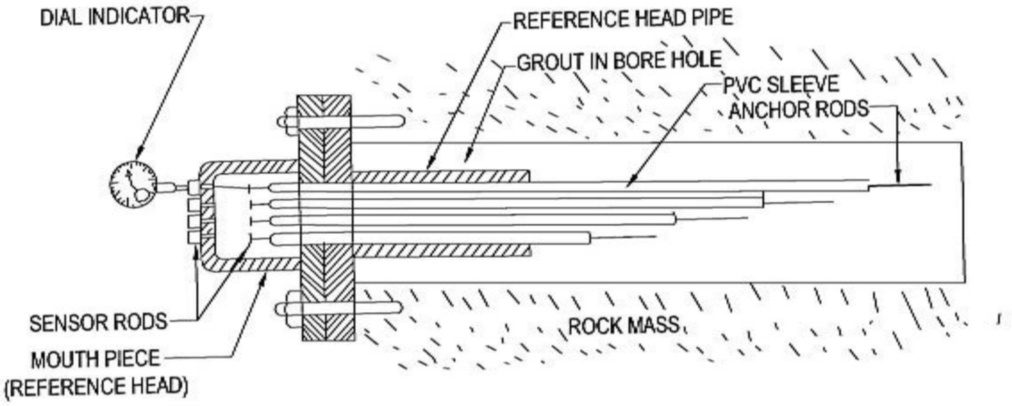


Figure 2-18. Extensometer mounted horizontally

Inclinometers are reliable and precise and are ideally suited to long-term monitoring of the position of a borehole over its entire length.

The probe has two accelerometers that detect the inclination angle of gravitational acceleration at the relative plane of their axis by measuring the tilt of the probe in two mutually perpendicular directions. The probe is also equipped with a pair of wheels that run inside grooves cut into in the casing, which keeps the probe free from rotating. The probe measures inclination of the casing at regular intervals by which the lateral movement with respect to the bottom of the casing is calculated. By making a series of readings over time, it is possible to monitor the rate of movement.

The primary requirement for accurate measurement is to extend the borehole below the depth of movement so that readings made from the end of the hole are referenced to a stable base. Precautions are also needed during the installation of the casing to maintain the vertical alignment of the grooves and to prevent spiraling. Readings are carried out by lowering a probe to the end of the hole and then raising it in increments equal to the length of the wheelbase of the probe. At each depth increment, the tilt angle and the displacement are measured. Finally, the total displacement at the top of the hole is calculated. A check of the results is then made by rotating the probe by 180° and taking a second set of readings.

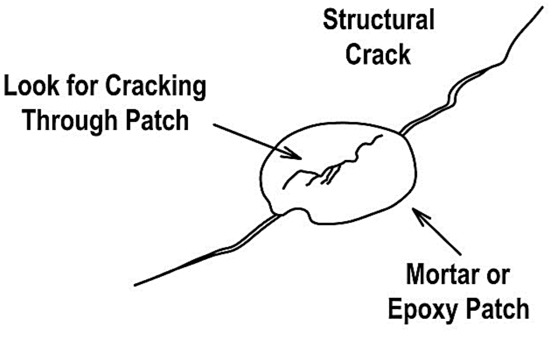


Figure 2-19. A simple epoxy patch used to monitor development of a structural crack in concrete

2.3.2.9 Extensometers

Extensometers consist of one or more rods anchored at different depths in a borehole and a reference head at the surface. Usually mounted straight up to measure vertical movement of the reference head in relation to the anchor zone(s), they can also be installed in other orientations (Figure 2-18). They are precise and can measure small movements at various depths accurately.

2.3.3 Joint or Crack Movement

Joint or crack movement is the horizontal or vertical change in position of one part of a structure in relation to another part of the structure. Usually, the measurement spans block joints or cracks in concrete structures, or cracks in earth structures.

2.3.3.1 Crack Measurement

The amount of movement of one side of a crack or joint in a concrete structure in relation to the other side is measured with reference points or crack meters. Many variations of grout or plaster patches can be used to evaluate whether a movement has taken place (Figure 2-19).

Reference points can be scratch marks on the concrete, metal pins, or metal plates on opposite sides of a joint or crack. The distance between the scratch marks is measured with a micrometer or dial gauge to evaluate the crack growth. Sometimes three points are used in a triangle to measure both the horizontal and the vertical movement.

Crack meters are commercially available devices that allow movement in two directions to be measured. A common device consists of two plastic plates (Figure 2-20). One plate is opaque and includes a grid. The other plate is translucent and has a set of cross hairs. The plates are fixed on opposite sides of the crack or joint with the

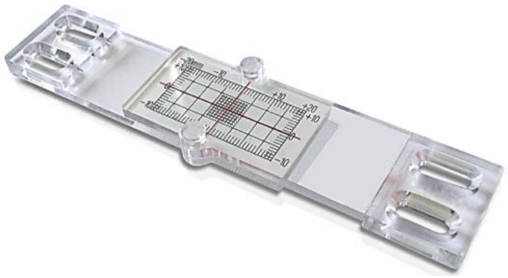


Figure 2-20. A two-plate mechanical crack meter

cross hairs set over the center of the grid. Movement is measured by noting the location of the cross hairs with respect to the grid. A variety of other crack meters including Carlson and vibrating wire sensors (Figure 2-21), dial gauges (Figure 2-22), and mechanical feeler gages may be used to measure the growth of cracks.

All these devices are easy to install and monitor. The accuracy and reliability vary depending on the details of the devices and measurements. Mineral deposits, iron staining, or efflorescence obscuring the instruments are frequent problems if seepage or leakage flow is present.

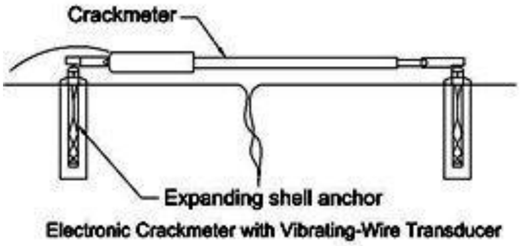


Figure 2-21. Illustration of an electronic crack meter with a vibrating wire transducer.

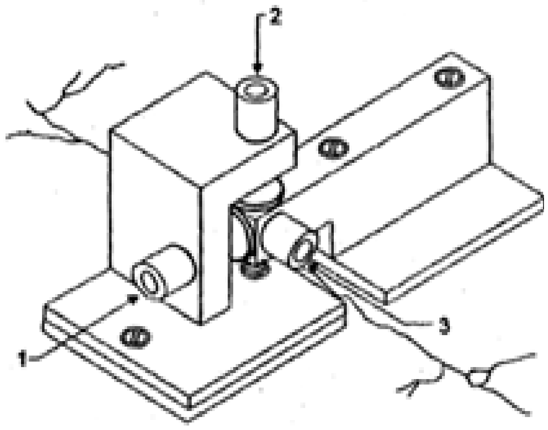


Figure 2-22. Illustration of a dial gauge crack meter showing ports 1, 2, and 3 for measurement in three directions

2.4 Reservoir / Tail water Elevations

Reservoir and tail water elevations should be measured to provide a continuous historical record of these factors. Water levels in the reservoir and in downstream waterways have a direct influence on the quantities of seepage and leakage through a dam and its foundations. When an established relation between the hydraulic head (the difference between upstream and downstream water levels) changes, usually a significant increase in seepage and leakage rates, a genuine problem might be the cause and needs to be investigated at once.

Measuring the water level in the reservoir on a regular basis, and recording this level at the time of each dam safety inspection, is needed for several reasons. Recording water elevations in downstream discharge channels (tail water elevations) is also important. These elevation data are used to interpret most instrumentation data, including the determination of uplift water pressure distribution beneath the dam. Uplift pressures and seepage rates are directly dependent from the difference between reservoir and tail water elevations.

Water levels may be measured by simple elevation gauges, such as fixed staff gauges or numbers painted on permanent structures in the reservoir, or they may be measured with more complex water-level sensing devices.

(Refer chapter on Hydro – Meteorological Instrumentation.)

2.4.1 Staff Gauge

A staff gauge to measure water level in a stream and a crest-stage gauge to record the highest water elevation is shown in Figure 2-23. The metal pipe and pole with a scale marked on it are some very simple, yet valuable, means to measure both the current gauge height (stream stage) and the peak gauge height during the last high water. It is a widely used low-tech piece of equipment that provides valuable information about the height reached by water in streams during large flows and reservoirs.

There are holes drilled in the bottom of the pipe to allow water to enter. Inside the pipe is a wooden rod with vertical distance markings. Some ground cork is placed in the pipe and when it rains water in both the stream and the pipe rises, thus floating the cork in the pipe. When the water stops rising and then falls, the cork sticks to the wooden rod at the highest point to which the water level rose.

Weather Conditions

Weather conditions including air and reservoir water temperature, precipitation, humidity, evaporation, and wind speed need to be measured to create a continuous historical record of these factors (WMO 2014). Because these factors do influence any dam's performance, they need to be recorded regularly and continuously. This will enable the interpretation of geotechnical and structural data with the actual environmental conditions that existed during the inspection. The details of Hydro-meteorological instrumentation have been provided in Chapter 7. Summary of sum of the important parameters is described below.

Figure 2-23. A staff gauge and crest-stage gage installed next to a stream

2.4.2 Precipitation

Precipitation is water released from clouds in the form of rain, freezing rain, sleet, snow, or hail. Most precipitation falls as rain.

2.4.2.1 Rainfall

The most common method of measuring rainfall is to use a series of gauges. Three types of gauges in general use are the standard gauge, the storage gauge, and the recording gauge. Standard or non-recording gauges, typically cylindrical containers 20.3 cm in diameter (Figure 2-24) are often used because of their low cost. Such gauges

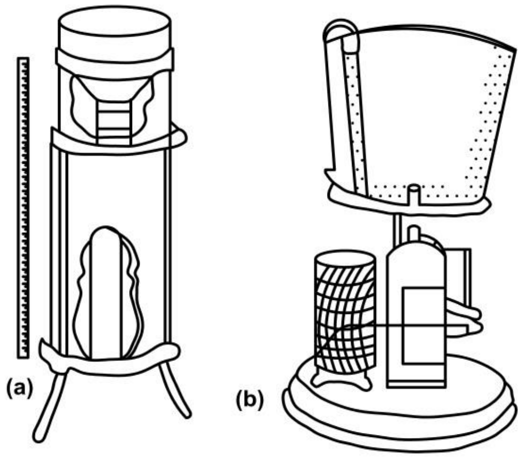


Figure 2-24. Types of rain gauges: (a) Cutaway of a standard non-recording gauge; (b) a weighing-type recording gauge with its cover removed to show the spring housing, recording pen, and storage bucket

should be read periodically, normally every 24 hours at the same time each day. The standard gauge magnifies rainfall depth 10-fold because it funnels the precipitation into an internal cylinder of that has a cross-sectional area 1/10th the size of the top opening.

Storage gauges have the same size opening as standard gauges but have a greater storage capacity, usually 1525 to 2540 mm of rainfall. These gauges can be read periodically, for example, once a week, once a month, or seasonally. A small amount of oil is usually added to gauges that are read less often than every 24 hours to suppress evaporation.

The use of recording gauges, which allow for continuous measurement of rainfall, is more limited because of their higher cost. Examples of recording rain gauges are the weighing-type (Figure 2-24b) and the tipping bucket gauge (Figure 2-25). The weighing-type gauge records the weight of water with respect to time with a calibrated pen on a clock-driven drum. The chart on the drum indicates the accumulated rainfall with time. Rainfall intensity is obtained by determining incremental increases in the amount per unit of time (typically 1 hour). A tipping bucket gauge records intensity, making a recording each time a small cup fills with water and then empties as it tips back and forth. Because about 0.2 seconds is required for the bucket to tip, high-intensity rainfall events might not be measured exactly.

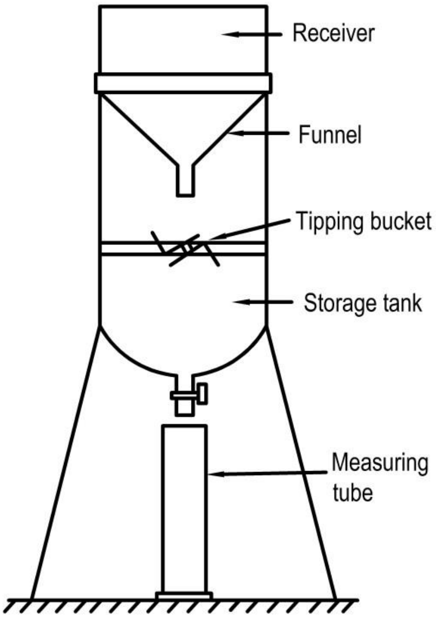


Figure 2-25. Schematic diagram of a typical tipping bucket rain gauge

2.4.2.2 Snowfall

Where solid precipitation is common and significant, several special modifications are used to improve the accuracy of measurements using conventional rain gauges. These modifications include the removal of the rain gauge funnel at the beginning of the snow season or the provision of a special snow fence to protect the catch from blowing out. Windshields around the gauge reduce the error caused by deformation of the wind field above the gauge and by snow drifting into the gauge. They are advisable for rainfall and essential for snow.

At remote locations, automated snow gauges are used. They have a large catch area which collects snow until a given weight is collected. When this critical weight is reached, it tips and empties the snow catch. This dumping trips a switch, sending a signal. The collection then repeats. If the catch container has a heater in it, it may measure the snow weight accurately. It is also possible to tip based on volume instead of weight by sensing fill volumes.

2.4.2.3 Evaporation

Because many areas of India depend on reservoirs to provide municipal water supplies and water for irrigation, evaporation losses are needed to determine whether the available storage volume is sufficient to meet water demands. The greatest evaporation rates occur in the driest regions of the country where water is less plentiful.

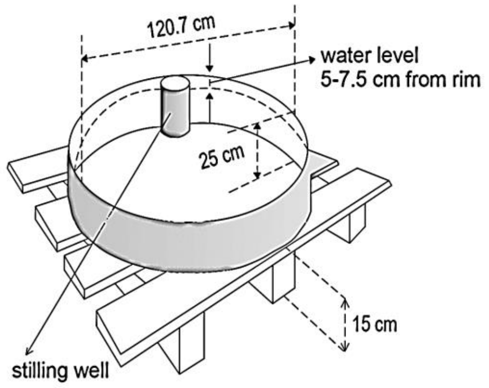


Figure 2-26. U.S. Weather Bureau Class-A Evaporation Pan

The U.S. Weather Bureau Class A pan evaporimeters (Figure 2-26) are used most often in India for the measurement of evaporation. In this approach, evaporation is measured from a pan, and a coefficient is applied to obtain an amount that applies to the reservoir. The standard Class A pan is a metal cylinder 122 cm in diameter and 25 cm deep. Water depth is maintained at 18 to 20 cm and measured daily with a hook gauge in a stilling well.

Because pan measurements usually do not reflect evaporation from large bodies of water, such as reservoirs, a coefficient is applied to the measured value. This coefficient usually ranges from 0.5 to 0.8. Average annual pan coefficients of 0.70 to 0.75 are often used for reservoirs when they have not been derived experimentally. However, the coefficient varies seasonally depending on ambient air temperatures and reservoir water temperatures.

2.5 Local Seismic Activity

Tremors of the soil caused by an earthquake are transferred to a dam and create added loadings and deformations. To enable further development and perfection of methods for dynamic analysis of dams, it is necessary to collect and analyze data on the response of dams to tremors. To assess the effects of earthquakes on the dam, the acceleration, displacements, and relative velocity of the reaction at various places in the dam and surrounding ground need to be measured and recorded.

Because earthquakes can have a considerable influence on the structural integrity and safety of a dam, any evidence of local seismic activity should be documented, and dam safety inspections and instrument observations should be conducted to figure out whether any damage has occurred.

Seismic instrumentation for a dam consists of strong motion *accelerometers*, broadband seismometers, and associated data acquisition and analysis systems that detect exceedance of allowed performance criteria as well as identify and verify structural behavior.

2.5.1 Accelerographs

These devices typically consist of three mutually perpendicular accelerometers, a recording system, and triggering mechanism. The instruments are usually set to be triggered at accelerations generated by nearby small earthquakes or more distant, larger earthquakes. They are expensive, especially considering that multiple instruments are needed to record dynamic response at several locations on a structure, a foundation, or abutments. The devices must be properly maintained so that they operate if an earthquake occurs. These devices are described by USACE (1987c) and Bartholomew and Haverland (1987), Batholomew et al. (1987).

Despite the progress in the dynamic analysis of dams, it is still not possible to reliably predict the behavior of dams during strong ground shaking because of the difficulty modeling the inelastic behavior of the structures and insufficient information on the spatial variation of ground motion and other factors. However, the factors that eventually lead dam to failure, as well as their severity and effect on the structure, can be measured and monitored with appropriate seismic instruments.

Fundamental features of a dam may be identified using the acquired seismic data such as the damping within the structure, amplification of the ground motion along the path from the foundation or abutments to the crest, wave propagation within the structure, differential motions between abutments, natural frequencies, mode shapes and so on. The collected information can be used to evaluate the structural response of the dam and to determine the warning level in a case critical states have been reached.

2.5.2 Seismographs

A simple seismograph that is sensitive to up-down motions of the earth can be understood by visualizing a weight hanging on a spring. The spring and weight are suspended from a frame that moves along with the earth's surface. Because the weight tends not to move because of its inertia, by measuring the difference in position between the frame and the weight, the motion of the ground can be determined.

Modern instruments use electronics to monitor the small motions generated by seismic activity. In some systems, the weight is held motionless relative to the frame by an electronic negative feedback loop. The motion of the weight in relation to the frame is measured, and the feedback loop applies a magnetic or electrostatic force to keep the mass motionless. The voltage needed to produce this force is the output of the seismometer. In other systems, the weight can move, and its motion produces a voltage in a coil attached to the mass that moves through the magnetic field of a magnet attached to the frame.

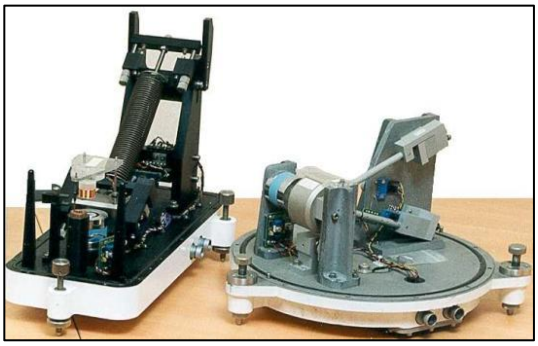


Figure 2-27. A long-period vertical seismometer (left) and a long-period horizontal seismometer (right)

Seismometers measure movement in horizontal direction (north-south or the east-west) and the vertical direction as well (Figure 2-27). However, sometimes motion in only the vertical direction is measured because it is less noisy and gives better records of some seismic waves.

The foundation of a seismometer is critical. The best mountings may be in deep boreholes, which avoid thermal effects, ground noise and tilting from weather and tides. Some instruments are often mounted in insulated enclosures on small buried piers of unreinforced concrete. Reinforcing rods and aggregates would distort the pier as the temperature changes. A site is always surveyed for ground noise with a temporary installation before pouring the pier and laying conduit.

Detailed description of seismic monitoring of dams is presented in chapter 5.

2.6 Stress and Strain

Design stresses may not always occur as expected in a completed dam. For this reason, special total pressure instruments are used to measure the actual stresses at selected locations, such as between a dam and its abutments or foundation, or between certain components of the dam.

The purpose of total pressure monitoring is to measure the total pressure (total load) on a contact surface or within the mass of the dam. Several types of devices (cells) are used to measure the static total pressure in a dam. The measured load can be caused by earth, water, or concrete. A dam's principal stresses can be evaluated based on data from specially placed and oriented pressure cells. The primary value of total pressure data is to verify design assumptions and to supply data for future design improvements.

Earth pressures within fill and against concrete structures are measured with earth pressure cells, which are also known as total pressure cells. They consist of two flexible diaphragms sealed around the periphery, with a fluid in the annular space between the diaphragms. Pressure is measured by the increase in fluid pressure behind the diaphragm with pneumatic or vibrating wire sensors. Earth pressure cells should have similar stiffness as the surrounding soil to avoid inaccurate measurements of in-situ stress caused by arching.

Soil pressures against structures are also measured with a Carlson-type cell. It consists of a chamber with a diaphragm positioned at the end. Deflection of the diaphragm is measured by a Carlson-type transducer and is converted to stress. Stress in concrete structures can be measured with total pressure cells or Carlson-type cells designed to have a stiffness like concrete. It can also be measured by over-coring.

The modulus of elasticity, creep coefficient, and the Poisson's ratio for concrete can be determined from the laboratory testing of concrete field cylinders. These values are needed to convert strain measurements to stress.

A variety of mechanical and electrical strain gauges are used to measure strain in concrete structures. Some of the instruments are designed to be embedded in the dam during construction, and others are surface mounted following construction. Strain gages are often installed in groups so that the three-dimensional state of strain can be evaluated.

The operation and limitations of stress and strain instruments are discussed by ASCE (2000), Bartholomew and Haverland (1987), Bartholomew et al. (1987), Dunnicliff (1988), USACE (1980), and USBR (1976 and 1977).

2.6.1 Types of Pressure (Stress) Measuring Devices

Measurement of stresses in the body of an embankment dam is of minor significance in relation to the determination of deformations. Exceptions to this are the contact zones between the filling material and the rigid constructions (concrete retaining walls, diaphragm walls, galleries, and pipelines). Furthermore, the measurement of pressures is difficult which results in uncertain accuracy of measurements. The greatest problem lies in the fact that results depend on the stiffness of the cell of the measuring instrument. Overestimation of stresses results if the stiffness of the cell is greater than the stiffness of the surrounding filling material. Underestimation occurs if the stiffness of the cell is smaller than the stiffness of the surrounding material. Under ideal conditions, the measuring cell has the same stiffness as the filling material, which in practice is difficult to achieve. Using a cylindrical cell with high stiffness and a low thickness to diameter ratio reduces this problem.

A variety of mechanical and electrical strain gauges are used to measure strain in concrete structures. Some of the instruments are designed to be embedded in the dam during construction, and others are surface mounted following construction. Strain gages are often installed in groups so that the three-dimensional state of strain can be evaluated (Figure 2-29).

An earth pressure cell consists of a flexible diaphragm backed by a fluid-filled chamber and a sensing device. Earth pressures are transmitted to the diaphragm, and the sensing device measures either the deflection of the diaphragm or the increase in pressure of the fluid enclosed behind the diaphragm. The sensing devices may be an electrical strain gauge, a vibrating wire gauge, or a hydraulic measuring system. The electrical strain gauge and vibrating wire gauge measure the deflection of the flexible diaphragm caused by the earth pressure acting on the diaphragm face. In the hydraulic measuring system, the stress in the material around the pressure cell is balanced by an automatically limited hydraulic pressure in the cell and supply line. The illustration in Figure 2-28 shows a typical resistance strain gauge earth pressure cell.

Soil pressures against structures are also measured with a Carlson-type cell, which consists of a chamber with a diaphragm on the end as shown in Figure 2-29. Deflection of the diaphragm is measured by a Carlson-type transducer and is converted to stress. Stress in concrete structures can be measured with total pressure cells or Carlson-type cells designed to have a stiffness like concrete.

A good pressure cell should be non-sensitive to the effect of temperature variations, impermeable to dampness, firm and durable, and simple to install. In practice, several distinct types of pressure measuring devices are used, including resistance strain gauges and pressure cells. Most of these devices work well at both embankment dams and concrete/masonry dams.

Special electrical or pneumatic/hydraulic readout devices display pressure measuring instrument output. When inspecting pressure-measuring devices, for a specific station, attention should be paid to any physical damage to electrical leads or the terminal block. Also, corrosion or excess of moisture should be addressed adequately.

Pressure data are analyzed by research and design engineers, and not by dam safety inspectors, so ordinarily onsite personnel will not be expected to interpret total pressure data or assess the adequacy of total pressure instrumentation.

2.7 Temperature

Temperature measurements of a dam, foundation, ambient conditions or instrumentation are used to reduce data from other instruments, increase precision, or to interpret results. For example, movements of concrete dams and changes in leakage at concrete dams are often related to changes in temperature. Temperature is also measured in concrete dams under construction to evaluate mix design, placement rates, and block and lift sizes; to time grouting of block joints; and to assess thermal loads (Figure 2-31).

Resistance thermometers or thermocouples can measure the temperatures of a dam, its foundation, and other instruments. The operation and limitations of these devices are described by Bartholomew and Haverland (1987), Dunnicliff (1988), USACE (1980), and USBR (1976 and 1977). The photographs of some of the instruments are shown on Figure 2-32.

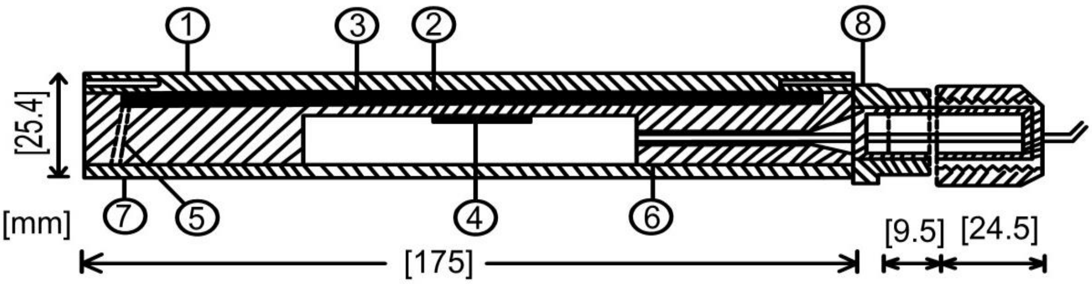
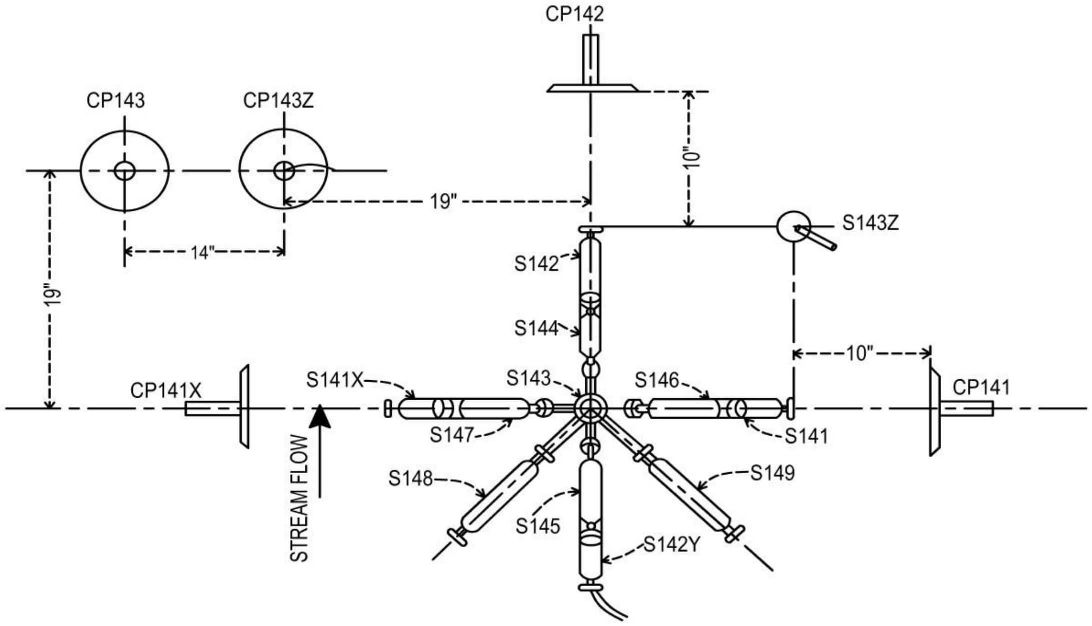
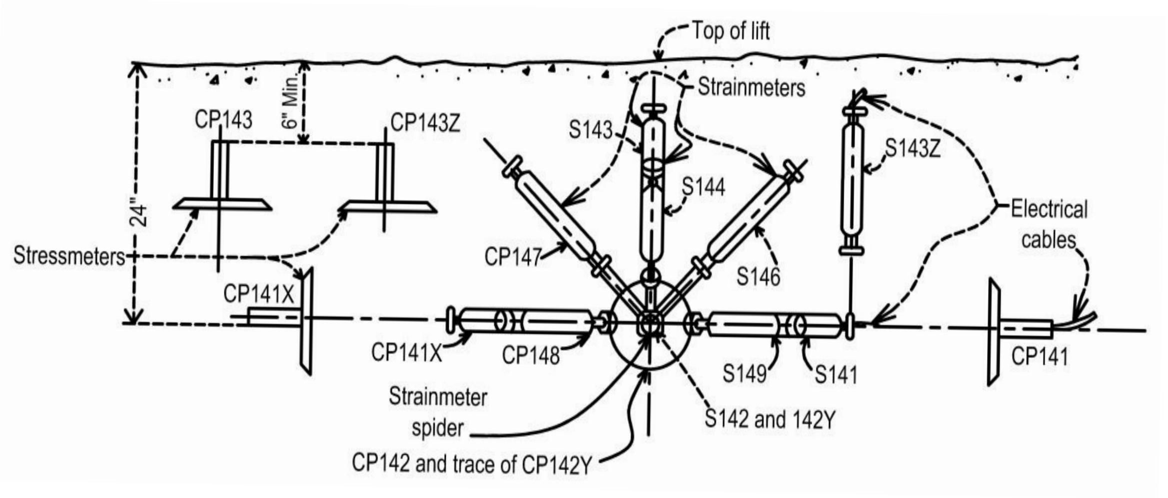


Figure 2-28. A typical resistance strain gauge earth pressure cell: (1) Upper plate; (2) space filled with mercury; (3) diaphragm, 0.75 mm thick; (4) measuring plate; (5) opening for mercury filling; (6) rubber water stop; (7) lower plate; and (8) welded end



Layout Plan



Elevation Drawing

Figure 2-29. Schematic of stress meter and strain meter

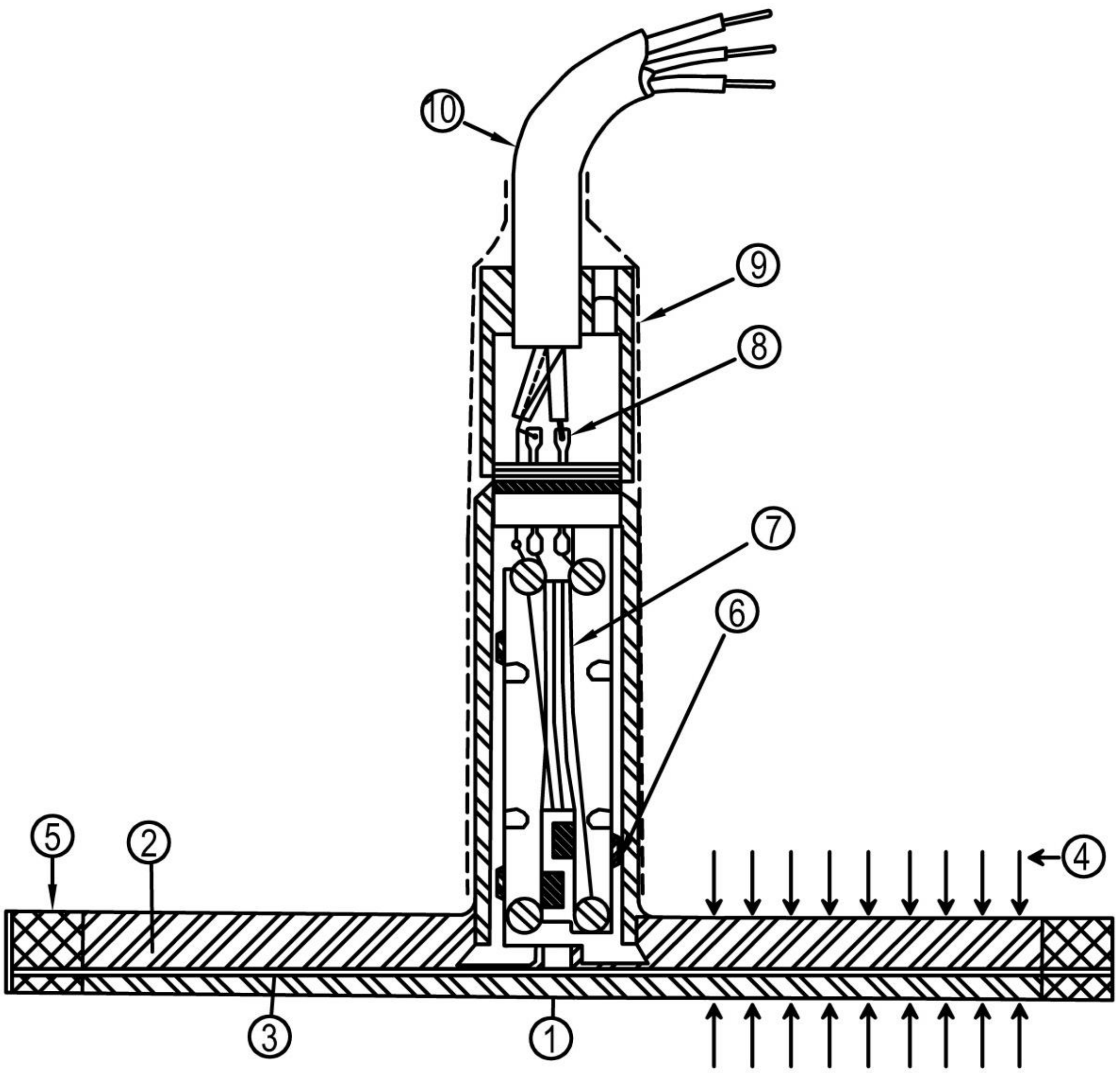


Figure 2-30. Carlson stress meter (after Golzé 1977). (1) Internal plate; (2) external plate; (3) mercury film; (4) stress being measured; (5) compressible material; (6) steel bar; (7) ceramic spool; (8) glass insulated terminals; (9) fabric cover; (10) conductor cable.

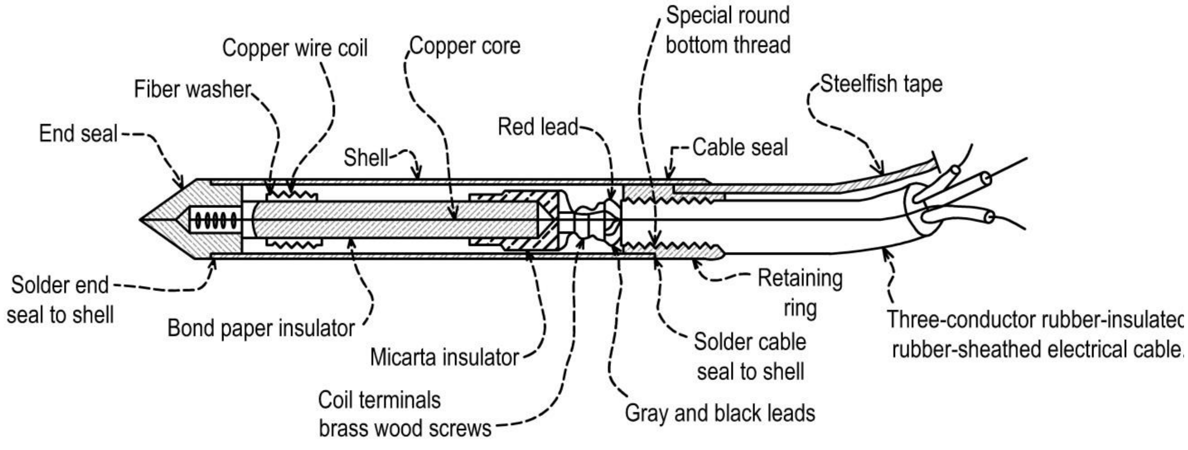


Figure 2-31. Thermometer

2.8 Summary of Critical Physical Data to be monitored

Certain key parameters are of primary concern regardless of the type of dam considered, e.g. seepage and external movement or deflection; others are relevant to a specific kind of dam, e.g. pore water pressures in relation to earthfill embankments. The relative significance of individual parameters may also reflect the nature of a problem under investigation, e.g. the settlement of an old embankment where progressive deformation is suspected.

Instruments for monitoring of all dams, to be installed retrospectively if necessary, should at least measure seepage and leakage flow rates and deformation of the dam crest. The latter provision is importance in detecting settlement on embankment crests, which is an indicator of possible internal distress and of local loss of freeboard.

The importance of seepage flow as a measurement quantity cannot be emphasized enough. Regular monitoring should be standard practice for all but the smallest of dams. Serious problems are invariably preceded by a detectable change in the seepage regime through or under the dam which is unrelated to changes in the retained water level or to percolation of precipitation falling on the downstream slope. Direct observation of the seepage quantity and turbidity is simple, with internal drain systems conducted to calibrated V-notch weirs. Ideally, several weirs are each positioned to collect the flow from specific lengths of the dam, allowing identification of the approximate location of any change in the seepage régime. A summary of physical parameters to be monitored at a dam is presented in Table 2-1.

2.9 Data Evaluation

All instrumentation data must be collected, processed, and evaluated promptly to be of value. Outdated, incorrect, or improperly evaluated data can be worse than no data at all, because these types of data can be misleading, and can result in false conclusions about the performance and safety of the dam.

Typical methods of data evaluation involve the plotting of instrumentation data in an array of continuous, historical sequences that plot cause and effect versus time (e.g., reservoir water level and piezometric pressures versus time). Data plots also may be used to correlate a variety of different physical data to show trends or problem areas (e.g., seepage, water pressure, and movement data may be correlated on the same data plot).

Dam design engineers should set ranges or limiting values for instrumentation data to indicate an acceptable level of performance (i.e., safety) for the dam. The dam safety inspector should be aware of these values and, in some cases, may recommend that they are assigned if none exist. Dam owners need to understand that exceeded values should trigger investigations and actions to find and correct the problem to avoid possible structural failures.

The detailed description of "Instrumentation data collection and management", "Monitoring data organization and analysis" is presented in Chapter 8 and Chapter 9 respectively.

Table 2-1. Parameters to be Monitored at Dams and the Suggested Instruments or Observation Techniques to be Used

Structure Type	Feature	Visual observation	Movements	Uplift and pore pressure	Water levels and flow	Seepage flows	Water quality	Temperature measurement	Crack and joint measurement	Seismic measurement	Stress-strain measurement
Embankment Dams	Upstream slope	●	●	●	●	–	–	–	–	●	–
	Downstream slope	●	●	●	–	●	●	●	●	●	–
	Abutments	●	●	●	–	●	●	●	–	●	–
	Crest	●	●	●	–	–	–	–	●	●	–
	Internal drainage system	–	–	●	–	●	●	●	–	–	–
	Relief Drain	●	–	●	–	●	●	–	–	–	–
	Riprap and other slope protection	●	–	–	–	–	–	–	–	–	–
Concrete and Masonry Dams	Upstream slope	●	●	–	●	–	–	●	●	●	●
	Downstream slope	●	●	●	–	–	–	●	●	●	●
	Abutments	●	●	●	–	●	●	–	–	●	●
	Crest	●	●	●	–	–	–	●	●	●	●
	Internal drainage system	–	–	●	–	●	–	–	●	–	–
	Relief drains	●	–	●	–	●	–	–	–	–	–
	Galleries	●	●	–	–	–	–	–	●	●	●
	Sluiceways/controls	●	–	–	●	–	–	–	–	–	–
Spillways	Approach channel	●	●	–	●	–	–	–	–	–	–
	Inlet/outlet	●	●	●	●	●	–	–	●	●	–

Structure Type	Feature	Visual observation	Movements	Uplift and pore pressure	Water levels and flow	Seepage flows	Water quality	Temperature measurement	Crack and joint measurement	Seismic measurement	Stress-strain measurement
	structure										
	Stilling basin	●	–	–	●	–	–	–	●	–	–
	Discharge conduit/channel	●	–	●	●	–	–	–	–	–	–
	Gate controls	●	–	–	–	–	–	–	–	–	–
	Erosion protection	●	–	–	–	–	–	–	–	–	–
	Side slopes	●	●	●	–	●	–	–	–	–	–
Outlets & Drains	Inlet/outlet structure	●	●	●	●	–	–	–	●	●	–
	Stilling basin	●	–	–	–	–	–	–	–	–	–
	Discharge conduit/channel	●	●	●	●	–	–	–	●	–	–
	Trash rack/debris controls	●	–	–	–	–	–	–	–	–	–
	Emergency systems	●	–	–	–	–	–	–	–	–	–
General Areas	Reservoir surface	●	–	–	–	–	●	–	–	–	–
	Mechanical/electrical systems	●	–	–	●	–		–	–	–	–
	Shoreline	●	–	–	–	–	●	–	–	–	–
	Upstream watershed	●	–	–	–	–	●	–	–	–	–
	Downstream channel	●	–	–	–	●	●	–	–	–	–

Table 2-2. Suggested Frequency[a,b] of Readings for Specified Instruments

Type of instrument	During Construction		During initial filling	During Period of Operation		
	Construction	Shutdown		Year 1	Years 2 to 3	Regular
Vibrating wire piezometers	W	M	W	BiW	M	M
Hydrostatic uplift pressure pipes	W	M	W	W	BiW	M
Porous-tube piezometers	M	M	W	W	M	M
Slotted-pipe piezometers	M	M	W	W	M	M
Observation wells	W	M	W	W	BiW	M
Seepage measurement (weirs and flumes)	W	M	W	W	M	M
Visual seepage monitoring	W	W	W	W	F	M
Resistance thermometers	W	M	W	W	M	M
Thermocouples	D	M	W	W	M	M
Carlson strain meters	W	W	W	BiW	M	M
Joint meters	W	W	W	BiW	M	M
Stress meters	W	M	W	BiW	M	M
Reinforcement meters	W	M	M	M	M	M
Penstock meters	W	M	M	M	M	M
Deflectometers	W	M	W	W	M	M
Vibrating wire strain gauge	W	M	M	M	M	**M**
Vibrating-wire total pressure cell	W	M	M	M	M	M
Load cell	W	M	W	BiW	M	M
Pore pressure meters	W	W	W	BiW		M
Foundation deformation meters	W	W	W	BiW	M	M
Flat jacks	D	W	W	BiW	M	M
Tape gauges (tunnel)	W	W	W/BiW	BiW	M	M
Whitmore gauges, Avongard crack meter	W	M	W	W	M	M
Wire gauges	W	M	W/M	W/M	M	M/Q
Abutment	W	M	W	W	M	M

Type of instrument	During Construction		During initial filling	During Period of Operation		
	Construction	Shutdown		Year 1	Years 2 to 3	Regular
deformation gauges						
Dial gauges, differential buttress gauges	W	M	W	W	M	M
Plumblines	D	W	D	W	BiW	M
Inclinometer	W	W	W	W	BiW	M
Collimation	Every two days for a month	M	W	BiW	M	M
Embankment settlement points	--[c]	--	M	BiM	Q	SA
Level points	M	Q	M	M/Y	BM/Q	BM
Multipoint extensometers	W	M	W	M	M	Q/SA
Triangulation			M	M	Q	SA
Trilateration (EDM)	--	--	BiW/M	M	Q	Q/A
Reservoir slide monitoring systems	--	--	M	M	M	Q
Power plant movement	--	--	M/W	M	M	M/Q
Rock movement	W	M	W	M	M	M

[a] These are suggested minimums. However, anomalies or unusual occurrences, such as earthquakes or floods, will require additional readings.

[b] D = daily, W = weekly, BiW = bi-weekly, M = monthly, Q = quarterly, SA = semi-annually, A = annually.

[c] Not applicable.

Normal Plumb Line

Measuring Table

Normal Plumb Line Automatic Readout

Automatic Water Level Logger

Automatic Weather Station

Strain Gauge

Tiltmeter

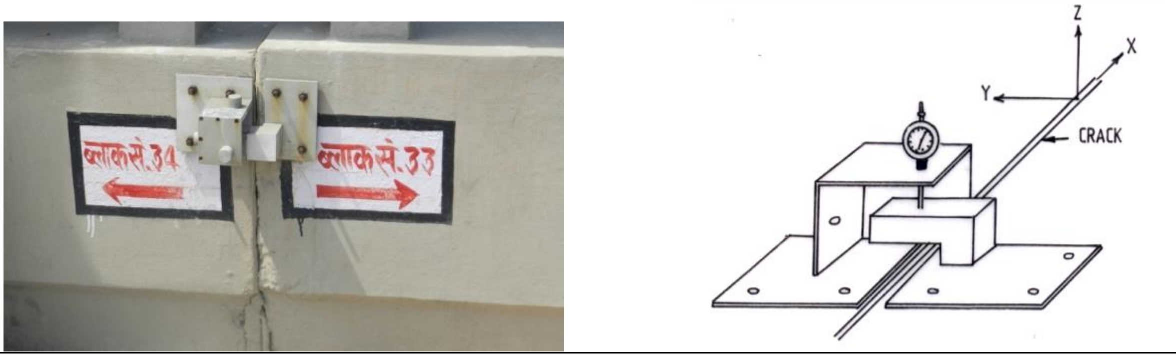
Figure 2-32: Photographs of Instruments

Vibrating Wire Pressure Cell

Vibrating Wire Temperature Gauge

Joint Meter - Mechanical

Strong Motion Accelerometer



3D – Mechanical Crackmeter

Figure 2-32 (Contd….) : Photographs of Instruments

Chapter 3. INSTRUMENTATION SYSTEM PLANNING: EMBANKMENT DAMS

Embankment dams generally include earth fill or rock fill dams with impervious earth cores and the fill with upstream concrete or asphalt concrete facing including boulder pitching. The main purpose of instruments installed within the embankment dams is to study whether or not the dam is behaving according to design predictions. Requirements for measurement depend on the type of information desired.

Earth dams differ from masonry and concrete dams due to relatively greater deformability and higher permeability of earth masses (excluding plastic clay hearting). Strains and displacements in earth dams are therefore much bigger, hence comparatively simple instruments can be used for measurements of strains and displacements. Distribution of stress in earth dams is more complex and the design analysis is based on radical simplification of the stress pattern and shape of rupture planes. Consequently, stress measurements require considerable judgment in interpretation. Seepage is of greater significance as it can cause internal erosion as well as increase in pore pressure resulting in instability.

There are some critical parameters which need to be measured for the purpose of monitoring. Generally, the similar type of instruments is suitable for earth and rockfill dams. For the latter, however, graded material is used between the rockfill and the instrument so that the instrument does not get damaged by the rock pieces.

No general rule can be given for the field measurement of dams as site conditions and problems vary from dam to dam. Types of field measurements often needed to evaluate the performance of embankments are briefly narrated below:

- Pore Water pressure
- Seepage/ drainage
    - Deformation
    - Internal movement
- Surface movement
- Reservoir and Tail water level
- Wave Height and evaporation.
- Seismic
- Stress and strains
- Rainfall

The planning and specification of a comprehensive set of instruments for monitoring the behavior of an embankment dam involve a logical sequence of decision steps:

Step 1. Define the primary purpose and objectives of instrumentation.

Step 2. Determine the measurements that are appropriate for the dam under consideration.

Step 3. Decide on the locations and the numbers of measuring points for the desired data.

Step 4. Take a decision on the time period the instrumentation is to be operational, i.e. long-term or short-term monitoring.

Step 5. Determine the best sensing mode in relation to the desired degree of response and required accuracy.

Step 6. Select the hardware that is appropriate to the task as defined in Steps 1 to 5.

Step 3 is the most important. Instruments must cover known critical features of the dam, but for purposes of comparison, a few should also be placed where “normal” behavior is expected. In the case of a new dam at least two sections should be monitored, including the major section. It is good practice to draft an ideal instrumentation plan in the first instance, and then to progressively drop the less necessary provisions until an adequate, balanced, and affordable plan evolves.

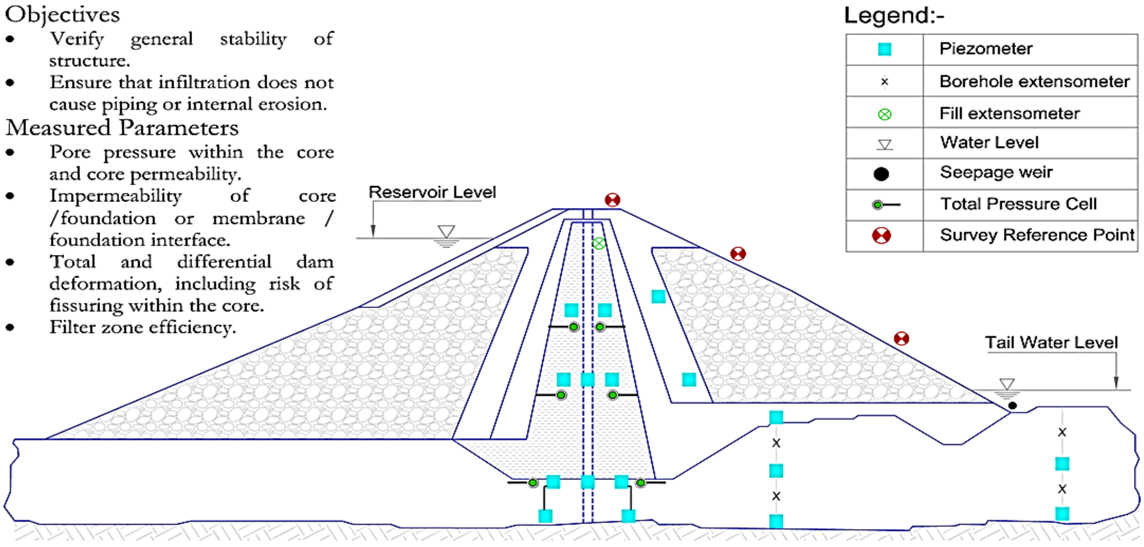
The level of instrumentation installed on embankment dams is invariably more comprehensive and more complex than that for concrete dams of comparable size. The instrumentation of embankment dams, from its selection through installation to data processing, is discussed in the context of surveillance in Penman et al. (1999).

At the installation and setting-to-work stage, success depends on attention to detail. Points to be considered and resolved in advance include procedures for the commissioning and proving of the instruments, for the determination of “datum” values and for the special training of monitoring personnel. Detailed consideration must also be given at this stage to data-handling procedures. It is advisable to consider instrumentation programs in terms of the overall system required, i.e. instruments, installation, commissioning, monitoring, and data management and interpretation.

A schematic instrument layout for the major section of a new earthfill embankment dam is shown in Figure 3-1. Comprehensive instrumentation programs of this type are described in Evans and Wilson (1992), Charles et al. (1992), and Charles et al. (1996). For new dams, a modest level of instrumentation is needed to give an adequate standard of warning of serious conditions that could lead to failure.

Earthfill dams are most often damaged or fail because of the creation of paths of concentrated seepage, originating soon after construction. This could occur from incorrect or negligent construction, because of errors in the design, or inaccurate assessment of local conditions. Concentrated paths of seepage can also occur during service conditions of the dam owing to excess deformations of earthen masses and the concrete structures that are connected to them.

Failings in design or construction which impinge upon structural integrity and safety will become clear at this early stage, given


Objectives
- Verify general stability of structure.
- Ensure that infiltration does not cause piping or internal erosion.

Measured Parameters
- Pore pressure within the core and core permeability.
- Impermeability of core /foundation or membrane / foundation interface.
- Total and differential dam deformation, including risk of fissuring within the core.
- Filter zone efficiency.

Figure 3-1. Illustration of parameters to be measured at the major cross section of an embankment dam

that a proper monitoring regime is in operation. First impounding should take place at a controlled and modest rate, with the response of dam and foundation closely monitored during filling and for a few years afterward.

The procurement and installation of all but the most basic level of instrumentation, i.e. provision for monitoring seepage and settlement, requires care in planning and execution. In the case of the more extensive instrumentation arrays common for larger dams, it is always advisable to plan in consultation with the design specialist manufacturers and suppliers. Considerable advantage is to be derived from entering a contractual arrangement with the selected provider to cover procurement, installation, setting-to-work and proving of the instrumentation. The contract may also be extended to include training of the technical staff who will then take responsibility for in-service monitoring and some time for operation and maintenance period, to ensure the reliability of system.

3.1 Instrumenting Existing Embankment Dams

Instrumentation of existing embankment dams, particularly those considered to be a significant potential hazard, is now a widespread practice. The limitations on the type of instruments that can be installed retroactively are clear, and the datum values against which later changes may be assessed now become those existing at the time of installation, sometimes many years after completion of the dam. This makes interpretation of an observed change in behavioral pattern harder than in the case of a dam that has been routinely monitored since the beginning of construction and first impoundment. The desirable minimal installation for retrospective instrumentation is recommended for monitoring seepage flows and, on embankments, crest settlement and deformation. It may in some instances be good to make further provision for measuring local piezometric and deformation profiles, e.g. where culverts and similar works run transversely through the body of the embankment.

3.2 Monitoring Seepage and Water Pressure

In the case of embankment dams, seepage takes place through the body of earthfill dams, as well as through the waterproof element of earthfill and rockfill dams. Some seepage is permissible if proper care have been taken to control it. However, uncontrolled seepage can endanger the

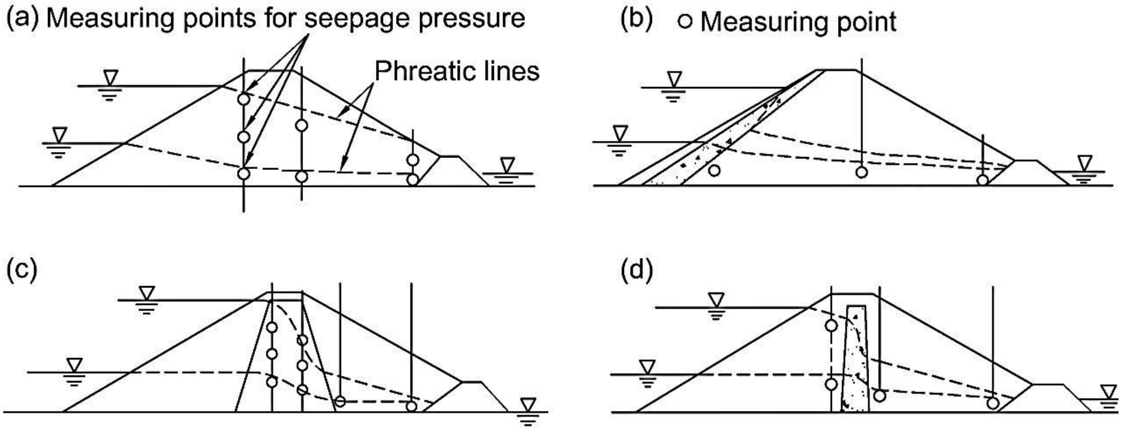


Figure 3-2. Instrumentation layout for measurement of the pore water pressure in embankment dams. (a) Homogenous; (b) sloping core; (c) broad central core; (d) narrow central core

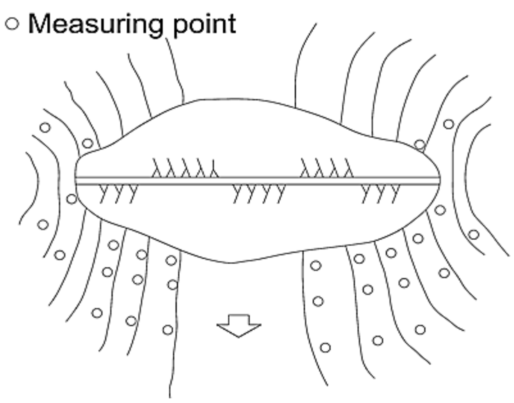


Figure 3-3. Layout for the bypass seepage and groundwater monitoring in an embankment dam

stability of a dam.

Schematic instrumentation layouts for measuring water pressure in distinct types of embankment dams are shown in Figure 3-2 and for monitoring bypass seepage and groundwater flow in Figure 3-3. At least, provision should be made for monitoring seepage flow captured by the external drainage system, and secured leveling stations should be set up at intervals of 20 or 25 meters along the crest for measuring settlement.

A fiber-optic temperature measuring system can be applied at existing dams as well as at new ones (Goltz et al. 2011). The most common application for existing dams is installation of the fiber-optic cable in the dam toe below a refurbished surface sealing or in existing standpipes. In the case of new embankment dams, the cable can be installed during the construction at locations where the monitoring will give the most useful information. Such places are: behind a waterproof facing, or behind an internal dam core made of natural or artificial material.

3.3 Monitoring Soil Stresses

Measurement of stresses in the body of an embankment dam is of minor significance in relation to determining the deformations. Exceptions to this are the contact zones between the filling material and the rigid constructions (concrete retaining walls, diaphragm walls, galleries, and pipelines). Furthermore, the measurement of pressures is connected with a number of difficulties, because of which results obtained are of dubious accuracy. The greatest problem lies in the fact that results depend on the stiffness of the cell of the measuring instrument.

If it exceeds the stiffness of the surrounding filling material, then the observed values may be higher than the real ones, and if it is smaller the results will be underestimated.

In an ideal case, the measuring cell should have the same stiffness as the filling material, which, in practice is difficult to attain. This problem can be moderated and eased by using a cylindrical cell with high stiffness, and with a low value of the thickness versus diameter ratio.

Moreover, a suitable cell should also fulfill other requirements: it must be non-sensitive to the effect of temperature variations, impermeable to dampness, firm and durable, and simple to install. An illustration of instrumentation layout for monitoring stresses in an embankment dam is shown in Figure-3-4.

The typical instrumentation details of a high earth dams are shown in Figures 3-5 to 3-10.

3.4 Indian Standards

Indian Standard IS: 7356-1 “Code of Practice for installation, maintenance and observation of instruments for Pore Pressure Measurements in Earth Dams and Rockfill dams, Part 1: Porous tube Piezometers” covers description of porous tube piezometers with connected accessories, the installation procedure and maintenance, method of taking observations, record and presentation of data for earth and rockfill dams.

Indian Standard IS: 7356-2 "Code of Practice for installation, maintenance and observation of instruments for Pore Pressure Measurements in Earth and Rockfill dams, Part 2: Twin Tube Hydraulic Piezometers" covers the details of procedures for installation, maintenance and observations of twin tube hydraulic piezometers installed in earth and rockfill dams for measuring pore pressures.

Indian Standard IS: 7436-1 "Guide for types of measurements for structures in river valley projects and criteria for choice and location of measuring instruments, Part 1: Earth and Rockfill Dams" covers the various types of measurements for monitoring the behavior of earth and rockfill dams and provides the guidelines for choice of instruments and their locations.

The Indian Standard IS: 7500 "Code of Practice for installation and observation of Cross Arms for Measurement of Internal Vertical Movement in Earth dams" covers the requirements of installation and observation of cross arms of the mechanical and electrical types of measurements of internal vertical movement of earth dams.

The Indian Standard IS: 8226 "Code of Practice for installation and observation of base plates for Measurement of Foundation Settlement in Embankments" gives the details of the installation and observation of baseplate apparatus for observing foundation settlement of dams and embankments resting on soil strata.

The Indian Standard IS: 12949 "Guidelines for Installation, Maintenance and observation of instruments for pore pressure measurements in earth dams and rockfill dams- Electrical pore pressure cells- vibrating wire type" covers the details of installation, observation and maintenance of electrical pore pressure cells (vibrating wire type) installed in earth and rockfill dams for measuring the pore pressures in the embankment and the foundation.

The typical instrumentation details of embankment dam are shown in Figure 3-5 to Figure 3-17

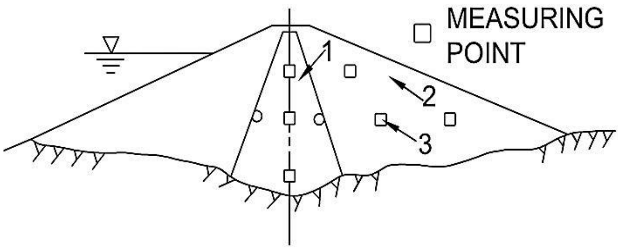


Figure 3-4. Monitoring layout for the stress in an embankment dam. 1) core; 2) dam shell, 3) dam body

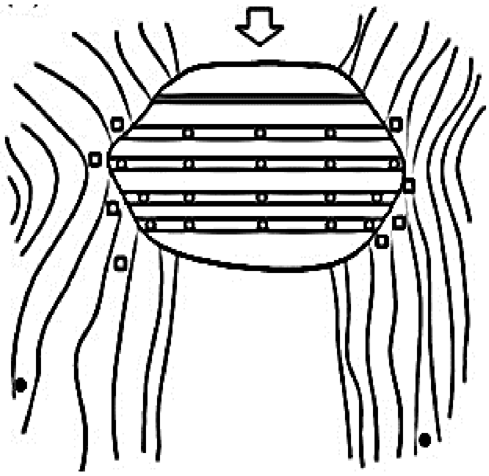


Figure 3-5. Layout of measuring points to monitor vertical movement of dams

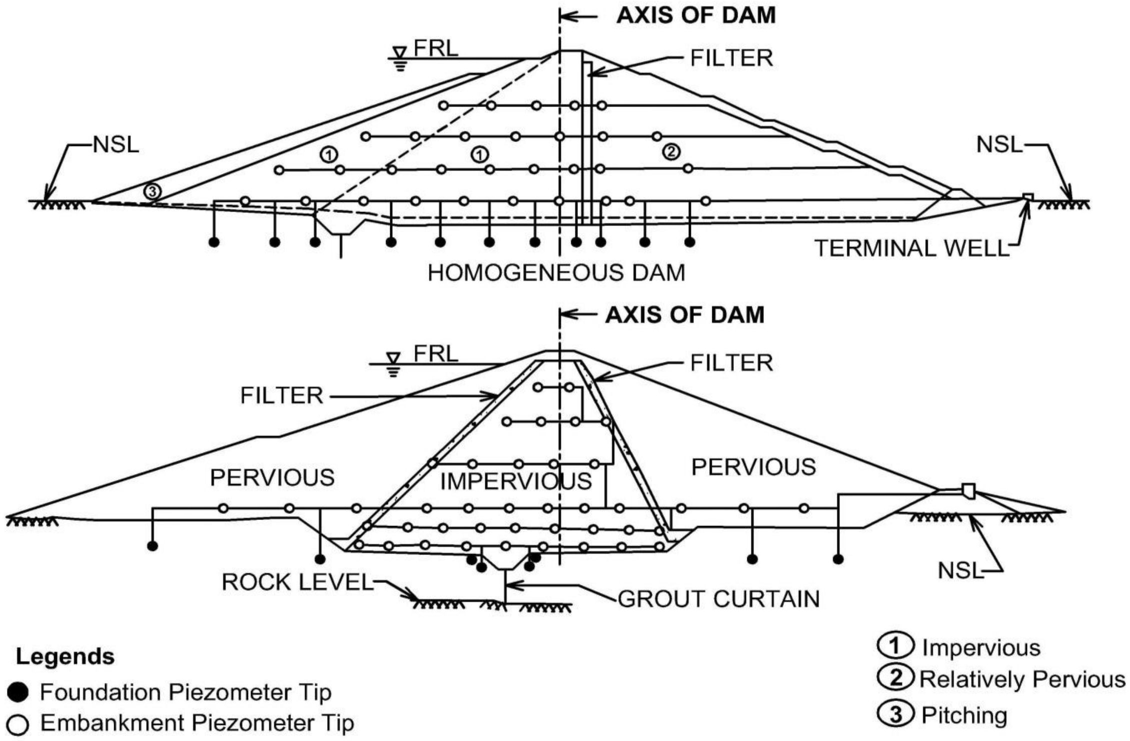


Figure 3-6. Typical Stations showing Piezometer Installation

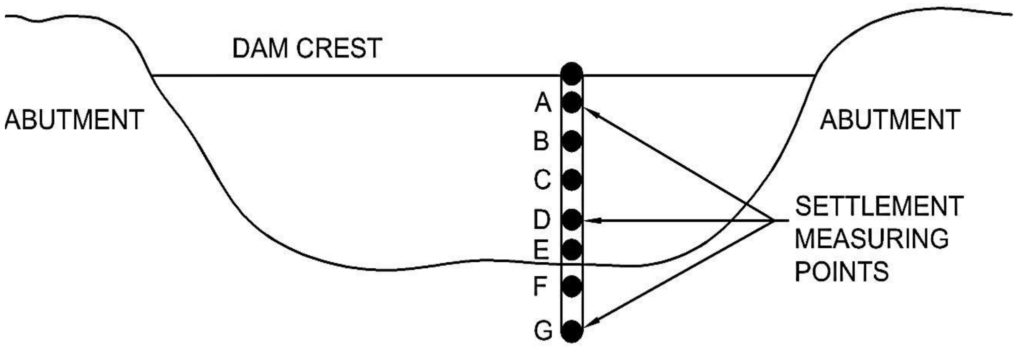
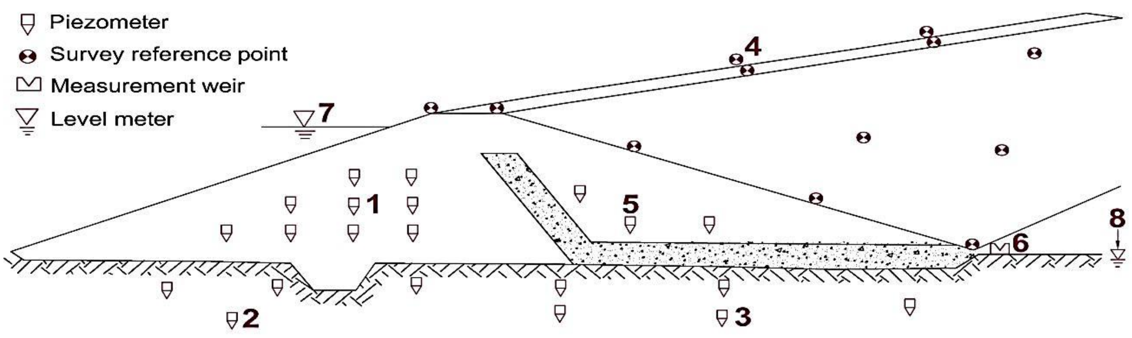
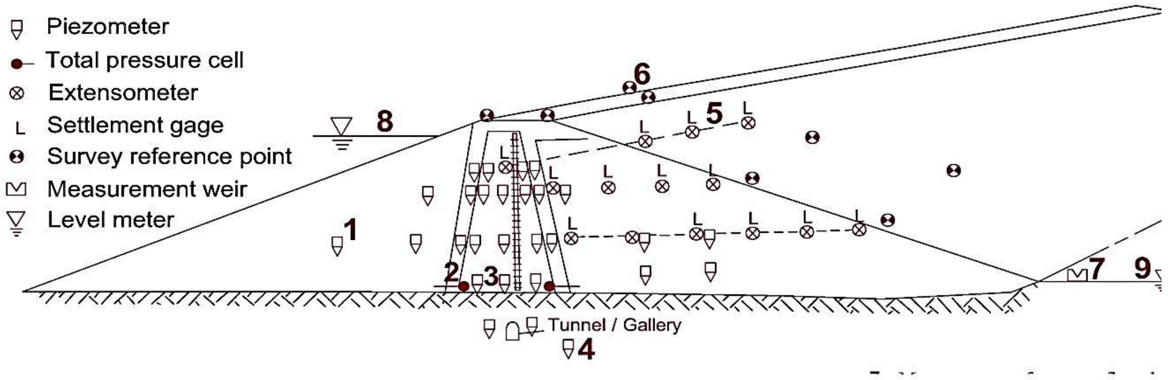


Figure 3-7. Embankment Settlement Monitoring Point Layout



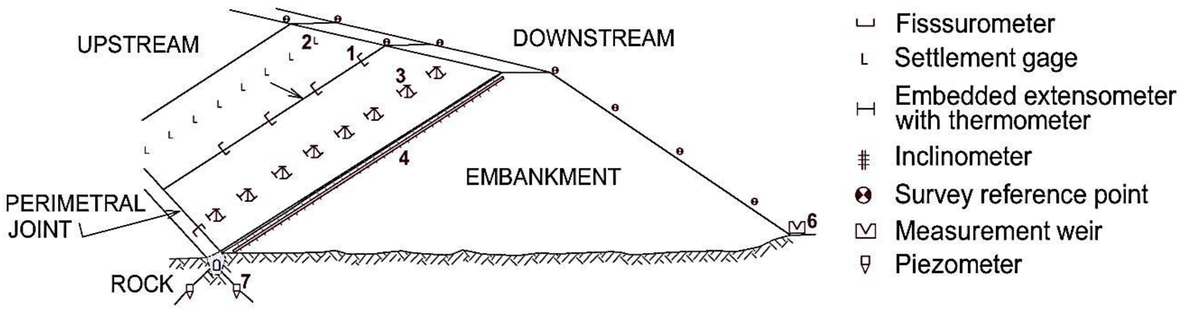
1. Pore pressure measurement for monitoring of upstream flow.
2. Pore pressure measurement for monitoring of seepage flow in foundation.
3. Monitoring of downstream flow in foundations through pore pressure measurement.
4. Displacement at crest and in slope - fissuring monitoring.
5. Pore pressure measurement in downstream slope to assess drain efficiency and rain effects.
6. Seepage flow measurement to help assessment of fissuring, internal erosion and site permeability effects.
7. Reservoir level measurement near a concrete structure (intake, etc.)
8. Downstream level measurement.

Figure 3-8 Homogeneous Dam – Overall Instrumentation Dam



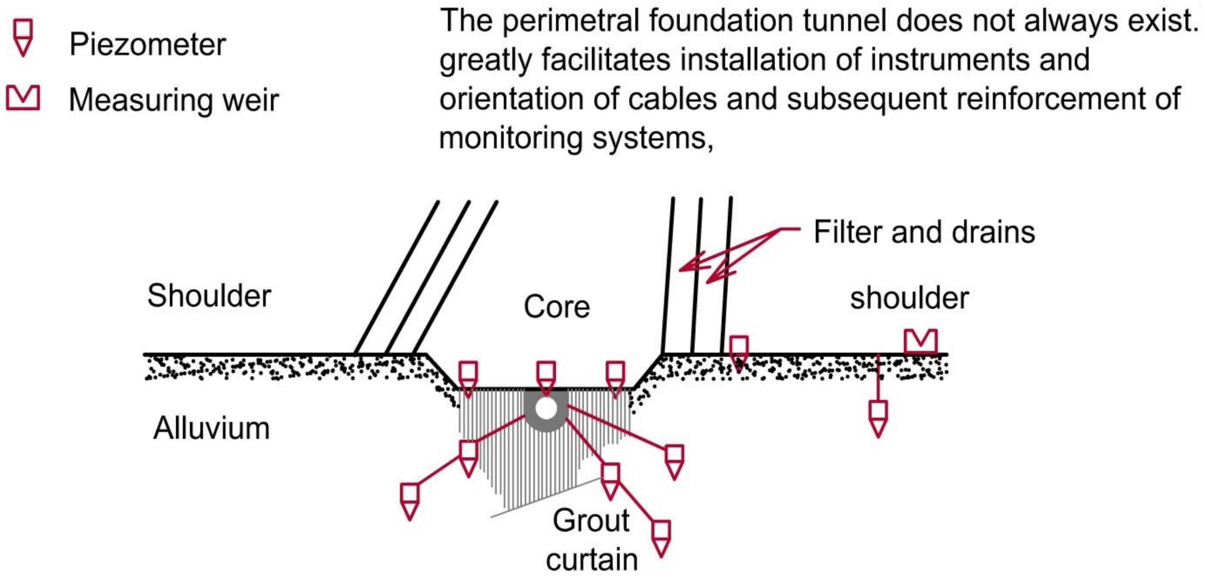
1. Pore pressure measurement for monitor flow conditions, homogeneity of each zone and efficiency of drains and core permeability.
2. Total pressure measurement to detect arching effects that can cause horizontal fissuring resulting from load transfer and hydraulic fracturing.
3. Permeability monitoring at core-foundation interface.
4. Flow monitoring in foundation - grout curtain efficiency (rock or alluvium)
5. Extensometric and settlement system to monitor internal movements and detect potential fissuring zones, especially in abutment zone.
6. Survey reference points and fissuring bench marks.
7. Measurement of seepage flow through dam.
8. Reservoir level measurement
9. Downstream level measurement.

Figure 3-9. Core Dam – Overall Instrumentation Diagram



1. Longitudinal, transverse (if necessary) and perimetral joint measurement
2. Tele-level profile to measure membrane and embankment vertical displacement
3. Line of extensometers cast in concrete to measure deformations and eventually assess strain
4. Inclined settlement clinometer tubing to monitor membrane deformation
5. Survey reference points
6. Seepage flow measurement to monitor internal erosion and membrane impermeability
7. Pore pressure measurement to monitor drainage in rock, alluvium in foundations and, in particular, grout curtain efficiency

Figure 3-10. Details of Overall Instrumentation of Embankment Dam with Impervious Membrane



The perimetral foundation tunnel does not always exist. greatly facilitates installation of instruments and orientation of cables and subsequent reinforcement of monitoring systems,

Figure 3-11. Core Dam with Perimetral Tunnel Positioning of Pore Pressure Sensors

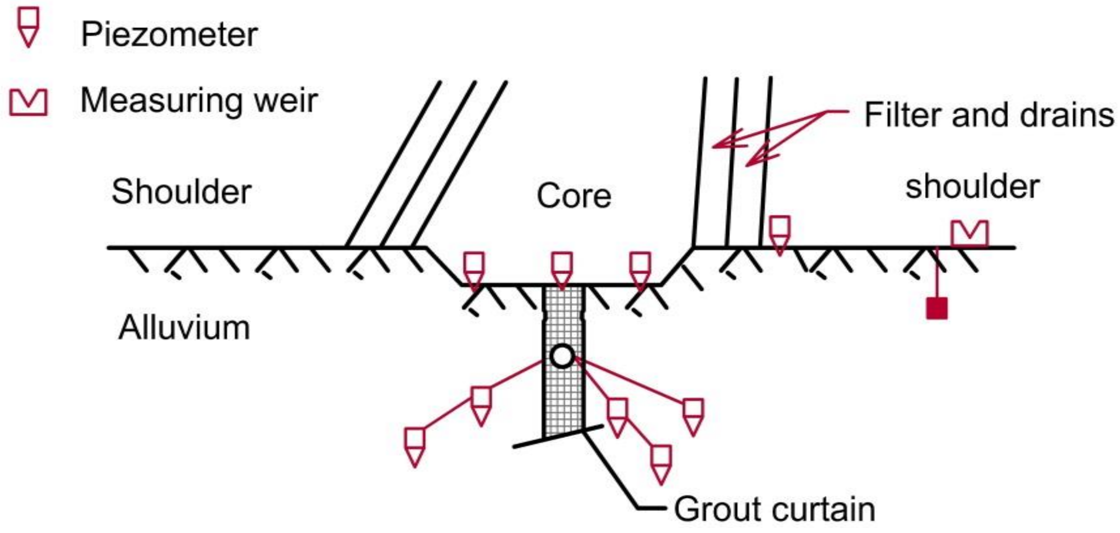
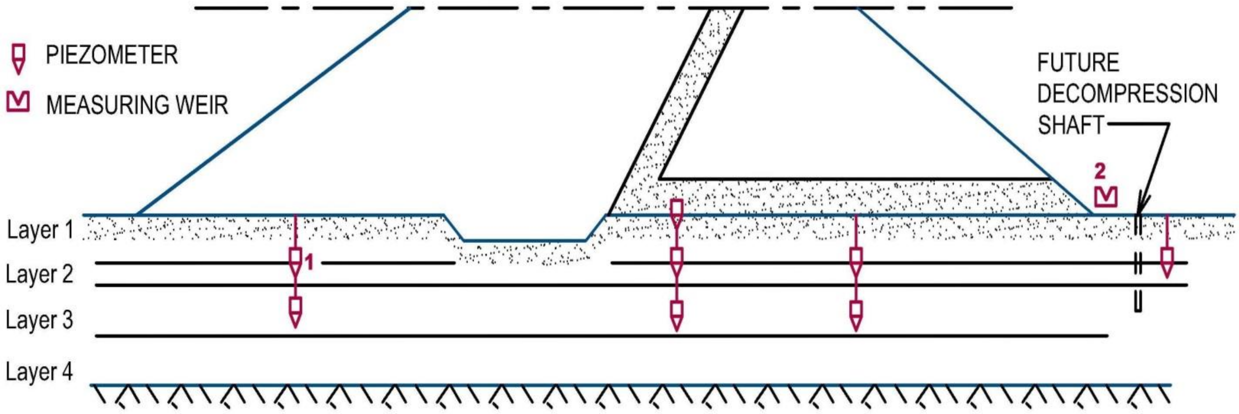


Figure 3-12. Core Dam with Foundation Tunnel Positioning of Pore Pressure Sensors



1. Number and location of pore pressure cells depend on permeability contrasts between layers 1, 2, 3 and 4, their number, their specific thickness and the size of the embankment.
2. Seepage flow measurement.

Figure 3-13. Homogeneous Embankment Dam – Foundation Monitoring

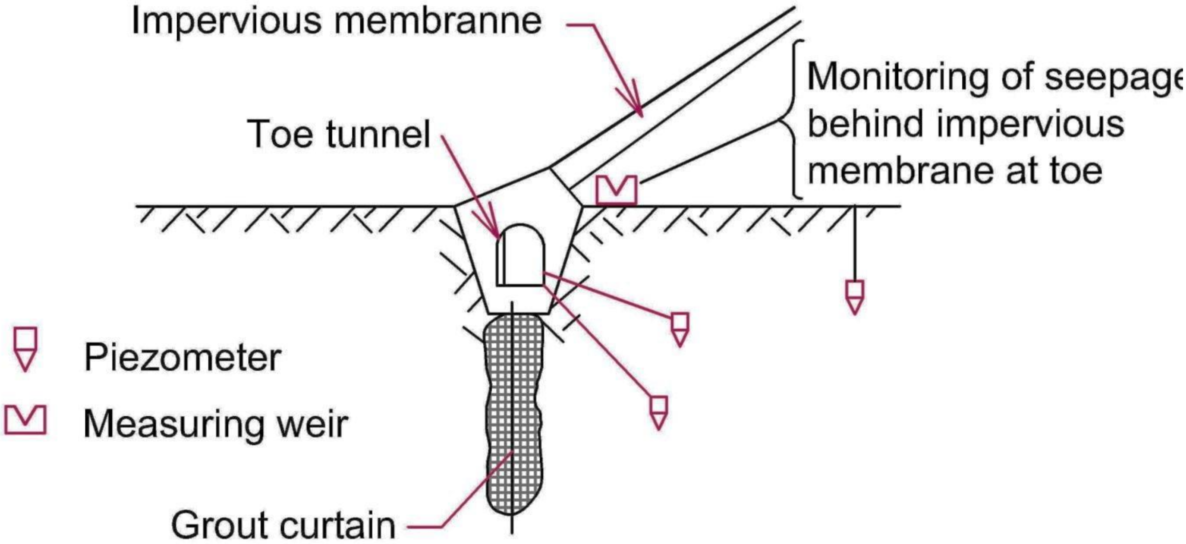


Figure 3-14. Impervious Membrane Dam with Toe Tunnel – Positioning of Pore pressure Sensors

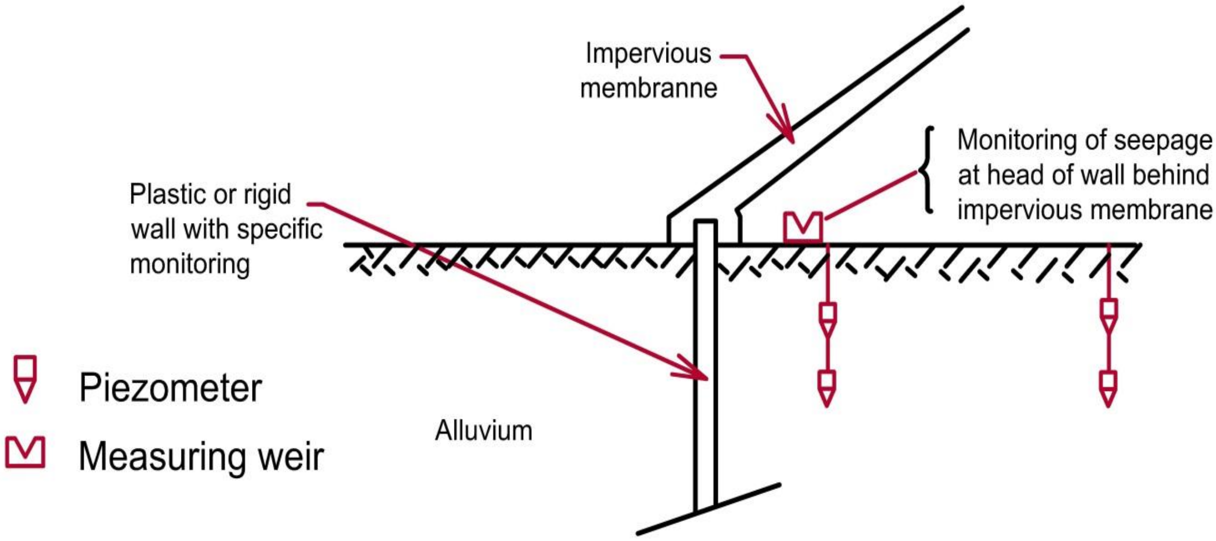


Figure 3-15. Impervious Membrane Dam with Cutoff Wall – Positioning of Pore pressure Sensors

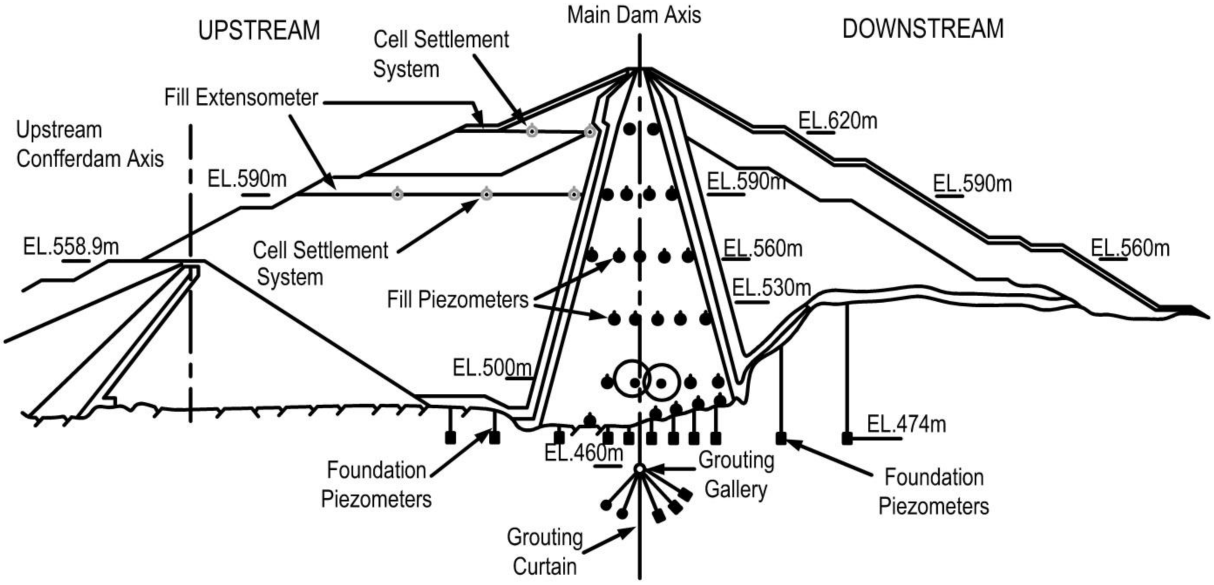


Figure 3-16. Typical Instrument Layout

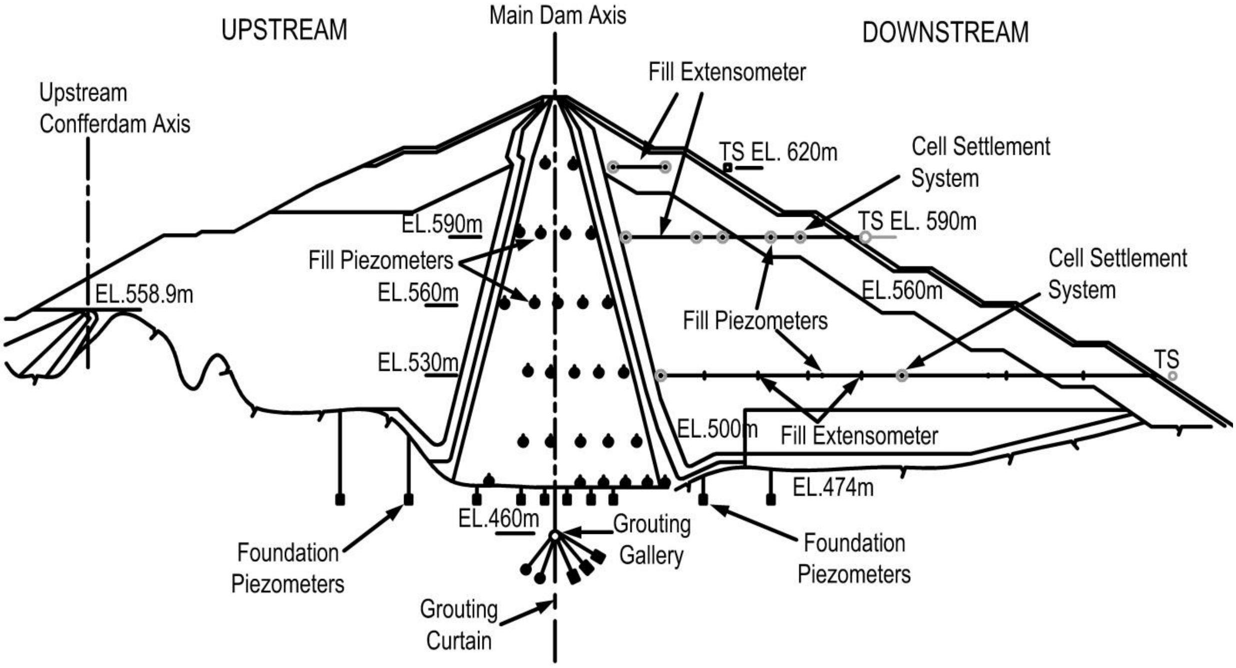


Figure 3-17. Typical Instrument Layout

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Chapter 4. INSTRUMENTATION SYSTEM PLANNING: CONCRETE AND MASONRY DAMS

The objective of instrumenting concrete and masonry dams is the same as that for embankment dams. The primary importance is the collection of data used to judge the safety of a dam. The secondary importance is the information that might help with the structural rehabilitation of a dam and to improvement of other existing dams and the design of new dams.

The various instruments used in concrete and masonry dams or listed in Table 4-1.

In the case of concrete and masonry dams, measured parameters include the temperature in the dam's body and foundation, strains, and deformations, formation and widening of cracks, the opening of joints, stresses (also in the foundation of arch dams), and pore water uplift pressure. Figure 4-1 shows a plan view of a gravity dam that illustrates possible uplift pressure measuring points.

There are two main methods for executing measurements:

1. With precise instruments that measure displacements of permanent bench marks set up on the surface of the dam, in galleries, in vertical shafts, in tunnels in the abutments, and in the measuring wells in the foundation.
2. With instruments that are built into the dam's body and the appurtenant structures by which the above-cited measurements can be carried out.

Regarding the location of the instruments,

Table 4-1. Monitoring Instruments used in Concrete and Masonry Dams

Sl. No.	Instrument	Purpose
1	Total Station, Survey markers, GPS	Measurement of relative movement between abutment and dam, different blocks of dam and absolute movement of dam
2	Borehole extensometer (vertical or inclined) I. Single point II. Multi point	Measurement of relative movement between dam and abutment, dam foundation and at any weakness zone (fault, shear zone, etc.,) in the foundation
3	Joint meter/ Crack meter	Measurement of movement along and across the joints/cracks
4	Leakage/Seepage measuring devices I. V notch weir II. Flow meters	Measurement of water flowing through the dam and from the foundation
5	Pressure Measuring Gauges	Measurement of Uplift pressure acting at base of dam and pore water pressure inside the dam
6	Temperature measuring devices	Measurement of temperature of concrete, air, reservoir water, seepage water
7	Plumb lines I. Direct II. Inverted	Measurement of deformation of dam and foundation
8	Strain/stress meters	Measurement of strain and stress at critical points
9	Inclinometer/Tiltmeter	Measurement of deformation of dam
10	Seismic Instruments I. Seismographs II. Accelerograph	Measurement of ground motion and dynamic response of dam to seismic forces

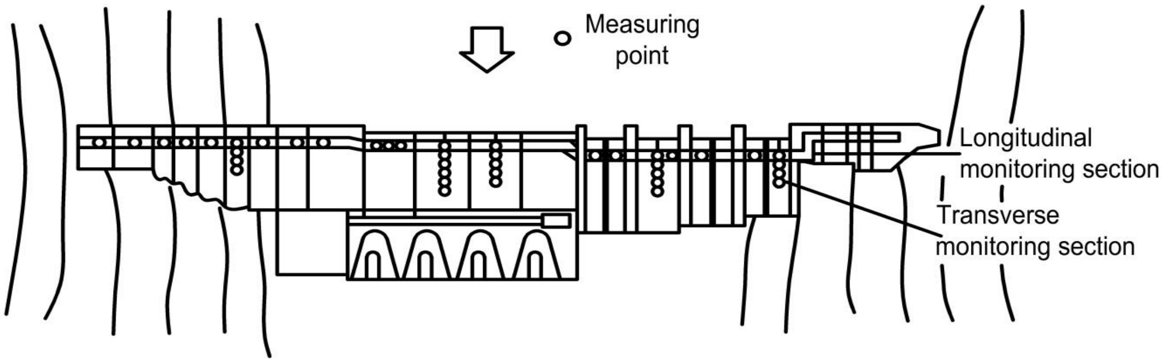


Figure 4-1. Plan view of a gravity dam showing uplift pressure measuring points

the same principles apply as for embankment dams. Monitoring devices should be concentrated in zones with the largest expected values of stresses and deformations, and in places where stresses have been calculated so that comparisons can be made between measured and computed values. The number of measuring points depends on the type, size, and complexity of the structure being monitored. The taller and more complex a structure the more instruments will be needed.

In the case of arch dams, which are more sensitive than gravity and buttress dams, it is necessary to perform more comprehensive monitoring. The number of instruments should be selected to ensure clear pictures of distributed stresses, deformations and temperatures in the dam's body as well as in its foundation. However, the number of instruments installed is of less importance than the choice of the right equipment, their proper installation at critical locations, and the correct interpretation of the resulting data within a well-implemented surveillance program.

4.1 Plumb Lines

The plumbline is a suitable and uncomplicated device for measuring deformations caused by forces of water and temperature variations. Both weighted plumblines and float-supported plumblines are used in practice. A weighted plumbline consists of a weight near the base of the dam suspended by a wire and dropped down through a vertical well from the dam's crest. For the float-supported plumbline or inverted plumbline, a float is installed in a tank at the top of the dam, connected with a wire to an anchor near the base of the dam. The measurements are made at stations, located in horizontal openings at various levels of the dam, to obtain a deflection along its entire height. The measurements are made with a sliding micrometer, provided either with a peep sight or with a microscope, set up in the measuring stations. The measured displacements indicate deformation of the structure with respect to the fixed end of the plumbline (USBR 1976 and 1977).

Plumblines are often used in gravity dams, as well as in arch-gravity dams. In the case of double-curvature arch dams, installing a vertical well for a plumbline is usually not possible, which is unfortunate because with this type of dam the deflection of the crest in relation to the foundation is a key factor in assessing the dam's behavior. Inclinometers have been used to circumvent this problem. However, more recently, displacements have been measured directly in inclined shafts using a controlled monochrome light beam (so-called laser plumbline).

4.2 Monitoring by Precise Survey Methods

It is possible to perform precise deformation surveys of the dam and its foundation. Using optical or electronic distance measuring equipment or lasers, relative vertical and horizontal movement of securely established surface stations can be determined. The layout of measuring points to monitor the vertical movement of dams is illustrated in Figure 4-2.

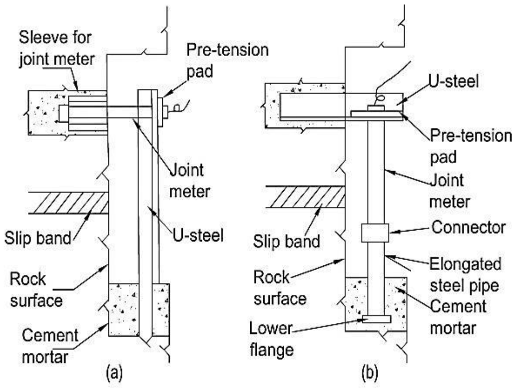


Figure 4-2. Joint meters used to measure (a) horizontal deformations, and (b) vertical deformations

Measurements are also made with plumblines, tangent line collimation, precise leveling, tape gages, and triangulation of deflection targets on the face of the dam. The relative movement and tilt of adjacent monoliths is also found using simple mechanical or optical joint-meters (Figure 4-3).

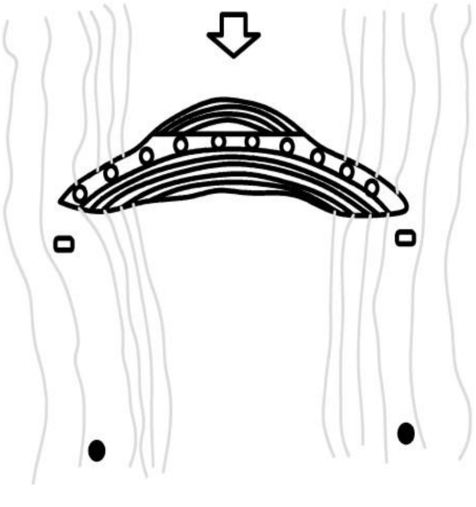


Figure 4-3. Layout of measuring points to monitor vertical movement of dams

For determining deformations of particular points of the dam, in relation to reference points outside the dam, we employ collimation, then triangulation measurements, as well as leveling measurements.

Collimation measurements are performed with a theodolite at measuring points at the dam's crest. At one of the abutments, a pier for the instrument is constructed, set up at a higher level than that of the crest, while at the opposite abutment, at the same level, a reference target is set up. These two points are positioned so that the line of sight between them passes through locations on the dam's crest where measurements are to be made. In the case of arch dams, owing to the curvature of the crest, more targets and piers are necessary (Golzé 1977). The deviation of the movable target from the line of sight yields the displacement of the point at the dam's crest. Three to four measuring points are usually set up, and the results are combined with those obtained from plumbline measurements.

More abundant data for displacements are obtained by triangulation measurements. For that purpose, a system of triangulation targets is placed on the surface of the dam (the crest and downstream face), as well as on the appurtenant structures. This system requires a net of instrument piers and a base line downstream of the dam (Golzé 1977). The instrument piers should be positioned to make collimation from each pier to as many measuring targets as possible. The number of piers is dictated by the nature and topography of the surrounding ground. Measurements must be carried out with precise instruments and methods, performed by well-trained, experienced and skilled surveyors. The results show deformations of the dam, in relation to the targets outside its body, and deformations of the canyon downstream of the dam, in the direction of the river flow and perpendicular to it.

Leveling measurements serve for determination of the vertical displacements of points of the structure in relation to off dam references, positioned sufficiently away from the zone in which we can expect settlements caused by the structures of the dam, as well as the water in the reservoir. Like triangulation measurements, leveling measurements also require the use of precise instruments and methods.

4.3 Surveillance with Embedded Instruments

A lot of surveillance instruments are available that are intended for embedding in the body of concrete dams. These instruments are continuously or regularly developed and improved. Therefore, in the following only the principal and most often used instruments, as typical representatives of groups of instruments, is described. Several types of instruments are used for measuring temperature in individual zones of the dam's body.

4.3.1 Stress and Strain measurement

In the United States, the most popular such instrument is the Carlson elastic wire instrument (Figure 2-30). This is a dual-purpose instrument in which the main element is an elastic music wire coil. The instrument takes advantage of the fact that the electrical resistance of steel wire varies directly with the temperature. This instrument can also be used for measuring tensile stresses because the changes in the electric resistance of the wire are also in direct dependence on the tension in the wire. In practice, this instrument has turned out to be a safe and stable instrument even in long-lasting service (Golzé 1977).These instruments have been used in many dams in India also. Layout of temperature measurement points for gravity dams is illustrated in Figure 4-4 and for arch dams in Figure 4-5. Layout of foundation temperature monitoring points for a gravity dam is illustrated in Figure 4-6.

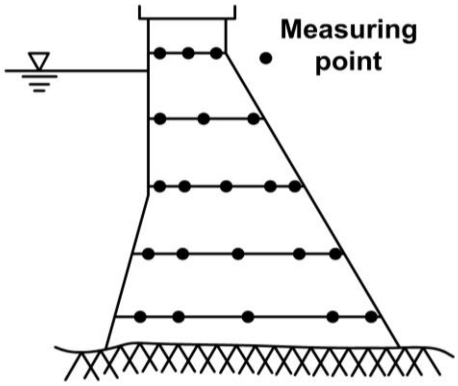


Figure 4-4. Layout of the temperature monitoring for a gravity dam

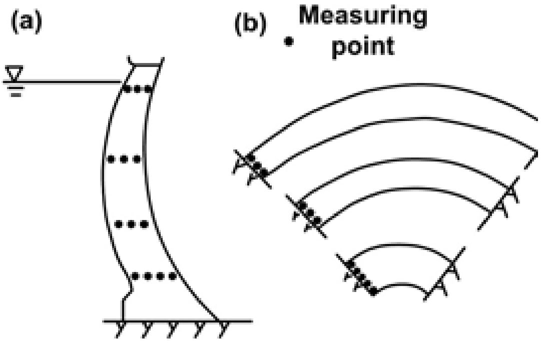


Figure 4-5. Layout of the temperature monitoring for an arch dam (a) Cantilever section; (b) arch section

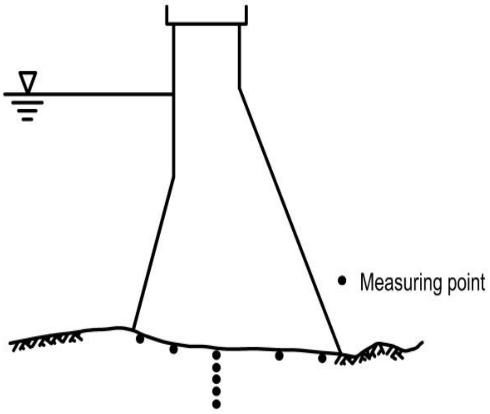


Figure 4-6. Layout of foundation temperature monitoring points for a gravity dam

In Europe, an instrument with a vibrating wire is used often. This instrument makes use of the fact that an increase in tension increases the frequency of vibration of the wire when plucked. The frequency is measured by use of a magnetic circuit. The measurements can be made by electrical readouts. For determination of stresses in each location of the dam's body, a group of 12 strain meters are usually embedded, of which 11 are connected to one support and incorporated in the form of a cluster. The twelfth strain meter is set up vertically near the cluster. Nine strain meters give complete information on strains in all directions, while three strain meters serve as a reserve, as well as for a check-up on the obtained results. Depending on the requirements and needs, it is also possible to incorporate a smaller number of strain meters, which will yield data in only certain directions. Then, based on the obtained data on strains, it is possible to calculate stresses, based on the known dimensions and characteristics of the strain meters.

A Carlson Stress Meter (Figure 2-30) is used for measuring compressive stresses. Its main elements are two flat steel plates, with a diameter of 15.7 cm, connected with a layer of mercury, about 0.5 mm thick. The central part of the upper plate has a very reduced thickness, and it behaves as a diaphragm. The external pressure, acting on the plates, creates a corresponding pressure in the mercury, which causes deflection of the diaphragm towards the external side, by which there comes about an activation of the device for measuring strains. This consists of two threads of steel wire, placed on sheaves (pulleys), connected by a steel frame. The deflection of the diaphragm tensions the wire from one of the threads while loosening the other, in equal proportion. The variation in tensioning changes the electric resistance of the two threads, which can be measured with Wheatstone's bridge, while the variation of the resistance is a measure of the deflection of the diaphragm. The resistance is not dependent on variation in the temperature because it equally influences the two coils (Golzé 1977; Hanna 1985; Sing and Sharma 1976).

The Carlson Stress Meter is usually employed for special purposes, such as measuring the vertical stresses at the base, i.e. foundation, and for comparison of results obtained with a strain meter. It is also used with arch dams for determination of the horizontal compressive stress in the thin elements near the crest. The Carlson Stress Meter is employed not only in concrete dams but also in embankment dams (Sing and Sharma 1976).

Instruments like strain meters are used to measure the opening of joints. However, with a wider measuring range, owing to the greater expected displacements, the sensitivity and accuracy of these instruments have been reduced. This type of instrument can also be embedded in a borehole in the foundation, just below the dam, with the task of measuring deformations in the rock foundation.

At some concrete dams in Europe, measurements are also made of the rotation of some reference axis in relation to certain horizontal or vertical planes. Such measurements are performed at selected places in the galleries using two types of instruments: clinometers and inclinometers. Clinometers, used for measuring changes of the angles in relation to the horizontal plane, are more often employed than inclinometers, used for measuring the angle of rotation in relation to the vertical (Hanna 1985).

4.3.2 Tiltmeter

Tiltmeters are precise instruments used to measure minor changes of inclination about the horizontal. They are installed on the concrete surfaces of the dam or inside inspection galleries, with proper anchoring into specially made and prepared boreholes.

Every tiltmeter cable is connected to receiving units by cables, which are, further on, connected with stations for recording, as well as with alarm units, which are activated while recording the abnormal behavior of the dam. Modern systems of tiltmeters are automated in relation to collecting data and remote control. Such a completely automated system of 20 biaxial tiltmeters was installed towards the end of 1992 (many years after its start-up in service) at the Boundary arch dam (USA). Biaxial tiltmeters are intended for measuring the vertical angle deflection, parallel and perpendicular to the proper planes, which are radial in relation to one reference cylinder, the axis of which (A) is presented in the central section (Sharma et al. 1994). Six tiltmeters have been installed in the gallery of the Boundary Dam, while others were put in place on the downstream slope. Owing to its inclination towards the downstream side, that has not been at all simple to carry out. The manufacturer of the tiltmeters has supplied system software for automatic reading, i.e. recording, of data at intervals determined by the user. The output data consist of values of the angle of deflection and the angle of inclination, measured in relation to the radial surface of the tiltmeter. Because the vertical section through the plane of tiltmeter is not uniform, and because of the three-dimensional effect, there has been developed a special method for exact calculation of the horizontal deflection based on the data obtained from the measurements. The obtained data are compared with the values that have been calculated by using the Finite Element Method, in which the model for calculations is permanently calibrated and adjusted based on the measured data. The final aim of the users of the dam was to obtain complete coincidence of the calculated data and measured data, which implies obtaining a model with a completely true and authentic presentation of the behavior of the dam.

4.3.3 Uplift Pressure

In the case of gravity concrete dams, it is also necessary to measure the value of the uplift pressure in the concrete - rock interface and in the dam's body, occurring owing to the penetration of water through cracks in the foundation and concrete, caused by a badly constructed grout curtain or because of poor functioning of the drainage. For that purpose, a system of pipes is installed in several blocks in the contact of the dam and the foundation, while the uplift is determined with measuring instruments. Also, piezometers can also be embedded, especially in smaller dams, of similar construction to those used for embankment dams. In the case of soil foundations, the uplift can also be measured with built-in cells for measuring pore pressure, which can be embedded at selected locations and in the dam's body, for measuring the pore pressure in the concrete.

4.4 Indian Standards

Indian Standard-IS: 6524 “Code of Practice for installation and observation of instruments for temperature measurements inside dams: Resistance type Thermometers” covers the details of installation and observation of resistance type thermometers of the embedded type for measuring the temperature in the interior of a concrete dam and such other structures.

The Indian Standard IS: 7436-2 “Guide for types of measurements for structures in river valley projects and criteria for choice and location of measuring instruments, Part 2: Concrete and Masonry Dams” lays down the types of measurements need to be done in concrete dams and masonry dams in river valley projects. Criteria for choice and location of the required measuring instruments are also given.

Indian Standard IS: 8282-1 “Code of Practice for installation and observation of pore pressure measuring devices in Concrete and Masonry Dams, Part 1: Electrical resistance type cell" covers the details of installation, maintenance and observations of resistance type pore pressure measuring devices in concrete and masonry dams.

Indian Standard IS: 8282-2 "Code of Practice for installation and observation of pore pressure measuring devices in Concrete and Masonry Dams, Part 2: Vibrating Wire type cell" covers the details of installation, maintenance and observation of vibrating wire type pore pressure measuring cells in concrete and masonry dams.

The Indian Standard IS: 10334 "Code of Practice for selection, splicing, installation and providing protection to the open ends of cables used for connecting resistance type measuring devices in concrete and masonry dams" covers the details of specifications of cables, mode of delivery, inspection and test to be carried out on the material used in the manufacture of cables as also on finished cable. Pre-embedment tests, cable end protection and fixing the size of conduits.

Indian Standard IS: 10434-1 "Guidelines for Installation, Maintenance and observation of Deformation measuring devices in Concrete and Masonry dams- Part 1- Resistance Type Joint meters" covers the details of installation, maintenance and observations of resistance type joint meters of the embedded type for measurement of joint movements at the surface and in the interior of concrete and masonry dams.

Indian Standard IS: 10434-2 "Guidelines for Installation, Maintenance and observation of Deformation measuring devices in Concrete and Masonry dams- Part 2- Vibrating Wire

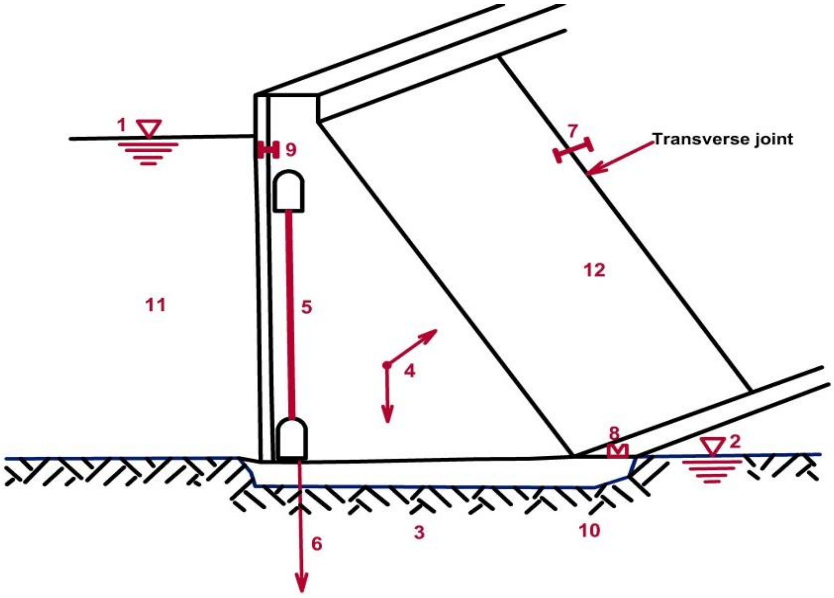
Type Joint meters" covers the details of installation, maintenance and observations of vibrating wire type jointmeters of the embedded type for measurement of joint movements at the surface and in the interior of concrete and masonry dam.

The Indian Standard IS: 13073-1 "Code of Practice for installation and observation of Displacement Measuring Devices in Concrete and Masonry Dams, Part 1: Deflection measurement using Plumblines" presents the details of the installation, maintenance and observation of direct and inverted plumb line for measurement of horizontal deflections of points inside a concrete or masonry dam.

The Indian Standard IS: 13232 "Code of Practice for installation maintenance and observation of electrical strain measuring Devices in Concrete Dams" covers the details of installation, maintenance and observation of electrical type strain measuring device suitable for embedment in concrete dams.

The Indian Standard IS: 14278 "Code of Practice for installation, maintenance and observation of Stress measuring Devices in Concrete and Masonry Dams" explains the details of installation, commissioning and observations procedures of unbonded strain gauge type and vibrating wire type stress meter in concrete and masonry dams.

The typical details of instrumentation of concrete dams are shown in Figure 4-1 to 4-11.



1- Measurement of reservoir level

2- Measurement of downstream level

3- Measurement of pore pressure to monitor uplift

4- Measurement of strain and temperature for monitor fissures

5- Tilt measurement (direct pendulum)

6- Displacement measurement to monitor sliding

7- Joint opening measurement

8- Seepage flow measurement to assess fissuring

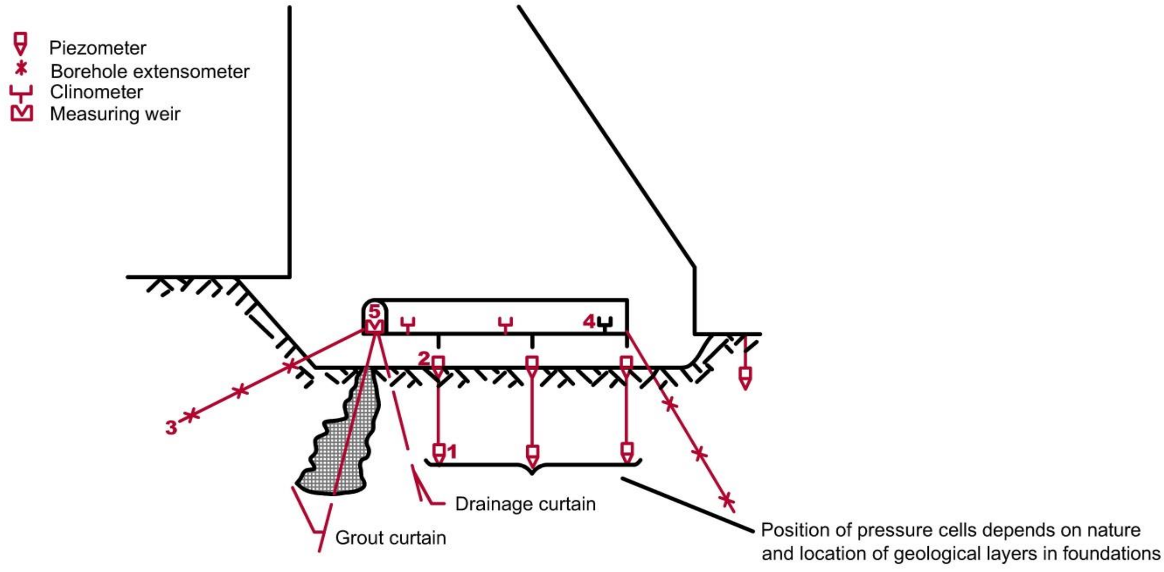
9- Measurement of bond between face and body of dam

10- Monitoring of downstream flow in foundations

11- Measurement of reservoir water temperature to assess thermal gradient and its effect on fissuring

12- Measurement of concrete temperature on downstream face in correlation with measurement 11

Figure 4-7: Concrete Gravity Dam– Overall Instrumentation Diagram



1- Monitoring of seepage in foundation by pore pressure measurement

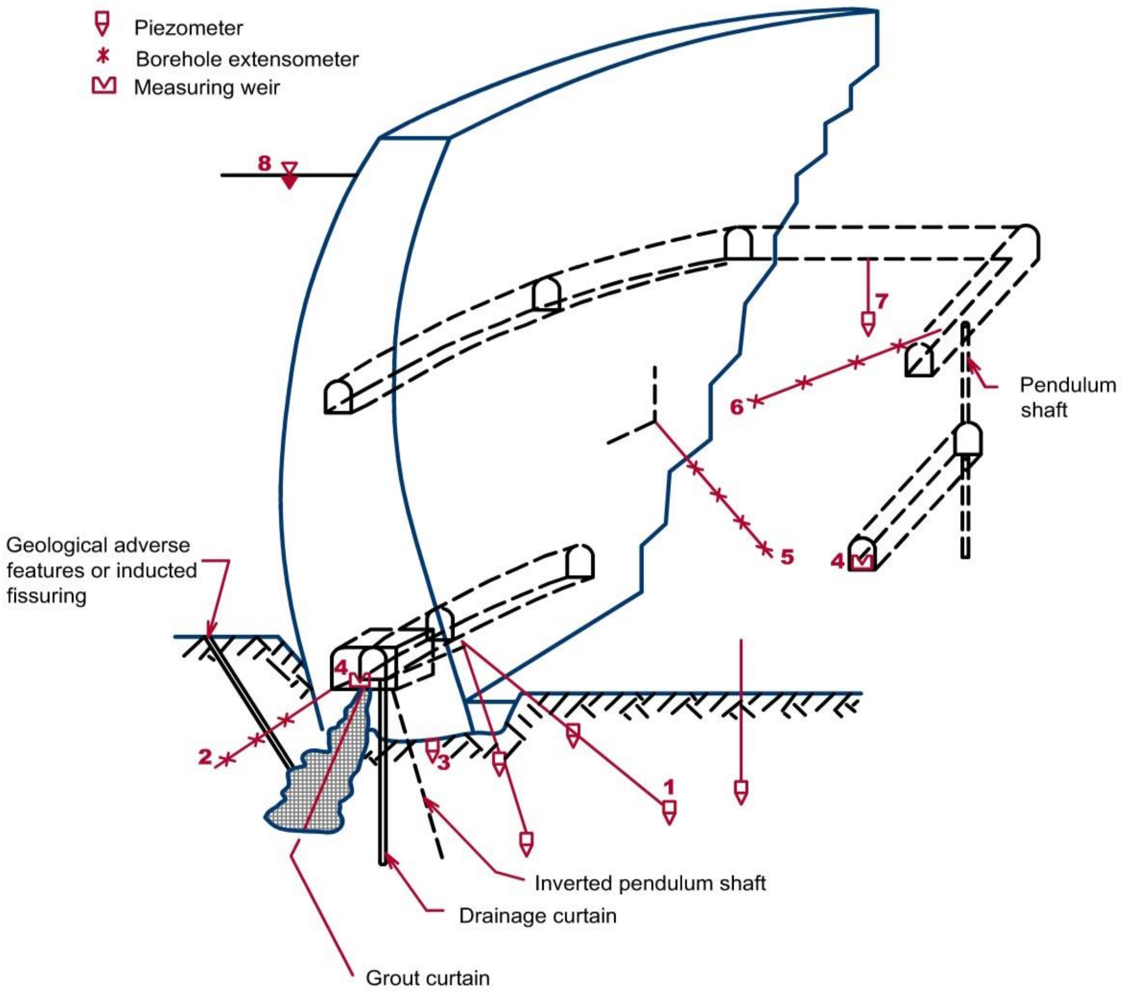
2- Pore pressure measurement at concrete-rock interface

3- Monitoring of movement caused by fissure opening, using borehole extensometers

4- Monitoring of rotation of dam base by highly sensitive leveling pots or fixed clinometers

5- Seepage flow measurement

Figure 4-8: Gravity Dam– Foundation Monitoring



1- Monitoring of flow downstream from grout and drainage curtains by pore pressure measurement

2- Monitoring of movement caused by fissure openings, using borehole extensometers

3- Pore pressure measurement at concrete-rock interface

4- Seepage flow measurement

5- Monitoring of foundation compressibility, using borehole extensometers

6- Monitoring of specific geological adverse features, using borehole extrnsometers

7- Pore pressure measurement for monitoring of grout curtain and abutment stability

8- Reservoir water level indicator

Figure 4-9: Concrete Dam – Foundation Monitoring

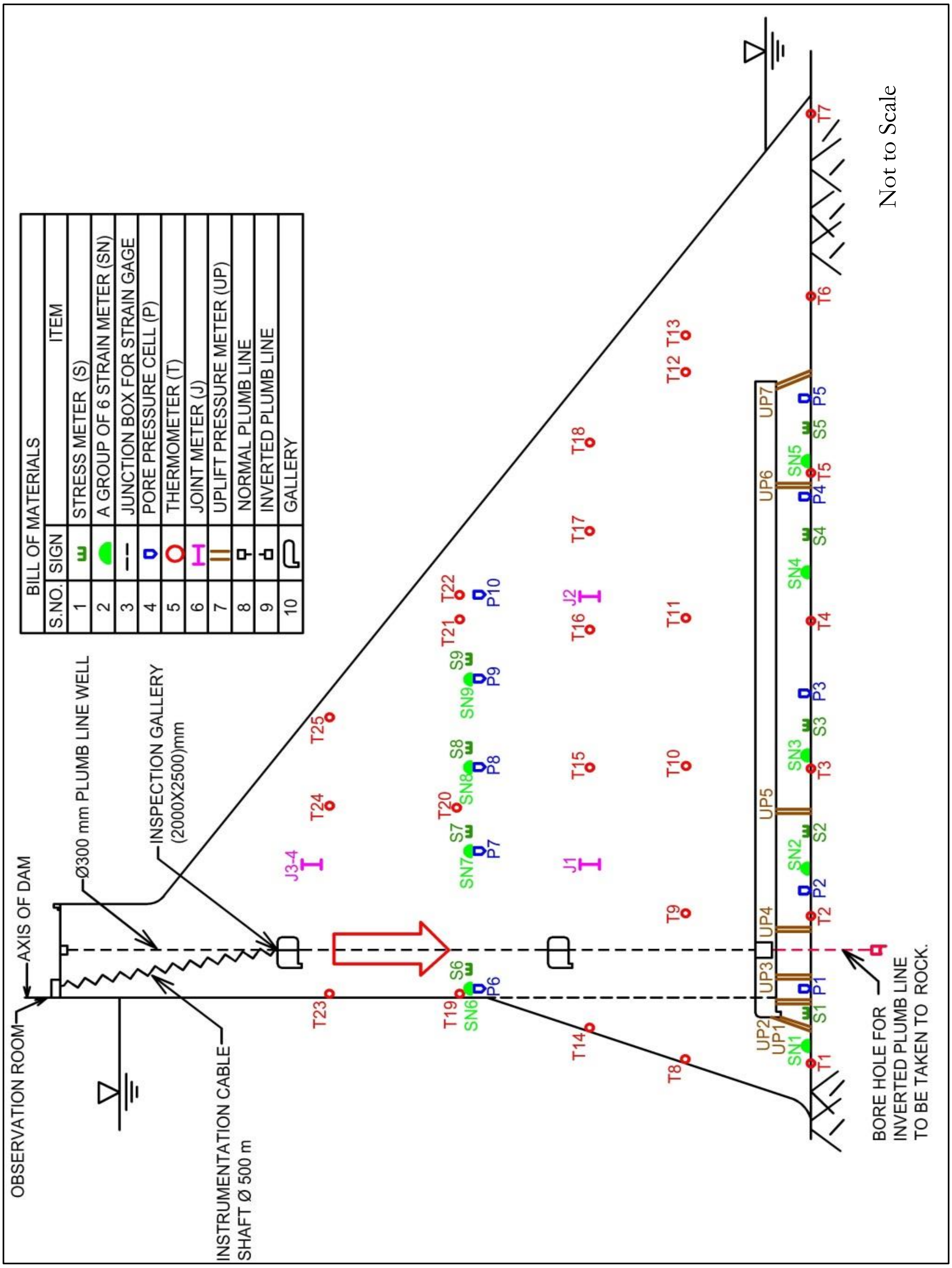


Figure 4-10: Typical Instrument Layout

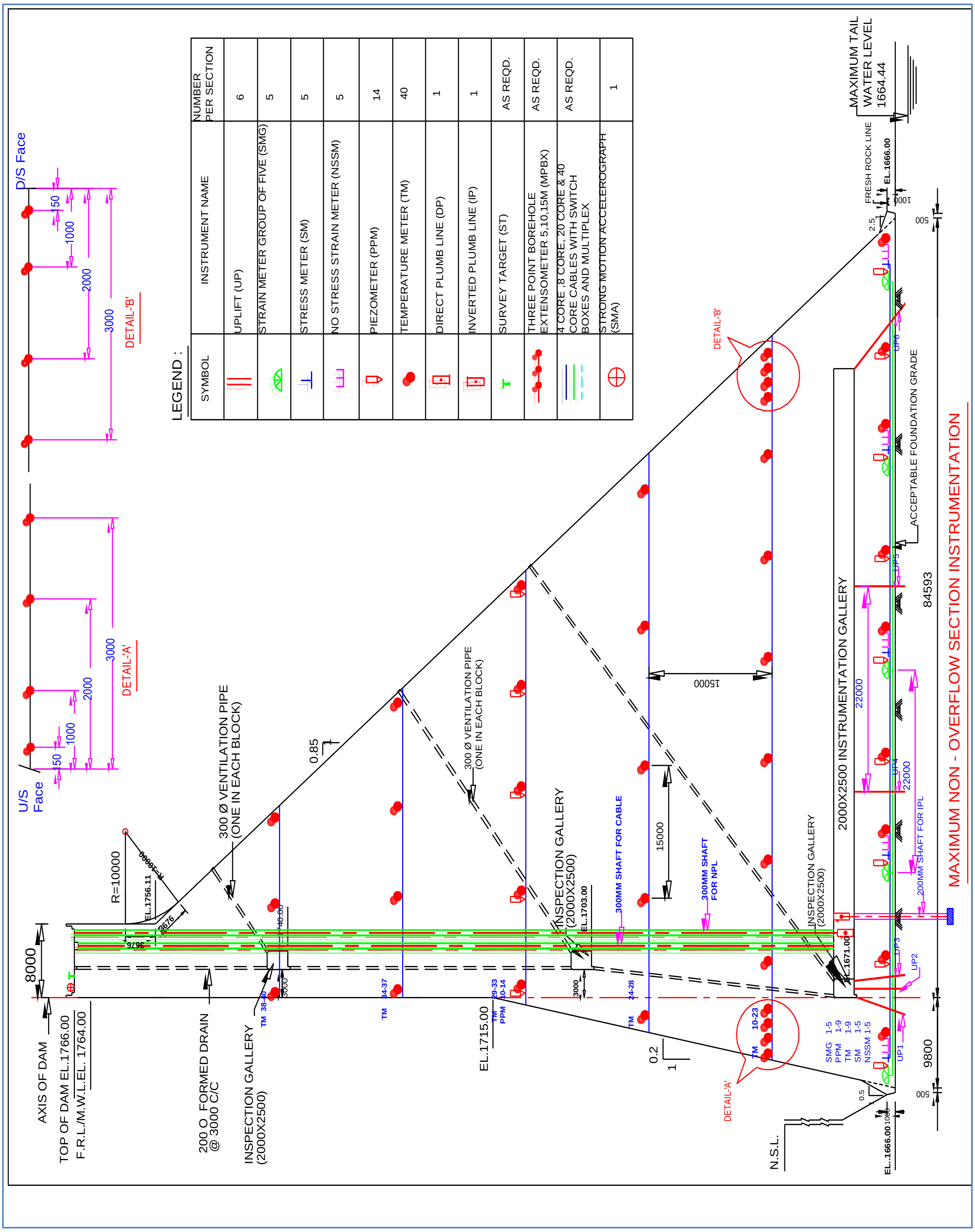


Figure 4-11: Typical Instrument Layout

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Chapter 5. INSTRUMENTATION SYSTEM PLANNING: SEISMIC MONITORING

During an earthquake, a dam is excited with vibrating motion from the ground shaking. ICOLD (2013) recommends a method of design that is based on dynamic analysis of the behavior of the dam during an earthquake. A difficulty with this design method is that all the physical parameters needed for the analysis are not known accurately and must be estimated. Moreover, the foundation of the structure is assigned an acceleration that is the same as its base, which is not realistic. More recordings of earthquake motions of dams and their foundations are needed, and more research is required on how to analyze a dam using numerical methods that take into account the dynamic properties of the material of which the structure is built.

The effect of earthquake on concrete dams are: (a) sliding at foundation of abutment, (b) openings at joint and cracks to leave uncontrolled leakage (c) failure by local crushing of some of the block or part getting displaced at their upper level (d) spillways and hydraulic controls getting damaged. Similarly, for embankment dam earthquake can lead to (a) liquefaction of the material of the foundation or the dam, (b) collapse due to slip surface in the slope or through foundations (c) encroachment in the free board and (d) uncontrolled leakage through cracks or at interface with structures or abutments. From these considerations, seismic forces are duly considered in the design of gravity, buttress, arch and other types of dams as well as earth dam and rockfill dams.

Having designed structures for seismic forces, it is also pertinent to measure the seismic activities in the course of performance of the structure specially so, as there has been school of thought suggesting that the filling up of reservoirs behind the dam accentuated the earthquake activity as was the feature in Koyna dam. From this angle seismological instruments are set up in different locations of any river valley projects and their observations are made at regular intervals and are continued even after the dam is constructed.

The main reasons for seismic monitoring of dams are the following:

1. The precise definition of the seismic activity of the site, i.e., the exact location of earthquake epicentres and their depths.
2. Defining the main earthquake parameters: epicenter location, magnitude, frequency characteristics and some indications of focal mechanisms.
3. Predicting the probable occurrence of future earthquakes.
4. Providing data on the dynamic behavior of the dam body for the purpose of objective evaluation of its functioning immediately after the occurred earthquake.
5. Verifying design parameters by the actual behavior of the dam body during an earthquake.

To provide this wide range of information, it is necessary to monitor the dam site with a local network of seismographs and accelerographs. The network of instruments needs to cover the considered area thoroughly. This network should start being operational at least two years prior to the beginning of construction of the dam and should continue to the end of filling of the reservoir, i.e. for a minimum of three years after putting the dam into effect. It is desirable, particularly in areas of high seismic activity that this network functions on a permanent basis.

The seismological stations distributed around the reservoir must record the seismic activity in the region of the dam and the reservoir. Several basic reasons are justifying this seismic instrumentation among which is the investigation of the normal seismic regime by these observations with the purpose of contributing to the seismotectonic investigations to define the seismicity of the seismogenic zone. Apart from this, this phase of investigations confirms or negates the existence of induced seismicity because of filling of the reservoir. If such seismicity does exist, its relationship with the normal seismic regime is defined. The results from these observations offer the possibility for making corrections of the main seismic activities. This type of investigations is performed by a network of seismological instruments distributed around the reservoir and telemetrically connected with the central recording station.

The strong motion instruments installed on the dam enable obtaining of basic data on its behavior during an earthquake, i.e., making decisions about further exploitation or the need for repair of the dam soon after the quake occurred.

The phase of seismic investigations during and after the construction of a dam refers to engineering aspects of the structure. It includes an installation of instruments (in the ground and at the base of the dam) for the recording of strong motions. The instruments are positioned at characteristic points of the base of the dam. The collected records are an invaluable parameter for verification of the mathematical model of the structure and its behavior under the effect of a real earthquake.

The seismic instruments for a dam site include Strong Motion Accelerograph (SMA) which records the ground acceleration at the installed location which is necessary to study the engineering aspect of the structure. The data are useful in establishing sub surface soil characteristics and predominant period at the site.

SMA consists of three-part accelerometers (one vertical and two horizontal components), a digitizer, and a recording

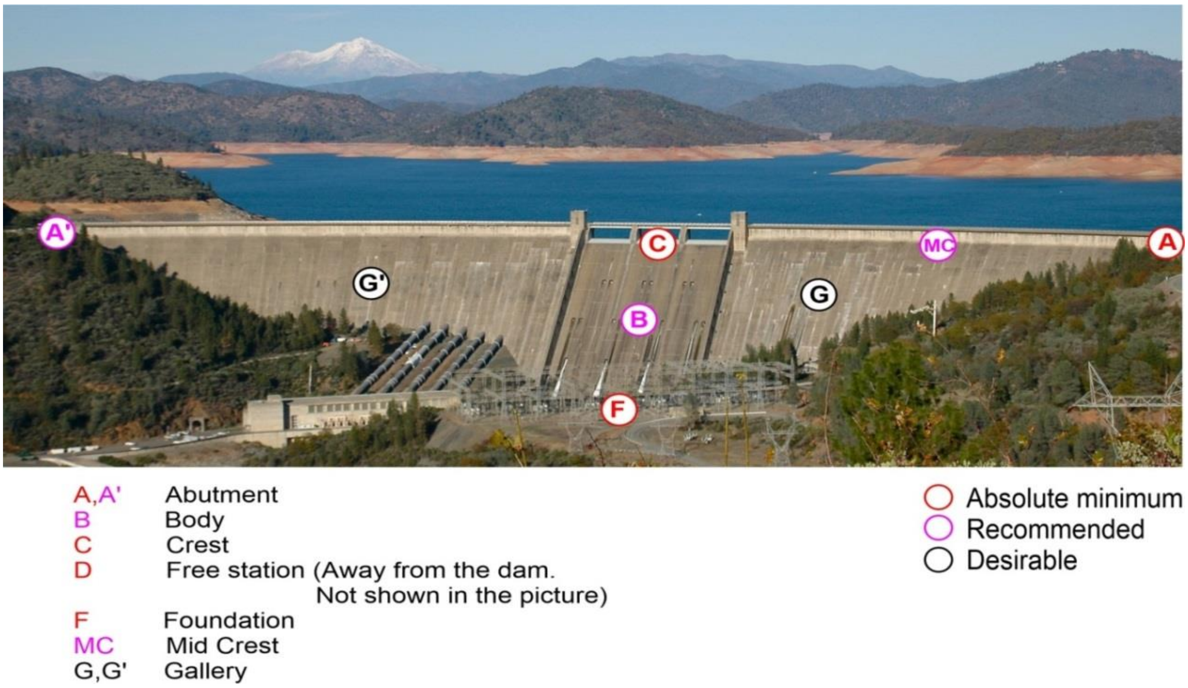

Figure 5-1. Recommended dam seismic instrumentation

unit sealed in a single unit. The data are stored in a mass storage media of the recording unit and these data can be downloaded at a later stage. The seismic data are analyzed using the appropriate software.

The seismic instrument needs to be operated continuously and maintained periodically as the high magnitude events occur rarely near the dam site.

The recommended dam seismic instrumentation at different points in the dam is shown in Figure 5-1. A minimum number of four SMAs should be installed at the abutment (A), Crest (C) and Foundation (F) of the dam and at a free field location (D) at least 3 to 4 times the height of the dam.

It is also recommended to install SMAs at the Abutment (A'), body (B) and Mid Crest (MC) of the dam as indicated in Figure 5-1. It is also desirable to install SMAs in the dam gallery (GG') as shown in the illustration. It is recommended to install one weak motion seismograph at the far field location (D) to monitor the seismicity in the region.

The placement of an accelerograph is also important. What is desired is the response of the dam, not the response of the accelerometer housing. Surface accelerograph are typically bolted to a concrete slab and enclosed in lightweight fibre glass housing.

Central Water and Power Research Station, Pune; National Geophysical Research Institute, IIT Roorkee and other specialized organisations have the expertise in installation and interpretation of the data and they should be contacted for installation and maintenance of accelerographs and Seismographs at dams.

An essential element of these instruments is their output information. It is desirable that these be in such a form that they could provide information on the intensity of an earthquake immediately after its occurrence. Based on this, a decision could be made regarding the further exploitation of the dam. For instance, if the dam is designed for a horizontal acceleration a = 0.15 g as a design parameter, and the maximum amplitude of recorded ground acceleration is less than this value, a decision can be made, with excellent reliability, for further exploitation of the dam with no particular repair or strengthening. However, when the recorded acceleration is greater than 0.15 *g*, it is desirable that there are no visible signs of damage to perform a special study and define the stresses and strains in the dam caused by the forces from the recorded earthquake.

The reason for installing instruments in dams is to monitor them during construction and operation. One of the specific applications of the measurement is to furnish data to decide if the complete structure will continue to function as intended. The processing of large masses of raw data can be handled by computer. The interpretation of the data requires careful examination of measurements as well as other influencing effects, such as reservoir operation, air temperature, precipitation, drain flow and leakage around the structure, contraction joint grouting, concrete placement schedule, seasonal shutdown during construction, concrete test data, and periodic instrument evaluations. The display of data should be both tabular and graphical and should be simple and readily understood. The data should be reviewed periodically by a professional engineer versed in the design, construction and operation of embankment dams and concrete/masonry dams.

5.1 Specifications

The instrument specifications depend on the observational goals and environmental conditions. The instruments deployed in the dam site should be robust and highly reliable as high magnitude events occur rarely near the dam. The broad specifications of strong motion accelerographs for the dam site are discussed here.

5.1.1 Maximum Acceleration

The maximum recording acceleration often referred to as full scale range must be higher than the peak acceleration corresponding to the seismic hazard at the site associated with the target return period. A return period of 100 years is appropriate. The vibration amplification occurring in the dam from base to crest and the accelerograph location should also be considered. A strong motion accelerometer with full scale range (user selectable) from 0.5 g to 4 g is needed.

5.1.2 Bandwidth

The lowest frequency that is measured should less than 10% of the fundamental natural frequency of the dam and lower than excitation frequencies of the earthquake spectrum. Recording from 0 Hz is recommended. Similarly, the upper frequency that is measured should be higher than the frequency of the highest mode of variation that contributes to the dam response and greater than the excitation frequencies of the earthquake spectrum. The strong motion accelerometer with frequency response flat (within +3 dB) to ground acceleration in the range of DC to 200 Hz is suitable.

5.1.3 Resolution

The acceleration resolution is given by the relation $\frac{2 \times \text{Maximum Acceleration}}{2^D}$ where D is the data bit resolution of the digitizer. It is recommended to select a digitizer with a resolution of 18 data bits or more.

5.1.4 Noise

The self-noise of the accelerometer and electronic components of the recording unit combined should be less than the recording resolution. The peak noise level must be considered rather than the root mean square value.

5.1.5 Recording Mode

The accelerographs may be operated in continuous data acquisition mode as there is no memory size restriction now-a-days. The storage media is configured in a ring buffer type so that the earlier data are erased when the memory is full. The operator should copy the data periodically so that the recorded data does not get erased and lost. The storage media size should be at least 32 GB or more. The size of the acceleration data recorded with 3 channels and 200 samples per second would be about 2 GB (after compression)

The accelerographs may function in a triggered mode as well. The setting up of a trigger level depends on many factors. It should be at least 10 times the acceleration resolution to avoid many false triggering. The trigger levels of the in-structure accelerographs may be increased because of the amplification that takes place in the dam.

Some accelerographs provide the facility to start recording only after the trigger level is reached simultaneously in two or three channels over a time window.

The duration of the pre-event length (before the acceleration reaches above the trigger level) is set sufficiently high based on the trigger level and the distance of the dam from the earthquake source zone. The pre-event length is set high for a higher trigger level and fact that the compression waves arrive before the shear waves and the former may not trigger the recording.

The duration of the post event length (after the acceleration has returned below the trigger level) is set sufficiently high based on the trigger level and periods of the natural mode of vibration of the dam that contributes to the dynamic response.

5.1.6 Timing

It is crucial that the data from all the accelerographs in the dam should be precisely time tagged so that data correlation can be performed. Global positioning system (GPS) cannot be used for in-structure installations as the antenna cannot be installed exposed to the sky. Some accelerographs provide GPS with very long antenna cables and amplifiers for such facilities. GPS antenna should be enclosed in weather proof sealed enclosure with lightning protection. Some accelerographs provide Precision Time Protocol (PTP) timing without the need for GPS antennas for every unit. The time accuracy of PTP should be better than 0.001 ms. The time inputs are provided through a common ethernet cable connecting every unit.

5.1.7 Power

Most of the accelerographs are provided with internal batteries to supply power during interruptions in AC mains supply. There are chances of gases corroding the electronic equipment and battery explosion. It is recommended to use an external battery for accelerographs. The batteries are charged by AC-DC chargers or solar modules (solar power may not be available for in-structure accelerographs. The battery capacity is chosen according to the requirement and it depends on the total power consumption of the accelerograph unit and time taken to re-establish the power.

5.1.8 Network

All the accelerographs may be connected to a network, and the data may be streamed to a central location. The operators shall monitor the PGA, PGV, and PGD of the sensors connected to the network in real time. The state of health of each accelerograph shall be viewed from the central location which will simplify the maintenance of the different units. The accelerographs shall be able to work in stand-alone mode also in the case of network failure.

5.1.9 Indian Standards

The Indian Standard IS: 1893-1984 has fixed up the criterion for design of Structures for resisting to earthquakes. Gravity dams, embankment dams and other buildings and constructions such as bridges etc., are covered. Whole country, India is divided into four seismic zones (IS: 1893 Part 1-2002) for adapting the seismic coefficient in the design of different structures.

The Indian Standard IS:4967-1968 does not provide any recommendation regarding the strong – motion instrumentation for embankment dams. However an absolutely minimum instrumentation scheme should provide accelerograph at one of the abutments and at the crest on the tallest section of the dam. This would provide information on the input excitation and the maximum response of the dam. In addition, settlements at the top of dam should be monitored.

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Chapter 6. INSTRUMENTATION OF EXISTING DAM

The responsibility of a dam engineer is not only to plan, design and construct a dam to acceptable standards but also to ensure its operation with a rigid dam safety surveillance programme. All these considerations stress the necessity to have some dependable means or tools, generally termed as instruments, available inside or on the surface of dam, which can provide us information about the conditions and behaviour of the structure. Periodical and regular monitoring of these instruments and analysis of the data obtained through these instrumentation with a diagnostic approach would help in understanding the health status of a dam.

In the recent years, there is a world-wide attempt to update the monitoring system either by mounting certain specific instruments on the dam and its abutments or by embedding them in the dam and the foundation. Unlike a dam under construction, to instrument the existing dam has certain physical limitation resulting in installation of only a few instruments. This may leave the dam still inadequately instrumented. The problem is more acute for older dams in which the materials have undergone changes and have been subjected to distress. Some of the old dams where distress were noticed and rehabilitation measures have been carried out, efficacy of these measures are required to be determined by appropriate monitoring system. Thus, instrumentation of existing dams may become necessary when it is in distress, to improve the monitoring system, or to study the long term behabiour of dams specially during comprehensive dam review programme.

Monitoring is one of the most important activities for dam safety evaluation and surveillance. Even though the basic principles for existing dam remain the same as new dam monitoring, improving existing dam monitoring is a somewhat different problem from monitoring new dams because specific problems such as logistic difficulties can arise and information on the actual past behavior of the dam is unavailable.

The safety of dams in operation has two specific aspects: the inevitable change in the characteristics of the materials due to aging, new situations, thermal and hydrostatic cycling, extraordinary events such as earthquakes, floods, etc.; their inadequacyin regard to the technical and technological state of the art that evolves with time.

The reason for the intervention can be of different nature, importance, and urgency, and in particular, the following must be considered:

- Inadequacy or absence of the monitoring system to collect information pertaining to the safety of the dam;
- Observed abnormal behavior (permanent displacements, cracks, etc.), abnormal seepage, leakage, etc.
- Investigation of behavior of dam for research purposes;

The adequacy of a monitoring system can only be judged objectively after obtaining exhaustive knowledge on the actual state of the dam foundation and reservoir. The points to be examined to obtain such knowledge include:

- Project documents;
- Visual inspections;
- Existing monitoring system;

- Instrumental records;
- Site and laboratory investigations (if necessary);
- Mathematical or physical models for behavior analysis (if necessary);
- Compliance with current regulations and modern practice.

The following three factors should be considered for planning the monitoring system:

- Reasons for intervention;
- Timing of the intervention;
- Approach to instrumentation

Instrumentation is of little use for the monitoring of dam safety unless there is an organization with the man-power and budget to take the readings and evaluate the results.

6.1 New or Updated Monitoring System

The guidelines used to select the type and position of instruments to be installed on a new dam can be applied for existing dams. The combination of technical, economic and organizational evaluations will identify the most appropriate solution for each case that is the best compromise between the optimal solution and that (or those) compatible with the economic commitment.

6.2 Recommendations on New Monitoring System

Complete knowledge of the actual situation of the dam obtained with the above-mentioned investigations (all or in part depending on the actual needs of the case in question), means that the design of the new monitoring system or updating of the existing one can be tackled rationally.

6.2.1 Need for Action

The reasons that more commonly lead the engineer to take action with reference to the improvement of the monitoring system include:

- Monitoring system inadequacy, insufficiency or absence (diagnostic and safety reasons);
- Research purposes;
- Elimination of unnecessary parts, and automation owing to logistic problems.

6.2.2 Measurable Quantities

1) Concrete or masonry dam

Parameters that can be monitored to point out possible critical or irregular situations for concrete or masonry dams:

- Storage level;
- Air and water temperatures;
- Reservoir bathymetry;
- Dam horizontal displacements;
- Dam vertical displacements;
- Dam rotations;
- Crack development in body of dam;
- Foundation horizontal displacements;
- Foundation vertical displacements;
- Relative movements between dam concrete and rock foundation;
- Seepage through the dam and the foundation;
- Uplift pressures;
- Leakage turbidity and chemical analysis.

2) Embankment dam

Quantities that can be monitored for embankment dams include:

- Storage level;

- Reservoir bathymetry;
- Interstitial pressures in the dam body and in the foundation;
- Seepage through the dam and the foundation;
- Foundation water table;
- Leakage turbidity;
- Dam settlements;
- Dam horizontal displacements;
- Displacements and/or cracking of concrete structures (spillways, etc.).

3) For other purposes

Parameters that can be monitored for study purposes or to widen knowledge are following.

a) Concrete or masonry dam

- Snow and rain;
- Atmospheric pressure;
- Humidity;
- Ice thickness;
- Joint movement;
- Stresses and strains in the dam body;
- Foundation rock deformations;
- Concrete temperature.

b) For embankment dams

- Air temperature;
- Snow and rain;
- Atmospheric pressure;
- Humidity;
- Water temperature;
- Ice thickness;
- Deformations;
- Total pressure.

6.2.3 Minimum Desirable Instrumentation

Factors of greatest importance to the safety of ***embankment dams*** and their spillways and outlet works are quantity and source of seepage, differential and total earth movements, water levels, pore pressure and water quality.

In respect of various concrete dam types, these factors are as given below:

Concrete and Masonry Gravity Dams: If a gravity or buttress dam maintains its structural integrity and is stable against sliding no safety hazard is anticipated. Contraction joints between blocks are much weaker than the mass concrete. Any indication of loss of structural integrity in the dam or foundation will manifest itself at the joints. Instruments should be installed in all gravity or buttress dams to monitor relative movement between blocks exhibiting indications of previous movement or where movements might be reasonable anticipated. These measurements of relative movements between blocks should be tied to other measurements that allow displacements of the dam relative to a remotely located fixed point to be determined. Other significant parameters that should be monitored in majority of gravity or buttress dams are uplift pressures, seepage flow (which may indicate open joints in the foundation or a crack in the concrete) and water quality for seepage, reservoir and tail waters. In case of indications of movement along any crack in the dam or foundation, additional monitoring devices should be installed to measure sliding or rotation along the plane.

Concrete Arch Dams: Arch dams behave monolithically. Displacement is the meaningful parameter that can be readily monitored. All concrete arch dams should have provisions for measuring displacements in the horizontal plane, relative movements between points within the dam and the movement of the dam relative to a remote fixed point, foundation movement and relative movement an any major joint in the dam or in its foundation. In addition, the quantity and location of all seepage flows from foundation and formed drains, and water quality of seepage, reservoir and tail water levels should be monitored.

Spillway and Outlet Works: Most spillway and outlet works structures experience some movement. Differential movement between structural elements within different portions of the same structure is a definite indication of structural distress. Means for monitoring differential, horizontal and vertical movements should therefore be installed at vital locations in all existing structures. When measurable seepage is flowing from spillway and outlet drains or adjacent points of a dam, quantities of flow and water quality data should be monitored. Existing dams should be examined from long-term dam safety point of view and retrofitted with instrumentation as dictated by their relative need on a site-specific basis.

6.2.4 Limitations

It is easy to plan instrumentation for a new dam. Practically there are no limitations. This is not the case with old dams. The fact that some existing dams contain only minimal or no instrumentation is not by itself is sufficient reason for installation of instruments at each and every dam. There must be sufficient reason for installing and monitoring instrumentation. It should be remembered that certain types of instrumentation that must be installed by drilling holes may pose risk to the structure. Proper evaluation is, therefore, very necessary. Installation of instrumentation at an existing concrete/masonry dam is generally more difficult and costly task than installation of similar instrumentation in an existing embankment dam. Therefore, it may become necessary that new instrumentation at an existing concrete/ masonry dam may have to be limited to surface devices. Many of the instruments like stress and strain meters, inverted pendulum, twin tube piezometers, cross – arm units etc., cannot be installed in an existing dam. Even if attempted, they do not serve the real purpose. Further, some of the vulnerable locations may be inaccessible for new instrumentation. One instrument which however can be installed is the piezometer. Evidently, programme for instrumentation of any old dam has to be site specific based on the following parameters but subject to above limitations.

- Age of the structure
- Condition of the structure
- Purpose of the structure
- Strategic importance
- Locational importance
- Functional importance
- Hazard potential etc.

6.2.5 Influencing Factors

The length, height and storage potential of a dam is very important. Medium and high dams need priority and denser instrumentation. Longer dams need instruments at more number of locations.

Age of the dam and its health status is one of the main considerations in deciding the extent of instrumentation. If the status of a dam is reported to be healthy, not much instrumentation is necessary. But a weaker dam in distress needs closer observations and hence more instruments to monitor the behaviour.

Locational importance like thickly populated, high cultivated and industrialized area lying on the downstream of the dam needs special attention. Similarly, functional importance like purpose of storage, type of structure etc., is to be considered while planning for instrumentation.

Finance, though an important factor, should not prevail over other factors directly related to the safety of the dam.

6.2.6 Monitoring System Inadequacy

While planning the monitoring network of an existing dam, it must be noted whether there are any parameters that are of fundamental importance to monitor safety and understand the behavior of the dam, that for some reason have not been monitored, or not monitored at the right points with the necessary frequency.

A significant example of this problem is found in older dams where foundation behavior (displacements, deformations, pressures) is not usually measured. Therefore, when the monitoring system is re-examined, this can no longer be neglected and the installation of new inverted plumb lines, long base extensometers, inclinometers, piezometers, etc., need to be considered. This is because the importance of foundation behavior for a dam might not have been understood in the past. Thermal load is another parameter that was sometimes neglected in the past.

In fact, for concrete dam, knowledge of temperature variations within the concrete mass is of primary importance (especially for thin dams) every time the behavior of the dam is monitored with deterministic type models.

Seismic effects were also usually ignored in the monitoring activities. Therefore, during the dam recheck, the enlargement of the monitoring network to acquire seismic parameters should be carefully considered (mostly if the seismic classification of the dam site has been changed since the dam was first conceived or constructed).

The great improvement of the technology and the state of the art, both in instrumentation and acquisition systems and in processing and interpreting the acquired data, enables nowadays an effective and timely check of dam behavior during a seismic event by means of the installation of a seismic monitoring network.

Using *in-situ* experimental tests (e.g. using mechanical exciters), the fundamental parameters of the actual dynamic behavior of the dam (natural frequencies, mode shapes, damping values) can be measured; numerical models can then be calibrated and used to evaluate the seismic threshold below which the dam can be considered safe and above which possible damages can occur.

Apart from these examples, at this point, it is best to check whether all the quantities referred above have been taken into account in the monitoring system in question, and to determine whether the facets of the existing monitoring system are inadequate on site specific conditions.

6.2.7 Monitoring System Redundancy

As already mentioned, updating a monitoring system involves also abandoning the collection of those measurements that are not used in anyway. However, this is not always an easy decision to make, as often it is considered best to continue collecting even those measurements that at that moment seem useless, but could become useful in the future. Therefore, the effort put into collecting all measurements possible (even those that are of no use at that moment) is seen as a future investment.

However, this does not include those measurements that are obtained by sensors that are not reliable from a functional point of view. These measurements should be abandoned so as not to create confusion or waste effort.

Instead, for those measurements that are valid from a numeric point of view, but useless (or not used) to monitor the dam behavior (for example, in many cases all extensometer measurements, important during construction and first filling of a dam but not during its normal operation). Each case must be considered individually to decide whether or not it is useful to collect such data. If however, these are not to be abandoned, then it is better to process them first and then file.

6.2.8 Timing of the Intervention

The time schedule for intervention on the monitoring systems should consider both the time needed to carry out the necessary investigations and the implementation and the appropriate interval within which some or all of these activities are to be repeated. It is, however, emphasized that the average time interval recommended for various phases of intervention must be completely re-examined if there are indications of inconsistent and/or abnormal dam performance representing a critical situation that would warrant urgent intervention.

6.2.9 First Reappraisal

Several factors need to be considered to decide for what is the reasonable time when the monitoring system in the dam must be reviewed or updated for the first time. These include the dam type and operating conditions, geographic location and deterioration of instruments, etc. Other significant factors that need to be taken into account include the increasing concern for public safety because of advancing land developments involving human settlements downstream of the dams, adverse effects of environmental factors on dam materials resulting in deterioration and degradation of material capacities, and continuing advances in instruments and techniques that enable more frequent and reliable comprehensive dam performance monitoring. Obviously, a time-span (number of years) can be established after which the existing monitoring systems and project conditions should be thoroughly re-examined to assess if any updating is warranted unless some critical problems develop that would compel earlier appropriate remedial action to restore safety conditions.

This can be considered a limit time-span that should not be exceeded. However, it is important to point out the opportunity to review more frequently the adequacy of the monitoring system; it must be taken into account the fact that a shorter period of time (such as 5-10 years) is usually sufficient for an effective analysis and comprehension of the dam behavior and, therefore, of the need of improvement of the operating monitoring system. As the dam gets older, partial re-examination at more frequent intervals will be necessary.

6.2.10 Subsequent Reappraisals

The question of how frequently the entire dam system should be re-examined following the first check of the dam and first intervention (if necessary) on the monitoring system should be decided to take into consideration the following factors:

- The dam continues to age and, therefore, would need more frequent site investigations and monitoring system updating.

- Duration of normal safe service operation of a dam. The greater the number of years of such safe operation, the more convincingly the dam demonstrates that it can properly and adequately meet environmental variations.

The following frequencies are suggested for system recheck:

- Every 5 to 10 years, carry out comprehensive or pertinent limited investigations in order to analyze the existing condition of the dam and the state of degradation (aging).

- Every 10 to 15 years, update the monitoring system if no significant defects revealed from the above-mentioned examination.

6.3 Approach to Instrumentation

There is no unique solution for the extension or updating of a monitoring system: different costs and delays generally correspond to the technical variants available, but the optimal solution can only be identified for the individual case. Thus it will be the task of the project manager to consider all the technically feasible alternatives, assessing their reliability, useful life, cost, time needed to complete the intervention, maintenance, modularity and possible automation, etc..

However, it should be noted that the difficulty of installing some instruments in an existing dam can be much higher than in the case of a dam under construction. The cost of the intervention is generally rather more substantial, and, in some cases, it may be technically impossible to carry out the installation of some instruments. This is generally related to the difficult accessibility to the points at which the measurements are to be performed. It depends on the type of the dam and the existence or absence of galleries, shafts, etc.

It seems likely that, in many cases, the accessibility considerations will dictate the solution to be chosen. The embedded-type instruments that are installed in the mass of the dam for internal monitoring, although commonly used in new dams, can be not suitable for existing ones. Apart from the fact that some of them are only relevant during construction or in the first stages of operation, their installation, for instance, in a mass of old concrete, may introduce a severe disruption of its characteristics and provide erroneous information. In some cases, measuring methods developed for structural non-destructive testing should be considered as an alternative to conventional techniques. Methods of measurement to be used should be compared not only on the basis of accuracy but also taking into consideration other difficulties (installation, severe environmental conditions, etc.) that can be of paramount importance.

It must be underlined that, when an instrument is modified or replaced, it is necessary to take care of the proper link between the measurements acquired before and after the intervention.

Following are a few considerations about particular problems in the instrumentation of existing dams.

6.3.1 Dam Movements

Horizontal movements can be best monitored with the use of direct and inverted plumb lines. However, it requires some kind of vertical opening in the body of the dam, although in many cases providing such an opening can be very expensive. In some dams, drainage wells or even elevator shafts can be used; in some cases, plumb-lines can be installed using external tubes fixed to the dam face. Possible alternatives include optical devices that can be well suited to an arch dam, topographic surveys, either conventional or with use of laser alignment techniques, and, in some cases, rotation measurements with clinometers and/or hydrostatic leveling system that are usually easy to perform and can be integrated with a vertical section to provide measure of displacement.

Vertical movements are usually not too difficult to monitor along the crest of the dam, although settlement readings within the core of an embankment may mean an insurmountable problem. Anyhow, internal settlement of an embankment dam after construction essentially takes place during the first years of operation and, afterward, external observation techniques could be adequate.

Relative movements between monoliths in concrete dams can be measured with superficial joint-meters in galleries or by mechanical gages at the faces, but, if this is considered not sufficiently representative of inner conditions, it is doubtful that a satisfactory bore hole device can be installed.

Monitoring of movements over cracks, for example, cracking of the upstream heel of the arch dam, can be made by sliding micrometers or similar instruments.

6.3.2 Foundation Movements

Again, inverted pendulums are the best option, together with borehole inclinometers and multiple-point extensometers. Foundation movement instrumentation is generally possible, its only drawback is the high cost involved usually.

6.3.3 Piezometers

Open standpipe and either electrical resistance or vibrating wire-piezometers present fewer difficulties than other types for their installation in an existing dam, and they are also more widely used. The open standpipe, electrical and hydraulic piezometers can be easily automated; the automatic reading of the pneumatic cones is more laborious and expensive.

6.3.4 Temperature

For the monitoring of the structure temperature, some of the alternatives are:

- Installation of thermal sensors in the body of the dam.
- Installation of thermal sensors on the external faces.

6.3.5 Stress Monitoring

Stress and strain measurements that are performed at various interior locations in a new dam will not be feasible in an existing dam because embedding stress and strain meters in the existing dam mass will be practically impossible.

6.3.6 Seismic Monitoring

In quite a few cases, the monitoring of an existing dam will include some kind of seismic surveillance. This will generally pose no serious problems, due to the type of instruments required and the ease of their installation.

6.4 The Order of Monitoring

Any advanced monitoring instrument is unable to replace careful visual inspection by engineers especially for complex and varied foundation and defective dam. In the coldest period of time, after melt, before the flood, at the time of the highest water level, after the flood, before frost, it is required to perform visual inspection for surface leakage, wetted surface, freeze, accumulation of snow, surface damage, etc., and make a record.

From engineering practice point of view, the most sensitive element for dam safety is the amount of leakage, the next is uplift and groundwater table, after that, it is foundation deformation, and then stress and strain, etc. This order is very important in real practice for existing dam because of that:

1) Magnitude monitored for the amount of leakage and uplift are the macro-figure and very intuitive.
2) In the case of dam top deformation and dam body stress and strain, they are hard to reflect the actual states of the concrete dam. The reason is that the deformation at dam top by water pressure and the temperature is bigger relatively, it hides the minor deformation of dam foundation. In dam base gallery, a dam foundation deformation is measurable.

However, dam foundation deformation is smaller that is hard to satisfy the requirement of accuracy. For stress and strainmeter fitted inside the dam, they apply to the elastic material. If crack happened near stress and strain- meter, stress and strain monitored went smaller, mistakenly thought that stress and strain went better.

3) The instrument fitted in old dam is either lagging behind or damaged (statistic data presents that the damage rate of instruments installed in dam is 50% ~ 70 %), some dams lack for instruments, moreover, even if certain instruments were supplemented, it was hard to coordinate the magnitudes monitored newly by new instrument with the previous actual behaviours of the dam.

   For instruments monitoring the amount of leakage and uplift, these kinds of issues almost don’t exist.

4) Furthermore, for several serious dam damages even dam failures, the accident alarms had not been got from the monitoring instruments because of several reasons. An obvious factor among these reasons was that damage often didn’t start or occur at the place monitored or from the element concerned about ahead of time.

Therefore, visual inspection by experienced engineers should go first to make macro-judgment, and then follow the order aforementioned to refer to data monitored by the instrument for further analysis. Dam safety inspector should combine visual inspection with data monitored by instrument and connect various minute phenomena together to perform the careful analysis.

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Chapter 7. HYDRO-METEOROLOGICAL INSTRUMENTATION

Availability of dependable hydro-meteorological data is crucial at the planning stage of any water resources project, as it forms the base for assessment of water availability and design flood. For existing dams, hydro-meteorological data is required for

1. Updating design flood based on observed flood records
2. Optimising water allocation based on inflow and evaporation measurements

Temperature and humidity data are used for estimation of evaporation. It is also required for modelling of structural distress, in case it develops. The monitoring of storm movement and associated rainfall forecast requires synoptic measurements taken in different countries at the same time. In order to synchronize with the global measurement schedule, scheduled time for meteorological observations in India are:

- For once daily recording: 8:30 am
- For twice daily recording: 8:30 am and 5:30 pm
- For thrice daily recording: 8:30 am, 2:30 pm and 5:30 pm

Meteorological instruments needed for a dam include rain gauge, snow gauge, evaporation pan, maximum and minimum temperature thermometer, dry bulb and wet bulb thermometer, wind vane and anemometer, barometer, sunshine recorder, automatic weather station.

7.1 Measurement of rainfall

The instrument used is the rain gauge. Rain gauges may be of the ordinary/ non-recording type or the recording type (also called Self Recording Rain Gauges). Amongst the recording type, natural syphon type rain gauge was in use in India. These days tipping bucket types are more common, the other option being the weighing bucket type.

7.1.1 Ordinary rain gauge

They have a least count of 0.1 mm and are recorded daily at 8:30 am. The detailed specifications are available in IS: 5225- 1992. The catch (a horizontal surface area which intercepts the rain) is 100 or 200 cm² in size (Figure.7-1). Inside, there is a funnel attached, which drains into a polyethene bottle. The bottles are available in capacity 2,4,6,8 or 10 litres. With different combinations of catch and the bottle size, the rain gauges are customized to suit regions from Jaisalmer (low rainfall) to Mawsynram, Meghalaya (high rainfall).

Figure 7-1. Indian Standard Ordinary Rain Gauge

7.1.2 Recording (automatic) rain gauges

Normally 1/10th of the total no. of gauges are of the recording type, due to the cost involved. In India, the natural syphon type recording rain gauges were in common use. The tipping bucket type is recommended by the US Weather Bureau, normally used in Automatic Weather Stations. They typically have a least count of 0.25 mm. The weighing type gauge is used more for research work.

7.1.2.1 Natural syphon type recording rain gauges

The Indian Standard detailing the gauge is IS: 5235-1992. These have the least count of 0.5 mm and 15 min. It is generally used in conjunction with an ordinary rain gauge (non-recording type) exposed close by. Rainwater enters the gauge at the top of the cover and is carried through the funnel to float chamber provided with a float. The recording pen is mounted on the stem of the float. As the water level rises in the receiver, the float rises and the pen records rain on a chart placed on a clock drum which revolves once in 24 hours (Figure.7-2).

The recording mechanism is mounted on the base and the base cover is provided with a gunmetal rim of about 203 mm. Dia. The funnel lifts off the base and carries a hasp, which is engaged with a staple on the base and padlocked. An angle iron piece with foundation bolt is provided for anchoring the rain gauge base to the ground.

A heating device should be installed inside the gauge if there is a possibility of freezing. This will prevent damage to the float and float chamber owing to water freezing and will enable rain to be recorded during that period.

Figure 7-2. Indian Standard Natural Syphon Rain Gauge

7.1.2.2 Weighing type recording rain gauge

A weighing-type precipitation gauge consists of a storage bin, which is weighed to record the mass. Certain models measure the mass using a (Figure.7-3) pen on a rotating drum, or by using a vibrating wire attached to a data logger. The advantages of this type of gauge are that it does not underestimate intense rain, and it can measure other forms of precipitation, including rain, hail, and snow. These gauges are, however, more expensive and require more maintenance than tipping bucket gauges.

Figure 7-3. Weighing Type Rain Gauge

7.1.2.3 Tipping bucket type recording rain gauge

This type of rain gauge generates an electric signal (i.e., a pulse) for each unit of precipitation collected, and allows automatic or remote observation with a recorder or a counter. The only requirement for the instrument connected to the rain gauge is that it must be able to count pulses. Thus, a wide selection of configurations and applications is possible for this measuring system. Solid precipitation can also be measured if a heater is set at the receptacle.

A light metal container is divided into two compartments and is balanced in unstable equilibrium about a horizontal axis. In its normal position, the container rests against one of two stops, which prevents it from tipping completely. The rain is led from a conventional collecting funnel into the uppermost compartment. After a predetermined amount of rain has fallen, the bucket becomes unstable in its normal position and tips over to its other position of rest. The compartments of the container are so shaped that the water can then flow out of the lower one leaving it empty (Figure.7-4). Meanwhile, the rain falls into the newly positioned upper compartment. The movement of the bucket, as it tips over, is used to operate a relay contact and produce a record that consists of discontinuous steps. The distance between each step represents the time taken for a pre-specified quantity of rain to fall. This quantity of rain should not be greater than 0.2 mm if detailed records are required. For many hydrological purposes, in particular, for heavy rainfall areas and flood-warning systems, 0.5 to 1.0 mm buckets are satisfactory.

- The main advantage of this type of instrument is that it has an electronic pulse output and can be recorded at a distance, or for simultaneous recording of rainfall and river stage on a water stage recorder.
- The disadvantages are:

    i. The bucket takes a small but finite time to tip, and during the first half of its motion, the rain is being fed into the compartment already containing the calculated amount of rainfall. This error is appreciable only in heavy rainfall.

    ii. With the usual design of the bucket, the exposed water surface is relatively large. Thus, significant evaporation losses can occur in hot regions. This will be most appreciable in light rains.

    iii. Because of the discontinuous nature of the record, the instrument is not satisfactory for use in light drizzle or very light rain. The time of beginning and ending of rainfall cannot be determined accurately.

Figure 7-4. Tipping Bucket Recording Rain Gauge

7.1.2.4 Exposure conditions for rain gauges

The exposure conditions should follow IS: 4986-2002. The rain gauge shall be placed on level ground and not on slope/ terrace / wall /roof. The rain gauge shall never be placed on a slope where the ground falls away steeply on the side of the prevailing wind. The distance between the rain gauge and the nearest object should be greater than 4 times the height of the object, but should never be less than 2 times the height of the object. At mountain and coasts, a belt of trees/wall on the windward side at a distance greater than 4 times its height; is needed for sheltering the gauge against wind. In mountains, the gauge is to be placed on a large, smooth, stable slope oriented in correspondence to the average slope and orientation of the surroundings.

7.1.3 Installation

The installation should be carried out conforming to the procedure mentioned in IS: 4986-2002. The rain gauge shall be fixed on a masonry/concrete foundation 600 mm x 600 mm x 600 mm sunk into the ground. The base of the gauge shall be cemented into this foundation so that the rim of the gauge is horizontal and exactly 300 mm above the ground level. In flood-prone areas, the level of the rain gauge shall be kept 300 mm above the maximum flood level. The rain gauge shall be protected from being damaged (particularly by stray cattle) by erecting a fence 5.5 m × 5.5 m around it. The rain gauge shall be kept locked and periodically painted to prevent its surface from corroding or deteriorating.

7.1.3.1 Errors in measurement

The errors that occur in measurement of rain with the ordinary rain gauge are:

i. Reduction of catch due to the wind
ii. Splash of rainfall in or out of rain gauge
iii. Instrument failure: blockage of funnel, overflow, leakage
iv. Reading taken at wrong time (attributing rainfall to a different day)
v. Incorrect reading of measuring cylinder
vi. Incorrect entry of data: wrong value or wrong date
vii. Accidental spill while pouring into cylinder

The errors met with in measurement of rain using a recording rain gauge are:

i. Funnel blocked or partly blocked
ii. Float imperfectly adjusted, syphoning at a rainfall volume not equal to 10 mm
iii. Individual pen traces not distinguishable during intense rainfall
iv. Clock error: stoppage / slow or fast
v. Float sticks in chamber: rainfall not recorded/recorded incorrectly
vi. Incorrect information extraction by observer from pen trace

The errors encountered in measuring rainfall using a recording rain gauge are corrected using the rainfall observed in the non-recording rain gauge.

7.1.4 Data validation for rainfall

Primary validation is carried out by comparisons at one observation point with pre-set limits or statistical range. Secondary validation comprises check for spatial consistency with the data from the surrounding stations.

7.1.5 Number of rain gauges required for a catchment

As per the World Meteorological Organization (WMO 168: 2008), the required minimum number of rain gauges to be installed for obtaining a representative measurement of rainfall for different physiographic regions are described below. For the coastal zones, there should be at least one rain gauge of the non-recording type covering an area of 900 km². At least one rain gauge of the recording type should be present within an area of 9,000 km². For the mountainous zones, the required minimum number of non-recording and recording rain gauges are one per 250 km² and one per 2,500 km², respectively. In the interior plains and hilly regions, at least one rain gauge of the non-recording type should be present in an area of 575 km²; over 5,750 km² at least one rain gauge should be of the recording type. For small islands having an area of 500 km² or less, there should be one non-recording rain gauge for every 25 km² area. At least one rain gauge of the recording type should be present in every 250 km². For urban areas, one rain gauge of the recording type should be installed for every 10-20 km² area. However, for the polar and arid zones, the density may be reduced to one non-recording rain gauge for every 10,000 km², with one recording rain gauge for every 100,000 km².

The minimum numbers of rain gauges specified by the Indian Standard (IS: 4987 – 1994) are mentioned below. One rain gauge covering an area of 500 km² is required for the plain regions. However, if the catchment lies in the path of low-pressure systems causing precipitation, the network should be denser, particularly in the upstream. In areas with average elevation 1 km above sea level, one rain gauge covering an area of 250 km² to 400 km² is required. In predominantly hilly areas with very heavy rainfall, one rain gauge covering 150 km² (except in rain shadow of high barriers) should be installed.

7.2 Measurement of snowfall

Where solid precipitation is common and substantial, a number of special modifications are used to improve the accuracy of measurements using an ordinary rain gauge. Such modifications include the removal of the rain gauge funnel at the beginning of the snow season or the provision of a special snow fence to protect the catch from blowing out (Figure.7-5). Windshields around the gauge reduce the error caused by deformation of the wind field above the gauge and by snow drifting into the gauge. They are advisable for rain and essential for snow.

At remote locations, automated snow gauges are used. They have a large catch area which collects snow until a given weight is collected. When this critical weight is reached, it tips and empties the snow catch. This dumping trips a switch, sending a signal. The collection then repeats. If the catch container has a heater in it, it may measure the snow weight accurately. It is also possible to tip based on volume instead of weight, with the appropriate sensing of fill volumes.

Another type of snow sensor called a snow pillow is used sometimes. It looks like a round bag lying on the ground. Inside the pillow is a liquid antifreeze agent. Usually, the snow pillow is connected to a manometer. The manometer reading varies based on how much snow has gathered on the pillow. This type of sensor works well for many locations but is more difficult to use in areas of hard blowing snow.

Figure 7-5. Snow Gauge

7.3 Measurement of evaporation

The equipment used to measure evaporation is called an evaporimeter or an evaporation pan.

7.3.1 Evaporation pan

An evaporation pan is used to hold water during observations for the determination of the quantity of evaporation at a given location. Such pans are of varying sizes and shapes, the most commonly used being circular or square. The instrument used for this purpose in India is Class A Pan Evaporimeter (IS: 5973- 1998). It is a round pan with 1220 mm diameter and 255 mm depth placed on wooden platform 100 mm high to allow circulation of air underneath. It is covered with a hexagonal wire mesh of galvanised iron to protect water from birds and animals (Figure.7-6). Water is filled up to the top of a point gauge using a measuring cylinder every day. For rainy days, water is removed from the pan using the measuring cylinder, in order to bring it back to the top of the point gauge. From the known water surface area of the pan and the known volume of water added / removed, evaporation is estimated in mm / day Evaporation from the Class A evaporation pan exceeds that from a reservoir or lake. The ratio between the pan evaporation and the lake evaporation is known as the pan coefficient and has a range of 0.6-0.8 with an average value of 0.7.

Figure 7-6.Indian Standard Evaporation Pan

7.3.2 Errors in measurement

The errors that may creep in while observing evaporation using a pan evaporimeter are:

i. Observer errors- overfilling or under filling of pan

ii. Instrument error

   a. Leakage from the pan

   b. Algae and dirt in water

ii. Birds drinking water, in case of damaged wire mesh

iii. Different depth of rainfall in pan and rain gauge due to splash or the wind

7.4 Measurement of temperature

In general, both the maximum and minimum temperatures are recorded. The average temperature of the day is estimated as an average of the two. The equipment most commonly used for the purpose is maximum and minimum temperature thermometer, although separate instruments for recording the daily minimum and the daily maximum temperatures can also be used.

7.4.1 The maximum and minimum temperature thermometer

The maximum and minimum temperature thermometer (IS: 7000-1973) is made of "U" shape glass tube, having two limbs - one filled with mercury and the other alcohol. It records the highest and lowest atmospheric temperatures in a day. As the temperature increases, the liquid expands forcing the mercury up the maximum scale. When the temperature falls, the liquid contracts and the mercury follows it back up the minimum scale. One limb of the thermometer reads the maximum temperature while the other limb is used to read the minimum temperature (Figure.7-7). The range of the thermometer should be between -35°C to +55°C with minimum readable graduation as 0.5°C. The current temperature can always be read at the top of the mercury column as in the case of a single tube thermometer.

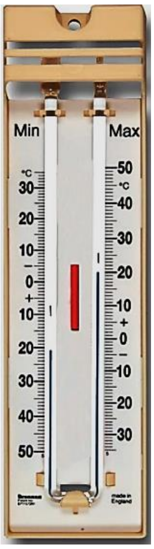


Figure 7-7. Maximum and Minimum Temperature Thermometer

There are two markers of magnetic material coated with rubber, which stick to their position indicating the maximum and minimum temperatures attained in a day. The markers have to be reset every day with the help of a magnet, to touch the mercury surface.

7.4.2 Thermograph

Bimetallic thermograph (IS: 5901-1970) is one of the most commonly used instrument for obtaining continuous recording of atmospheric temperature. A thin bimetallic helix (usually made of invar and brass or invar and steel welded together) is held at one end with the other end left free. Its curvature changes in proportion to the variation in atmospheric temperature, as brass expands much more than invar for a particular rise of temperature. This is mechanically magnified and the movement is used to control the operation of a recording pen. The pen traces the variation of temperature through 24 hours on a graduated chart mounted on a clockwork mechanism (Figure.7-8). The recording mechanism ensures that the movement of the pen on the chart is linear in the range of -20° C to +60° C. The least count is 0.2° C and the accuracy is ±1°C.

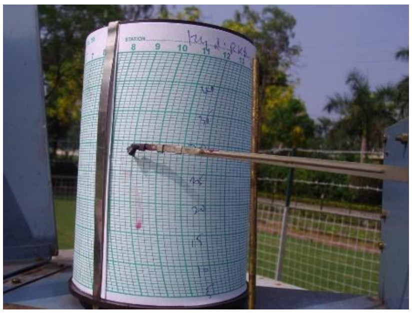


Figure 7-8. Chart and Pen trace of Bimetallic Thermograph

7.4.3 Errors in measurement

The errors which may occur when maximum and minimum temperatures are read using a maximum and minimum temperature thermometer are:

i. Error in reading meniscus: Observer reading meniscus in maximum and minimum thermometer, in place of the index

ii. Error in registering data

iii. Break in mercury thread of dry, wet or maximum temperature thermometer

iv. Break in spirit column of minimum temperature thermometer or bubble in the bulb

7.5 Measurement of relative humidity

Measurement of relative humidity are carried out in general with the help of dry and wet bulb thermometers. For obtaining a continuous record, hair hygrograph are used. For obtaining instantaneous humidity values, psychrometers are used.

7.5.1 Dry and Wet Bulb Thermometer

Dry and Wet Bulb Thermometer (IS: 5725-1970) is the instrument most commonly deployed for the purpose. Handheld psychrometers are used for instantaneous values; hydrometers are used for a continuous record of humidity change throughout the day.

The dry and wet bulb thermometer use two mercury thermometers, the bulb of one of which is continuously kept wet using a moist muslin cloth, the other end of the cloth being dipped in a pot of water (Figure.7-9). For a known air pressure (obtained from measurement or the elevation of the recording station) relative humidity is estimated by the dry bulb temperature (ambient air temperature, that dictates the saturated moisture content of air) and the wet bulb depression

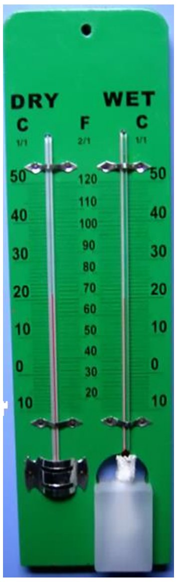


Figure 7-9. Dry and Wet Bulb Thermometer

(difference between the temperature recorded by the dry bulb and the wet bulb, indicating the extent of saturation of ambient air).

7.5.2 Hair Hygrograph

The hair hygrograph (IS: 5900-1970) provides a continuous recording of relative atmospheric humidity. It utilizes the reaction of human hair to humidity, as the length of the hair is known to increase with increasing relative humidity. Increase in length of a strand of human hair held firmly between jaws and passing through a hook is used to measure the variation in relative humidity. The arrangement ensures that the strand of hair is always held in moderate tension. The hook moves with the change in length of the hair strand. A lever arrangement is used to magnify the motion. The magnified motion is transmitted to a pen-arm, equipped with a pen at the end (Figure.7-10). Two specially designed opposed quadrants are used as linkages between the system of levers connecting the hair strand to the recording pen. In this way, the non-linear elongation of the hair element is transformed into linear movement of the pen. The pen traces are marked on a graduated chart, mounted on a clockwork mechanism. The chart records the variation in relative humidity for 24 hours, and is changed in the morning every day. Readings are obtained with a least count of 1%; the accuracy of the equipment is expected to be around ±5%.

Figure 7-10. Hair Hygrograph

7.5.3 Errors in measurement

The errors include all the errors mentioned under temperature recording using thermometers. In addition, there may be the following errors

i. Muslin covering wet bulb is not adequately saturated

ii. Muslin becomes dirty or gets covered by oily substance

7.5.4 Data validation for temperature

Primary validation for temperature data is carried out by checking for the following errors:

i. Dry bulb temperature should be greater than or equal to the wet-bulb temperature

ii. Maximum temperature should be greater than or equal to the minimum temperature

iii. Maximum temperature recorded at the maximum temperature thermometer should be greater than or equal to the dry bulb temperature at the time of recording

iv. Minimum temperature recorded at the minimum temperature thermometer should be less than or equal to the dry bulb temperature at the time of recording

v. Maximum temperatures can generally be expected not to exceed

   a. 50°C in summer

   b. 33°C in winter

7.6 Housing for thermometers

The Stevenson's screen or thermometer screen is used for housing dry and wet bulb thermometer, maximum-minimum thermometer thermograph, and hygrograph. It is made up of wood, having a size of 60 cm × 75 cm × 82.5 cm with spaces in between the wooden louvers for proper circulation of the air, conforming to IS: 5948-1970.

The shelter is painted white and placed at a height of 1.2 m from the ground (Figure.7-11). It should open towards the north, to avoid direct sunshine on the instruments. The screen is designed to provide an enclosure with uniform temperature as that of the outside air. The walls of the screen are double louvered and the floor is that of staggered boards. The roof is double layered with provision for ventilation between the two layers.

Figure 7-11. Stevenson's Screen

7.7 Measurement of wind direction

The equipment in use for measurement of the wind direction is the wind vane (IS: 5799-1970). Wind direction is recorded by an arrow mounted on bearings on a vertical axis to allow free rotation with the changing the direction of the wind (Figure.7-12). Wind direction is noted based on the compass direction from which it orignates. The direction of the wind is specified relative to the true north at the place of observation and is generally expressed as a bearing in degree from true north (in a clockwise direction) or as a compass point using 8, 16 or 32 points according to the accuracy required.

Figure 7-12. Wind Vane

The complete instrument is sturdy to withstand exposure in the open to widely varying climates both at inland and coastal stations. The fin and horizontal arm assembly are balanced about its axis of rotation. It should be free from any bias towards any particular position. The instrument is generally fixed 3 m above the ground. The distance between the wind instrument and any obstruction should be at least 10 times the height of the obstruction.

7.8 Measurement of wind speed

A cup counter type anemometer is normally deployed for measuring the wind speed. The specifications are provided in (IS: 5912-1997). The instrument measures total run of wind passing at the point of observation through mechanical counter of the range 0 to 9999.9 km. The counter is housed in a

Figure 7-13. Cup Counter Anemometer

metallic box with a window to observe digits. A steel spindle carries the cup assembly and drives the lay shaft by worm and wheel, the worm is pinned onto the spindle (Figure.7-13). The unit is calibrated to read km/hr depending on the worm-wheel configuration. The differences between counter reading in an interval of 3 minutes at the time of observation are noted to estimate the instantaneous wind speed while the differences in counter readings after a lapse of 24 hours is recorded to estimate the average daily wind speed. The instrument is generally fixed about 3 m above the ground.

7.8.1 Errors in Measurement

The errors which may be expected to occur in a measurement are:

i. Observer error in reading counter
ii. Arithmetic error in calculating wind speed
iii. Poor maintenance or equipment damage resulting in reduced revolutions

7.8.2 Data validation for the wind

Primary validation of wind data may be done by checking for the following errors:

i. Wind speed should be zero where wind direction is “0” (calm)
ii. Wind speed should not exceed 5km/hour where wind direction is variable
iii. Wind speed in excess of 200km/hour should be considered suspect

7.9 Measurement of sunshine hours

It is usually carried out using the Campbell-Stokes Sunshine Recorder (IS: 7243-1974). Duration of sunshine is measured using a spherical glass lens. The rays of the sun get concentrated to a thin pencil while passing through it and burn a specially made chart with markings of hours of the day (Figure.7-14). Different charts are used for recording sunshine during the summer and the winter months.

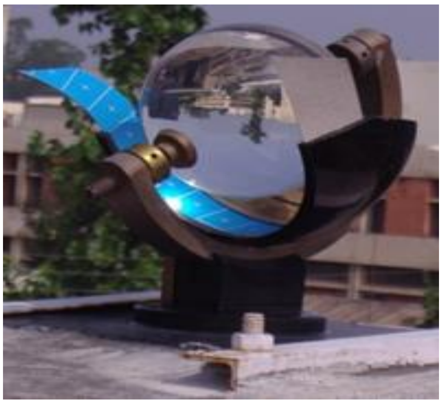


Figure 7-14. Campbell Stokes Sunshine Recorder

7.9.1 Errors in measurement

The common errors in measurement are:

i. Use of wrong chart resulting in burn reaching edge of chart
ii. Extraction of wrong information from chart by the observer

7.9.2 Data validation for sunshine hours

Primary data validation for sunshine hours can be carried out as:

i. Sunshine records before 0500 hours and after 1900 hours are rejected
ii. Daily totals greater than 14.0 hours are rejected

7.10 Measurement and recording of weather parameters together

Measurement of weather parameters can alternatively be achieved using an Automatic Weather Station (SP: 61-1994), requiring minimal human intervention. With the advent of digital technology, and increase in the cost of human labour, these are gaining popularity by the day. These instruments can record and store information on all the weather parameters at chosen observation interval as per requirement (Figure.7-15). The data stored in local data storage can be retrieved at a later date using portable memory devices like pen drive/memory card. Optionally, they may be equipped to transmit the data to an observatory/office. It may transfer data in real-time via a local link to a computer system or via telecommunications or satellite systems. GPRS/GSM mobile phone technology is also in use for the purpose. These days they are mostly equipped to run on solar panels, with battery support. They can be installed at far-flung locations without needing any observer – making it a convenient choice.

Figure 7-15. Automatic Weather Station

The parameters which are measured using automatic weather station include:

i. Rainfall
ii. Maximum & minimum temperature
iii. Humidity
iv. Wind direction
v. Wind speed
vi. Air pressure
vii. Pan evaporation
viii. Sunshine Hours
ix. Incoming Solar Radiation
x. Outgoing Terrestrial Radiation
xi. Cloud height
xii. Visibility

Automatic weather stations are used for increasing the number and reliability of surface observations. They achieve this by:

i. Increasing the density of an existing network by providing data from new sites and from sites that are difficult to access and inhospitable
ii. Supplying, for manned stations, data outside the normal working hours
iii. Increasing the reliability of measurements by using sophisticated technology and modern, digital measurement techniques
iv. Ensuring the homogeneity of networks by standardizing the measuring techniques
v. Satisfying new observational needs and requirements
vi. Reducing human errors
vii. Lowering operational costs by reducing the number of observers
viii. Measuring and reporting with high frequency or continuously.

7.11 Measurement of water level of the reservoir

The water level recorders may be of the manual or the automatic type.

7.11.1 Manual type water level measurement

The common manual type water level recorders (IS: 15118-2002) include staff gauge and wire gauge.

7.11.1.1 Staff gauge

The gauge may be vertical or inclined. The markings are made either on a staff rigidly fixed to a structure or on the body of the wall or pier (Figure.7-16). It should be clear, accurate, distinctive, easy to read from a distance and permanent.

Figure 7-16. Staff Gauge

7.11.1.2 Wire gauge

In this type of gauge, a weight is lowered by a reel to touch the water surface. A mechanical counter notes the rotation of the wheel which is proportional to the length of the wire released.

7.11.2 Automatic water level recorders

These instruments provide a continuous record of the water level over a specified period of time e.g. a day or a week for mechanical versions to a few months together for the digital ones. The commonly used automatic water level recorders are float gauge, bubble gauge, ultrasonic echo sounder and radar gauge.

These days digital water Level Recorder has become more popular for measurement/ logging of real-time water level data with date and time stamping. It comes with different ranges up to 10 to 300 meters. It can be configured via user-friendly PC-based software within lab environment as well as field using Laptop.

7.11.2.1 Float gauge

This has been described in detail in IS: 15118-2002. This used to be the most common type of water level recorder. In this type of gauge, a float operating in a stilling well is balanced by a counterweight, connected through a wire. The wire passes over a pulley, causing it to rotate with a change of water level. The rotation is converted into linear movement through mechanical linkages. A pen trace provides a continuous record of the water level on a chart. The chart, mounted on a drum runs on a clockwork mechanism (Figure.7-17).

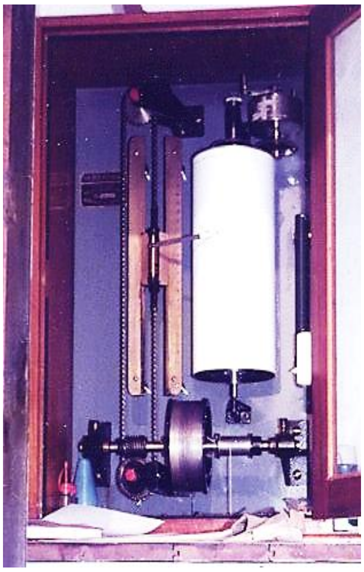


Figure 7-17. Recorder of Float Gauge

7.11.2.2 Bubble gauge

The specifications for the gauge are available in IS: 15118-2002. Here, compressed air or gas is made to bleed out at a very small rate through an outlet fixed at the bottom of the water (Figure.7-18). A pressure gauge measures the gas pressure, which is proportional to the height of the water column. A change in water surface elevation causes a change in pressure. A servo mechanism readjusts the bleeding rate to the original. The pressure gauge reads the new water depth and transmits it to a recorder.

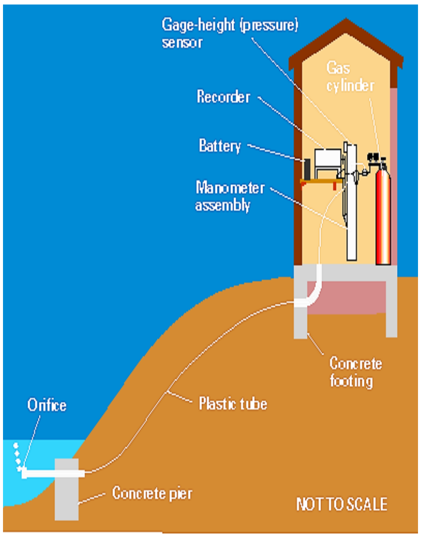


Figure 7-18. Bubble Gauge

7.11.2.3 Ultrasonic echo sounder

This should conform to IS: 14359-1996. The system uses ultrasonic pulses transmitted by the transducer to the surface to be monitored, and those reflected back from the surface. The time period between transmission and reception of the sound pulses is directly proportional to the distance between the transducer and surface. A microcontroller calculates this time period for all echoes received and analyses them to ascertain the correct reflection from the material surface. The instrument uses this data as the basis for providing control outputs and displays in usable engineering units. The distance is determined from the velocity of sound and the time period of travel.

This sensor is easy-to-install, having the advantage of providing non-contact measurement with high measuring accuracy (Figure.7-19). The instrumentation is maintenance free as well. However, the ultrasound speed is affected by temperature and humidity of the transmission medium. Also, the measured range is relatively smaller, being about 0.25 to 12 m. the precision available is of the order of ± 0.15 % of the full scale. The absolute error is less than 2 cm for a measurement range of less than 13 m; while for a measurement range of greater than 14 m, it is more than 2 cm.

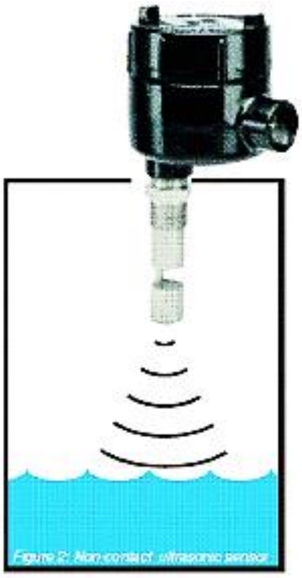


Figure 7-19. Ultrasonic Water Level Recorder

7.11.2.4 Radar Gauge

The measurement procedure of a radar gauge is based on the pulsed radar principle. It is done in pulses, (called the pulse procedure), where a transmitter sends out a short microwave pulse followed by a period when the receiver picks up the signals reflected by the water. The received signal is then conveyed to the integrated evaluation system (Figure.7-20). The time taken by the pulse for travel relates to the distance travelled to and from the surface of the water.

Although costlier than other options, this instrument has become the most popular water level recorder of the day, providing non-contact measurement with a wide range of operation and high accuracy. The precision and absolute error lie between ± 3 to 10 mm. The suitable range of operation extends up to 90 m. The measurements are insensitive to fog, precipitation, and air temperature fluctuation. The radio wave used for this application (frequency 24 to 26 GHz) is harmless to humans and wildlife. The installation can be carried out with minimal construction work.

Figure 7-20. Radar Type Water Level Recorder

7.12 Measurement of seepage

Measurement of seepage through the dam can be made through the use of hydraulic structures like a weir. A weir is an overflow structure built across an open channel. It has a specific size and shapes with a unique free-flow, head-discharge relationship. The edge or surface over which the water flows is called the crest. With weirs, water levels are measured and discharge obtained there from using established relationships.

Weirs can be used for both high flows with the discharge measured by the water stage in the pool behind the weir or for volumetric flows in extremely low flow conditions as well. The commonly used weir types include V-notch weir, rectangular notch weir, trapezoidal notch weir, broad crested weir, Parshall flume and venturi flume.

7.12.1 V-Notch Weir

The specifications for the structure are provided in IS: 14673 – 1999. It uses the principle of gravitational discharge of water over a triangular notched weir plate (Figure.7-21). Simple in principle, it is a low cost and robust instrument. For a given profile size and shape, discharge is a function of the head of water at the weir. Because of its triangular shape, the weir measures the low and the high flows with the same degree of accuracy. The construction of the structure and its maintenance does not require a high degree of skill and can easily be done. The water is led to the weir through a straight approach channel.

Figure 7-21. V-Notch Weir

7.12.2 Rectangular Notch Weir

The specifications for rectangular weir are available in IS: 9108-1979. It can be of the suppressed type covering the entire channel width (Figure.7-22). Alternatively, it can be of the contracted type having a rectangular notch cut into it that contracts the flow, and adds to the head loss. To have accurate measurements, the channel upstream should be large enough to allow the water to approach the weir in a smooth stream, free from eddies. These weirs usually have higher discharge values. The discharge nappe

Figure 7-22. Rectangular Notch Weir

should be fully ventilated and not submerged. The tail water level should be low enough to ensure that it does not interfere with the free discharge of the jet.

7.12.3 Trapezoidal Notch Weir

This is a fully contracted weir, which can be conceptualized as a combination of a rectangular and triangular weir. These are less accurate than rectangular and v-notch weirs, but more stable (Figure.7-23). They are used when the discharge is too large for a rectangular weir. The most common of the type is the Cipolletti weir, having a side slope of 1:4. The effects of end contraction are compensated for by the trapezoidal notch shape. So, the mathematical correction for end correction is not required, making the equation simpler.

Figure 7-23. Trapezoidal Weir

7.12.4 Broad Crested Weir

A major drawback of the sharp-crested weir is its inherent difficulty in maintaining the crest in its original condition for a long period. This difficulty is overcome by the use of a wider crest. This type of weir has been described in IS: 13084 – 1991 and IS: 14974-2001. Here, the streamlines run parallel to each other at least for a short distance, so that a hydrostatic pressure distribution may be assumed at the control section. These weirs are used for discharges higher than that measured by the sharp crested weir (Figure.7-24).

While these weirs offer the advantages of cost-effective installation, durability, and capability of passing floating debris, they also suffer from a few disadvantages. The channel upstream is prone to sediment deposition and the head loss across the weir is higher than that for their sharp crested counterpart.

Figure 7-24. Broad Crested Weir

7.12.5 Parshall Flume

The Parshall flume is suited to measure flows from channels with low gradient because it can operate with a high degree of submergence without loss of accuracy. The specifications are available in IS: 14371 – 1996.

The flume consists of three sections, viz., a converging inlet section followed by a rectangular throat section, leading to a divergent outlet section. The converging section is level, the throat flood inclines downward and the flood of diverging section slopes upward (Figure.7-25). It has the following advantages:

i. No sand or silt, whether suspended or rolling, gets deposited in the flume.

ii. Loss of head is very small in comparison to weirs

iii. A wide range of capacities is in the offer as a pre-calibrated device.

iv. The flow measurements are not influenced by the velocity of approach.

v. It has a longer life.

However, it is relatively more expensive and needs a high degree of workmanship. The accuracy of flow measurements is limited.

The flume is constructed of sheet metal, masonry or reinforced concrete.

Figure 7-25. Parshall Flume

7.12.6 Venturi Flume

The details are presented in IS: 6063 – 1971. As water passes through this flume, there is a slight surface slope in the converging section, a rather sudden depression in the "throat" section, and a rise in the diverging section (Figure.7-26). The actual loss of head is small. The estimation of the flow depends upon the velocity and wetted cross-sectional area at two points in the flume. So, two gauge readings are necessary. If the flume is designed to change the flow from subcritical to the supercritical state during its passage through the flume, a single measurement at the throat (the critical section) is sufficient for computation of discharge. If the throat section is sufficiently long to establish parallel flow, critical conditions occur in the throat. To ensure that the critical depth occurs at the throat, the flumes are usually designed in such a way as to form a hydraulic jump on the downstream side of the structure. These flumes are also called 'standing wave flumes'.

Figure 7-26. Venturi Flume

7.13 Measurement of streamflow

Though not directly related to the instrumentation at a dam site, measurement of stream flow often assumes an important role for the authorities in charge of monitoring a dam. The measurement of discharge can be either direct or indirect. Here, the discussion is limited to the direct measurement techniques. A general guidance on the choice of a method suitable for a particular type of reach is available in IS: 9922 - 2010. The commonly used techniques include the area velocity method, the dilution technique, the electromagnetic method and the ultrasonic method.

7.13.1 Requirements of a good gauge and discharge site

In order to obtain reliable estimates of river discharge for a long time, a gauge and discharge site should have the following characteristics:

i. Adequate length of channel relative to the regular cross-section

ii. Uniform velocity distribution across the channel width

iii. Avoidance of places influenced by tides, confluences, seasonal weed growth
iv. Presence of flood banks, to confine the maximum discharge in the channel
v. Stability of the banks
vi. Uniformity of section of the approach channel

7.13.2 Area Velocity Method

The relevant specifications have been provided in IS: 1192 - 1981. The direct measurement techniques for a reasonably wide river in a relatively flatter stretch most commonly involve area velocity methods. It involves computation of channel discharge through measurement of flow area and measurement of flow velocity. After dividing the width of the river into a number of smaller sections to take care of the variation of flow velocity across the channel width, the flow area is estimated by multiplying the width of each section with its depth (IS: 15118 - 2002). Measurement of representative flow velocity for each section is carried out (IS: 3910 - 1992) in the best possible way that meets the requirement and resources available. The simplest is a measurement of flow velocity at the water surface (within 0.5m) using a float. The average velocity over the section is generally considered as 0.85 times the surface velocity. For better estimation, one point measurement involving measurement of velocity at 0.6 times the depth of water from the surface is carried out using a current meter, which may be of the vertical axis or the horizontal axis type. The measured velocity is considered to represent the average velocity of flow over the vertical section at which the measurement is taken. For larger streams with greater depths, two-point measurement i.e., measurement of velocity at 0.2 times and 0.8 times the depth of water measured from the surface is done. The average velocity through the vertical section is the average of these two measurements. For more accurate measurements, multi-point measurement is done and the average velocity is estimated from a plot of velocity against depth, measured at pre-decided intervals. For finding out the number of sections, care should be taken to check that the width of each section is less than or equal to 1/20th of the stream width, the discharge through each section is less than or equal to 1/10th of the stream discharge and the difference of velocities in adjacent segments is not more than 20%.

7.13.2.1 Measurement of stream velocity using current meter

The detailed specifications can be read from IS: 3918 - 1966. The main types are the vertical axis meters and the horizontal axis meters. Both types use a make-and-break contact to generate an electric pulse for indicating the revolutions of the rotor. The velocity is estimated using the instrument constants. These days, digital types with direct display of velocity are also available.

Meters should be recalibrated after three years or 300 hours of use or if their performance is suspect. Velocity is observed at one or more points in each vertical by counting revolutions of the rotor during a period of not less than 30 seconds. Where the velocity is subject to large periodic pulsations the exposure time should be increased.

For shallow channels, the current meter should be held in the desired position by means of a wading rod. For channels too deep or swift to wade, it should be positioned by suspending it from a wire or rod from a bridge, cableway or boat.

When a boat is used, the meter should be held so that it is not affected by disturbances to the natural flow caused by the boat. After the meter has been placed at the selected point in the vertical, it should be allowed to become aligned with the direction of flow before readings are started.

If the oblique flow is unavoidable, the angle of the direction of the flow normal to the cross-section should be measured and the measured velocity should be corrected.

Smaller meters of 5 cm diameter cup assembly (pygmy meters) run faster and are useful in measuring velocities with low water depth.

7.13.2.2 Vertical axis meters

The instrument consists of a series of conical cups mounted around a vertical axis that rotate in a horizontal plane (Figure.7-27). The normal range of velocities that can be measured varies between 0.15 to 4.0 m/s. The accuracy of these instruments is about 1.5%, which improves to 0.30% at speeds in excess of 1.0 m/s. They should be used in places where there is an appreciable vertical component of the velocity.

Figure 7-27. Vertical Axis Current Meter

7.13.2.3 Horizontal axis meters

The instrument consists of a propeller mounted at the end of a horizontal shaft, rotating on a vertical plane. The sizes vary widely. For measuring velocities in the range of 0.15 m/s to 4.0 m/s the propeller diameters have a range of 6 to 12 cm (Figure.7-28). These instruments are fairly rugged and are not affected by oblique flow up to 15°. The accuracy is about 1%, which increases to 0.25% at a velocity of 0.3 m/s.

Figure 7-28. Horizontal Axis Current Meter

7.13.3 Dilution techniques

The technique has been detailed in IS: 15898 (Part 1) – 2012. For hilly streams with considerable variation of velocity across width and depth, this method is suitable. A known amount of environment-friendly tracer which does not get absorbed by bank materials/vegetation and which can be detected at very small concentration is introduced at an upstream location. After allowing it to flow through a sufficiently long reach to ensure complete mixing, the concentration is measured at a downstream location. The common tracers are

i. Chemicals (IS: 15898 (Part 3) – 2012) like common salt, Sodium Dichromate

ii. Fluorescent dyes (IS: 15898 (Part 4) – 2012) like Rhodamine-WT, Sulpho-Rhodamine B Extra and

iii. Radioactive materials (IS: 15898 (Part 2) – 2012) like Bromine-82, Sodium-24, Iodene-132.

Compared to the chemical tracers, the fluorescent dyes can be accurately detected at smaller concentrations, (Figure.7-29) and

Figure 7-29. Dilution Technique of Velocity Measurement

the radioactive tracers at much smaller concentrations. The method of injection may be either sudden injection or continuous injection (IS: 9163 (Part1)-1979).

7.13.4 Electromagnetic method

The specifications for the method are available in IS: 16138 - 2013. This is one of the modern techniques for measurement of stream discharge which is easy and more accurate. A channel section is instrumented with large coils buried at the bottom to generate a magnetic field, and electrodes at the end of the channel to measure the voltage generated. Taking advantage of the Faraday's principle which mentions that electricity is generated when a conductor moves across a perpendicular magnetic field, (Figure.7-30) small voltages of the order of millivolts are measured at the sides of the channel when a discharge passes through the section. An electromagnetic meter can deliver velocity measurements and may be used in exactly the same manner as a current meter.

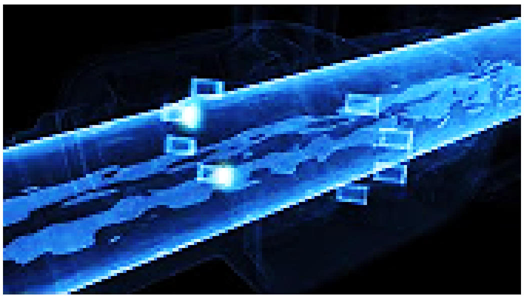


Figure 7-30. Electromagnetic Method of Velocity Measurement

7.13.5 Ultrasonic method

In this method two transducers capable of transmitting and receiving ultrasonic signals are fixed at the same level on two banks of a river, one being slightly upstream of the other (Figure.7-31). The distance between transmission and receipt of sound signals are measured accurately. The stream flow velocity is estimated considering that it acts to aid the sound velocity along one path and oppose the same during the return.

Figure 7-31. Ultrasonic Method of Velocity Measurement

7.14 Measurement of suspended sediment load

For a better assessment of the service life of the reservoir and for planning preventive measures to control excessive sedimentation, a need to assess a load of suspended sediments entering into the reservoir from the different streams which enter into the reservoir may crop up. The details are available in IS: 4890-1968.

Measurement of suspended sediment can be done using instantaneous or grab sampler (IS: 3913-2005) or time integrating sampler.

i. Time-integrating samplers(Figure.7-32) can be either Depth-integrating sampler (e.g. US DH-48, US DH-59, US DH-49 samplers)

ii. Automatic single-stage sampler

iii. Pump sampler

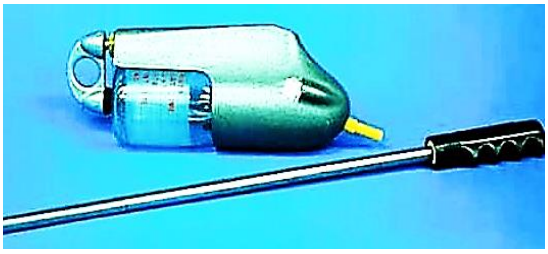


Figure 7-32. Depth Integrating Suspended Sediment Sampler

Measurement of suspended sediment at the laboratory involves either filtration or evaporation. Generally, it involves less uncertainty than bed load sampling. The variation of concentration across the width is small (less than 10-15%) for wide streams, but it may be high (differing by 70% from average) for small streams. Suspended sediment load is obtained by multiplying mean concentration in the vertical at centre with discharge through the strip.

The location for measurement of sediment concentration may be

i. Single vertical at midstream
ii. Single vertical at point of greatest depth
iii. Verticals at ¼, ½ and ¾ width
iv. Verticals at 1/6, ½ and 5/6 width
v. Four or five verticals equally spaced across the stream
vi. Verticals at middle sections of equal discharge

The level at which mean concentration is obtained varies with flow, sediment, and fluid conditions. In general, the location of sampling points in the vertical are:

i. At 0.6 times the depth below the surface for one point method of sampling,
ii. At 0.2 and 0.8 times the depth below the surface for two point method of sampling, and
iii. Three point method: at surface, bottom and mid depth

For two point sampling, the mean concentration is estimated as

$$\boldsymbol{C_s = \left(\frac{3}{8}C_{0.2D} + \frac{5}{8}C_{0.8D}\right)}$$

For three point sampling at the surface, bottom and mid-depth, the mean sediment concentration is given as:

$$\boldsymbol{C_s = \left(\frac{1}{4}C_{Surf} + \frac{1}{2}C_{Mid} + \frac{1}{4}C_{Bot}\right)}$$

The frequency of sampling depends on the stream type and the flow conditions. In general, variation is more in small streams draining small areas. For large streams, variations are generally less. But for both types of streams, the concentration vary rapidly in an erratic manner during rising stage of the flood. The present practice regarding frequency observation is a day to a week for normal flow, 30 min to 12 hours for rising flood, 2 hours to 24 hours for falling flood. However, it all depends on the agency, purpose, nature of stream and funds available.

Chapter 8. INSTRUMENTATION DATA COLLECTION AND MANAGEMENT

8.1 Introduction

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

8.2 Data Collection

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

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

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

8.2.1 Manual Data Collection

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

8.2.2 Stand Alone Dataloggers

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

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

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

8.2.3 Real-time Monitoring Networks

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

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

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

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

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

8.2.4 Advantages and Disadvantages

Table 8-1 summarizes some of the advantages and disadvantages of the three data collection methods described above. The objective in designing a monitoring program is to use the best tools for the intended purpose. Many dam projects use a combination of the data collection methods depending upon the monitoring needs for the parameters that are being measured.

Table 8-1. Summary of Data Collection Methods, Advantages and Disadvantages

Data Collection Method	Advantages	Disadvantages
Manual Readings	• Generally simple to perform and do not require high level of expertise • Personnel are already on site for regular visual observations • Data quality can be evaluated as it is collected	• Labor intensive for data collection and reduction • Not practical to collect frequent data • Potential for errors in transposing data from field sheets into data management/ presentation tools • May be impractical for remote sites where personnel are not frequently on site
Standalone Data loggers	• Frequent and event-driven data collection • Consistent data collection and electronic data handling • Equipment is fairly inexpensive and simple to set up	• Requires some expertise to configure dataloggers • Data quality cannot be evaluated until it is collected from the field • Potential for lightning strikes • Power source needs to be considered

Data Collection Method	Advantages	Disadvantages
Real-time Monitoring Networks	- Frequent and event-driven data collection - Consistent data collection and electronic data handling - Real-time display and notification (24/7) - Reduces labor effort for data collection and processing - Can remotely change the monitoring frequencies and data collection configurations as needed - Allows for rapid evaluation of monitoring results	- Automation may encourage complacency if overall monitoring program is not well defined or understood - Requires a higher level of expertise to install and maintain - Higher cost of installation and periodic maintenance - The importance of frequent routine visual inspections may be overlooked or discounted somewhat due to the real-time presentation of automated instrument readings - Potential for lightning strikes - Power source needs to be considered

8.3 Data Management and Presentation

Collecting reliable data is very important, but the data must also be carefully managed and evaluated in a timely manner to effectively monitor the project performance. Data collected but not processed or evaluated right away does not serve the purpose of dam safety. Quick and effective analysis of the data is crucial to maintaining the safety of the project.

Many dam owners maintain the analyzed, documented data at a central office with copies at the project site, whereas many others maintain the data only at the project site.

Successful management of collected instrumentation and monitoring data to measure the performance involves the following:

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

8.3.1 Data Management

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

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

8.3.2 Database software

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

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

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

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

8.3.3 Data Processing

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

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

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

8.3.4 Data Maintenance

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

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

- General information such as drawings; date(s) of installation; initial measurements and testing; manufacturer's calibration data; borehole logs; model number and manufacturer; wiring schematics, etc.
- Instrument maintenance records including routine maintenance activities; calibrations of instruments; cleaning of foundation drains; replaced readouts; removal of vegetation; cleaning of approach channels of weirs; outages, reservoir drawdowns, major maintenance; installation of drains, flushing of pieozmeters, and redirecting flow, etc. These are often sources of changes in recorded data. Maintenance records also provide documentation of schedules, reasons for repair (such as damage from vandalism or construction), and information for future maintenance and may also provide support to explain abrupt changes in readings.
- Significant project event records such as records of floods, earthquakes, major construction, and remediation must be maintained. These will provide information on the performance of the project under these loads and can provide critical empirical information to help with calibration of dam safety analyses that are intended to evaluate and prepare for future extreme events.
- Data evaluation reports, or performance reports, are the tangible product of instrumentation programs. As such, managers must ensure their maintenance and availability to all personnel respon
- sible for some aspect of the dam safety and performance of the project.

8.3.5 Data Presentation

Tabular

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

Graphical

As the total number of collected readings increases, plots of the data may provide the best method of data evaluation. In addition, identification of trends and cyclic responses can be difficult using tabular data. Data managed in an electronic system (spreadsheet or database) can easily be plotted for evaluation. Some spreadsheet programs can be formatted to allow a dynamic environment where plots are instantaneously updated as data is entered.

Plots are usually preconfigured with database tools so that the most up-to- date data can be viewed and compared instantaneously with other parameters to rapidly identify changes in performance.

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

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

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

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

Cross-Sections

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

8.3.6 Photos and Diagrams

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

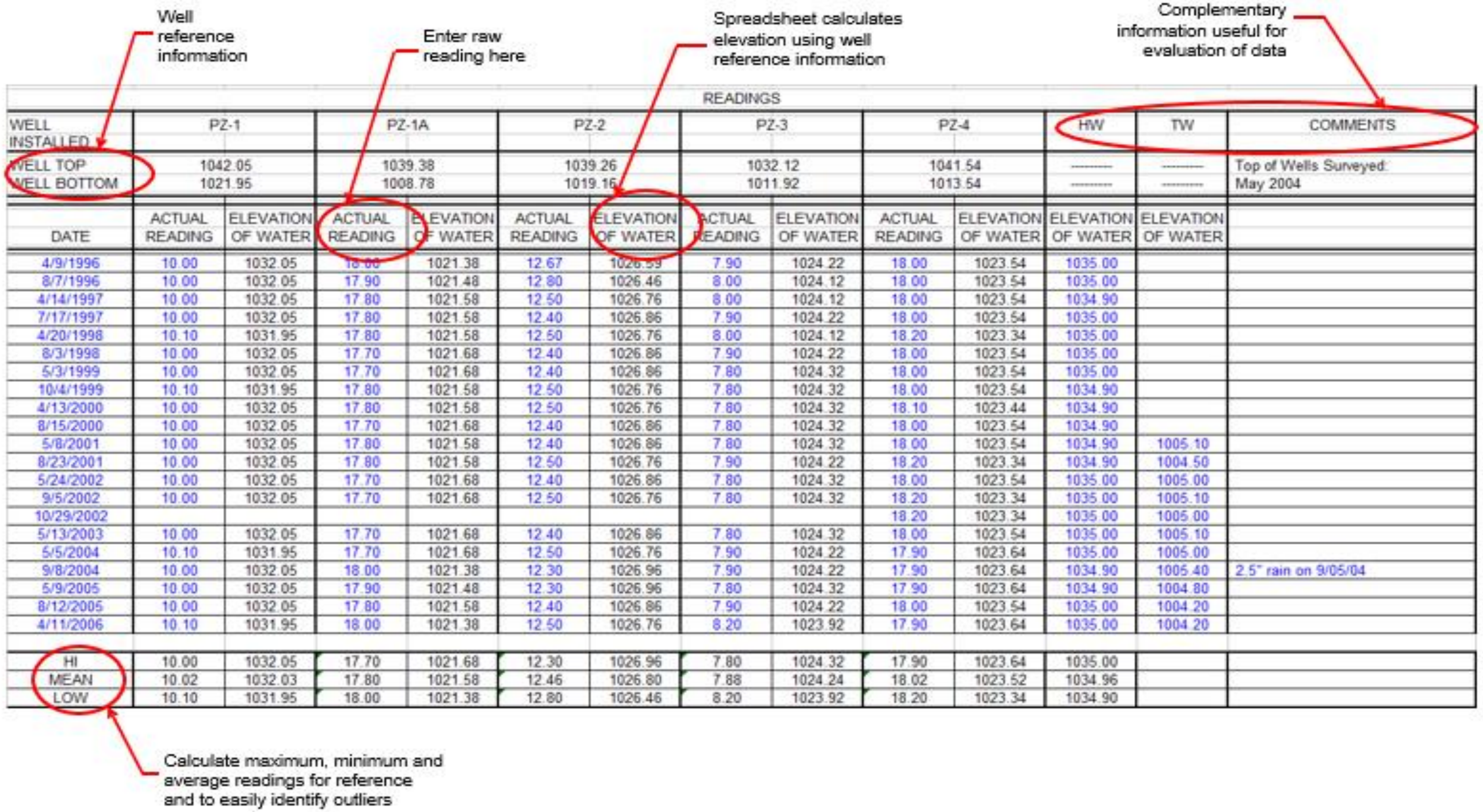
Figure 8-2 presents examples of a time-history plot as well as important complementary data and a plot of two different parameters other than time. Figure 8-3 shows an example of a cross-sectional plot. Note in Figure 8-3 that the vertical and horizontal scales are different.

This can be done to improve presentation of the data while still facilitating clear evaluation of the data.

8.4 Critical Data Analysis

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

Analysis of the data includes evaluation of trends such as levels increasing or decreasing with time; response to changing headwater and/or tail water levels; cyclic responses to project reservoir levels; responses to changes in temperature; effects of precipitation on project response; effects of construction activities; effects of changes in project operations, etc. These represent a few of the potential responses of a project as portrayed through the surveillance and instrumentation data. The data should be evaluated in terms of detecting a developing failure mode or potentially unsafe condition, and the general health of the project.



READINGS

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

Figure 8-1 Shows an example of a simple spreadsheet used to manage and evaluate piezometer readings.

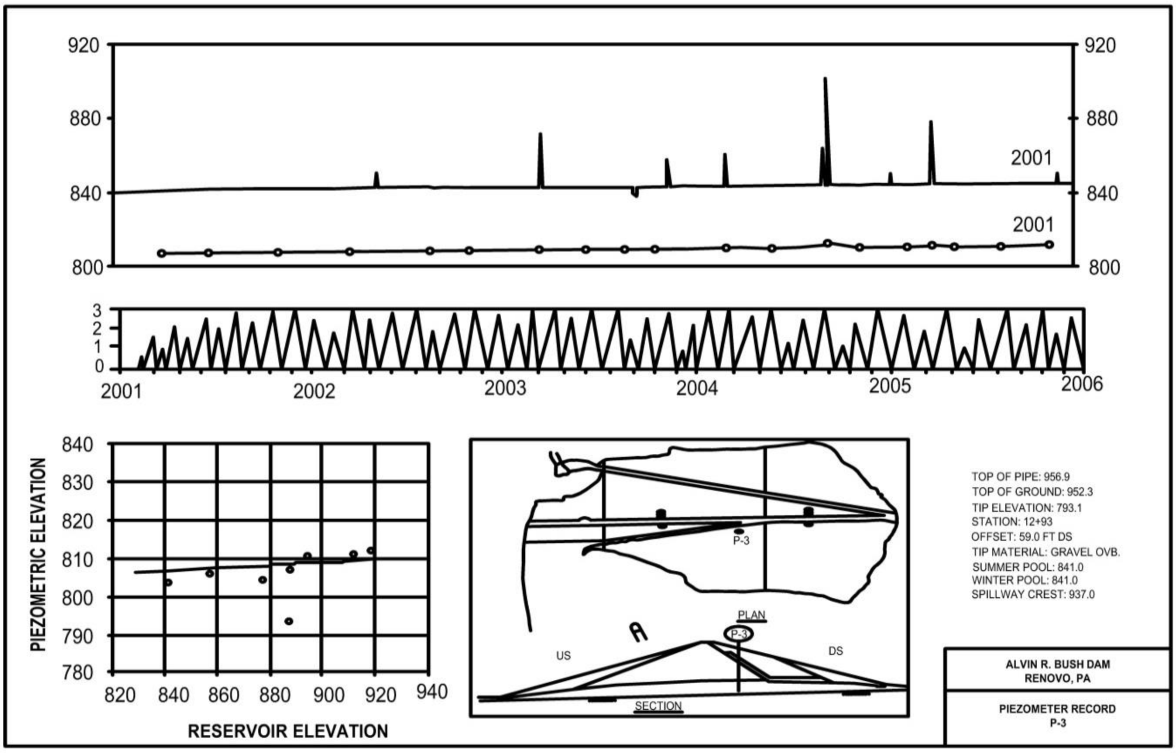

Figure 8-2. Example of a time-history plot with location and correlation data

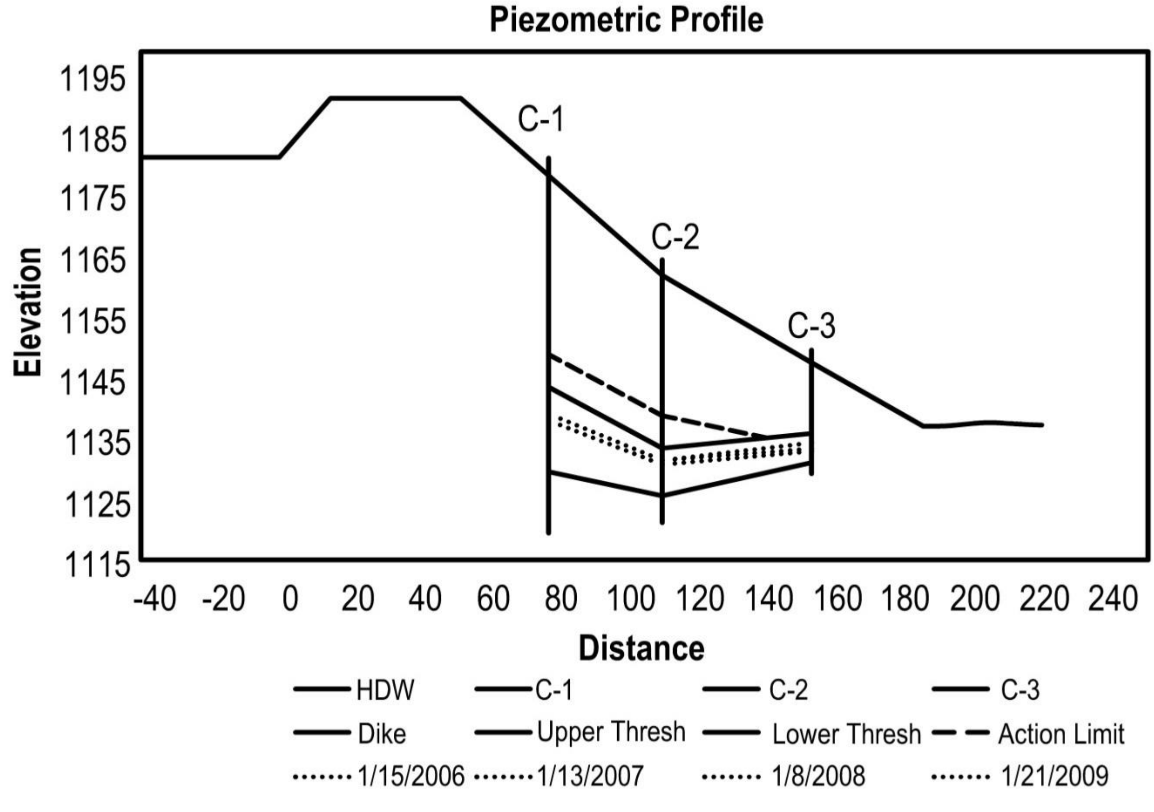

Figure 8-3. Example of a cross-section plot

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Chapter 9. MONITORING DATA ORGANISATION AND ANALYSIS

9.1 Introduction

The responsibility of a dam engineer is not only to plan, design and construct a dam to acceptable standards but also to ensure its operation with a rigid dam safety surveillance programme. All these considerations stress the necessity to have some dependable means or tools, generally termed as instruments, available inside or on the surface of dam, which can provide us information about the conditions and behaviour of the structure. Periodical and regular monitoring of these instruments and analysis of the data obtained through these instrumentation with a diagnostic approach would help in understanding the health status of a dam.

Instrumentation of any dam is meaningless unless it is correlated with its analysis under various conditions extending from construction to filling and steady flow to draw down conditions. The response of the dam to the changes in loading and unloading conditions must be anticipated establishing critical values of stress, strain and deformation. This helps in specifying the range and the sensitivity of the instruments to be installed and to monitor the response of the dam. Properties of materials in compacted state, amounting to quality control data, are complimentary to the design values.

9.1.1 Design Aspects

The conventional design of an embankment dam normally confines itself to its stability analysis that is, locating critical potential shear failure surface within embankment and foundation, which gives minimum factor of safety. Whereas the stability of the dam is of utmost concern, it is necessary that the stresses and deformations of the dam are also calculated and measured to ensure that they are both within the "ultimate" and 'serviceability" limits.

Similarly the design of gravity dams is limited to its stability analysis at various levels of different loading conditions. The analysis is carried out using the deterministic method of calculations, working out the vertical stresses at the heel and the toe, the shear friction factor and the safety against overturning. A linear variation in vertical stresses from upstream to downstream is assumed. As a consequence the variation in shear stresses is parabolic and cubic in horizontal stresses. The modulus of deformation, generally, does not figure in the design computations.

The common practice is to carry out a pseudo-dynamic analysis to take the effect of earthquake into account. An equivalent horizontal component of the acceleration due to earthquake is worked out and a force equal to mass x acceleration is supposed to be acting at its center of gravity. A slightly more refined method takes the response spectra into account. A rigorous dynamic analysis is done only for high / important dams.

The speed of construction is another factor which plays an important part in stability of embankment dams as it directly affects the dissipation of pore water pressures. The faster the rate of construction, the slower the dissipation of pore pressures. Sometimes, due to one reason or the other, the construction work is delayed or stopped abruptly. This leads to dissipation of pore pressures and consolidation of embankment constructed. The stresses and deformations in an embankment dam would be very different if it is constructed in one go compared to construction carried out in several stages or relatively at a slower rate. In very wet weather or when borrow area soils contain moisture content higher than the permitted value, the rate of construction depends upon pore pressures which need to be controlled through instrumentation.

Similarly in the concrete dam, the stresses and deformations depend upon the heat of hydration and pre cooling of ingredients and post cooling besides the construction schedule and the lift height etc. The higher the cement content, the higher the heat of hydration and higher the tensile stresses. The faster the construction, the longer it takes for the dam to come to ambient temperature.

Since the instrumentation monitors parameters like pore water pressure, deformation, total stresses, settlements profile, etc., at particular locations, it is essential that the dam be analysed using techniques which will yield these parameters so that the measured parameters could be compared with the calculated ones.

The instrumentation programmes of concrete dams normally measures the stresses, the temperatures, the uplifts, the deformations, the tilts and the settlements.

9.1.2 Numerical Modelling

Numerical Modelling has emerged a powerful tool for analysis, assessment of exacting potential and the interpretation of instrumentation data. For this, the geometry, construction methodology and its sequence and material properties are modeled. This type of analysis, besides taking more realistic material characteristics into account such as anisotropy, linearity and plasticity, can handle large deformations and failures very efficiently. ICOLD (1986), described the finite element method for stability analysis. The selection of material characteristics is the key to success of the method.

9.1.3 Back Analysis for Calibration

Back Analysis actually means redoing design calculations from data monitored by instrumentation. Hence it is desirable that a well-designed small-scale instrumentation programme be planned and executed to obtain some instrumentation data in the early stages of construction. These data may be used for Back Analysis and verification / calibration of the model. The plan for such instrumentation has to be carefully prepared both in terms of location and instruments.

Back Analysis has produced reliable mathematical models to aid the design calculations. These models help in predicting behavior and for extrapolations from earlier situations. Besides, improving safety and economics of future designs, differential settlement, cracking and risk of hydraulic fracturing in embankment dams can be prevented.

9.1.4 Dynamic Loading

In order to take care of dynamic conditions due to earthquake or blasting, the instrumentation and the analysis, both, deserve a special consideration. Whereas instrument sensors have limitations with regard to their response time, data loggers or computer systems can be used for collecting instrumentation data at required intervals.

For carrying out the analysis effectively, additional data in respect of the earthquake accelerograph and dynamic properties of materials are required. The field instrumentation therefore should include strong motion accelerographs and structural response recorders so that the records of earthquake occurrences and the response of the structure become available.

9.1.5 Dynamic Analysis

It is possible to model the layer-by-layer construction and compaction of an earthen dam. It is possible to incorporate the speed and delays or layoffs during construction. Once the construction is over, the reservoir can be impounded at a planned speed, because the speed at which the reservoir gets filled up, also matters. After the reservoir is filled, the seepage can be set in and pore water pressure allowed to develop. The analysis of the dam can be carried out and pore water pressure, stresses and deformations calculated in the body of the dam and the foundations. These parameters can be compared with those actually measured.

9.2 Monitoring Data Analysis

9.2.1 The Purposes of Monitoring Data Analysis

The reason for installing instruments in dams is to monitor them during construction and operation. One of the specific applications of measurement is to furnish data to determine if the complete structure will continue to function as intended. The processing of large masses of raw data can be efficiently handled by computer methods. The interpretation of the data requires careful examination of measurements as well as other influencing effects, such as reservoir operation, air temperature, precipitation, drain flow and leakage around the structure, construction joint grouting, concrete placement schedule, seasonal shutdown during construction, concrete test data, and periodic instrument evaluations. The display of data should be both tabular and graphical and should be simple and readily understood. The data should be reviewed periodically by a professional engineer versed in the design, construction, and operation of the embankment and/or concrete dams.

9.2.2 Automatic Data Acquisition

Considerations and reasons for automating the data collection system for structural performance monitoring instrumentation in a dam include one or more of the following:

- Decreases labour required to measure and portray data
- Decreases the elapsed time between measuring data and interpreting data
- Provide automatic warning if limiting values for readings are exceeded.
- Allows more frequent readings without increased cost to help isolate spurious readings
- Transmit data to another location for evaluation
- Decreases error in data collection and reduction
- Enables continuous long-term collection of data at the required intervals
- Enables direct feeding of data into a computer database for interpretation of charts.

9.2.3 Evaluation of Measurement Data

9.2.3.1 Monitoring data variation with time

Monitoring data variation with time in measurements are investigated for the purpose of appropriate safety control.

A certain representative monitoring data organization, process, and analysis are shown in Figure 9-1 to Figure 9-14. These figures are introduced as references for the management of monitoring data. Co-relation between various parameters like leakage, quantity, reservoir water level and time are presented in Figure 9-15 to Figure 9-19.

Regardless of the type of dam, the most basic and important measurement item for safety control is leakage from the foundation rock as described below.

Typical patterns of increase in leakage in response to increasing in reservoir level after the start of filling are shown in Figure 9-1 to

Figure 9-19. A stable situation can be assumed if the rate of increase remains constant (2) or increases gradually (3). Close attention is required if the rate of increase rises abruptly (4).

9.2.3.2 Relationship between leakage and reservoir level

After measurements have been accumulated to some extent, trends can be seen more clearly by focusing on leakage at constant reservoir level (Figure 9-19-2). A stable situation can be assumed when leakage decreases gradually (1) or remains nearly constant (2). Causes must be identified if leakage increases gradually (3), and counter-measures must be taken urgently if leakage increases abruptly (4).

In the first filling of the reservoir, however, accumulation of measurements may not be sufficient and the period of constant reservoir level is generally short. Therefore, investigation of the trend of leakage at constant reservoir level, as depicted on Figure 9-19-2, is often difficult. In such a case, a correlation diagram with reservoir level on the vertical axis and measured leakage on the horizontal axis may be drawn to check for any abrupt changes in the trend. Figure 9-15 - Figure 9-19 shows the proper correlation between leakage and reservoir water level. Such co-relations are very useful for interpretation.

9.2.3.3 The number of monitoring times after the start of filling and measurement elements

Past incidents of dam accidents indicate that the first filling of the reservoir is the most important period of safety control.

Dams that experienced accidents during the first filling include the Malpasset Dam (France, completed in1954, burst in1959) the Viont Dam (Italy, completed in 1960, overflowed as a result of a landslide into the reservoir in 1963), and the Teton Dam (the USA, completed in 1975, burst in 1976).

In the normal situation, the specific monitoring elements are expected to become stable with time as depicted in Figures 9-5 and Figure 9-6.

From the dam safety monitoring point of view, it is, therefore, customary to measure a greater number of items with greater frequencies during the first filling and measure a smaller number of items with lower frequencies as the measurements become stable.

9.2.3.4 Other precautions

For safety control, the amount of leakage and the turbidity of leakage are important.

The turbidity of leakage observed at the drainage holes set up in the inspection gallery of a dam body and at the ground surface downstream may indicate local seepage failure in the foundation or the dam body. When an increase in turbidity is observed, close attention should be paid, even if the leakage is small at the time.

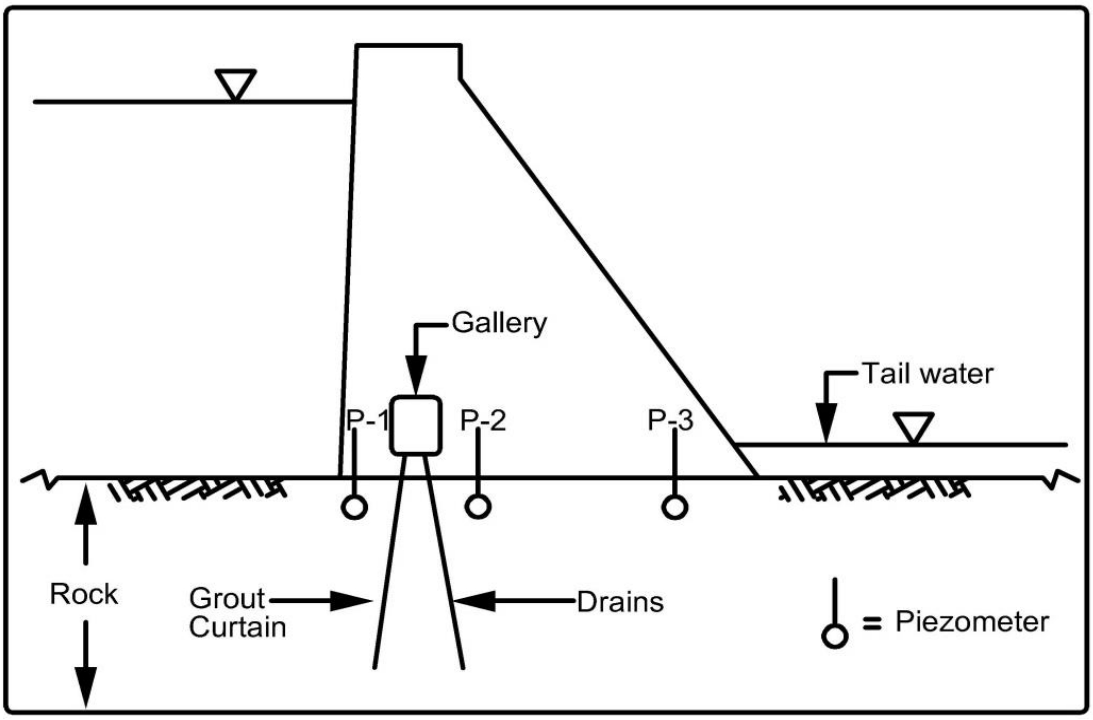
9.3 Data analysis and Evaluation Summary

Certain relationships normally exist among various factors that act upon dams. These relationships are outlined below in Table 9-1.

Table 9-1 Cause and Effect relationship for data interpretation

Interrelated Physical Factors	How Their Relationships Affect Data interpretation
Water Pressure/ Reservoir And Tail-water Levels/ Precipitation	• Water pressure in or under an embankment, or under a concrete dam, is related to reservoir and tail-water levels. • Water pressure in the abutments of a dam is related to reservoir and tail-water levels. • Water pressure in the slopes of a dam is directly related to reservoir level. • Precipitation and local ground water may influence water pressure in or under embankments, under concrete dams, in dam abutments, and in the slopes of a dam.
Water Pressure movement	• As water pressure increases within an embankment, or in a dam's foundation or abutments, the effective shear strength available to resist movement is reduced. If this shear strength is reduced to less than driving forces, movement will occur.
Water Pressure/Seepage/ Reservoir Level/ Precipitation	• Seepage normally is directly related to the reservoir level. • Precipitation often results in a temporary increase in the seepage flow. • Decreasing seepage flow and increasing water pressure under the dam or in its abutments indicate that the drainage or exit control systems are losing their effectiveness. • Decreasing seepage flows and decreasing water pressure under the dam or in its abutments indicate that the infiltration of reservoir water into the foundation or abutments is decreasing (possibly due to siltation of the reservoir basin).
Movement/Reservoir **Level**	• Normally, as the reservoir level increases, a concrete dam will deflect in the downstream direction. • Reservoir-level increases normally will not cause embankment dams to deflect significantly. • For very high earth and rockfill embankment dams, measured movements may be influenced by reservoir-induced settlement. • As a general rule of thumb, post construction settlement of an embankment dam should not exceed 1% of the height of the dam • An acceptable value of lateral deflection after filling is difficult to predict for any size of embankment dam • The key consideration for an embankment dam is that vertical settlement or lateral deflection of the crest should decrease in rate over time for a constant loading condition. A sudden or even gradual increase in the rate of vertical or lateral movement should be cause for further evaluation • The predicted piezometer levels will obviously vary with size and type of dam, height of reservoir, etc., and acceptable ranges cannot be quantified except on an individual basis.

Interrelated Physical Factors	How Their Relationships Affect Data interpretation
Movement/Temperature	• Concrete expands as temperature increases, and contracts as temperature decreases. • In locations with large differences between summer and winter temperatures, concrete monoliths in a dam will move, causing joints and cracks to open in the winter and close in the summer. • In the summer, as the temperature of the downstream face of a dam increases, the concrete near the downstream face will expand. Meanwhile, because the reservoir keeps the upstream face at a more constant temperature, there is little or no expansion of the concrete near the upstream face. This differential expansion of concrete may cause the top of the dam to move or rotate slightly upstream.
Seepage/Temperature	• The seepage or leakage through the cracks and joints of a concrete dam is inversely related to the temperature of the air/concrete/water. • For dams founded on fractured rock that experience seasonal changes in water temperature, there will often be an increase in flow from foundation drains during the winter.
Seepage/ Water Pressure/ Turbidity /Solutioning	• Turbid flow or increasing turbidity levels may indicate changes in seepage flows and water pressure. • Any sudden change in water pressure should be followed by seepage flow inspections. • A steady increase in seepage, with no increase in turbidity, indicates that seepage should be tested for the presence of dissolved solids.
Seismic Activity/Seepage **Movement/Water Pressure**	• Ground motion can cause a dam to move or deform, resulting in damage and/or structural instability and failure. Such movement can also damage seepage control features. • Seepage rate increases, increasing turbidity, or a large increase in water pressure could all indicate that damage has occurred to the structure. • Leakage/ Seepage is sensitive to earthquakes and is an important factor affecting the stability of dam body and its foundation • Case studies show that leakage/seepage and pore pressures often changes as a result of ground shaking. Usually they increase after an earthquake • In most cases, the increase is only temporary and will decrease or become stable over time and it may last from several days to a few years until a stable condition is reached
Construction Activity	• During construction or rehabilitation activities, high water pressures, sudden changes in water pressure or seepage, and/or unexpected movements would indicate the possible development of unsafe conditions.



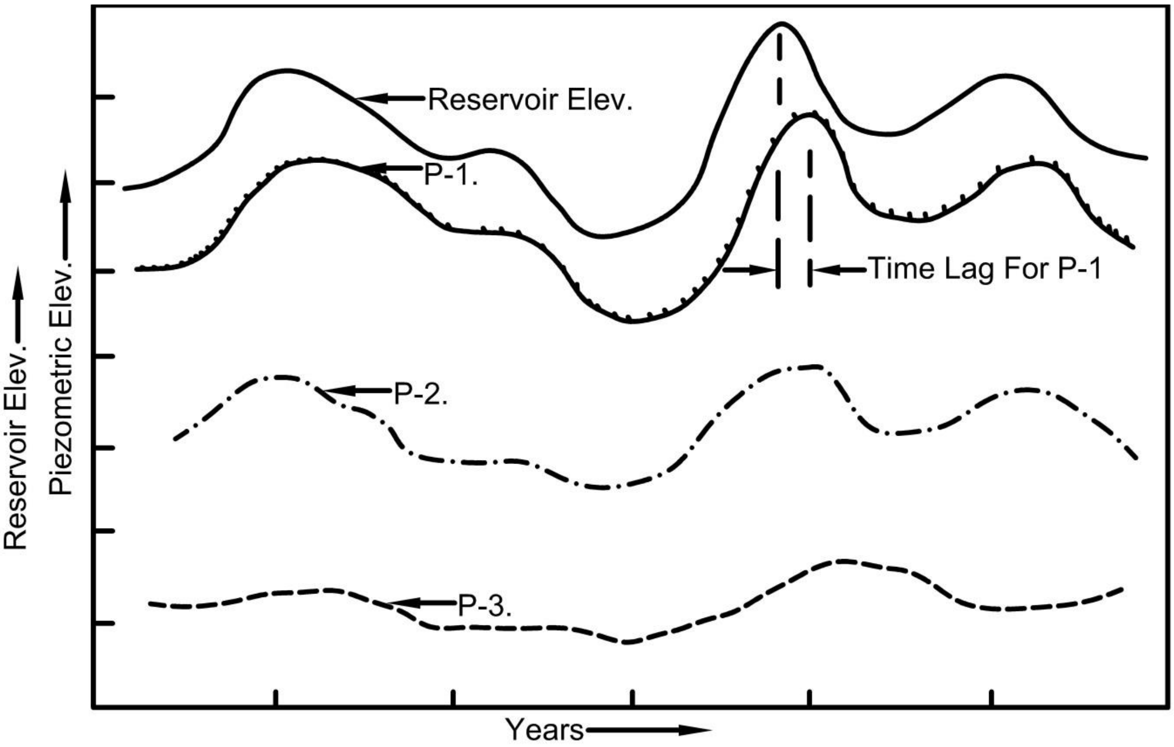


Figure 9-1. Plot of seepage v/s reservoir elevation for a concrete dam

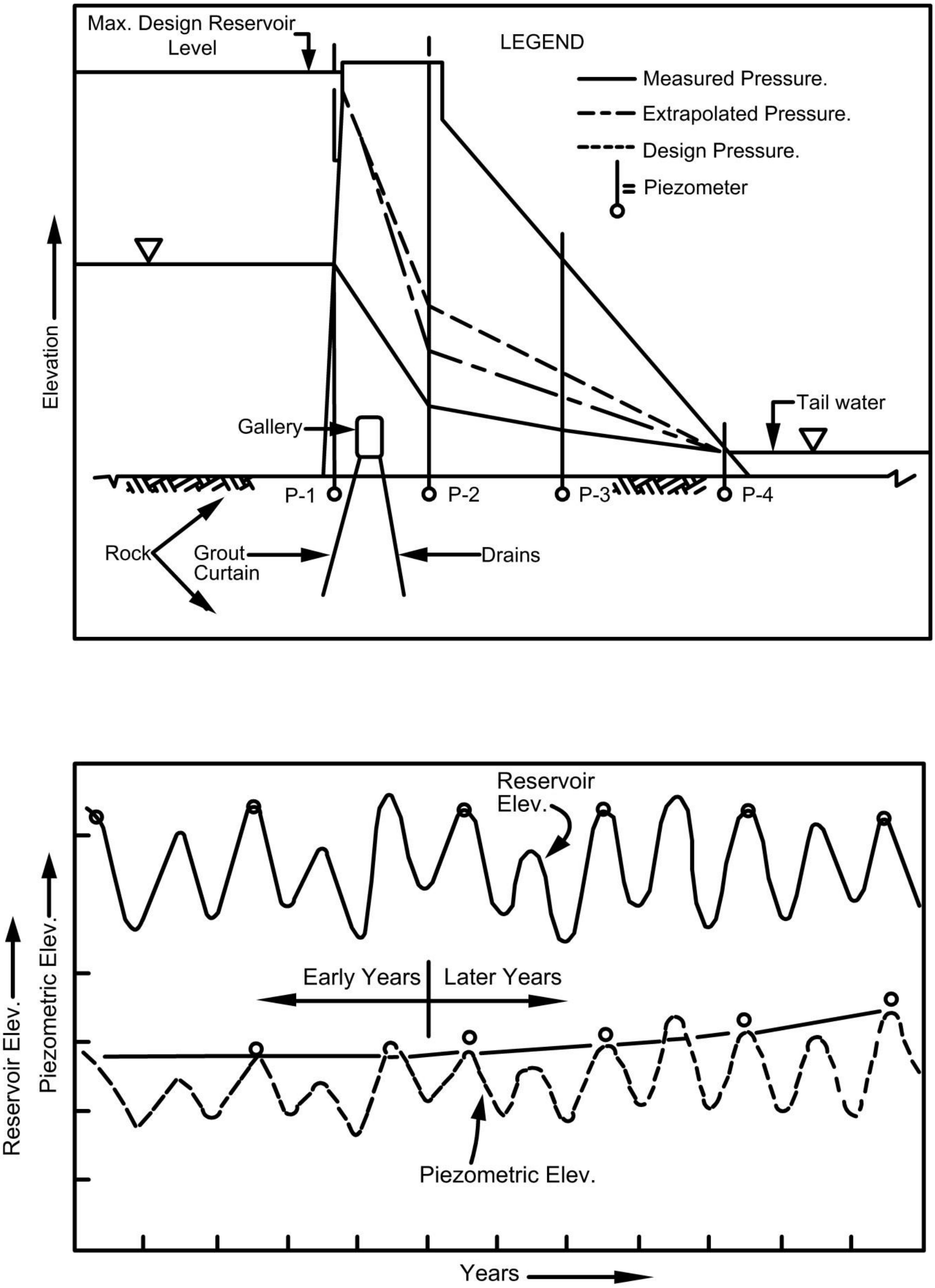


Figure 9-2. Piezometric pressure extrapolation for a concrete dam

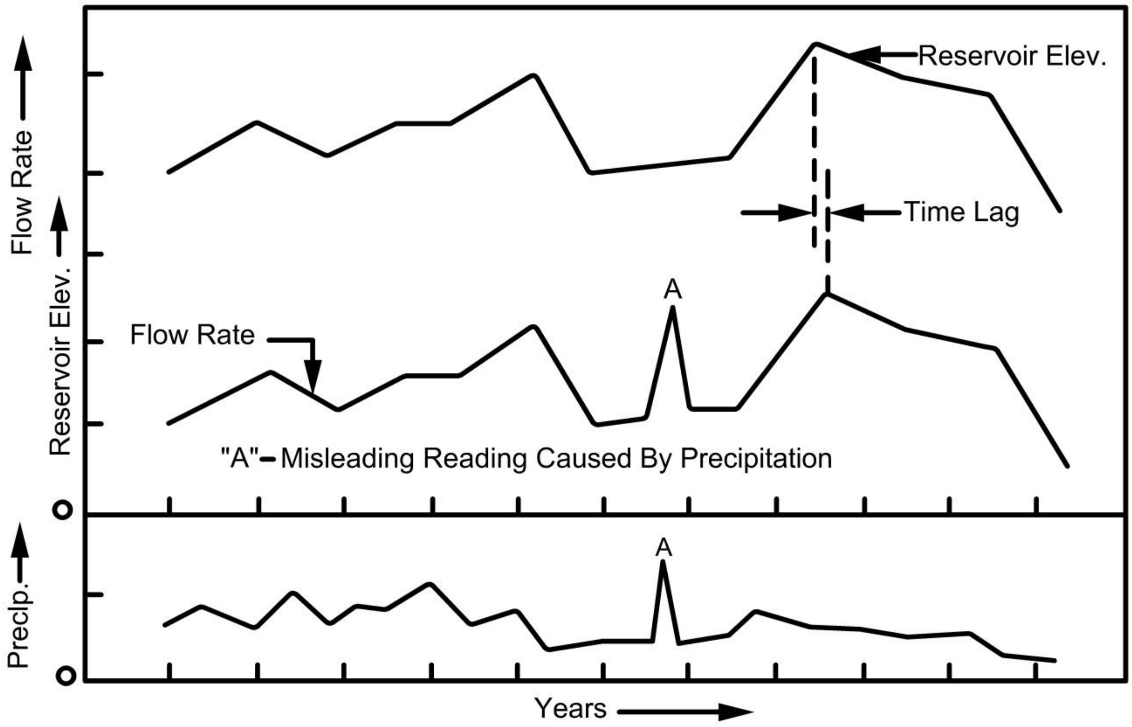


Figure 9-3. Time lag between reservoir level and flow rate for concrete dam

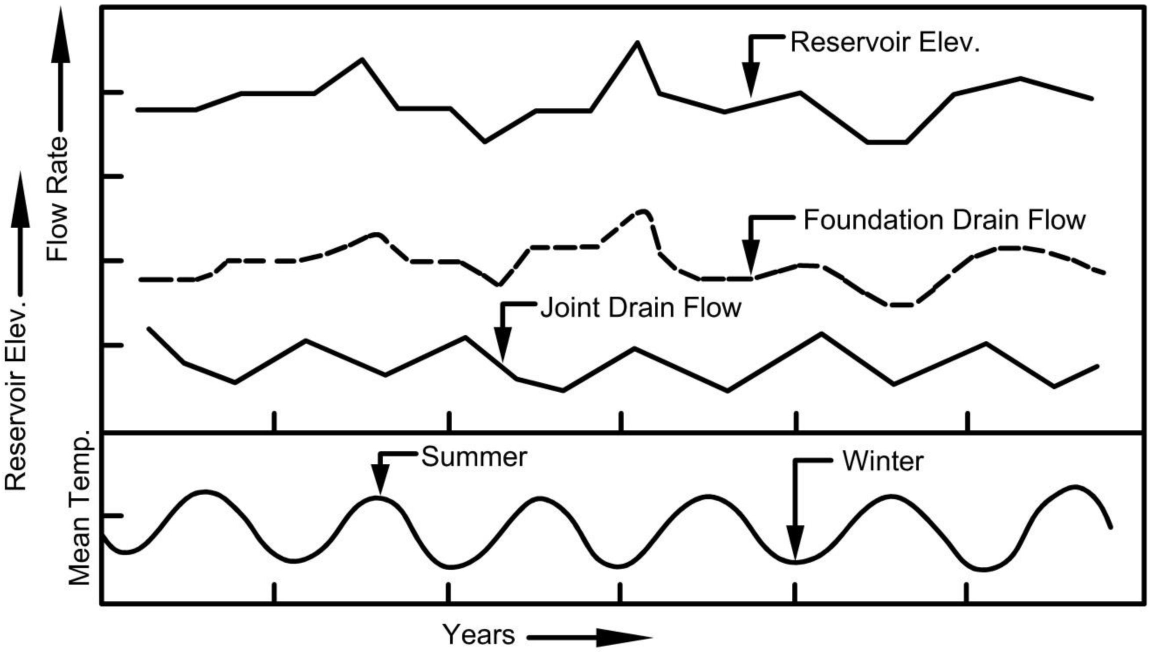


Figure 9-4. Seepage data plot

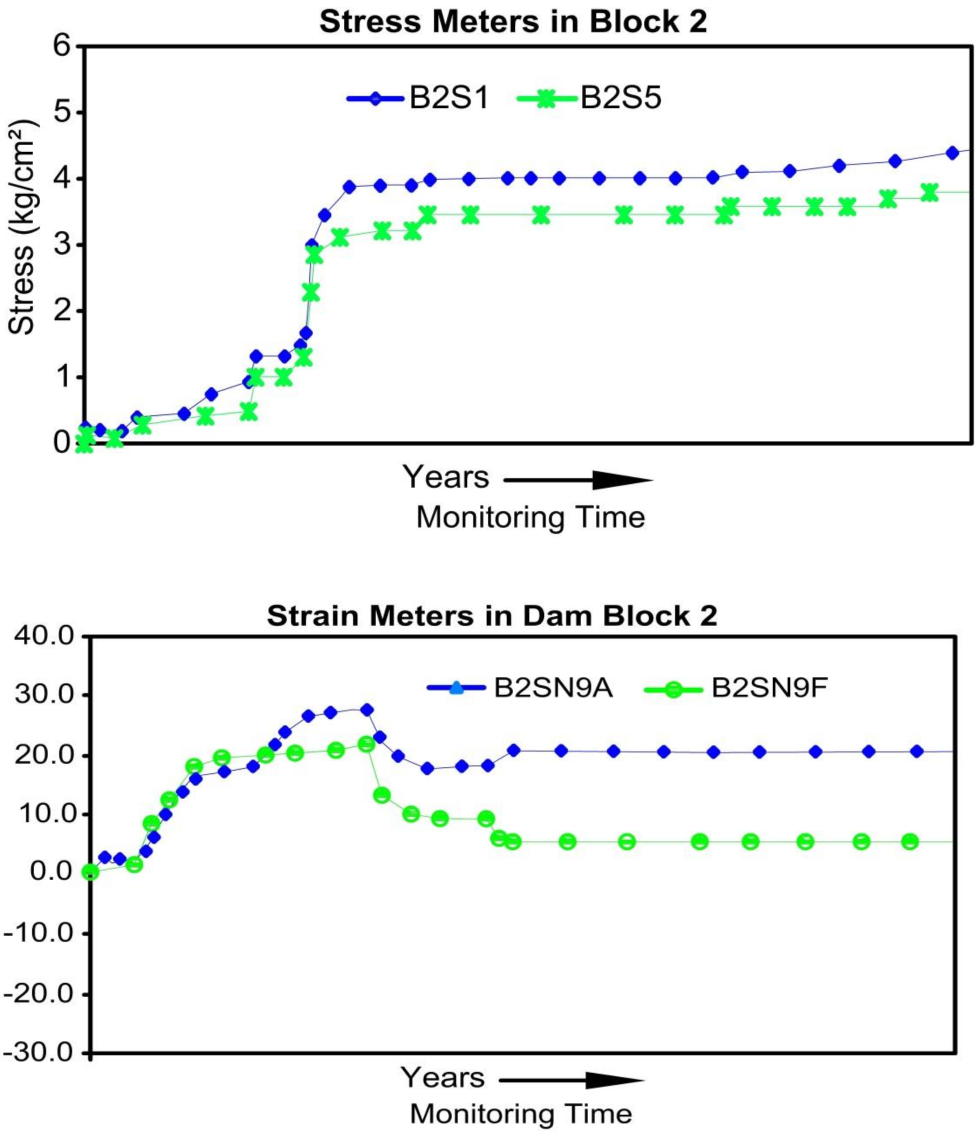


Figure 9-5. Correlation between Stress/Strain and Time for a concrete dam

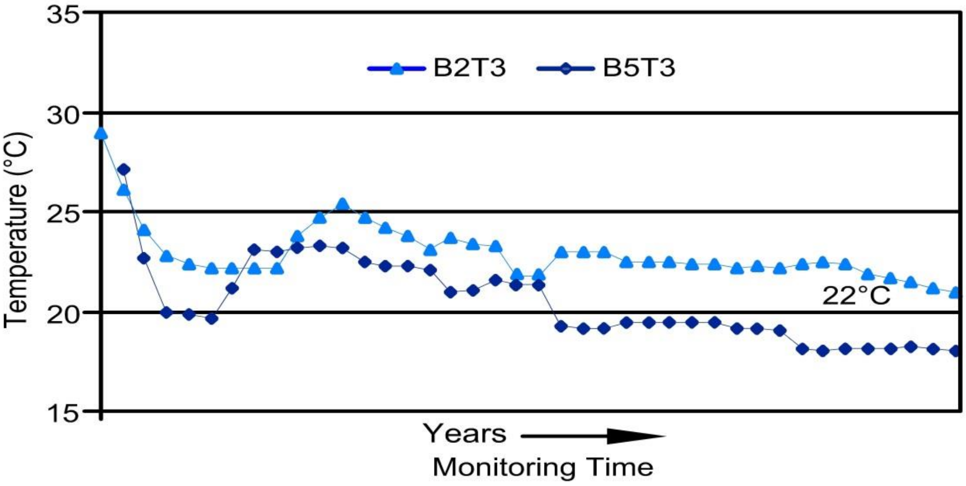
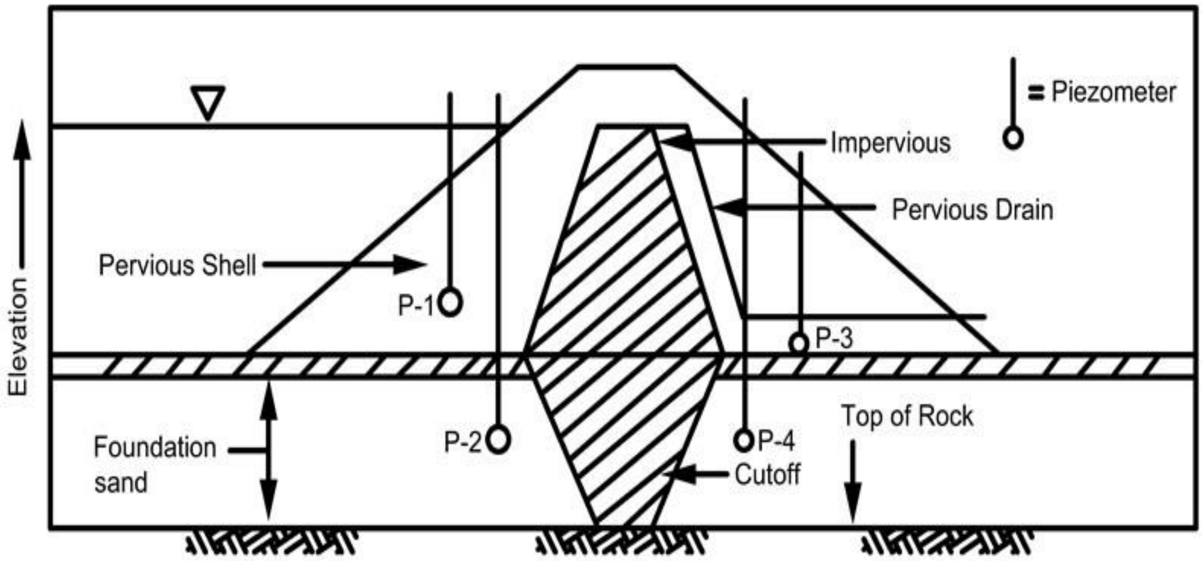


Figure 9-6. Concrete Dam Temperature Variation



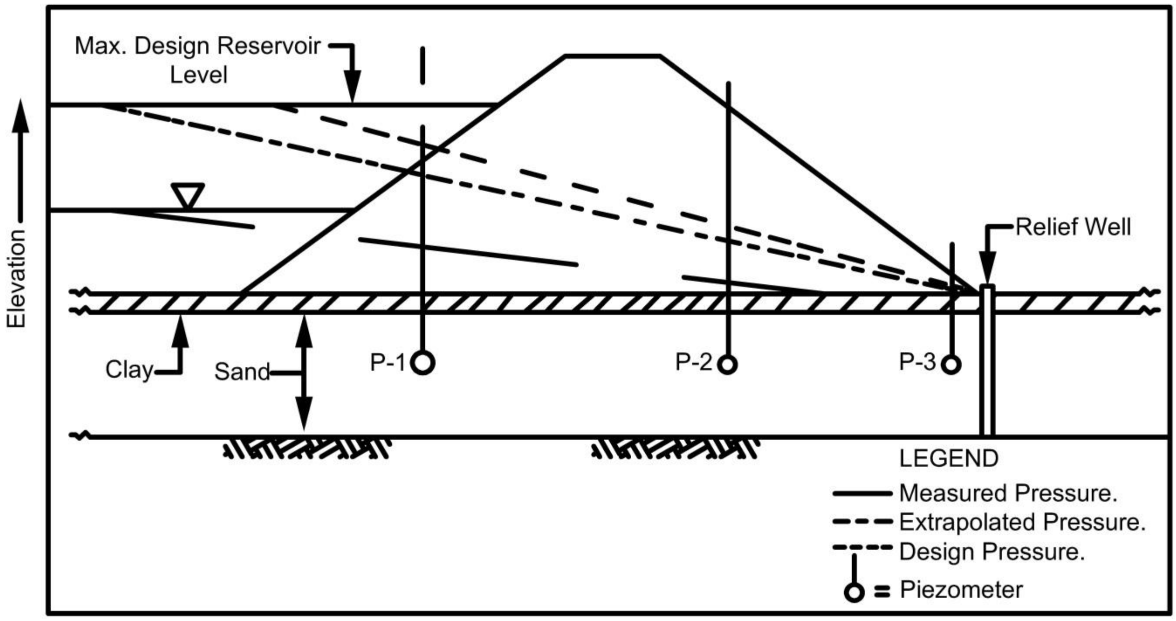


Figure 9-7. Piezometric pressure extrapolation for an embankment dam

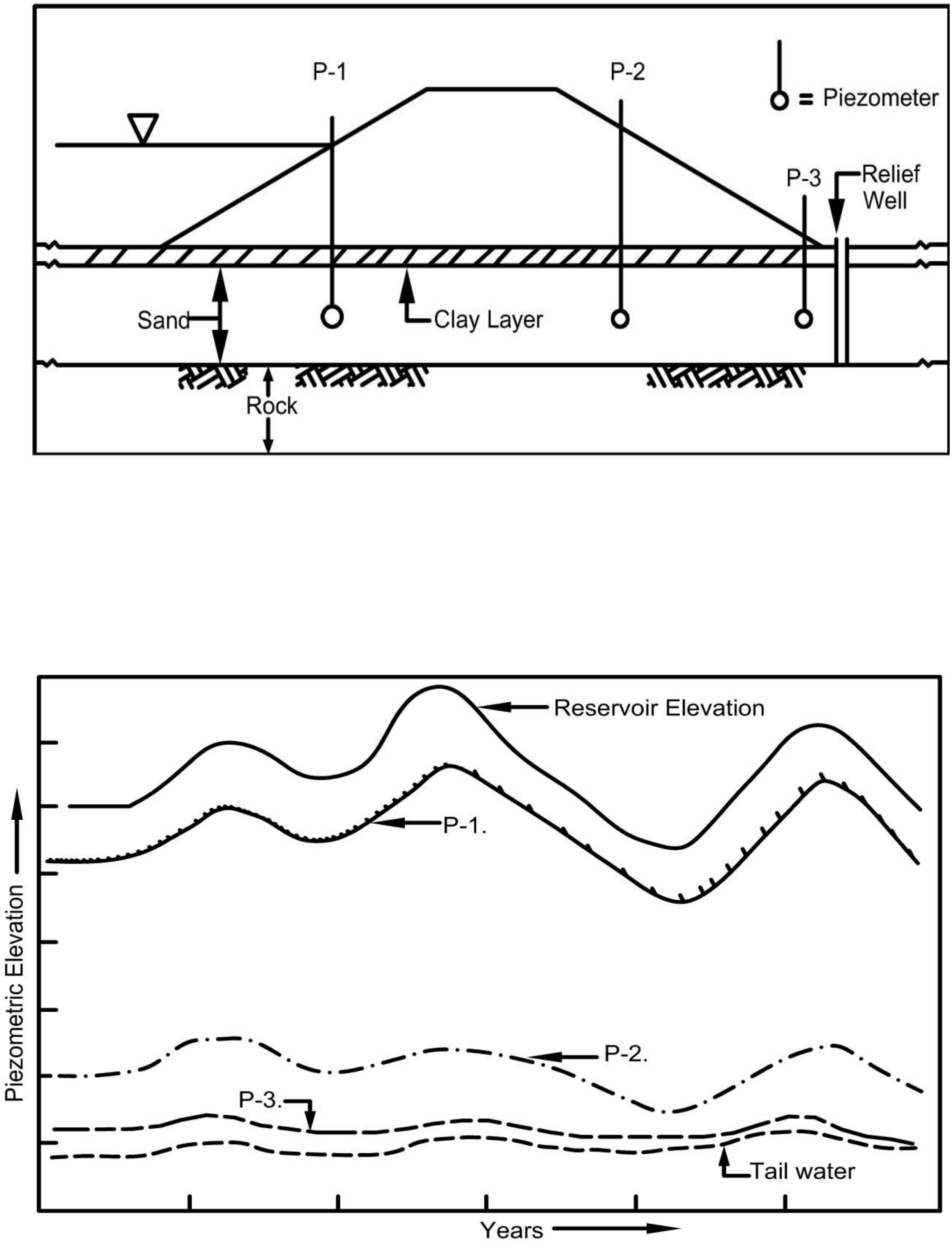


Figure 9-8. Piezometric pressure variation for embankment dam with clay layer in the foundation

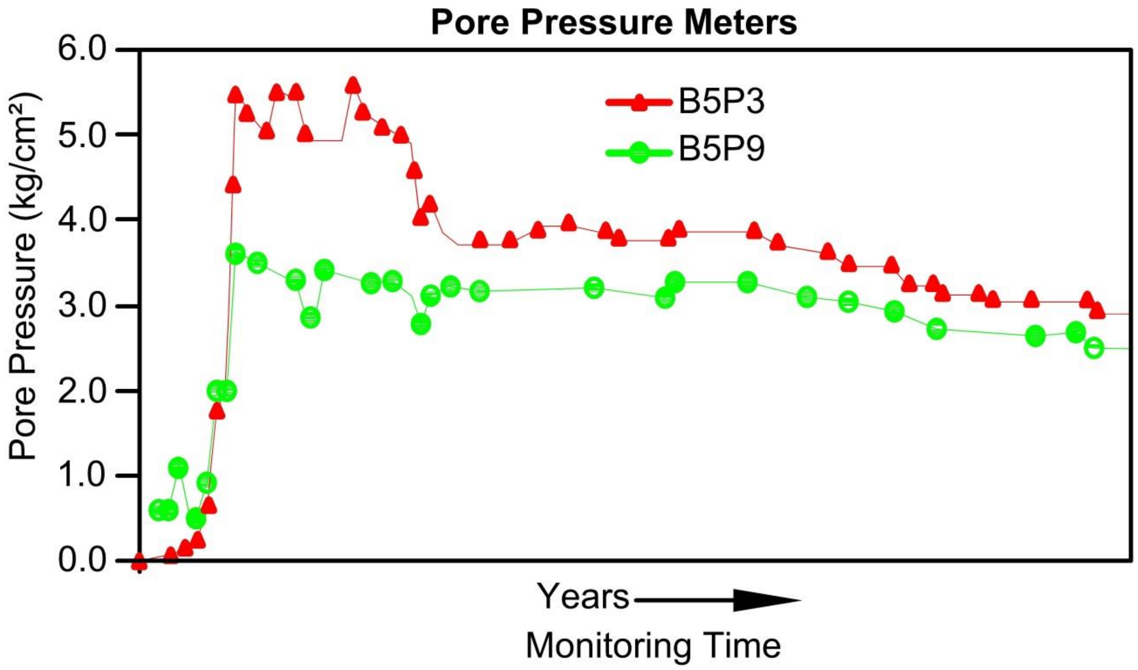


Figure 9-9. Piezometer Reading

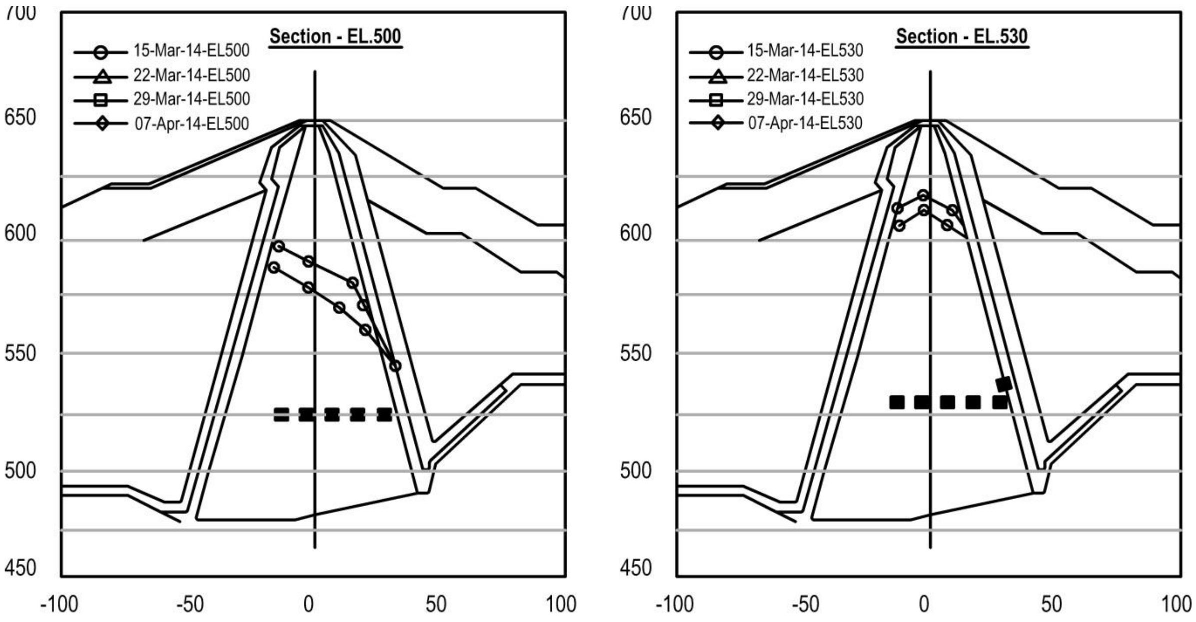
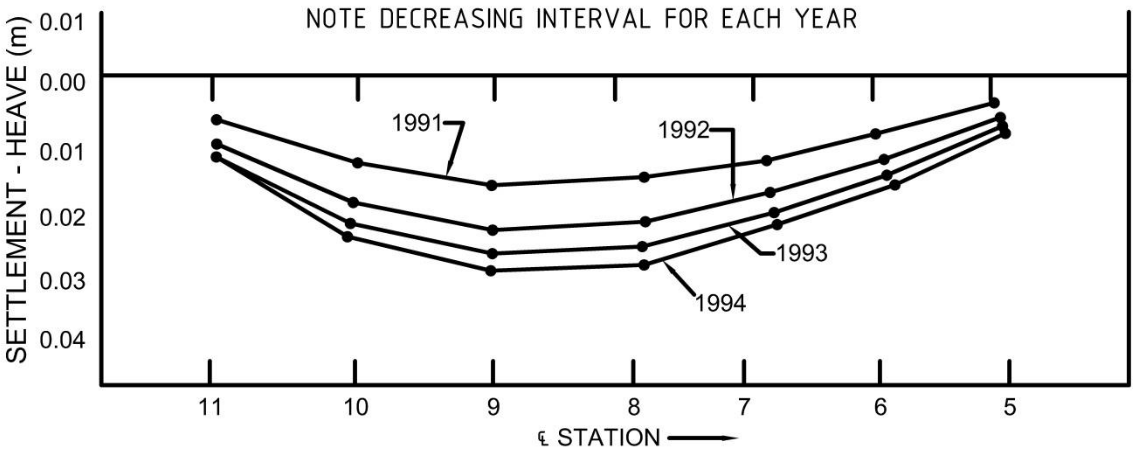
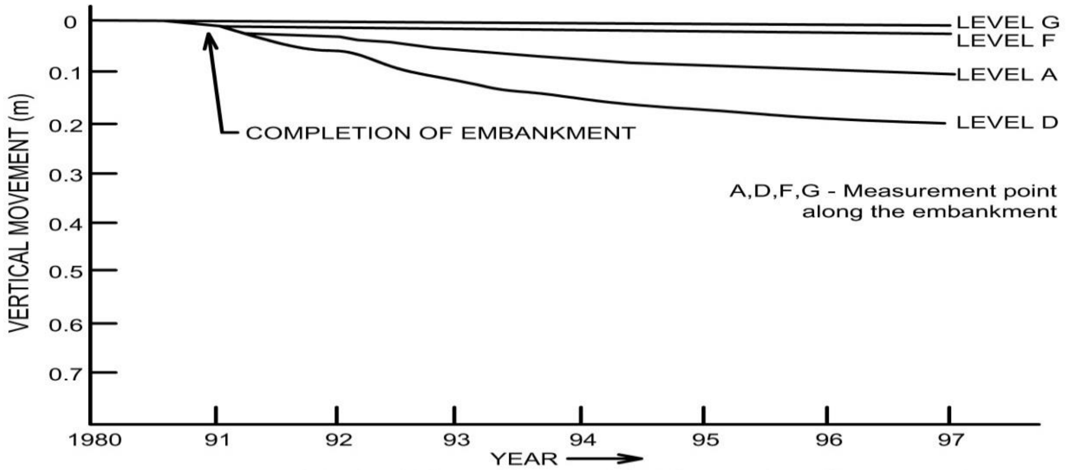


Figure 9-10. Pore Pressure Distribution in Clay Core of Dam

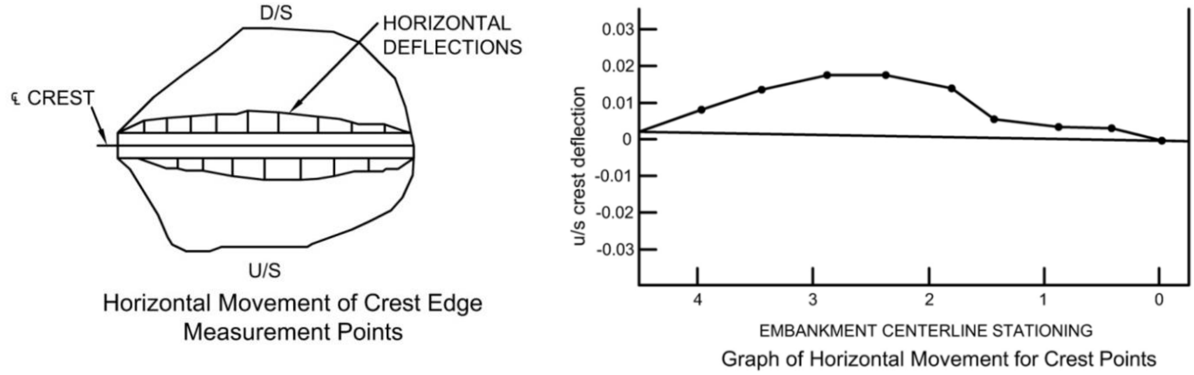


Profile View of Measurement Point Settlement



Typical Plot of Normal Settlement or Compression

Figure 9-11. Embankment Settlement Plot



Horizontal Movement of Crest Edge Measurement Points

Graph of Horizontal Movement for Crest Points

Figure 9-12. Embankment Horizontal Deformation

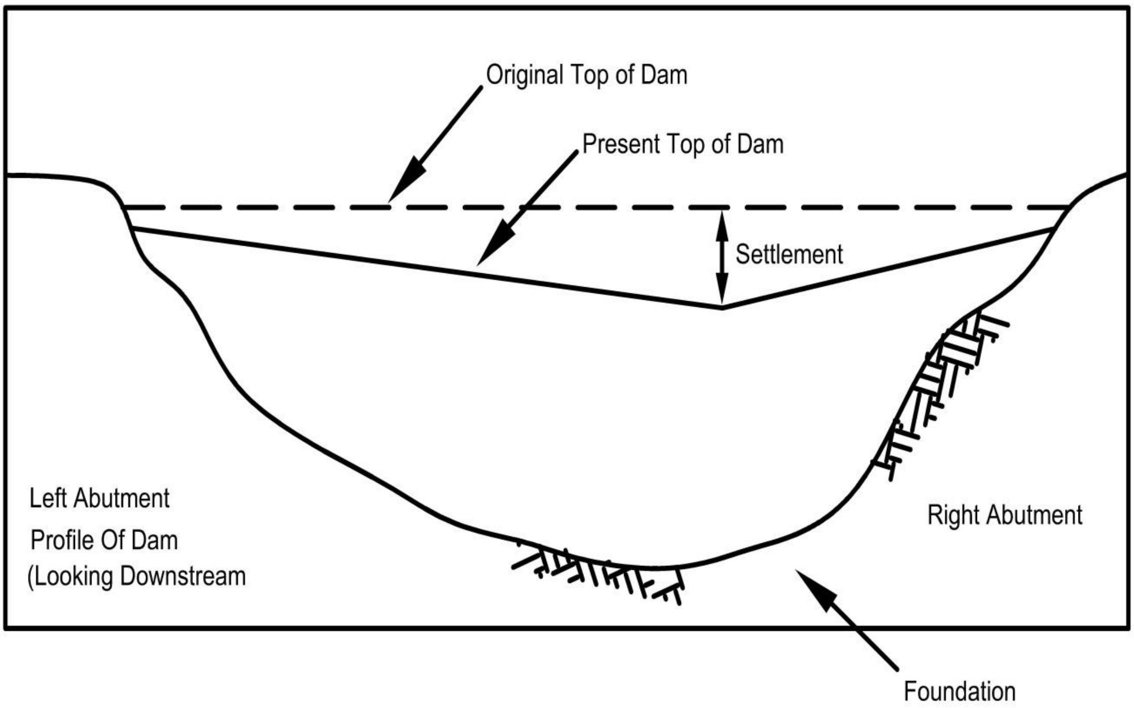


Figure 9-13. Vertical settlement movement plot

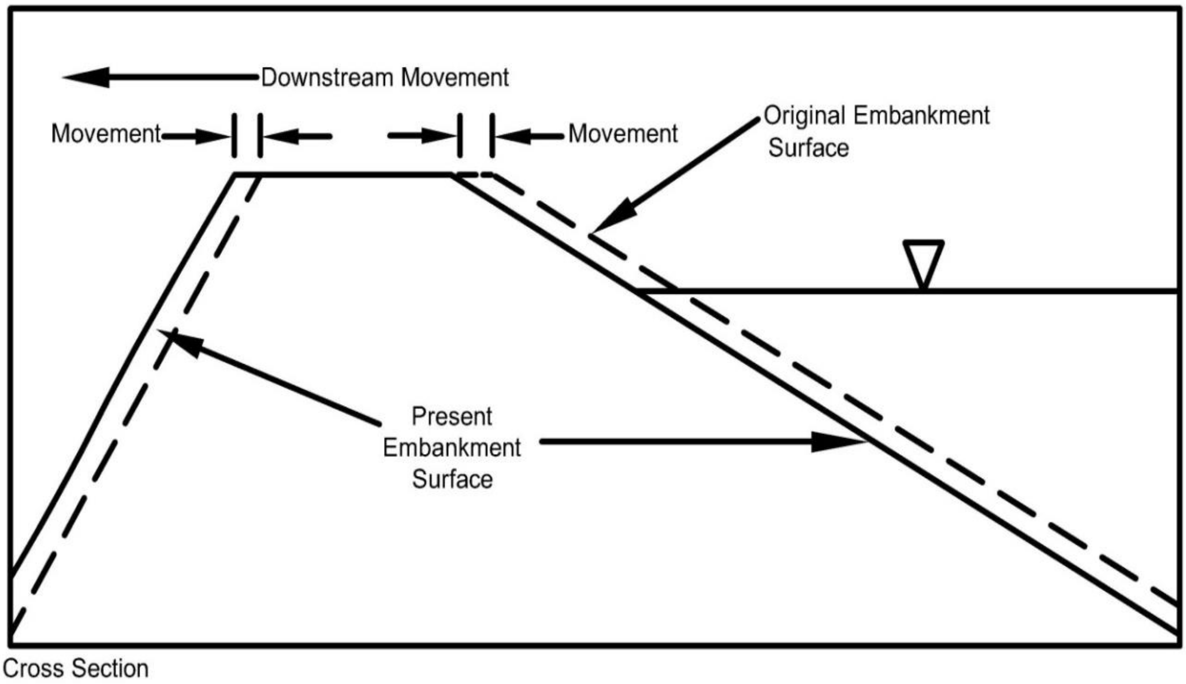
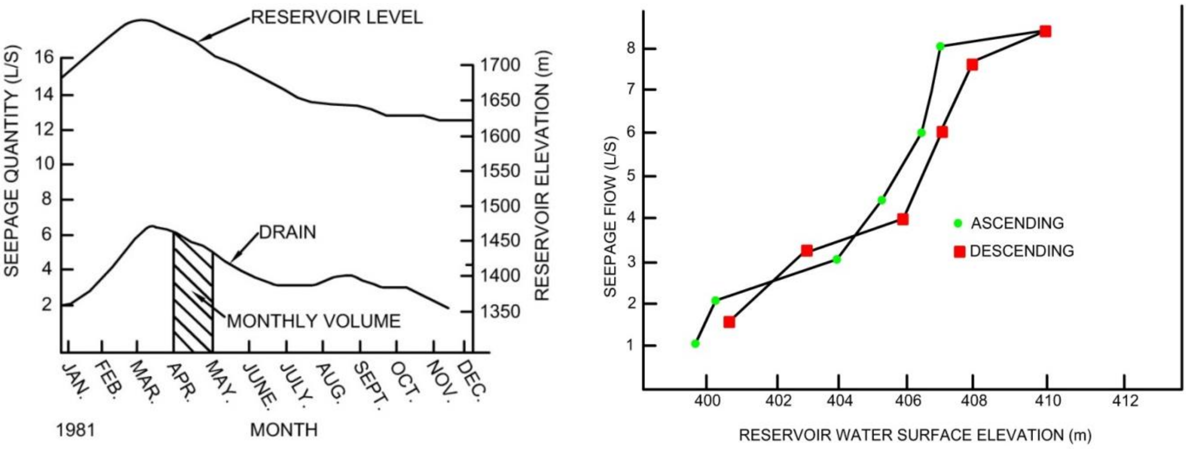


Figure 9-14. Horizontal downstream movement plot



Rate vs. Time Plot

Seepage Flow vs. Reservoir Elevation

Figure 9-15. Correlation between Leakage Quantity and Reservoir Water Level

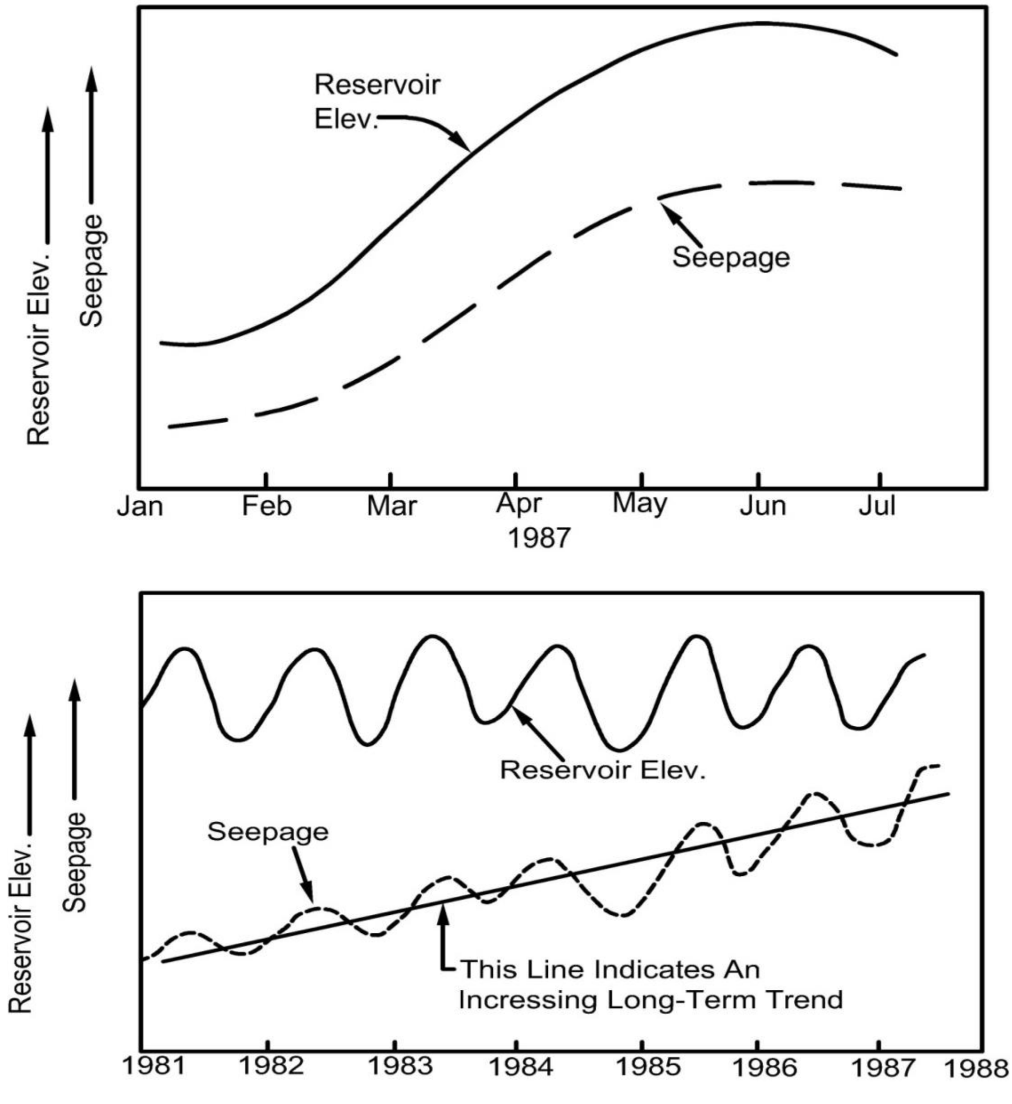


Figure 9-16. Plot of Seepage Vs Reservoir level over time –short term and long term trends

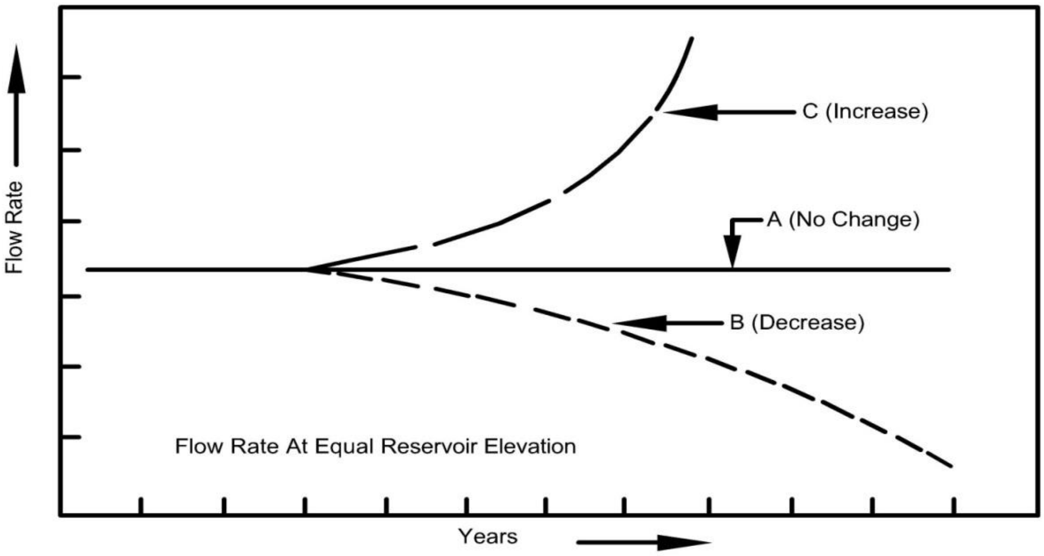


Figure 9-17. Seepage flow rate at constant reservoir elevation versus time

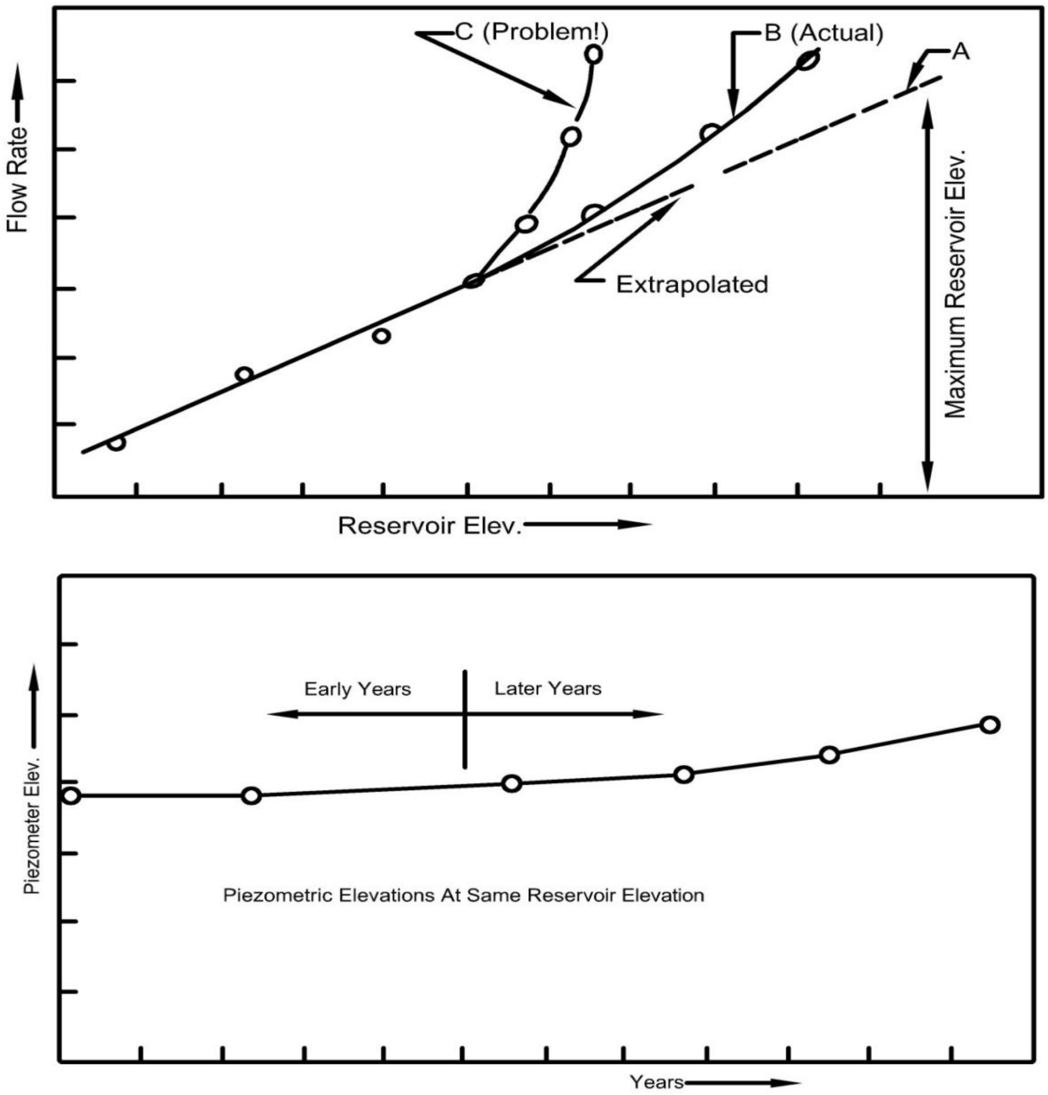


Figure 9-18. Seepage volume Vs Reservoir level plot

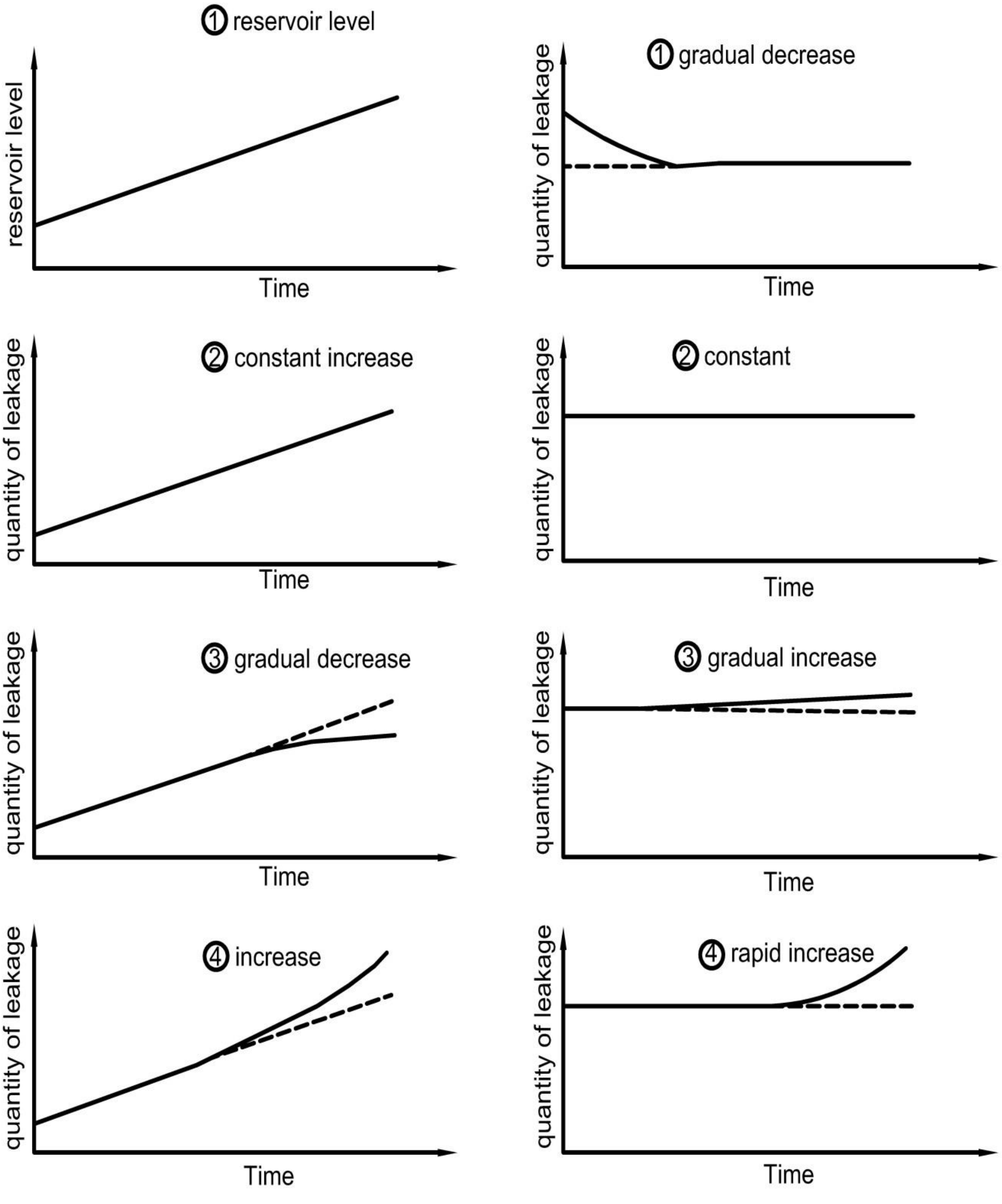


Figure 9-19. Correlation between Leakage Quantity and Time

Figure 9-19-1. In the Case of Reservoir Water Level Increases

Figure 9-19-2. In the Case of Reservoir Water Level Remain Constant

Chapter 10. AUTOMATION OF INSTRUMENTATION

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

The simplest level of automation is to use a data logger to read and store data for one or more instruments in an area. The data are periodically manually retrieved by removing (changing out) the data storage device and taking it to a computer, or by bringing a laptop computer to the data logger. (In some instances, the data logger itself is swapped out so as to retrieve the collected data by pen drive.) These simple data logger installations are fairly inexpensive and have low power requirements, which allow them to be fairly compact. This arrangement is appropriate when frequent readings of one or more instruments are desired, and real-time evaluation of the data is not required.

The next level of sophistication in automation is to have data automatically read at one or more locations at a dam site, and then transmitted to a convenient central location at the site. The central computer typically is the main data storage location. Transmittal approaches from the remote units to the central computer may be by radio or by hard-wire, or by a combination of the two approaches. The amount of "intelligence" residing in the remote units may vary greatly, from "less sophisticated" units that just respond to "orders" from the central computer, to "more intelligent" units that independently decide when readings are to be taken and transmitted, perhaps depending on the characteristics of recent data. Of course, there is a tradeoff between less sophisticated units that tend to be more compact, less expensive, and less likely to malfunction, and the more intelligent units that have greater capabilities. Performance limits can be entered into the central computer (and remote units), enabling real-time data evaluation.

Personnel at the central computer can see limit violations and system status information, and the central computer can also send out notifications regarding such information by text message, email, Web site posting, automated telephone call, etc.

The highest level of sophistication in automation is to not only have the data collected at a central location at the site, but also to make the data available to people at remote locations. Telephone / mobile communications allow a number of remote users to contact the central computer and download data, change reading frequencies, request that readings be taken at that time (if possible, based on the system configuration), etc. Telephone communication, although convenient, may be fairly expensive over time; may not be available during emergency situations, such as during a flood or post-earthquake, when readings may most be desired; and usually requires periodic initiation of contact by the remote users (i.e., it is not automatic). Another common communication alternative is to use satellites. Such communication is one-way communication (from the site to the remote users); therefore, no changes in reading frequencies, requests for instantaneous readings, or other two-way communications with the central computer are possible. However, routine transmittal of data to remote computer systems can be accomplished without operator involvement, inexpensively, and reliably. Data can then be posted to Web sites for broad access, if desired. It is a good idea to have both satellite and telephone communications because this provides a back-up communication source if problems occur.

Again, performance limits can be entered into the system, allowing real-time data evaluation. Alarm notifications, system status information, etc., can be transmitted by text message, email, Web site posting, automated telephone call, etc.

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

10.1 Power for remote equipment

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

10.2 Vandalism

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

Figure 10-1: Photograph of Satellite communication and solar panel installation in Vallakadavu observatory Kerala

10.3 Lightning protection

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

10.4 Notification protocols

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

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

- Pressure transducers placed down standpipes allow observation wells and open-standpipe piezometers to be automated.
- Pressure transducers can be integrated into the lines of hydraulic piezometer systems.
- Pressure transducers can be used with weirs and flumes to replace staff gauges.
- Vibrating-wire joint meters, strain gauges, or other electrical devices may be used to replace measuring between fixed points with calipers, micrometers, etc.
- In-place inclinometers can allow automation of existing inclinometer casing installations.

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

Advantages associated with the automation of instruments include:

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

Disadvantages sometimes associated with automation:

- Costs may be increased. Lightning

problems, vandalism, poor system design, poor system installation, poor or expensive system support, etc. can lead to automation costs that far exceed what is necessary simply to obtain the necessary readings manually. In most instances, it is not wise to choose automation simply because it is assumed that money will be saved, because experience typically shows this does not occur.

- Automation can lead to reduced human presence at the dam site, which may mean other adverse situations (which can only be detected by visual inspection) are less likely to be noticed in a timely fashion.
- When automation systems have problems, there are often not enough people available to obtain all the readings manually during the interim. Also, data files get polluted with bad data in significant amounts and on an ongoing basis until the problems are remedied.
- Manufacturers of automation systems may go out of business or discontinue certain products, making future repair and support of a system a problem.
- In some instances, the presence of an instrumentation automation system at a dam site, and all the maintenance and other activities required to keep it fully operational, can divert the attention of the dam operating personnel from the central task of looking after the health of the dam to the task of continually looking after the health of the automation system.

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

- A realistic assessment of the costs and benefits of automation.
- A manual (backup) reading capability for all automated instruments, independent of the automation system, in the event problems occur with the automation system, and to provide a means to check anomalous automated data.
- A well-conceived design that addresses threats to the system. Lightning and vandalism are usually the biggest concerns, but all potential threats to the system must be adequately dealt with.
- Redundancy in communication links, using both telephone and satellite, where real-time remote data evaluation is desired.
- A system that is as simple as possible and consistent with the data needs.
- As scope for the automation project that is as limited as possible. Instruments should not be automated just because they can easily be tied into the system. Before long, a small, simple project can become a big, overly complex project.
- Careful assessment of the technical capabilities of automation system equipment suppliers.
- Careful consideration of the future support and maintenance needs of the automation system

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

A typical automation plan for instrumentation of DRIP dams is shown in Figure 10-2 to Figure 10-4.

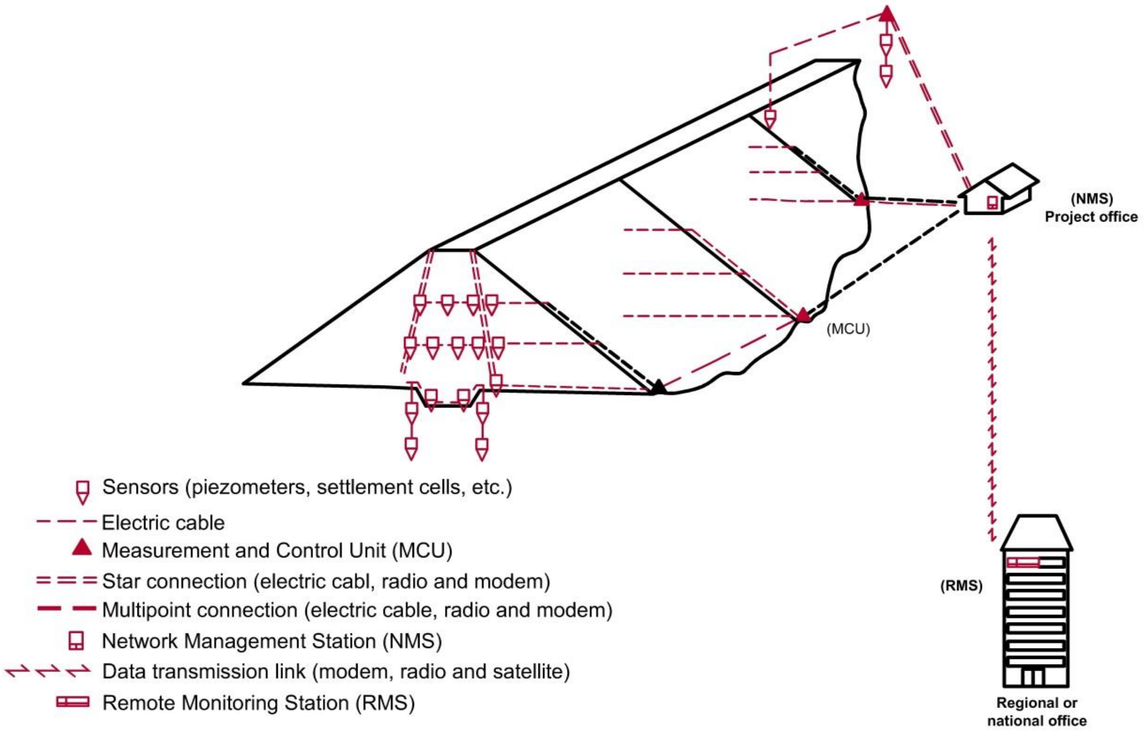


Figure 10-2. Typical Configuration for Data Acquisition and Remote Surveillance of a Dam

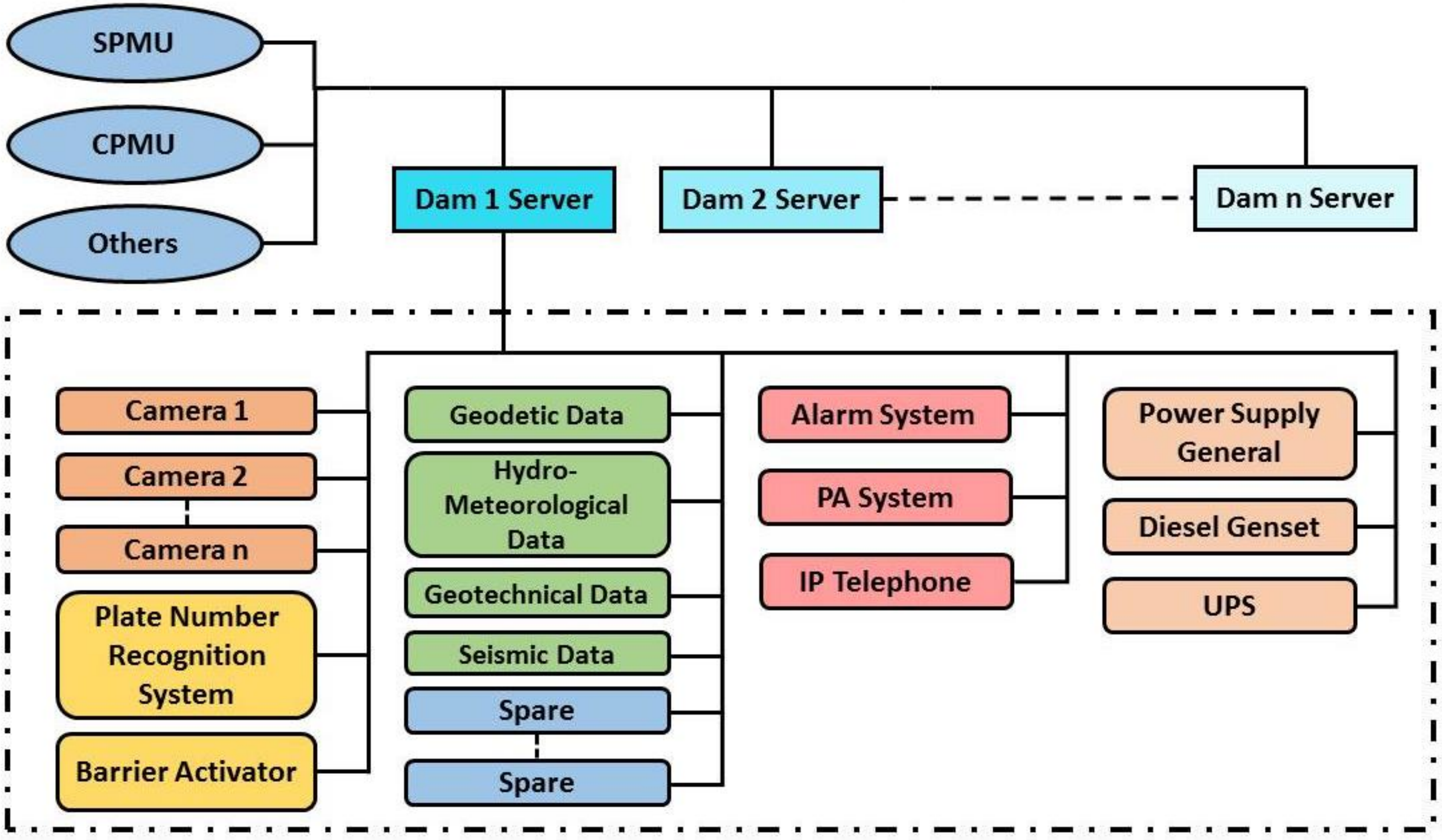


Figure 10-3. General Instrumentation and Surveillance System proposed for DRIP Dams

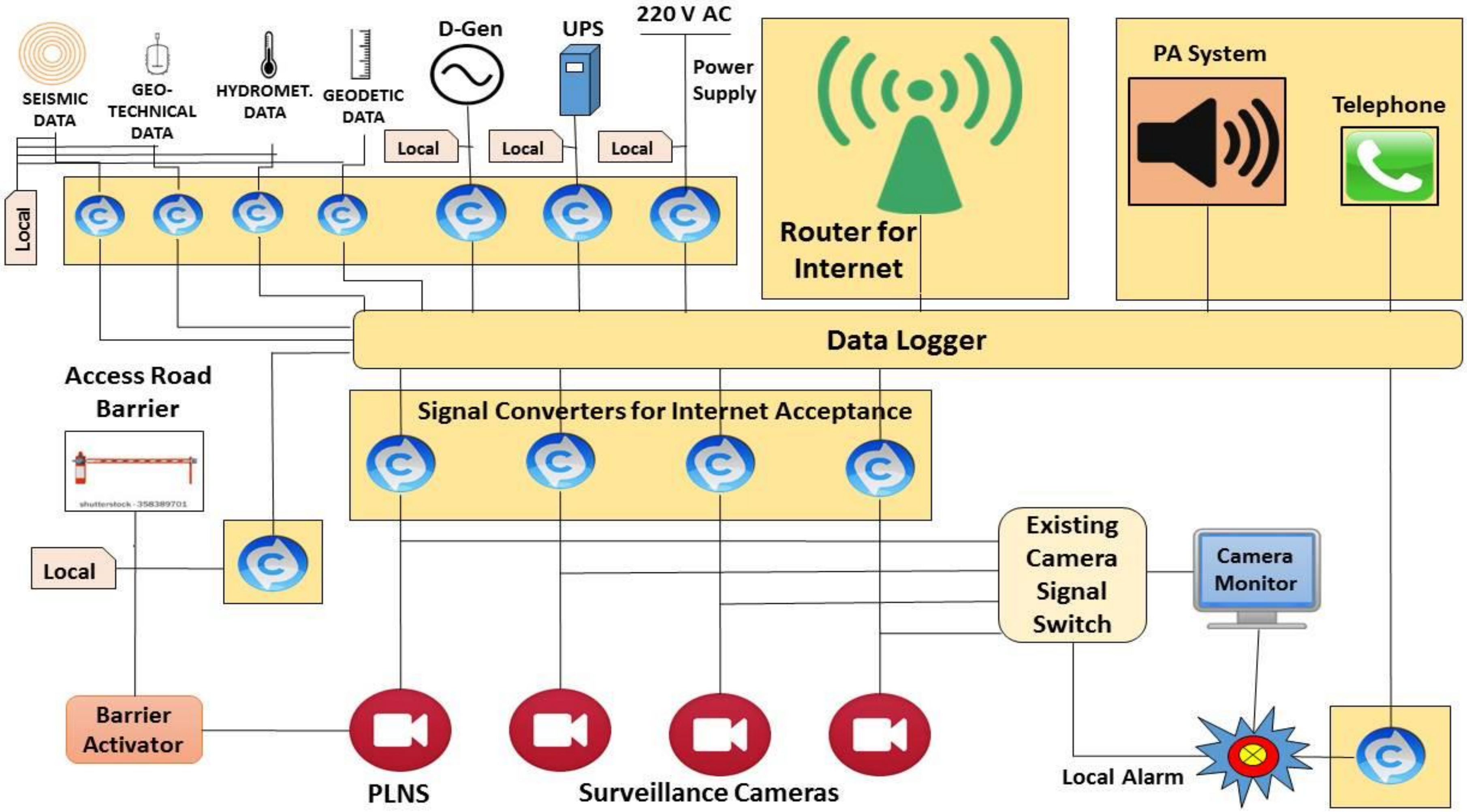


Figure 10-4. Integrated Instrumentation and Surveillance System for automated warning system for DRIP Dams

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Chapter 11. SUMMARY

The importance of a well-planned monitoring installation as an essential component of the maintenance and operation of a dam, particularly in an aging structure where early warning signs of failure may be detected, is widely accepted and in many countries, enforced by legislation.

11.1 Need for Dam Instrumentation

Catastrophic dam failure through the uncontrolled release of the impoundment will threaten life and property downstream. The safe functioning of a dam is an important matter of economic benefit and public safety. There are many historical cases of dam failures where early warning signs of severe problems might have been detected if a good monitoring program had been in place. Knowing that a dam is performing as expected is reassuring to dam owners, and the ability to detect a change in this performance is essential because the dam owner is directly responsible for the consequences of a dam failure. Therefore, a good dam safety monitoring program should be a key part of every dam owner's risk management program.

Deformation, settlement, water seepage, the diurnal and seasonal changes in reservoir levels, seismic activity and the aging of the structure all affect the health of the dam. Variations in the behavioral characteristics of the structure may be indicative of impending dam failure, and it is the primary goal of the monitoring system to detect such changes.

The use of instrumentation as part of dam safety programs is growing as the technology of instrumentation and ease of use improves. At an existing dam, instrumentation data help to design a monitoring program that offers more comprehensive and timely information to evaluate the on-going performance of the dam. With this information, dam owners can improve the efficiency of the operation and maintainence of their dams.

A few rules follow that can help guide the design of an instrumentation program:

- The purpose of the instrumentation program and underlying geotechnical and structural problems that create the need for instrumentation must be defined first.

- The instrumentation program must be comprehensive and carefully planned so that all the parameters that influence complications are measured.

- The data collected must be reduced to a convenient form, and the results must be available to the concerned authorities without unnecessary delay.

- There should be close cooperation between the designers, instrumentation specialists, monitoring data analysts, and site authorities to achieve the goal of the instrumentation program.

The checklist given in Appendix A summarizes the steps that need to be taken for systematic planning of an instrumentation system to monitor dam performance.

11.2 Managing Risks

An effective dam safety monitoring program is essential for dam owners to manage the risks associated with the operation and maintenance of a dam. The use of instrumentation can improve the dam owner's ability to monitor the on-going performance of the dam by providing more comprehensive and timelier information. Attributes of instrumented monitoring that can make it the best choice in relation to a situation include:

- Quantitative data are obtained for use by dam safety personnel in evaluating the ongoing performance of the dam.
- Data on the performance of foundation and interior of structures can be obtained.
- The instrumented data collection can be long-term in nature so that a steady stream of repeatable data can be produced for detection of subtle trends that may develop slowly over time.
- The collection of instrumentation data can be automated allowing for more frequent (near real time) surveillance of a dam's performance under both normal and extreme loading conditions.

Monitoring needs vary over the distinct phases that occur during the life of a dam. These phases typically include design, construction, first reservoir filling, long-term (normal operations), and dealing with unexpected performance. Instrumented monitoring can be an effective tool for obtaining the information needed during these separate phases. In addition to monitoring the performance of the dam, instrumentation data can also be valuable for litigation purposes or for research studies

11.3 Data Acquisition and Management

Logical planning of data acquisition and processing is essential if the aim of an instrumentation program is to be fully realized. Unless observations are reliable and the information is interpreted quickly, the value of a program will be severely diminished. Operating procedures must be carefully defined and the individual responsibilities of personnel defined. Within the operating plan, the frequency of monitoring should be chosen on a rational basis, reflecting the importance of the individual parameters under scrutiny. It is, in any event, subject to amendment in the context of the information retrieved.

Detailed prescription of periodicity is a question of common sense allied to engineering judgment. An excess of data will prove burdensome and may confuse critical issues; too little information will raise more questions than it resolves. Excessive complexity in a system, whether in terms of equipment or the operating skills needed, similarly diminishes its utility. A reasonable balance is therefore always needed, and care must be taken to ensure that the "system" remains sufficiently responsive and flexible. The monitoring routine should support observations at the different seasons and with significant changes in the reservoir water level.

Routines for quick processing of field data must be set up, considering the best form of presentation. Charts/Graphs and overlays are the most satisfactory method, with parameters plotted against reservoir water levels and precipitation. Illustrative schematic diagrams are shown in Johnston et al. (1999). It may sometimes prove useful to superimpose predetermined "safe limit" envelopes for certain key parameters (e.g. pore water pressures) on such plots

11.4 Conclusion

Some of the important conclusions are as follows:

1. Deformation, seepage/leakage quantity and quality, uplift pressure, pore water pressure, temperature, reservoir level and seismicity are the most important parameters to be measured and monitored in dams, whether they are new or existing.
2. Each dam is unique. Type and nature of the dam decides the number of instruments to be used and at what locations they are to be embedded in the dam
3. Masonry dams, because of their inherent heterogeneous nature, embedded instruments such as strain or stress meters etc., may not give the desired results. But at the same time deformation studies, could be done by the use of precision geodetic survey system, such as triangulation, pendulum, collimation, etc., and the dam's behavior understood properly
4. Concrete dams being more homogenous could give better results with embedded instruments The instruments should be of proven quality, and must be embedded carefully and precisely under expert supervision
5. Displacements of dam at any point or time are classically associated with reservoir water load, or temperature effect. Other causes include earthquakes, soil movements, abnormal seepage or structural failure
6. Deformation besides being obtained by precision geodetic survey can also be found out indirectly by plumb lines in case of masonry and concrete dams and by tiltmeter in case plumb lines are not installed in existing dams.

   The data obtained from these instruments give very valuable and reliable results of deformation in two mutually perpendicular directions
7. Deformation is preferably obtained by precision geodetic survey. It can also be found out indirectly by plumb lines in case of masonry and concrete dams and by tiltmeter in case Plumb lines are not installed in existing dams. The data obtained from these instruments give very valuable and reliable results of deformation in two mutually perpendicular directions. It is possible to separate the components of deformations due to hydrostatic pressure and the component due to other causes from the observed reading of plumb lines
8. Instrumentation Data must be collected periodically and analysed for assessing the safety of dam
9. Interpretation of the results must be made carefully and compared with the design parameters and specialized analysis carried out specially for existing dams. Deflections obtained from measurements of plumb lines and tilt meters should be well within the safe permissible limits

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REFERENCES

ASCE (2000). *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance.* Task Committee on Instrumentation and Monitoring Dam Performance, American Society of Civil Engineers, Reston, Virginia, United States.

Bartholomew, C. L., and Haverland, M. L. (1987*). Concrete Dam Instrumentation Manual.* United States Department of the Interior, Bureau of Reclamation, Engineering and Research Center, Denver, Colorado, United States.

Bartholomew, C. L., Murry, B. C., and Goins, B. L. (1987*). Embankment Dam Instrumentation Manual.* United States Department of the Interior, Bureau of Reclamation, Engineering and Research Center, Denver, Colorado, United States.

Bassett, R. (2012). *A Guide to Field Instrumentation in Geotechnics, Principles, Installation and Reading*. CRC Press, Boca Raton, Florida, United States.

Bolt, B. A., and Hudson, D. E. (1975). "Seismic instrumentation of dams." *Journal of the Geotechnical Engineering Division*, ASCE, 101(11), 1095-1104.

Charles, J. A., Tedd, P., and Watts, K. S. (1992). "The role of instrumentation and monitoring in safety procedures for embankment dams." in Parr, N. M. et al. (ed.), *Water Resources and Reservoir Engineering*, Proceedings of the Seventh Conference of the British Dam Society, Stirling, England, June 24-27, 1992, British Dam Society, London, United Kingdom, 311-320.

Charles, J. A., Tedd, P., Hughes, A. K., and Lovenbury, H. T. (1996) "Investigating embankment dams; a guide to the identification and repair of defects." *Building Research Establishment Report CI/SFB 187*, Construction Research Communications, Watford, United Kingdom.

Choquet, P. and Taylor, R. (2014). "Automatic Data Acquisition Systems (ADAS) for dam and levee monitoring." *Geo-Congress 2014 Technical Papers*, American Society of Civil Engineers, Reston, Virginia, United States, 180-191.

Dunnicliff, J. (1993). *Geotechnical Instrumentation for Monitoring Field Performance*. John Wiley and Sons, New York, United States.

Evans, J. D., and Wilson, A. C. (1992). "The instrumentation, monitoring and performance of Roadford Dam during construction." in Parr, N. M. et al. (ed.), *Water Resources and Reservoir Engineering*, Proceedings of the Seventh Conference of the British Dam Society, Stirling, England, June 24-27, 1992, British Dam Society, London, United Kingdom, 157-166.

Federal Emergency Management Agency (FEMA),(1993) *Federal Guidelines for Dam Safety,* Publication Number FEMA 93,

Federal Energy Regulatory Commission (FERC),(2005) *Engineering Guidelines for the Evaluation of Hydropower Projects,* "Dam Safety Performance Monitoring Program – Chapter 14," Revision 1, 1

Golzé, A. R. (ed.) (1977). *Handbook of Dam Engineering.* Van Nostrand Reinhold Company, New York, United States.

Goltz, M., Aufleger, M., Dornstadter, J., and Mangarovski, O. (2011). "Distributed fiber optic temperature measurements in embankment dams with central core- new benchmark for seepage monitoring." *Proceedings of the Symposium SLOCOLD-MACOLD*, Skopje, Slovenia, 17 November 2011, Slovenian National Committee on Large Dams, Macedonian Committee on Large Dams, 123-132.

Hanna, T. H. (1985). *Field Instrumentation in Geotechnical Engineering.* Volume 10 of the Series on Rock and Soil Mechanics, Trans Tech Publications, Zurich, Switzerland.

Hartog, A. H. (2017). *An Introduction to Distributed Optical Fibre Sensors*. CRC Press, Boca raton, Florida, United States.

Hughes, A. K., Hewlett, H. W. M., Morris, M. W., Sayers, P., Moffat, A. I. B., Harding, A., and Tedd, P. (2000) Risk Management for UK Reservoirs. *Report C452*, Construction Industry Research and Information Association (CIRIA), London, United Kingdom.

ICOLD (1983). "Deterioration of dams and reservoirs -examples and their analysis." *Miscellaneous Report*, Portuguese Committee on Deterioration of Dams and Reservoirs, International Commission on Large Dams, Paris, France.

ICOLD (1988). "Dam monitoring – general considerations." *Bulletin 60*, Committee on Monitoring of Dams and their Foundations, International Commission on Large Dams, Paris, France.

ICOLD (1989). "Monitoring of dams and their foundations – State of the art." *Bulletin 68*, Committee on Monitoring of Dams and their Foundations, International Commission on Large Dams, Paris, France.

ICOLD (1992). "Improvement of existing dam monitoring – recommendations and case histories." *Bulletin 87*, Committee on Monitoring of Existing Dams, International Commission on Large Dams, Paris, France.

ICOLD (2000). "Automated dam monitoring systems – guidelines and case histories." *Bulletin 118*, Committee on Automated Dam Monitoring Systems, International Commission on Large Dams, Paris, France.

ICOLD (2009). "Surveillance: basic elements in a 'dam safety' process." *Bulletin 138*, Committee on Dam Surveillance, International Commission on Large Dams, Paris, France.

ICOLD (2011). "Seismic observation of dams – guidelines and case studies." *Bulletin 113*, Committee on Seismic Aspects of Dam Design, International Commission on Large Dams, Paris, France.

ICOLD (2011). "Reservoirs and seismicity – state of knowledge." *Bulletin 137*, Committee on Seismic Aspects of Dam Design International Commission on Large Dams, Paris, France.

ICOLD (2011). "Small dams – design, surveillance, and rehabilitation." *Bulletin 157*, Committee on Small Dams, International Commission on Large Dams, Paris, France.

ICOLD (2013). "Selecting seismic parameters for large dams—guidelines (revision of Bulletin 72)." *Bulletin 148*, Committee on Seismic Aspects of Dam Design, International Commission on Large Dams, Paris, France.

ICOLD (2014). "Dam surveillance guide." *Bulletin 158*, Committee on Dam Surveillance, International Commission on Large Dams, Paris, France.

ICOLD (2006). *World Register of Dams*. http://www.icold-cigb.net/GB/world_register/world_register_of_dams.asp.

Institution of Civil Engineers (1990). *Geotechnical Instrumentation in Practice: Purpose, Performance, and Interpretation*. Proceedings of the Conference Geotechnical Instrumentation in Civil Engineering Projects, Nottingham, United Kingdom, 3-5 April 1989.

Johnston, T. A., Millmore, J. P., Charles, J. A., and Tedd, P. (1999) *An Engineering Guide to the Safety of Embankment Dams in the United Kingdom (2nd ed.)*. Construction Research Communications, Watford, United Kingdom.

Kilpatrick, F. A., and Schneider, V. R. (1983). "Use of flumes in measuring discharge." *Techniques of Water-Resources Investigations, Book 3, Chapter A14*, U.S. Geological Survey, Reston, Virginia, United States.

Kofler, B. (2010). "Automated monitoring, strategy and procedure employed by Verbund-Austrian Hydro Power." *Proceedings of the 8th ICOLD European Club Symposium*, 22-23 September 2010, Innsbruck, Austria, 531-535.

Mathur, G.N, Chawla, A.S, Sundaraiya, E. (2004) *Instrumentation of Dams,* Publication No.287, Central Board of Irrigation and Power

Novak, P., Moffat, A. I. B., Nalluri, C., and Narayanan, R. (2007). *Hydraulic Structures (4th ed.)*, Taylor & Francis, Milton Park, Abingdon, Oxon, United Kingdom.

Pelton, F., et al.,(2000) *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance,* ASCE, Reston,

Penman, A. D. M., Saxena, K. R., and Sharma, V. M. (1999). *Instrumentation, Monitoring, and Surveillance: Embankment Dams*. Oxford & IBH Publishing Company, New Delhi, India.

Pircher, W. (2001). "Trends in dam surveillance." *Hydropower and Dams*, International Hydropower Association, United Kingdom, 7(3), 81-84.

Robertshaw, A. C., and Dyke, T. N. (1990). "The routine monitoring of embankment dam behavior." In *Proceedings of the Conference on the Embankment Dam*, British Dam Society, London, 177-184.

Stateler, J. N. (2014). "Embankment dams – Chapter 11: Instrumentation and monitoring." *Design Standards No. 13*, United States Department of the Interior, Bureau of Reclamation, Engineering and Research Center, Denver, Colorado, United States.

Tanchev, L. (2014). *Dams and Appurtenant Hydraulic Structures* (2nd ed.). CRC Press, Boca Raton, Florida, United States.

Texas Commission on Environmental Quality (2006). *Guidelines for Operation and Maintenance of Dams in Texas*. Austin, Texas, United States.

USACE (1987). "Management of water control systems." *Engineering Manual EM 1110-2-3600*, Department of the Army, Washington, D.C

USACE (1997). "Hydrologic engineering requirements for reservoirs." *Engineering Manual EM 1110-2-1420*, Department of the Army, Washington, D.C.

USACE (2008). "Coastal engineering manual: Part II - Chapter 2 - Meteorology and wave climate." *Engineering Manual EM 1110-2-1100*, Department of the Army, Washington, D.C.

USBR (1981). "Freeboard criteria and guidelines for computing freeboard allowances for storage dams." *ACER Technical Memorandum No. 2*, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, United States.

USBR (1977). *Design of arch dams.* U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, United States.

USACE (1980). "Instrumentation for concrete structures." *Engineer Manual 1110-2-4300*, U.S. Department of the Army, Corps of Engineers, Washington, D.C.

USACE (1995). "Instrumentation of embankment dams and levees." *Engineer Manual 1110-2-1908*, U.S. Department of the Army, Corps of Engineers, Washington, D.C.

USBR (1976). *Design of Gravity Dams - Design Manual for Concrete Gravity Dams.* U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, United States.

USBR (2014). "Embankment dams - Chapter 11: Instrumentation and monitoring." *Design Standards No. 13*, U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, United States.

USBR (1988). "*Training Aids for Dam Safety, Module – Instrumentation for Embankment and Concrete Dams.",* U.S. Department of the Interior, Bureau of Reclamation, Denver, Colorado, United States.

USSD (2002). *General Guidelines for Automated Performance Monitoring of Dams.* Committee on Monitoring of Dams and Their Foundations United States Society on Dams, Denver, Colorado, United States.

U. S. Weather Bureau (1957-1960). "Rainfall intensity-frequency regime." *Technical Paper 29 (Parts 1-5)*, Washington, D.C.

WMO (2008). "Guide to hydrological practices, volume I: Hydrology – from measurement to hydrological information, 6th ed." *WMO-No. 168*, World Meteorological Organization, Geneva, Switzerland.

WMO (2010a). "Manual on stream gauging: Volume I – fieldwork." *WMO-No. 1044*, World Meteorological Organization, Geneva, Switzerland.

WMO (2010b). "Manual on stream gauging: Volume II – computation of discharge." *WMO-No. 1044*, World Meteorological Organization, Geneva, Switzerland.

WMO (2014). "Guide to meteorological instruments and methods of observation." *WMO-No. 8*, World Meteorological Organization, Geneva, Switzerland.

Appendix A. CHECKLIST FOR INSTRUMENTATION PLANNING

The steps that need to be taken for systematic planning of an instrumentation system to monitor dam performance are summarized in this appendix in the form of the following checklist (modified from Dunnicliff 1993):

Step number	Description
1.	Define the Project Conditions
	a) Project type b) Project layout c) Subsurface stratigraphy and engineering properties d) Groundwater conditions e) Status of nearby structures or other facilities f) Environmental conditions g) Planned construction method h) Knowledge of crisis situation
2.	Predict Mechanisms that Control Behaviour
	a) Prior to developing a program of instrumentation, one or more working hypotheses must be prepared for mechanisms that are likely to control behaviour. b) The hypotheses must be based on a comprehensive knowledge of project conditions, as described above.
3.	Define the Geotechnical Questions that Need to be Answered
	c) Every instrument on a project should be selected and placed to aid in answering a specific question. Before considering measurement methods, a listing should be made of geotechnical issues that are likely to arise during the design, construction, or operation phases.
4.	Define the Purpose of the Instrumentation
	i) Benefits during the design i. Definition of initial site conditions ii. Proof testing iii. Fact-finding in crisis situations j) Benefits during construction i. Safety ii. Observational method iii. Construction control iv. Provision of legal protection v. Measurement of fill quantities vi. Enhancing public relations

Step number	Description
	vii. Advancing the current practice k) Verifying satisfactory performance after construction is complete
5.	Select the Parameters to be Monitored
	a) Pore-water pressure or joint water pressure b) Total stress within soil mass c) Total stress at contact with structure or rock d) Stress within rock mass e) Vertical deformation f) Horizontal deformation g) Tilt h) Strain in soil or rock i) Load or strain in structural members j) Temperature
6.	Predict Magnitudes of Change
	a) Predict maximum value, thus instrument range b) Predict minimum value, thus instrument sensitivity or accuracy c) Determine hazard warning levels
7.	Devise Remedial Action
	a) Devise action for each hazard warning level, ensuring that labor and materials will be available b) Determine who will have contractual authority for initiating remedial action c) Ensure that communication channel is open between design and construction personnel d) Determine how all parties will be forewarned of planned remedial actions
8.	Assign Tasks for Design, Construction, and Operation Phases
	a) Assign supervisory responsibility for tasks by instrumentation specialist b) Plan liaison and reporting channels c) Plan who has overall responsibility and contractual authority for implementation
9.	Select Instruments
	a) Plan for high reliability: i. study the suggested recipe for reliability ii. maximum simplicity iii. do not allow the lowest cost to dominate the selection iv. maximum durability in installed environment

Step number	Description
	v. minimum sensitivity to climatic conditions vi. good past performance record vii. consider transducer, readout unit, and communication system separately viii. is reading necessarily correct? ix. can calibration be verified after installation? a) Discuss application with manufacturer b) Recognize any limitations in skill or quantity of available personnel c) Consider both construction and long-term needs and conditions d) Ensure proper conformance e) Ensure minimum interference to construction and minimum access difficulties f) Determine need for automatic data acquisition system g) Plan readout type and arrangements, consistent with required reading frequency i. Plan need for spare parts and standby readout units ii. Evaluate adequacy of lead time iii. Evaluate adequacy of time available for installation iv. Question whether the selected instrument will achieve the objective
10.	Select Instrument Locations
	a) Identify zones of primary concern b) Select primary instrumented sections c) Select secondary instrumented sections d) Plan quantities to account for less than 100% survival e) Arrange locations to provide early data f) Arrange locations to provide cross-checks g) Avoid nonconformance or weakness at clusters
11.	Plan Recording of Factors that May Influence Measured Data
	a) Construction details b) Construction progress c) Visual observations of expected and unusual behavior d) Geology and other subsurface conditions e) Environmental factors
12.	Establish Procedures for Ensuring Reading Correctness
	a) Visual observations b) Duplicate instruments c) Backup system

Step number	Description
	d) Study of consistency e) Study of repeatability f) Regular in-place checks
13.	List the Specific Purpose of Each Instrument
	a) At this point in the planning, it is useful to question whether all planned instruments are justified. The purpose of each planned instrument should be described. b) If no practical, specific purpose can be found for a planned instrument, it should be removed.
14.	Prepare Budget: Include Costs for:
	a) Planning monitoring program b) Making detailed instrument designs c) Obtaining instruments d) Making factory calibrations e) Installing instruments f) Keeping up and calibrating instruments on a regular schedule g) Creating and updating data collection schedule h) Collecting data i) Processing and presenting data j) Interpreting and reporting data k) Deciding on implementation of results
15.	Write Instrument Procurement Specifications
	a) Assign responsibility for procurement i. construction contractor ii. owner iii. design consultant iv. instrument suppliers acting as assigned subcontractors b) Select specifying method i. descriptive specification, with brand name and model number ii. descriptive specification, without the brand name and model number iii. performance specification c) Select basis for deciding on price i. Negotiation ii. bid d) Write specifications e) Plan factory calibrations f) Plan acceptance tests when instruments are first received and determine

Step number	Description
	responsibility
16.	Plan Installation
	a) Prepare systematic installation procedure well in advance of scheduled installation dates, including list of required materials and tools b) Prepare installation record sheets c) Plan staff training d) Coordinate plans with contractor e) Plan access needs f) Plan protection from damage and vandalism g) Plan installation schedule
17.	Plan Regular Calibration and Maintenance
	a) Plan calibrations during service life i. readout units ii. embedded components b) Plan maintenance i. readout units ii. field terminals iii. embedded components
18.	Plan Data Collection, Processing, Presentation, Interpretation, Reporting, and Implementation mentation
	a) Plan data collection i. prepare preliminary detailed procedures for collection of initial and subsequent data ii. prepare field data sheets iii. plan staff training iv. plan data collection schedule v. plan access needs b) Plan data processing and presentation i. determine need for automatic data processing ii. prepare preliminary detailed procedures for data processing and presentation iii. prepare calculation sheets iv. plan data plot format v. plan staff training c) Plan data interpretation i. prepare preliminary detailed procedures for data interpretation d) Plan reporting of conclusions i. define reporting requirements, contents, frequency

Step number	Description
	e) Plan implementation i. verify that all Step 7 items are in place
19.	Write Contractual Arrangements for Field Instrumentation Services
	a) Select field service contract method b) Write detailed specifications
20.	Update Budget
	Planning is now complete, and the budget for all tasks should be updated considering all planning steps.

Appendix B. INDIAN STANDARDS RELATED TO DAM INSTRUMENTATION

A list of Indian Standards related to dam instrumentation is given in Table B-1.

Table B-1. Indian Standards Related to Dam Instrumentation

Standard number	Year published	Description
IS: 1191	2003	Hydrometric determinations -- vocabulary and symbols
IS: 4967	1968	Recommendations for seismic instrumentation for river valley projects
IS: 6524	1972	Code of practice for installation and observation of instruments for temperature measurements inside dams; resistance type thermometers
IS: 6532	1972	Code of practice for design, installation, observation and maintenance of uplift pressure pipes for hydraulic structures on permeable foundations
IS: 7356-1	2002	Code of practice for installation, maintenance and observation of instruments for pore pressure measurements in earth dams and rockfill dams, Part 1: Porous tube piezometers
IS: 7356-2	2003	Installation, observation and maintenance of instruments for pore pressure measurements in earth and rockfill dams - code of practice, Part 2: Twin tube hydraulic piezometers
IS: 7436-1	1993	Guide for types of measurements for structures in river valley projects and criteria for choice and location of measuring instruments, Part 1: For earth and rockfill dams
IS: 7436-2	1997	Guide for types of measurements for structures in river valley projects and criteria for choice and location of measuring instruments, Part 2: Concrete and masonry dams
IS: 7500	2000	Code of practice for installation and observation of cross arms for measurement of internal vertical movement in earth dams
IS: 8226	1976	Code of practice for installation and observation of base plates for measurement of foundation settlement in embankments
IS: 8282-1	1976	Code of practice for installation, maintenance and observations of pore pressure measuring devices in concrete and masonry dams, Part 1: Electrical resistance type cell

Standard number	Year published	Description
IS: 8282-2	1996	Installation, maintenance, and observations of pore pressure measuring devices in concrete and masonry dams - code of practice, Part 2: Vibrating wire type cell
IS: 10334	1982	Code of practice for selection, splicing, installation and providing protection to the open ends of cables used for connecting resistance type measuring devices in concrete and masonry dams
IS: 10434-1	2003	Installation, maintenance, and observation of deformation measuring devices in concrete and masonry dams - guidelines, Part 1: Resistance type joint meters
IS: 10434-2	1996	Guidelines for installation, maintenance, and observation of deformation measuring devices in concrete and masonry dams, Part 2: Vibrating wire type joint meter
IS: 12169	1987	Criteria for design of small embankment dams
IS: 12949	2013	Code of practice for installation, maintenance and observation of instruments for pore pressure measurements in earth dams and rockfill dams: Electrical pore pressure cells - vibratory wire type
IS: 13073-1	2002	Installation, maintenance, and observation of displacement measuring devices in concrete and masonry dams - code of practice, Part 1: Deflection measurement using plumb lines
IS: 13073-2	2000	Code of practice for installation, maintenance and observation of displacement measuring devices for concrete and masonry dams, Part 2: Geodetic observation - crest collimation
IS: 13232	1992	Installation, maintenance, and observations of electrical strain measuring devices in concrete dams - Code of practice
IS: 14248	1995	Guidelines for instrumentation of barrages, weirs
IS: 14278	1995	Stress measuring devices in concrete and masonry dams - Installation, commissioning and observations - Code of practice
IS: 14750	2014	Code of practice for installation, maintenance, and observation of seepage measuring devices for concrete/masonry and earth/rockfill dams
IS: 14793	2013	Code of practice for installation, maintenance, and observation of the instruments for vibration studies other than earthquakes

Appendix C. INDIAN STANDARDS RELATED TO METEOROLOGICAL INSTRUMENTATION

Table C-1 Indian Standards Related to Meteorological Instrumentation

Standard number	Year published	Description
IS: 4849	1992	Meteorology - Rain measures - Specification
IS: 5225	1992	Meteorology - Raingauge, non recording - Specification
IS: 5235	1992	Meteorology - Raingauge, recording - Specification
IS: 5793	1970	Specification for Aneroid Barometers
IS: 5798	1970	Specification for Mercury Barometers
IS: 5799	1970	Specification for Windvane
IS: 5900	1970	Specification for Hair Hygrograph
IS: 5901	1970	Specification for Thermograph, Bimetallic
IS: 5912	1997	Specification for Anemometer, Cup Counter
IS: 5924	1998	Specification for Clock Mechanism and Drums for Meteorological Instruments
IS: 5945	1970	Specification for Barograph, Aneroid
IS: 5946	1992	Meteorology - Whirling psychrometer - Specification
IS: 5947	1970	Charts for recording meteorological instruments
IS: 5948	1970	Specification for Thermometer Screens
IS: 5973	1998	Pan evaporimeter - Specification
IS: 6805	1973	Specification for Assmann Psychrometer
IS: 6806	1973	Specification for Snow gauge
IS: 6871	1992	Wind Equipment - Distant Indicating - Specification
IS: 7243	1974	Specification for Sunshine Recorder

Standard number	Year published	Description
IS: 7244	1974	Specification for Thermometer for Mercury Barometer
IS: 8336	1977	Specification for Thermoelectric Pyranometer
IS: 8693	1978	Specification for Net Pyrradiometer
IS: 8754	1992	Electrical Anemograph - Specification
IS: 9085	1979	Specification for Correction Slide for Mercury Barometers
IS: 10473	1983	Specification for Cloud Searchlight
IS: 11121	1984	Specification for Pyranograph, Bimetallic
IS: 11875	1986	Specification for Diffuse Pyranometer
IS: 11876	1986	Specification for Airmeter
IS: 12781	1989	Marine Bucket for Sea Surface Temperature Measurement - Specification
IS: 13436	1992	Sensitive Anemometer - Specification
IS: 13448	1992	Meteorology - Thermoelectric pyrheliometer - Specification
IS: 13459	1992	Angstrem pyrheliometer - Specification
IS: 15216	2002	Balloons - Meteorological
IS: 15243	2002	Velocity Scale Set for Meteorological Purposes
IS: 15253	2002	Dew Gauge - Specification
SP 61	1994	General guidelines for automatic weather stations

Appendix D. GLOSSARY OF TERMS FOR INSTRUMENTATION OF DAMS

The purpose of this glossary is to offer a common vocabulary of terms normally used in dam instrumentation terms for use within and among Central and State Government agencies. Included terms are general and apply to all dams, regardless of size, owner, or location.

Abutment – The part of the valley side against which the dam is constructed. The left and right abutments of a dam are defined with the observer looking downstream from the dam.

Appurtenant structures – Structures associated with the dam including the following:

a) Spillways, either in the dam or separate therefrom;

b) Reservoir and its rim;

c) Low-level outlet works and water conduits such as tunnels, pipelines or penstocks, either through the dam or its abutments or reservoir rim;

d) Hydro-mechanical equipment including gates, valves, hoists, and elevators;

e) Energy dissipation and river training works; and

Auxiliary spillway – Any secondary spillway that is designed to be infrequently operated, in anticipation of some degree of structural damage or erosion to the spillway that would occur during operation.

Barrage – While the term barrage is borrowed from the French word meaning “dam” in general, its usage in English refers to a type of low-head, dam that consists of many large gates that can be opened or closed to control the amount of water passing through the structure, and thus regulate and stabilize river water elevation upstream for diverting flow for irrigation and other purposes.

Berm – A flat part of the slope of an embankment or cutting.

Bill of quantities – A means of listing and quantifying the volume and type of work in a piece of construction so that its cost or value can be determined.

Boil – A disruption of the soil surface caused by water discharging from below the surface. Eroded soil may be deposited in the form of a ring (miniature volcano) around the disruption.

Cavitation – A process that damages concrete or metal by the formation of bubbles in a water flow, created when offsets or irregularities exist on a flow surface exposed to high velocities.

Chimney drain – A vertical or inclined layer of permeable material in an embankment to control drainage of the embankment fill.

Cofferdam – A temporary structure that encloses all or part of the construction area so that work can proceed in dry conditions. A diversion cofferdam diverts a stream into a pipe, channel, tunnel, or another watercourse.

Compaction – Mechanical action that increases soil density by reducing voids.

Concrete lift – The vertical distance between successive horizontal construction joints.

Conduit – A closed channel to convey water through, around, or under a dam.

Construction joint – The interface between two successive placements or pours of concrete where bond, and not permanent separation, is intended.

Construction – Building a proposed dam and appurtenant structures capable of storing water.

Contact grouting – Filling, with cement grout, any voids existing at the contact of two zones of dissimilar materials, i.e., between a concrete tunnel lining and the surrounding rock.

Core wall – A wall built of impervious material, usually of concrete or asphaltic concrete in the body of an embankment dam to prevent seepage.

Creep – A process of deformation that occurs in many materials where the load is applied over an extended period.

Cutoff trench – A foundation excavation later to be filled with impervious material to limit seepage beneath a dam.

Cutoff wall – A wall of impervious material usually of concrete, asphaltic concrete, or steel sheet piling constructed in the foundation and abutments to reduce seepage beneath and next to the dam.

Dam – Any artificial barrier including appurtenant works constructed across rivers or tributaries thereof with a view to impound or divert water; includes barrage, weir and similar water impounding structures but does not include water conveyance structures such as canal, aqueduct and navigation channel and flow regulation structures such as flood embankment, dike and guide bund.

Dam failure – Failures in the structures or operation of a dam which may lead to an uncontrolled release of impounded water resulting in downstream flooding affecting the life and property of the people.

Dam incident – All problems occurring at a dam that have not degraded into 'dam failure' and including the following:

a) Structural damage to the dam and appurtenant works;

b) unusual readings of instruments in the dam;

c) unusual seepage or leakage through the dam body;

d) change in the seepage or leakage regime;

e) boiling or artesian conditions noticed below an earth dam;

f) stoppage or reduction in seepage or leakage from the foundation or body of the dam into any of the galleries, for dams with such galleries;

g) malfunctioning or inappropriate operation of gates;

h) occurrence of any flood, the peak of which exceeds the available flood discharge capacity or 70% of the approved design flood;

i) occurrence of a flood, which resulted in encroachment on the available freeboard, or the adopted design freeboard;

j) erosion in the near vicinity, up to five hundred meters, downstream of the spillway and waste weir; and

k) any other event that prudence suggests would have a significant unfavorable impact on dam safety.

Dam inspection – On site examination of all components of dam and its appurtenances by one or more persons trained in this respect and includes inspection of non-overflow section, spillways, abutments, stilling basin, piers, bridge, downstream toe, drainage galleries, operation of mechanical systems (including gates and its components, drive units, cranes), interior of outlet conduits, instrumentation records and record-keeping arrangements of instruments.

Dam owner – The Central Government or a State Government or public sector undertaking or local authority or company and any or all such persons or organizations, who own, control, operate or maintain a specified dam.

Dam safety – The practice of ensuring the integrity and viability of dams such that they do not present unacceptable risks to the public, property, and the environment. It requires the collective application of engineering principles and experience, and a philosophy of risk management that recognizes that a dam is a structure whose safe function is not explicitly determined by its original design and construction. It also includes all actions taken to identify or predict deficiencies and consequences related to the failure and to document, publicize, and reduce, eliminate, or remediate to the extent reasonably possible, any unacceptable risks.

Densification – A means of improving the strength of soil by making it denser, usually by physical compaction.

Design and Construct – A form of contract in which the contractor undertakes both the design and the construction of the work.

Design water level – The highest water elevation, including the flood surcharge, that a dam is designed to withstand.

Design wind – The most severe wind that is possible at a reservoir for generating wind set-up and run-up. The determination will include the results of meteorological studies that combine wind velocity, duration, direction and seasonal distribution characteristics in a realistic manner.

Diaphragm wall – A cutoff wall of flexible concrete constructed in a trench cut through an embankment or the foundation.

Diversion dam – A dam built to divert water from a waterway or stream into a different watercourse.

Earthfill dam – An embankment dam in which more than 50% of the total volume is formed of compacted earth layers.

Effective crest of the dam – The elevation of the lowest point on the crest (top) of the dam, excluding spillways.

Embankment dam – Any dam constructed of excavated natural materials, such as both earth-fill and rock-fill dams, or of industrial waste materials, such as a tailings dam.

Embankment zone – An area or part of an embankment dam constructed using similar materials and similar construction and compaction methods throughout.

Emergency repairs – Any repairs that are temporary in nature and that are necessary to preserve the integrity of the dam and prevent a failure of the dam.

Emergency spillway – An auxiliary spillway designed to pass a large, but infrequent, volume of flood flow, with a crest elevation higher than the principal spillway or normal operating level.

Extensometer – An instrument used to detect, usually small, movements of a structure or a mass of rock or soil.

Failure mode – A potential failure mode is 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.

Fetch – The-straight-line distance across a body of water subject to wind forces. The fetch is one of the factors used in calculating wave heights in a reservoir.

Filter – One or more layers of granular material graded (either naturally or by selection) so as to allow seepage through or within the layers while preventing the migration of material from adjacent zones.

Flap gate – A gate hinged along one edge, usually either the top or bottom edge. Examples of bottom-hinged flap gates are tilting gates, and fish belly gates so called from their shape in cross section.

Flashboards – Structural members of timber, concrete, or steel placed in channels or on the crest of a spillway to raise the reservoir water level but intended to be quickly removed, tripped, or fail in case of a flood.

Flip bucket – An energy dissipater found at the downstream end of a spillway and shaped so that water flowing at a high velocity is deflected upwards in a trajectory away from the foundation of the spillway.

Flood hydrograph – A graph showing, for a given point on a stream, the discharge, height, or another characteristic of a flood with respect to time.

Freeboard – Vertical distance between a specified stillwater (or other) reservoir surface elevation and the top of the dam, without camber.

Gabion – Rectangular-shaped baskets or mattresses fabricated from wire mesh, filled with rock, and assembled to form overflow weirs, hydraulic drops, and overtopping protection for small embankment dams. Gabion baskets are stacked in a stair-stepped fashion, while mattresses are placed parallel to a slope. Gabions have advantages over loose riprap because of their modularity and rock confinement properties, thus giving erosion protection with less rock and with smaller rock sizes than loose riprap.

Gallery – A passageway in the body of a dam used for inspection, foundation grouting or drainage.

Gate – A movable water barrier for the control of water.

Geomembrane – An impermeable geosynthetic composed of one or more synthetic sheets.

Geosynthetic – A planar product manufactured from a polymeric material used with soil, rock, earth, or other geotechnical engineering related material as an integral part of a project, structure, or system.

Geotextile – Any fabric or textile (natural or synthetic) when used as an engineering material in conjunction with soil, foundations, or rock. Geotextiles have the following purposes: drainage, filtration, separation of materials, reinforcement, moisture barriers, and erosion protection.

Gravity dam – A dam constructed of concrete or masonry that relies on its weight and internal strength for stability.

Grout – A fluidized material that is injected into soil, rock, concrete, or other construction material to seal openings and to lower the permeability and to provide additional structural strength. There are four major types of grouting materials: chemical; cement; clay; and bitumen.

Grout blanket – An area of the foundation systematically grouted to a uniform shallow depth.

Grout cap – A concrete filled trench or pad encompassing all grout lines constructed to impede surface leakage and to provide anchorage for grout connections.

Grout curtain – One or more zones, usually thin, in the foundation into which grout is injected to reduce seepage under or around a dam.

Height of dam – The difference in elevation between the natural bed of the watercourse or the lowest point on the downstream toe of the dam, whichever is lower, and the effective crest of the dam.

Hydraulic fracturing – Hydraulic fracturing in soils is a tensile parting that is created because of increased fluid pressure. Initiation or propagation cracks in the core sections of earthen dams because of hydraulic fracturing affect adversely the structural safety of the dams.

Hydraulic gradient – The change in total hydraulic pressure per unit distance of flow.

Hydrology – One of the earth sciences that encompasses the natural occurrence, distribution, movement, and properties of the waters of the earth and their environmental relationships.

Hydrometeorology – The study of the atmospheric and land-surface phases of the hydrologic cycle with emphasis on the interrelationships involved.

Hydrostatic pressure – The pressure exerted by water at rest.

Inclinometer – An instrument, usually consisting of a metal or plastic casing inserted in a drill hole and a sensitive monitor either lowered into the casing or fixed within the casing. The inclinometer measures the casing's inclination to the vertical at different points. The system may be used to measure settlement.

Instrumentation – An arrangement of devices installed into or near dams that enable measurements that can be used to evaluate the structural behavior and performance parameters of the structure.

Internal erosion – A general term used to describe all the various erosional processes where water moves internally through or adjacent to the soil zones of embankment dams and foundation, except for the specific process referred to as *backward erosion piping*. The term internal erosion is used in place of a variety of terms that have been used to describe various erosional processes, such as scour, suffusion, concentrated leak piping, and others.

Jet grouting – A system of grouting in which the existing foundation material is mixed in situ with cementitious materials to stabilize the foundation, or it improve its water-tightness.

Karstic – An adjective to describe a limestone rock mass in which large openings have been caused over geological time by ground water dissolving the rock.

Large dam – A dam which is above 15 m in height, measured from the lowest part of the general foundation area to the top of dam; or a dam between 10 m to 15 m in height that satisfies at least one of the following, namely

- the length of the crest is not less than 500 m;
- the capacity of the reservoir formed by the dam is not less than one million cubic meters;
- the largest flood discharge dealt with by the dam is not less than 2000 m^3/s;
- the dam has particularly challenging foundation problems; or
- the dam is of unusual design.

Liquefaction – A condition whereby soil undergoes continued deformation at a constant low residual stress or with low residual resistance, because of the buildup and maintenance of high pore-water pressures, which reduces the effective confining pressure to a very low value. Pore pressure buildup leading to liquefaction may be due either to static or cyclic stress applications, and the possibility of its occurrence will depend on the void ratio or relative density of a cohesionless soil and the confining pressure.

Low-level outlet (bottom outlet) – An opening at a low level from a reservoir used for emptying or for scouring sediment and sometimes for irrigation releases.

Maintenance – Those tasks that are generally recurring and are necessary to keep the dam and appurtenant structures in a sound condition and free from defect or damage that could hinder the dam's functions as designed, including adjacent areas that also could affect the function and operation of the dam.

Maintenance inspection – Visual inspection of the dam and appurtenant structures by the owner or owner's representative to detect apparent signs of deterioration, other deficiencies, or any other areas of concern.

Masonry dam – Any dam constructed mainly of stone, brick, or concrete blocks pointed with mortar. A dam having only a masonry facing should not be referred to as a masonry dam.

Maximum storage capacity – The volume, in millions of cubic metres (Mm^3), of the impoundment created by the dam at the effective crest of the dam; only water that can be stored above natural ground level or that could be released by failure of the dam is considered in assessing the storage volume; the maximum storage capacity may decrease over time because of sedimentation or increase if the reservoir is dredged.

Meteorology – The science that deals with the atmosphere and atmospheric phenomena, the study of weather, particularly storms and the rainfall they produce.

Normal storage capacity – The volume, in millions of cubic meters (Mm^3), of the impoundment created by the dam at the lowest uncontrolled spillway crest elevation, or at the maximum elevation of the reservoir at the normal (non-flooding) operating level.

Outlet – A conduit or pipe controlled by a gate or valve, or a siphon, that is used to release impounded water from the reservoir.

Outlet gate – A gate controlling the flow of water through a reservoir outlet.

Outlet works – A dam appurtenance that provides release of water (generally controlled) from a reservoir.

Parapet wall – A solid wall built along the top of a dam (upstream or downstream edge) used for ornamentation, for the safety of vehicles and pedestrians, or to prevent overtopping caused by wave runup.

Peak flow – The maximum instantaneous discharge that occurs during a flood. It is coincident with the peak of a flood hydrograph.

Penstock – A pressurized pipeline or shaft between the reservoir and hydraulic machinery.

Phreatic surface – The free surface of water seeping at atmospheric pressure through soil or rock.

Piezometer – An instrument used to measure water levels or pore water pressures in embankments, foundations, abutments, soil, rock, or concrete.

Piping –The progressive development of internal erosion by seepage.

Plunge pool – A natural or artificially created pool that dissipates the energy of free falling water.

Post-tensioned anchors – A system of anchored stressed steel tendons or bars within or attached to a structure to provide structural support.

Pre-stressed structure – A structure containing elements that have been pre-loaded with stressed steel tendons, bars or jacks.

Pressure relief pipes – Pipes used to relieve uplift or pore water pressure in a dam foundation or in the dam structure.

Principal spillway – The primary or initial spillway engaged during a rainfall-runoff event that is designed to pass normal flows.

Radial gate – A gate with a curved upstream plate and radial arms hinged to piers or other supporting structure. Also known as a Tainter gate.

Rehabilitation – Work that aims to restore the service life of a structure, as opposed to maintenance, which seeks to restore the status quo, and upgrading whose purpose is to maximize the performance within the physical limits of the structure.

Repairs – Any work done on a dam that may affect the integrity, safety, and operation of the dam.

Reservoir – Any water spread that contains impounded water.

Reservoir Storage – The retention of water or delay of runoff in a reservoir either by the planned operation, as in a reservoir, or by temporary filling in the progression of a flood wave. Certain types of storage in reservoirs are defined as follows:

a) **Active storage** – The volume of the reservoir that is available for some use such as power generation, irrigation, flood control, and water supply. The bottom elevation is the minimum operating level.

b) **Dead storage** – The storage that lies below the invert of the lowest outlet and that, therefore, cannot readily be withdrawn from the reservoir.

c) **Flood surcharge** – The storage volume between the top of the active storage and the design water level.

d) **Inactive storage** – The storage volume of a reservoir between the crest of the invert of the lowest outlet and the minimum operating level.

e) **Live storage** – The sum of the active and the inactive storage.

f) **Reservoir capacity** – The sum of the dead and live storage of the reservoir.

g) **Surcharge** – The volume or space in a reservoir between the controlled retention water level and the highest water level. Flood surcharge cannot be retained in the reservoir but will flow out of the reservoir until the controlled retention water level is reached.

Riprap – A layer of large rock, precast blocks, bags of cement, or other suitable material, placed on an embankment or along a watercourse as protection against wave action, erosion, or scour.

Rockfill dam – An embankment dam in which more than 50% of the total volume is made up of compacted or dumped cobbles, boulders, rock fragments, or quarried rock larger than 3-inch size.

Roller compacted concrete dam – A concrete gravity dam constructed using a dry mix concrete transported by conventional construction equipment and compacted by rolling, usually with vibratory rollers.

Rubble dam – A stone masonry dam in which the stones are not shaped or coursed.

Saddle dam (or dike) – A subsidiary dam of any type constructed across a saddle or low point on the perimeter of a reservoir.

Scour – The loss of material occurring at an erosional surface, where a strong flow is found, such as a crack in a dam or the dam/foundation contact. Continued flow causes the erosion to progress, creating a larger and larger eroded area.

Seismometer – An instrument that measure the motion of the ground, including those of seismic waves generated by earthquakes, volcanic eruptions, and other seismic sources. Records of seismic waves allow seismologists to map the interior of the Earth, and locate and measure the size of these different sources.

Seepage – The internal movement of water that may take place through a dam, the foundation or the abutments, often emerging at the ground level lower down the slope.

Settlement – The vertical downward movement of a structure or its foundation.

Sinkhole – A depression in the ground showing subsurface settlement or particle movement, typically having clearly defined boundaries with a sharp offset.

Toe drain – A system of pipe or porous material along the downstream toe of a dam used to collect seepage from the foundation and embankment and convey it to a free outlet.

Toe of dam – The junction of the downstream slope or face of a dam with the ground surface, which is also referred to as the downstream toe. The intersection of the upstream slope with ground surface is called the heel or the upstream toe.

Top thickness (top width) – The thickness or width of a dam at the level of the top of the dam (excluding corbels or parapets). In general, the term thickness is used for gravity and arch dams, and width is used for other dams.

Uplift – The hydrostatic force of water exerted on or underneath a structure, tending to cause a displacement of the structure.

Weir, measuring – A device for measuring the rate of flow of water. It consists of a rectangular, trapezoidal, triangular, or other shaped notch cut into the top of a vertical, thin plate over which water flows. The rate of flow is calculated from the measured height of water above the weir crest

Appendix E. SUPPLIERS OF GEOTECHNICAL INSTRUMENTATION FOR DAMS

A list of suppliers supplying geotechnical instrumentation used to monitor conditions at dams is provided in Table C-1.

Table E-1. List of Suppliers Supplying Geotechnical Instrumentation for Dams

Name	Office	Telephone number	Website address
RST Instruments Ltd.	11545 Kingston St., Maple Ridge, British Columbia, V2X0Z5, Canada	+1 604-540-1100	www.rstinstruments.com
Eyasco Inc.	125 Hangar Way, Suite 290 Watsonville, California 95076, USA	+1 831-687-0186	www.eyasco.com
Innovative Geotechnical Instrumentation	B 970 Sector A, Mahanagar, Lucknow, Uttar Pradesh 226006, India	+91 0522 407 0774 +91 0522 305 519	www.innogeo-india.com
SysTel Instrumentation Services Pvt. Ltd.	2/102 Sahara State, Jankipuram, Lucknow, Uttar Pradesh 226021, India	+91 0522 495 3344	www.sisplgroup.com
Encardio-Rite Electronics Pvt. Ltd.	A-7 Industrial Estate, Talkatora Road, Lucknow, Uttar Pradesh 226011, India	+91 52 2266 1039 4 2	www.encardio.com
Exploration Instruments LLC	2808 Longhorn Blvd. Suite 304, Austin, Texas78758, USA	+1 512-346-4042	www.expins.com
Power House Tool, Inc.	626 Nicholson Street, Joliet, Illinois 60435, United States	+1 815-727-6301	www.powerhousetool.com
Micro Measurements	PO Box 27777, Raleigh, North Carolina 27611, USA	+1 919-365-3945	www.vpgsensors.com
Associated Instrument Manufacturers India Pvt. Ltd.	Naimex House, A-8, Corporate Office, Industrial Area, Mohan Cooperative Industrial Estate, Mathura Road, Okhla Phase III, Okhla Industrial Area, New Delhi, Delhi 110020, India	+91 11 3081 0200	www.aimil.com
Slope Indicator Co. Rep. in India	C16A Kalkaji, New Delhi 110019, India	+91 11 2643 5279 +91 11 2643 5280	www.slopeindicator.com

Name	Office	Telephone number	Website address
Ultra-Technologies Pvt. Ltd.			
GEONOR	Grinidammen 10, 1359 Eiksmarka, Norway	+47 67 15 92 80	www.geonor.no
Sensors & Measurements Enterprises	A-65 (1) Talkatora Industrial Estate Talkatora Road Lucknow, Uttar Pradesh 226011, India	+91 98385 62636	www.smegeotech.com
Interfels GmbH	Am Bahndamm 1, 48455 Bad Bentheim, Germany	+49 5922 99417	www.interfels.de
Progressive Machine Tools Pvt. Ltd.	5, Industrial Estate, Jagdishpatti, NH 56, Jaunpur, Uttar Pradesh 222002, India	+91 05452 220 479	www.pmtpl.com
NBG Systems GmbH	Acess Industrial Park, Zweilanderstrasse 1, 3950 Gmund, Austria	+43 2852 30412	www.nbg-systems.com
Info-Electronics Systems India Pvt. Ltd.	P-18, 1st Floor, Green Park Extension, New Delhi, Delhi 110016, India	+91 11 2619 7981	www.info-electronics.co.in www.info-electronics.com
Leica Geosystems, Elcome Technologies Pvt. Ltd.	Elcome House, A-06, Infocity, Sector 34, Gurgaon, Haryana 122002, India	+91 124 412 2222	www.elcometech.com
Sigma Industries	18, Kshipra Society, Karvenagar, Pune, Maharashtra 411041, India	+91 960 488 4769	www.sigma-ind.com
Smartec SA	Via Pobiette 11, CH-6928 Mann, Switzerland	+41 91 610 18 00	www.smartec.ch
Telemac SA	10, Avenue Eiffel, 77220 Gretz-Armainvilliers, France	+33 1 64 06 40 80	www.telemac.fr
Roctest Ltd.	680 Birch Street, Saint-Lambert, Quebec, Canada J4P 2N3	+1 450 465 1113	www.roctest.com
Geokon Inc.	48 Spencer St., Lebanon, New Hampshire 03766, USA	+1 603-448-1562	www.geokon.com
Sensornet Ltd.	340 Centennial Ave, Elstree, Borehamwood WD6 3TJ, U.K	+44 (0)20 8236 2550	www.sensornet.co.uk
Record Tech Electronics	B-18, Industrial Estate, Roorkee, Uttarakhand 247667, India	+91 13322 67507	www.recordtek.com

Appendix F. SUPPLIERS OF HYDROLOGICAL AND METEOROLOGICAL INSTRUMENTATION FOR DAMS

A list of suppliers of hydrological and meteorological instrumentation used to monitor conditions at dams is provided in Table D-1.

Table F-1. Suppliers of Hydrological and Meteorological Instrumentation for Dams

Name	Address	Telephone number	Website address
Dynalab	G2 Bld,C/3,Bramha, Memories, Bhosale Nagar, Pune, Maharashtra, 411007, India	+91 020 553 7109	dynalabweathertech.com
SGS Weather and Environmental Systems	29, Ground Floor, South Ex Plaza-II, South Extension Part -II, New Delhi, Delhi 110049, India	+91 112 625 7072 +91 112 625 6073 +91 112 625 0803	www.weather-india.com
K.R. Instruments	No. 270, 21st Main, 2nd Cross, 2nd Stage, B. T. M. Layout, Bengaluru - 560 076, Karnataka, India	+91 802 668 4492	www.krinstruments.com
U.K. Engineering Works	Maktoolpuri, Roorkee 247667, Haridwar, Uttarakhand, India	+91 42422 50712	www.ukengineeringworks.com
Shanghai Toyou Industry Co., Ltd	Room209, B Building, Cangyuan Industrial Area, No. 951 Jianchuan-Minhang District, Shanghai, 200240 China	+86 215 471 6991	www.toyouindustry.com
Rickly Hydrological Company	1700 Joyce Avenue Columbus, Ohio 43219, USA	+1 800-561-9677	www.rickly.com
Raj Instruments	No. 40, Ghanshyam Estate, near Viratnagar Cross Road, Bapunagar, Ahmedabad, Gujarat 380023, India	+91 792 274 1522	www.rajinstruments.com
SUTRON Corp.	22400 Davis Drive Sterling, Virginia 20164, USA	+1 703-406-2800	www.sutron.com
	D-128-129, 1st Floor, Okhla Industrial Area, Phase-1, New Delhi, Delhi 110020, India	+91 114 175 9224 +91 114 175 9450	www.sutron.com
Teledyne Isco	4700 Superior Street, Lincoln Nebraska 68504, USA	+1 402-464-0231	www.teledyneisco.com

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Appendix G. VENDORS OF SEISMIC INSTRUMENTATION FOR DAMS

A list of vendors of seismic instrumentation used to monitor conditions at dams is provided in Table below.

Table G-1. Vendors of Seismic Instrumentation for Dams

Name	Address	Telephone number	Website address
Seismic Instruments, Inc.	7501 N Capital of Texas Hwy, Austin, Texas 78731, USA	+1 512-342-1819	www.seismicinstruments.com
Canterbury Seismic Instruments	149 Rutherford Building, University of Canterbury, Christchurch 8041, New Zealand	+64 3 364 3575	www.csi.net.nz
Kinemetrics Inc.	222 Vista Avenue, Pasadena, California 91107, USA	+1 626-795-2220	www.kmi.com
ESG Solutions	20 Hyperion Court, Kingston, Ontario, K7K 7K2, Canada	+1 613-548-8287	www.esgsolutions.com
GEM Systems	135 Spy Court, Markham, Ontario, Canada, L3R 5H6	+1 905 752 2202	www.gemsys.ca
GeoSIG Ltd.	Wiesenstrasse 39, 8952 Schlieren, Switzerland	+41 44 810 21 50	www.geosig.com
Seismic Systems Service	1939 4th Street, Simi Valley, California 93065, USA	+1 805-531-9994	www.seismicsystems.net
SYSCOM Instruments SA	Rue de l'Industrie 21, 1450 Sainte-Croix, Switzerland	+41 24 455 44 11	www.syscom.ch
SUTRON Corp.	22400 Davis Drive Sterling, Virginia 20164, USA	+1 703 406-2800	www.sutron.com
	D-128-129, 1st Floor, Okhla Industrial Area, Phase-1, New Delhi, Delhi 110020, India	+91 114 175 9224 +91 114 175 9450	www.sutron.com
Trimble Navigation Limited	10368 Westmoor Drive, Westminster, Colorado 80021, USA Unit 318, Time Tower M.G.Road, Gurgaon 122001, India	+91 124 4524300	www.trimble.com
Guralp Systems Limited	Midas House, Calleva Park, Aldermaston, Reading, RG7 8EA, United Kingdom	+44 118 981 9056	www.guralp.com

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Central Dam Safety Organization

Central Water Commission

Vision

To remain as a premier organization with best technical and managerial expertise for providing advisory services on matters relating to dam safety.

Mission

To provide expert services to State Dam Safety Organizations, dam owners, dam operating agencies and others concerned for ensuring safe functioning of dams with a view to protect human life, property and the environment.

Values

Integrity: Act with integrity and honesty in all our actions and practices.

Commitment: Ensure good working conditions for employees and encourage professional excellence.

Transparency: Ensure clear, accurate and complete information in communications with stakeholders and take all decisions openly based on reliable information.

Quality of service: Provide state-of-the-art technical and managerial services within agreed time frame.

Quality Policy

We provide technical and managerial assistance to dam owners and State Dam Safety Organizations for proper surveillance, inspection, operation and maintenance of all dams and appurtenant works in India to ensure safe functioning of dams and protecting human life, property and the environment.

We develop and nurture competent manpower and equip ourselves with state of the art technical infrastructure to provide expert services to all stakeholders.

We continually improve our systems, processes and services to ensure

DRIP

Dam Rehabilitation & Improvement Project