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Sensitivity	0.05°F typical.	0.3°F typical.	0.16°F to 0.8°F typical; 3 ft spatial resolution typical.
Accuracy	±0.5% F.S. typical.	±0.5°F typical.	±0.16°F to 0.8°F, depends on cable length and measurement time.
Repeatability	±0.025% F.S. typical.	±0.5°F typical.	±0.16°F typical.
Accuracy/ Repeatability[c]	Suitable for long lead.	Can be damaged by transient.	Internal readout averaging typically a few seconds to 1 h, considerably increases accuracy and spatial resolution.
Longevity[d]	YYYYY	YYY	Unknown (YYYYY?)
Maintenance requirements	Verify surface cable integrity.	Verify surface cable integrity.	Verify surface cable integrity.
Relative expense[e]	Instrument: $$ Readout: $$$ ADAS: $$$ to $$$$	Instrument: $ Readout: $$ ADAS: $$$ to $$$$	Instrument: $ (price of fiber optic cable only) Readout and ADAS: $$$$$

[a]"Current practice or legacy" refers to common practice in current U.S. applications. However, legacy instruments may still be in use and available and may have some advantages in particular applications.
[b]General methods of reading output: can include manual, on-demand, and output that can accommodate ADAS (Automated Data Acquisition Systems).
[c]Accuracy/Repeatability considerations: include thermal exposure and long-term stability.
[d]Longevity: Y, 1 year or less; YY, 1–5 years; YYY, 5–10 years; YYYY, 10–15 years; and YYYYY, more than 15 years.
[e]Relative expense: $, $1–$199; $$, $200–$999; $$$, $1,000–$2,999; $$$$, $3,000–$9,999; and $$$$$, more than $10,000.

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Table 5-3. (*Continued*) Instrument Comparison.

	Instrument Name
	Pan-type gauges, Section 5.3.9.2
PRECIPITATION	
Parameter measured	Rainfall/snowfall
Common applications	Measure daily evaporation/precipitation.
Current practice or legacy instrument?[a]	Current
Installation specifics/ease of installation	Pan must be re-filled to known level if used for measuring evaporation.
General considerations	Steel cylinder 47.5 in. diameter, 10 in. height.
General methods of reading output[b]	Visual, portable readout or ADAS.
Sensor options	Graduated vertical scale and/or low-range VW or 4–20 mA pressure transducer.
Sensitivity	0.025% F.S. typical.
Accuracy	±0.1% F.S. typical.
Repeatability	±0.025% F.S. typical.
Accuracy/ Repeatability[c]	Transducer must be vented for barometric correction.
Longevity[d]	YYYY
Maintenance requirements	Visual inspection, periodic (5 year?) transducer re-calibration.
Relative expense[e]	Instrument: $$$ Readout: $$$ ADAS: $$$ to $$$$

[a]"Current practice or legacy" refers to common practice in current U.S. applications. However, legacy instruments may still be in use and available and may have some advantages in particular applications.
[b]General methods of reading output: can include manual, on-demand, and output that can accommodate ADAS (Automated Data Acquisition Systems).
[c]Accuracy/Repeatability considerations: include thermal exposure and long-term stability.
[d]Longevity: Y, 1 year or less; YY, 1–5 years; YYY, 5–10 years; YYYY, 10–15 years; and YYYYY, more than 15 years.
[e]Relative expense: $, $1–$199; $$, $200–$999; $$$, $1,000–$2,999; $$$$, $3,000–$9,999; and $$$$$, more than $10,000.

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	Instrument Name		
	Weighing bucket gauges	Tipping bucket gauges	Manual precipitation gauges
Bucket Gauges, under Section 5.3.9.2 (Rain Gauges)			
Parameter measured	Rainfall/snowfall	Rainfall/snowfall	Rainfall/snowfall
Common applications	Measure daily precipitation.	Measure daily precipitation.	Measure daily precipitation.
Current practice or legacy instrument?[a]	Current	Current	Current
Installation specifics/ease of installation	Preferably 5 ft above ground, antifreeze added to bucket if snow is collected. Bucket must be emptied periodically.	Requires heating in freezing zones, unlimited measuring capacity.	Must be emptied.
General considerations	12, 24, or 30 in. capacity bucket with 6–12 in. orifice.	12, 24, or 30 in. capacity bucket with 6–12 in. orifice.	Graduated plastic cylinder.
General methods of reading output[b]	Portable readout or ADAS.	Portable readout or ADAS.	Visual scale.
Sensor options	VW or strain gauge load cell.	Pulse signal.	No sensor option.
Sensitivity	0.025% F.S. typical.	0.01 in. typical.	0.01 in. typical.

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Table 5-3. (*Continued*) Instrument Comparison.

	Instrument Name		
	Weighing bucket gauges	Tipping bucket gauges	Manual precipitation gauges
Accuracy	±0.1% F.S. typical.	±1% up to 2 in./h typical.	0.05 in. typical.
Repeatability	±0.004 in. typical.	±1% up to 2 in./h typical.	±0.05 in. typical.
Accuracy/ Repeatability[c]	Good temperature stability. Windshield improves accuracy.	Level installation is required. Inlet can become contaminated or blocked.	Freezing and wind-induced errors.
Longevity[d]	YYYYY	YYYY	YY
Maintenance requirements	Visual inspection, remove dirt and particles from weighing bucket.	Visual inspection, remove dirt and particles from filter protecting the tipping bucket.	Visual inspection.
Relative expense[e]	Instrument: $$$$ Readout: $$$ ADAS: $$$ to $$$$	Instrument: $$ Readout: $$$ ADAS: $$$ to $$$$	Instrument: $ Readout: N/A ADAS: N/A

[a]"Current practice or legacy" refers to common practice in current U.S. applications. However, legacy instruments may still be in use and available and may have some advantages in particular applications.
[b]General methods of reading output: can include manual, on-demand, and output that can accommodate ADAS (Automated Data Acquisition Systems).
[c]Accuracy/Repeatability considerations: include thermal exposure and long-term stability.
[d]Longevity: Y, 1 year or less; YY, 1–5 years; YYY, 5–10 years; YYYY, 10–15 years; and YYYYY, more than 15 years.
[e]Relative expense: $, $1–$199; $$, $200–$999; $$$, $1,000–$2,999; $$$$, $3,000–$9,999; and $$$$$, more than $10,000.

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	Instrument Name				
	Head (staff) gauges	Float systems	Bubbler systems	Submerged pressure transducer	Ultrasonic and radar level sensing
RESERVOIR AND TAILWATER LEVELS, under Section 5.3.2.2 (Water Level Measurements)					
Parameter measured	Water level	Water level	Water level	Water level	Water level
Common applications	Reservoir level	Reservoir level	Reservoir level	Reservoir level	Reservoir level
Current practice or legacy instrument?[a]	Current	Current	Current	SDI-12	Current
Installation specifics/ease of installation	Graduated scale mounted vertically. Must be readable from distance.	Float attached to a chain in a stilling well, activating a rotary encoder.	Tubing lowered in pipe mounted to vertical or inclined wall.	Transducer suspended in pipe mounted to vertical wall.	Transducer suspended in pipe mounted to vertical wall.
General considerations	Generally, 2 1/2 in. wide. Must be made with durable material and indelible graduations and markings.	Float must be installed in a stilling well.	System comprises air compressor and pressure transducer. Submerged portion is maintenance-free.	Vented pressure transducer requires periodic replacement of desiccant cartridge.	Mounted on holding bracket above water surface. Instrument maybe susceptible to lightning or transient damage.
General methods of reading output[b]	Visual scale.	Stand-alone unit or ADAS.	ADAS	Portable readout or ADAS.	Portable readout or ADAS.
Sensor options	No sensor option.	Rotary encoder (absolute or incremental/relative).	Analog (4–20 mA or 0–5 VDC) or digital (RS485) outputs.	VW or analog (4–20 mA or 0–5 VDC) or digital (RS485) outputs.	4–20 mA, 0–10 VDC or digital output, 0.3–20, 50 or 100 m (1 to 65, 164 or 328 ft) typical.

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Table 5-3. (*Continued*) Instrument Comparison.

	Instrument Name				
	Head (staff) gauges	Float systems	Bubbler systems	Submerged pressure transducer	Ultrasonic and radar level sensing
Sensitivity	0.01 or 0.1 ft.	0.01 ft typical.	0.05% reading with minimum of 0.01 ft typical.	0.025% F.S. typical.	0.025% F.S. typical.
Accuracy	0.01 or 0.1 ft.	0.01 ft typical.	0.05% reading with minimum of 0.01 ft typical.	±0.1% F.S. typical.	±0.1 to 0.2% F.S. typical.
Repeatability	±0.01 or 0.1 ft.	±0.01 ft typical.	±0.05% reading with minimum of 0.01 ft typical.	±0.025% F.S. typical.	±0.025% F.S. typical.
Accuracy/ Repeatability[c]	Graduated marks every 0.01 or 0.1 ft, depending on distance of observation.	Good temperature stability.	Desiccant must be replaced periodically.	Transducer can be absolute or vented for barometric correction.	Repeatability can be affected by water surface and environment.
Longevity[d]	YYYY	YYYY to YYYYY	YYYY	YYYY	YYYY to YYYYY
Maintenance requirements	Visual inspection.	Visual inspection, cleaning, functional check.	Visual inspection, periodic (5 year?) transducer recalibration.	Visual inspection, periodic (5 year?) transducer recalibration.	Visual inspection, periodic (5 year?) transducer recalibration.
Relative expense[e]	Instrument: $$ Readout: N/A ADAS: N/A	Instrument: $$$ Readout: $$$ ADAS: $$$ to $$$$	Instrument: $$$ Readout: $$$ ADAS: $$$ to $$$$	Instrument: $$ Readout: $$$ ADAS: $$$ to $$$$	Instrument: $$ Readout: $$$ ADAS: $$$ to $$$$

[a]"Current practice or legacy" refers to common practice in current U.S. applications. However, legacy instruments may still be in use and available and may have some advantages in particular applications.
[b]General methods of reading output: Can include manual, on-demand, and output that can accommodate ADAS (Automated Data Acquisition Systems).
[c]Accuracy/Repeatability considerations: Include thermal exposure, and long-term stability.
[d]Longevity: Y, 1 year or less; YY, 1–5 years; YYY, 5–10 years; YYYY, 10–15 years; and YYYYY, more than 15 years.
[e]Relative expense: $, $1–$199; $$, $200–$999; $$$, $1,000–$2,999; $$$$, $3,000–$9,999; and $$$$$, more than $10,000.

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	Instrument Name
	Multiprobe water-quality instruments, Section 5.3.2.2
TURBIDITY/WATER QUALITY	
Parameter measured	Temperature, conductivity, dissolved oxygen, pH, oxidation–reduction potential, turbidity, and water level.
Common applications	Characterize seepage waters.
Current practice or legacy instrument?[a]	Current
Installation specifics/ease of installation	Submerged in water.
General considerations	Recent models need no maintenance or recalibration, except periodic wiper replacement for the turbidity sensor.
General methods of reading output[b]	Portable readout or ADAS.
Sensor options	RS-232, SDI-12, RS-485, USB.
Sensitivity	Sensor-dependent.
Accuracy	Sensor-dependent.
Repeatability	Sensor-dependent.
Accuracy/Repeatability[c]	Fouling (oil, sediments, biofilms) of measuring surfaces can compromise accuracy. Individual sensors have different maintenance requirements.
Longevity[d]	YYYY
Maintenance requirements	Visual inspection, periodic (yearly?) sensor recalibration.
Relative expense[e]	Instrument: $$$$ Readout: $$$ ADAS: $$$ to $$$$

[a]"Current practice or legacy" refers to common practice in current U.S. applications. However, legacy instruments may still be in use and available and may have some advantages in particular applications.
[b]General methods of reading output: Can include manual, on-demand, and output that can accommodate ADAS (Automated Data Acquisition Systems).
[c]Accuracy/Repeatability considerations: Include thermal exposure, and long-term stability.
[d]Longevity: Y, 1 year or less; YY, 1–5 years; YYY, 5–10 years; YYYY, 10–15 years; and YYYYY, more than 15 years.
[e]Relative expense: $, $1–$199; $$, $200–$999; $$$, $1,000–$2,999; $$$$, $3,000–$9,999; and $$$$$, more than $10,000.

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Table 5-3. (*Continued*) Instrument Comparison.

	Instrument Name
	Modern high-resolution digital accelerographs
SEISMIC MEAUSUREMENTS	
Strong-Motion Accelerographs (High-Resolution Digital Accelerographs), Section 5.3.8.4	
Parameter measured	Seismic response.
Common applications	Measure movement, pressure, and load.
Current practice or legacy instrument?[a]	Current
Installation specifics/ease of installation	Units can be stand-alone (combined recorder and accelerometer) or multichannel recorder with separate triaxial accelerometers. Units can be mounted vertically or horizontally.
General considerations	Flat response DC to 200–600 Hz typical. Rugged, solid-state MEMS accelerometers not subject to aging.
General methods of reading output[b]	Single-point network control. Remote communication possible (modem, ethernet, etc.). Automatic alerting. Distributed recording.
Sensor options	Traditional spring and coil force-balance accelerometer, or MEMS capacitive accelerometer. Measuring range: ±4*g* range typical.
Sensitivity	1.25 V/g (differential) typical for MEMS sensors. Similar for force-balance sensors.
Accuracy	±0.1 to 1.0% F.S. typical.
Repeatability	Usually not specified.
Accuracy/Repeatability[c]	MEMS sensors operating range from −40°C to 85°C.
Longevity[d]	YYYYY Rugged, solid-state MEMS accelerometers not subject to aging.
Maintenance requirements	Low-maintenance comprehensive system self-test MEMS sensors do not need recalibration.
Relative expense[e]	Instrument and ADAS: $$$$$

[a]"Current practice or legacy" refers to common practice in current U.S. applications. However, legacy instruments may still be in use and available and may have some advantages in particular applications.
[b]General methods of reading output: Can include manual, on-demand, and output that can accommodate ADAS (Automated Data Acquisition Systems)
[c]Accuracy/Repeatability considerations: Include thermal exposure, and long-term stability.
[d]Longevity: Y, 1 year or less; YY, 1–5 years; YYY, 5–10 years; YYYY, 10–15 years; and YYYYY, more than 15 years.
[e]Relative expense: $, $1–$199; $$, $200–$999; $$$, $1,000–$2,999; $$$$, $3,000–$9,999; and $$$$$, more than $10,000.

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CHAPTER 6
GEODETIC MONITORING

> Measure what is measurable, and make measurable what is not so.
>
> Galileo Galilei

Geodetic monitoring methods for dam deformation monitoring consist of ground-surveying instruments and procedures used to detect horizontal and vertical movement over a series of fixed points forming a survey control network. The fixed points may be monuments along a dam crest, appurtenant structures, or abutments.

Geodetic engineers and land surveyors are challenged with the task of providing horizontal and vertical position information to the dam owner and engineer as performance indicators of movement. In this chapter, both geodetic engineers and land surveyors, although professionally distinct, are referred to as "surveyors," and geodetic surveys are referred to as "surveys." In practice, the geodetic engineer bears the responsibility for program management, and the land surveyor makes the measurements.

Surveys to a high order of accuracy may be geo-referenced, where possible, to a geodetic control framework as part of good practice. Not all geodetic monitoring surveys are tied to such a framework, but the survey procedures are similar. What do geodesy and geodetic surveys add to a dam performance plan?

A geodetic survey for dam monitoring advises the owner and engineer about movement. It must be repeatable and accurately related within a reliable geodetic system. The type of survey will depend on location and prior surveys. Surveys may be based on a local system in areas where they cannot be geo-referenced. Such surveys have been widely accepted and are still

in use today. Where a reliable geodetic system is available, best practice is to survey within that system.

There are special cases. Dams in seismically active areas are more likely to have regulations or standard practice for relating surveys to a geodetic system such as a state plane coordinate system. These systems are resurveyed occasionally, and adjustments are made to coordinates of control stations that affect the coordinates of surveys tied to these networks.

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6.1 GENERAL

"Geodetic surveying is a survey in which account is taken of the figure and size of the earth. Geodetic surveys are usually prescribed where the areas or distances involved are so great that the results of desired accuracy and precision can be obtained only by the processes of geodetic surveying" (ACSM 1989).

"Geodesy, also named geodetics, is a branch of applied mathematics and earth sciences. It is the scientific discipline that deals with the measurement and representation of the Earth, including its gravitational field, in a three-dimensional time-varying space. Geodesists also study geodynamical phenomena such as crustal motion, tides, and polar motion. For this they design global and national control networks using space and terrestrial techniques while relying on datums and coordinate systems" (ACSM 1989).

SOLUTIONS 4.0

Surveys are typically needed for large projects spanning distances in excess of 7 to 9 mi (11.2–14.5 km) that require accurate techniques and precise survey instrumentation owing to the curvature of the earth. Large infrastructure projects such as dams and reservoirs require surveys appropriate for their size and connection to a larger utility distribution or flood control system.

Control surveys establish geodetic coordinates on monuments that are then remeasured time and time again to monitor horizontal and vertical movement of the monuments. Not every monitoring survey is as stringent as a control survey; however, the techniques, equipment, instrumentation, and care of work should match the survey requirements. Surveys require careful field and office procedures for error adjustment.

Surveys are classified by orders of accuracy and are dependent on the type of project and reporting requirements. This can best be answered by asking what is being monitored and the realistic tolerances. Dams will have different tolerances and expected accuracies compared to a railroad condition survey.

In some states, surveys are required by law to be referenced to a local/regional/state geodetic system. These surveys are tied (by measurement) to the geodetic system such as a state plane coordinate system or a national

geodetic framework. Fully understanding the difference in datums and coordinate systems is necessary. Surveys have specific guidelines for selection of equipment, execution, and type and amount of measurements to properly define and classify a survey.

Initial surveys tied to a geodetic network provide the framework for all future surveys. Each subsequent survey reports movements compared to the previous and initial surveys.

Repeatability is the cornerstone of dam surveys. Repeatability can only be achieved if the previous surveys are reliable and properly executed. A repeatable survey is one that uses the same measurement techniques and procedures for each survey in order to determine and report trends in horizontal and vertical movement of a dam or structure. Of all the errors in measurement that can be made, the easiest type of error to remove from a survey is the systematic error. Repeatability is the key factor in eliminating systematic errors.

In dam-monitoring surveys, a geodetic system improves the reliability of measurements. A local system not tied to a geodetic system may work well; however, it could limit the surveyor with newer equipment and technology. Regions of frequent earthquakes or subsidence require special care so one can analyze the positional location and accuracies of the network in which the dam is located.

6.2 SURVEY METHODS, OLD AND NEW

SOLUTIONS 4.0

Historically, many conventional methods have been used to obtain survey measurements to monitor movement. Some of the most widely used methods are triangulation, trilateration, collimation, and other alignment techniques. Commonly used instruments for those methods, shown in Fig. 6-1, were transits, plane tables and alidades, and theodolites to measure horizontal and vertical angles, steel tapes to measure distance, and optical levels and graduated rods to measure elevations.

Older theodolites, which could only measure angles, are now largely being replaced by co-axial total stations (theodolites with built-in electronic distance measurement [EDM]) that can measure angles and distances at the same time and record the measurements in a digital file. Older levels that required manual readings off a graduated rod are now being replaced by electronic levels with digital readings off bar-coded rods that greatly reduce the errors in readings.

Regardless of the advances in surveying technology in the recent years, the historic methods must be understood by the surveyor so that consistency is maintained and data from previous surveys is not lost over the life span of the monitoring project. A surveyor must be able to retrace the previous surveys in order to understand the characteristics of a specific

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Plane Table and Alidade Transit

Fig. 6-1. Early instruments

measurement and the errors and reasonable accuracies to expect when comparing to current surveys. An example of this would be a modern surveyor using GPS to compare a measurement that was made in the initial survey using a steel tape. It must be understood that this is not a fair assessment of a distance because taping was a more common practice at the time of the original survey and likely more accurate than using GPS to measure the distance. The same could be said for using a total station to read the same distance that was taped. In most cases, the taped distance will be more accurate and preserved in such a way that any deviation from the original would not necessarily be mistaken as actual movement. The correct tool for the job must be used, and it must be fully understood that unrealistic movements may emerge when comparing new to historic surveys. Newer technology does not always equate to a more accurate measurement.

As software and instrumentation capabilities improve, it may be feasible and more efficient to replace older methods. Historic methods required more time and field crew members to accomplish.

An example is replacing a plumbline. At two concrete arch dams (Duffy 1999), retro-reflective prisms were installed on the face of each dam to measure the x, y, and z displacements on the face of the dam at various heights. This was done in lieu of plumbline measurements that had been taken historically but were decidedly hazardous for personnel to obtain. The new "plumbline" measurements are obtained at the same time as the horizontal and vertical measurements on the crest of the dam, thereby accomplishing both tasks simultaneously. The precision and accuracy of the dam face measurements improved with this method because the physical limitations of acquiring the plumbline readings often introduced error into the measurements.

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Current methods of geodetic monitoring are commonly defined by the type of instrument used to complete the survey; however, the monitoring survey is usually a combination of multiple instrument types, such as total stations, levels, and GPS. Current monitoring projects have the benefit of great advances in technology. The advance in software and robotic instrumentation, combined with the internet and wireless communication, allows the surveyor the opportunity to automate most monitoring projects and remotely control the measurement scheme. It may be more costly up front, but automating a geodetic system greatly reduces labor costs of a field crew traveling to a project to conduct a monitoring survey. Automation not only reduces cost but also provides an expeditious and redundant measurement that can be conducted daily or continuously as needed. Compared to annual and biannual on-site surveys, an automated system does not sacrifice accuracy, but it pays for itself in a short period of time and is most useful in remote areas.

6.3 TOTAL STATIONS

A total station is the modern version of what previously was known as a transit or theodolite. This instrument is an electronic optical instrument used in surveying to obtain angle and distance measurements from the instrument to a specific point that typically has a prism attached to a rod or other device at the point that is being measured. Robotics technology is now the heart of the modern total station, and it allows the instrument person to operate the station by remote control from a distance away. This modernization has reduced the number of crew members needed to conduct typical survey work and allows one person alone to operate the instrument and the rod. Reflectorless technology is now available with limited use to measurement movement depending on surfaces being measured along with distance and angle of deflection. Reflectorless observations can reach locations on a dam face with limited accuracy and repeatability.

Automatic target recognition (ATR) is now a standard on most modern total stations. ATR is integrated into the optics of the total station and uses a charge-coupled device (CCD) video camera that when pointed near a target/prism determines the ATR offset and correctly points the instrument to the exact center of the target/prism. This allows for automated systems to be used because the operator can program predetermined angles for the instrument once programmed. Then, the instrument can turn to its target, and the correction will be made automatically by the ATR mode.

A typical application in dam monitoring allows a survey crew to measure vertical and horizontal angles and measure distances to reflectors or prisms at specific key locations on a dam. These measurements are collected

in sets of angles and distances and measured multiple times in direct and reverse modes to reduce calibration and reading errors. The total station can be used to reach most locations on a dam to measure targets or prisms along the downstream face of a dam. Most targets are permanently mounted on the structure itself or can be placed on a monument to be measured. The total station can be used to check the alignment of a dam by sighting down straight rows of monuments or it can be used to provide coordinates of points on the dam and abutments.

Trigonometric leveling is done using a total station to derive elevations calculated from the vertical angles and slope distance measurements. The accuracy of the elevations will depend on how precisely the total station can measure vertical angles. This method of determining vertical positions can be very useful if applied correctly. In a situation where accessibility is restricted, such as when monitoring a heavily traveled road surface on a dam crest, monitoring points can be set along the edge of the road and measured from a reference point close to the site to keep personnel safe and allow measurements to be taken without disrupting traffic. In situations with large numbers of monitoring points that need to be measured frequently, it is useful and cost effective to combine horizontal and vertical measurements in one operation.

The advantages of using a total station is that it allows the surveyor to measure distances to remote locations that may be difficult to reach with conventional methods. The frequency and amount of measurements to be collected will be important in deciding whether to use a conventional total station or a robotic model. The robotic and automated capabilities of some total stations provide additional benefits when designing a monitoring system on a large or frequently monitored site.

The ability to measure both horizontal and vertical positions accurately in one field operation can be very cost effective. A project that might take a two-person crew 2 to 3 days to measure conventionally (using a total station for horizontal measurements and a level for vertical measurements) might only take one person an hour or two to measure using a robotic, semi-automated system. Depending on the frequency of the monitoring, the somewhat more expensive robotic system may pay for itself quickly compared to the labor costs occurred with other methods.

As mentioned above, the introduction of robotics to the total station allows a geodetic engineer/surveyor to set a total station at a permanent or semi-permanent location and the instrument can complete a measurement cycle of multiple points along the face of a dam. This is typically done with software applications either onboard the total station or with the attachment of a field computer/data collector. Raw measurements including horizontal and slope distances, vertical and zenith angles, and horizontal angles are collected and then calculated into a usable value using coordinate geometry in the software.

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A typical reading output can be either the raw measurements or coordinates collected in the field. Further analysis is required to reduce errors and provide a true measurement and a coordinate of where the measurement was made. Modern total stations can be left in place and attached to an ADAS and can be operated and viewed in real time through software applications from remote locations using server applications and internet-based programs.

When designing a monitoring system, it is best to utilize equipment with digital data-collection systems. This eliminates substantial errors related to handwritten notes and provides a backup system for the data, possibly saving revisiting the site. Data-collection systems need to be reviewed for flexibility of methods of collection and output formats. A careful review of the process the data output goes through is needed to note whether the software performs automatic corrections to raw data that may not be obvious but unwanted.

Operation and maintenance will not be drastically different between various total station manufacturers. The success and reliability of a geodetic monitoring plan is having well-trained survey personnel who have high regard for their instrumentation and equipment and a clear understanding of what and why they are measuring. Most modern total stations are durable and weatherproof, but special care must be taken in operating, transporting, and storing such instruments. Regular calibration checks, along with proper care and cleaning, are done as often as possible or at the start of a monitoring survey. In the case of an ADAS, where the total station is left on a pillar or permanently mounted, weekly and monthly preventive maintenance is part of the geodetic monitoring plan.

ICE Solutions 40 - 50

Careful review of calibrations and errors in measurement cycles is part of the analysis for determining if an instrument is reading correctly. Equipment logs and a good routine for maintenance will promote the longevity of the total station. Site conditions and the maintenance plan will determine the longevity and the type of total station to be used. Total stations must be weatherproof and capable of operating in extreme temperature changes. The total station is an effective and efficient instrument if used correctly in dam monitoring.

6.3.1 Procurement

Consulting with established owners and case studies of different manufacturers is informative before purchasing a total station. Important considerations and questions are part of any informed procurement.

6.3.1.1 Precision. Is EDM precision good enough to achieve the accuracy required for the distances to be measured? Is the angular precision good enough to measure both horizontal and vertical angles with sufficient

accuracy so that horizontal and vertical displacements can be measured with one method of measurement (one visit per point)? Is the angular precision good enough for measuring the angles accurately enough so that few repetitions of measurements are required?

6.3.1.2 Frequency and Quantity of Measurements. Will it be used on a new site requiring monthly measurements or an existing site that is measured twice per year? How many monuments are there to measure? How many instrument setup positions will it require to measure all the monuments? How many work hours will it take to measure manually versus an automated or semi-automated method?

6.3.1.3 Software and Hardware Capabilities. Does the total station allow for electronic data collection? How flexible are the data-collection and data-output methods?

6.3.1.4 Site Conditions. Is the total station readily accessible or remote? In what type of climate is it located— will there be heat wave problems? Is it safe for personnel?

When designing a new monitoring system (or updating an old one), the choice of which total station to use is important. Newer models of total stations that are automated can be costly up front, but when cost is analyzed over the life of a monitoring project, a total station might be the best choice.

SOLUTIONS 4.0

6.4 LEVELS

A level is an optical–electric instrument that is used to measure differences in height between two given points with respect to a reference elevation using the technique known as leveling. Leveling is typically done with a level set up over a tripod. The surveyor sights a staff or rod with a numbered scale or bar code to obtain a reading. There are several types of levels: spirit level, automatic level, and digital level. The two most commonly used in dam monitoring are the automatic level and the digital level.

Automatic levels make use of a compensator that ensures that the line of sight remains horizontal once the operator has roughly leveled the instrument (to within 0.05°). Three level screws are used to level the instrument. The surveyor sets the instrument up quickly and does not have to re-level the instrument after each sight on a rod at another point. The compensator also reduces the effect of minor settling of the tripod to the actual amount of motion instead of leveraging the tilt over the sight distance. Automatic levels have become standard in the last 25 years.

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Digital levels electronically read a bar-coded scale on the staff. These instruments are the electronic version of the automatic level, but they include a data recording capability. This feature removes the requirement for the operator to read a scale and write down the value, which reduces errors. The measurements are made to bar-coded rods and horizontal distances are measured, along with difference in elevations. The digital level may also compute and apply refraction and curvature corrections. This has drastically improved the accuracy and reliability of more precise elevation measurements.

The vertical position (elevation) of a monitoring point can be measured using differential leveling methods or with a total station (trigonometric levels). The trigonometric leveling technique was previously discussed in Section 6.3 *Total Station*. A level is used estimate movement by measuring differences in elevation from a primary benchmark outside the area of influence. The elevations are recorded and later adjusted in the office and compared to previously measured elevations.

Typically, elevations from leveling are the most accurate geodetic measurements. Confidence can be placed on this method because of the accuracy specifications, procedure, and adjustment procedures used with a level. Elevations derived from leveling are more consistent and are typically within a few millimeters of the original elevation of a monument.

The advantages of using a level are greater accuracy as stated above. The elevations derived from total stations and GPS are not the same as a direct reading that is achieved from leveling. The cost per instrument is much less than that of a total station; however, this type of instrument requires at least two people to survey. The reliability of a level depends on the care, transportation, and storage of the instrument. Leveling has a very long track record of providing reliable measurements for dam monitoring. Technology gains have increased the measurement accuracy and data-collection ability. A disadvantage of digital levels is the time it takes to make a measurement.

A level used by a surveyor monitoring a dam needs to have several methods for importing and retrieving data. Multiple user formats should be available when selecting the right instrument, along with the ability to store measurements on an internal memory or type of data card reader. User-defined formats add flexibility to the leveling process and allow for efficient data exchange with field instruments to office computers.

Level operation and maintenance are much simpler. Simple calibration checks are made prior to each level run for a movement survey. It is helpful to include in the field notes and report the serial number of the level along with the collimation error adjusted for that particular level run.

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6.4.1 Procurement

Consulting with established owners and case studies of different manufactures are informative before purchasing a level. Important considerations and questions are part of any informed procurement.

6.4.1.1 Precision. The precision of the level must be good enough to achieve the accuracy needed for the planned elevations to be measured. Will the instrument achieve the accuracy needed? Performance specifications are based on DIN 18723, which specifies standard deviation height measuring per one kilometer of double leveling.

The accuracy of differential leveling methods is usually expressed as a maximum loop closure statement. The National Geodetic Survey outlines the criteria to follow to achieve certain orders of accuracy when establishing new benchmarks (National Geodetic Survey, NGS 1994). First- and second-order criteria are used to generate elevations on the reference points that one would use to start and check in one's level circuit. Movement surveys on monitoring points are usually performed to the third-order criteria.

6.4.1.2 Frequency and Number of Measurements. The frequency and number of measurements depend on the answers to the following questions:

- Could the vertical position be measured at the same time that horizontal positions are measured (one visit per point)?
- Will it be used on a new site requiring monthly measurements or on an existing site that is measured less frequently?
- How many monuments are there to measure?
- What are the distances and terrain between monitoring points and reference points?
- How many work hours will it take to measure manually versus an automated or semi-automated method?

6.4.1.3 Software and Hardware Capabilities. Does the level allow for electronic data collection and processing? How flexible are the data-collection and data-output methods? Will the software allow for careful analysis and adjustment procedures required by the accuracy standards? When considering advanced computer systems, the software and firmware capabilities of the instrument require definition.

When designing a new monitoring system (or updating an old one), the choice of which level to use is important. Newer models of levels that are electronic are not a major cost compared to the overall value that can be achieved. Levels are not left in place as part of an ADAS, but they are a

primary tool used by a survey crew for establishing elevations on projects and are recommended for use in movement monitoring.

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6.5 GLOBAL POSITIONING

GPS, based on a satellite navigation system, is now widely used for dam monitoring. The system returns geo-referenced positions in any weather conditions at any location on the earth. GPS is maintained by the United States government and is freely accessible for many applications. The system provides for monitoring surveys to connect GPS receivers to Continuously Operating Reference Stations (CORS) that are permanently mounted to the ground with deep drill-braced monuments and provide precise reference frames to the postprocessing of GPS data files. These stations are maintained by local and scientific agencies, and some are tied into a national network by the NGS.

The advent of GPS has given the surveyor the ability to transport accurate horizontal control to a monitoring site from greater distances than traditional triangulation and trilateration networks. This control is almost always more accurate and less costly, and it is independent of weather conditions. GPS is especially effective in establishing and verifying geodetic control used at nearly all monitoring sites that have sufficient sky view. The initial investment in GPS is substantial, and agencies or companies performing monitoring surveys usually require several monitoring sites or other types of survey projects to justify this investment. This is especially so in the case of most dams and reservoirs, which will require a four-receiver system to be economical. Positional accuracy in this type of network ranges from 0.12 to 0.20 in. (3 to 5 mm) in the semi-major axis at two standard deviations.

To offset this cost investment, users can sometimes take advantage of existing CORS in many areas around the world where both a large population base and earthquake activity exist together. These stations have been established by large government agencies or scientific organizations to help solve regional problems related to seismic or subsidence activity. Most of these systems have automated the collection and processing aspects of the GPS data through phone modems or wireless radio and data-processing centers. The data can be retrieved via the internet at no charge to the user in many instances.

A second way to reduce costs with GPS is to establish on-site CORS by creating two reference points that surround the project, as shown in Fig. 6-2. By leaving two GPS units operating continuously (during the survey duration) at these reference points, only one or two survey personnel are needed to create a very dependable and accurate system for measuring horizontal displacements. Testing has shown that the horizontal positioning

Fig. 6-2. CORS setup

Fig. 6-3. RTK setup

using this technique is more accurate than the more traditional "bridged" network that uses the short vectors created between monitoring points. This method is also a more reliable adjustment because only adjustments of vectors between fixed or constrained reference points occur and not between vectors established between monitoring points themselves.

Another example of GPS related to structural monitoring involves concrete gravity dams. Static GPS systems have been designed to continuously monitor long-term movement in gravity dams from changes in reservoir level, thermal effects, and wind.

Real-time GPS systems capable of measuring small movement at up to 10-Hz sampling rates are available and are likely to become another tool in measuring earthquake effects in real time on embankment and concrete dams in future practice.

A real-time kinetic (RTK) system, shown in Fig. 6-3, requires a GPS base station that is broadcasting from a known reference location to a roving GPS unit(s) within radio range. The position of the rover is broadcast in real time at about a 1 s interval. These controlled conditions include

- Rover and base separated by less than two miles,
- Well-modeled tilt of the local geoid,
- Mean position of multiple readings, and
- Fixed-height tripods.

For any of these GPS methods, the use of the precise orbital ephemeris increases the horizontal positioning accuracy significantly to the level of 0.12 to 0.20 in. (2 to 3 mm) in the semi-major axis at two standard deviations. Other key considerations included in producing this level of GPS position accuracy are

- Horizon elevation mask (15 to 20°),
- Survey time at monument (minimum of 30 min), and
- Multipath error (reduced with choke-ring-style antennas).

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GPS cannot produce vertical positions accurately over relatively short distances compared to using a level. However, some applications using RTK techniques show promise in the 0.4 to 0.6 in. (10 to 15 mm) range vertically under properly controlled conditions. RTK may prove useful during construction of large embankment dams when settlement from loading and compaction is expected to be fairly large.

6.6 LIGHT DETECTION AND RANGING

Light detection and ranging (LiDAR) is used in remote-sensing applications and measures distance to a surface by illuminating a target with a laser. Reflected light is analyzed to determine a distance to provide a high-resolution three-dimensional digital maps and terrain models. LiDAR has applications in geomatics, geology, seismology, forestry, and many other remote-sensing and contour-mapping needs. LiDAR can be utilized in terrestrial, airborne, and underwater applications. The benefits of LiDAR include detailed mapping of the character of the ground and structures from a remote application where access to an area is not feasible such as penstocks and tunnels, modeling of surface areas prone to earthquake damage, and terrain models that can be created over large areas and archived for future evaluation of movements after an earthquake.

LiDAR has been used in dam monitoring, along with sonar, optical, and hydrographic survey data, to provide digital terrain models of the above and below water surfaces of dams and their foundations. This technology is rapidly advancing and is a cost-effective addition to the standard dam-monitoring plan.

The terrestrial LiDAR technique uses a 3D scanner, shown in Figs. 6-4 and 6-5, to collect data on the shape and appearance of an object by scanning the object with millions of measurements to define the shape and size. The scanner collects distance information about a surface within its field of view. The image that is created by a 3D scanner allows for a 3D position of each point in the image. The scans are referenced to a common system, registered, and merged together to create a model. The scanner can be used for monitoring movement on any type of dam. Scan data can be measured, archived, and compared to future or past scan data.

Concrete dams can be scanned using existing movement survey control points and related to conventional measurements. In addition to analyzing the traditional points of interest, any portion of the point cloud may be analyzed. Scans of concrete dams can be analyzed several ways:

- Vertexes can be placed on points of interest that are clearly identifiable. The vertexes can be exported and saved in a text file for comparison to future scans.

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Fig. 6-4. Terrestrial scanner
Source: Courtesy of Leica Geosystems HDS, reproduced with permission.

Fig. 6-5. Terrestrial scanner in use

- When a successive scan is done, the vertex file can be imported from the text file into the new scan, and any movement can be seen visually in the point cloud on each point of interest.
- A complex mesh can be created on the structure and archived. Once a successive scan is done and a new complex mesh is created, the original complex mesh can be overlaid to detect changes.
- The survey control lines being used with traditional equipment can be incorporated into the point cloud and used to report measurements using a cross-section method with a virtual reference plane created in the software.

Embankment dams can be scanned using existing movement control points and compared to measurements made by other techniques. In addition to analyzing the traditional points of interest, any portion of the point

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cloud can be analyzed. Scans of embankment dams can be analyzed several different ways:

- Vertexes can be placed on points of interest that are clearly identifiable, such as high points of rocks on the face of the dam.
- The vertexes can be exported and saved in a text file for comparison to future scans.
- When a second scan is done, the vertex file can be imported from the text file into the new scan and any movement can be seen visually in the point cloud on each point of interest, clearly showing whether the rock face settled between the two scan periods at the vertex location.

A complex mesh can be created and archived. Once a second scan is done and a second complex mesh is created, the original complex mesh can be loaded to identify changes, clearly showing whether any portion of the rock face settled between the two scan periods.

Accuracy of a single measurement is approximately 0.5 in. (6 mm) at a range of 3 to 150 ft (1 to 50 m). Higher accuracy may be achieved using software to average thousands of points on the object of interest.

There are limitations to this method. Water absorbs the laser light and yields no information. Consequently, the scanner will not measure points on a water surface. Also, the range of scanning distance varies by scanner. Most scanners will produce accurate scans to 1,000 ft (300 m). Scanners will not operate properly in heavy vibration conditions, including in high winds.

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6.6.1 Scanner Position

The scanner operates like a traditional total station in respect to setting it up over a known survey point and backsighting a known survey point. The scanner can also calculate its setup position using resection from two or more survey control points. A twin target pole with 3 in. targets is used to target the backsight survey point or resection points.

6.6.2 Targeting

Targeting is used to join multiple scans together with higher accuracy than relying solely on the traverse points of the scanner. Additional targeting is required on high-accuracy jobs with multiple setups. The different types of targets available are

- 6 in. (0.15 m) hemispheres,
- 6 in. (0.15 m) spheres,
- 6 in. (0.15 m) planar targets (magnetic and adhesive),
- Black-and-white paper targets,
- 3 in. (0.07 m) planar targets (magnetic and adhesive), and
- 3 in. (0.07 m) twin target poles.

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6.6.2.1 Target Distance Limits. Target choice depends on the distance of the scanner from the target. A 3 in. 0.07 m) target may be used when the target is 150 ft (45.7 m) or less from the scanner, but 6 in. (0.15) targets should not be placed more than 500 ft (152.4 m) from the scanner.

6.6.2.2 Cloud-to-Cloud Targets. Targets can be established virtually in clouds within the software after the field scanning is complete if there are unique points that can clearly be identified in multiple scans. This office process usually takes longer than the time it would have taken for the field surveyor to place targets in the scan area before the scan. For efficiency, it is always better to place the targets in the scans in the field; however, the requirements of a project may change after the field scans are complete. Cloud-to-cloud targeting is an option to increase accuracy in the office. Figs. 6-6 and 6-7 provide examples of dam LiDAR scans.

6.7 FUTURE TRENDS

Advances in remote sensing and electronics have opened numerous doors in geodetic monitoring. High-accuracy achievements and advances in spatial resolution have given the surveyor more tools to add to the monitoring plan. Two major remote-sensing applications are LiDAR and interferometric synthetic aperture radar (InSAR). Recent advances in electronics and computing processors make these techniques more affordable and readily available. Future geodetic technologies such as terrestrial 3D surveys with high-definition scanners and airborne LiDAR surveys will provide new options in the way surface monitoring is done. As a supplement to standard geodetic monitoring, 3D high-definition scans and detailed models of large land areas and structures can be made for monitoring movement.

Airborne LiDAR surveys tied to ground GPS stations are becoming a more cost-effective way to create digital terrain models (DTMs) and high-resolution ground models to identify ground features associated with slope movements. Color-coded LiDAR relief maps are being used to detect instability in terrain features or structures themselves. Another trend is InSAR that may further alter the way surface monitoring is done by using ground-based or satellite measurements to the ground over a time series to detect movement in regional land areas and some large dams.

As drone technology becomes more available and widely used for spatial applications, imagery resolution will become more effective for some ground-monitoring applications.

On a much larger scale, plate tectonics and volcanic movements are monitored using real-time GPS networks. These networks are based on a

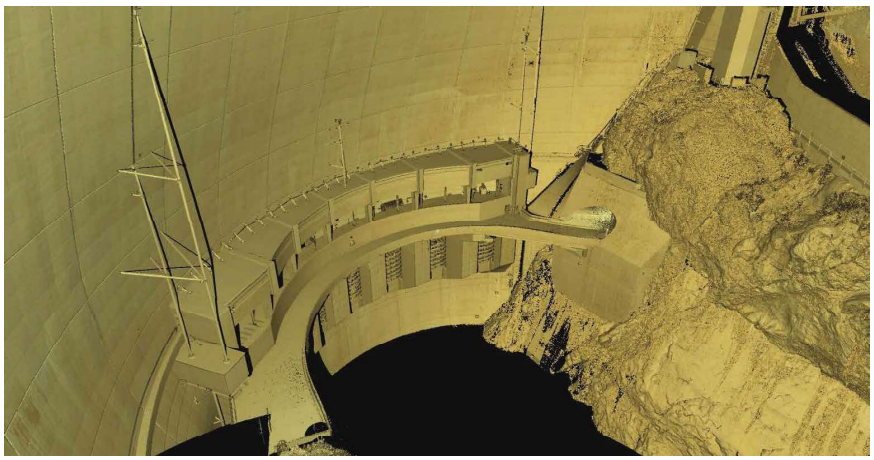

Fig. 6-6. Arch dam scan
Source: Courtesy of Seattle City Light, reproduced with permission.

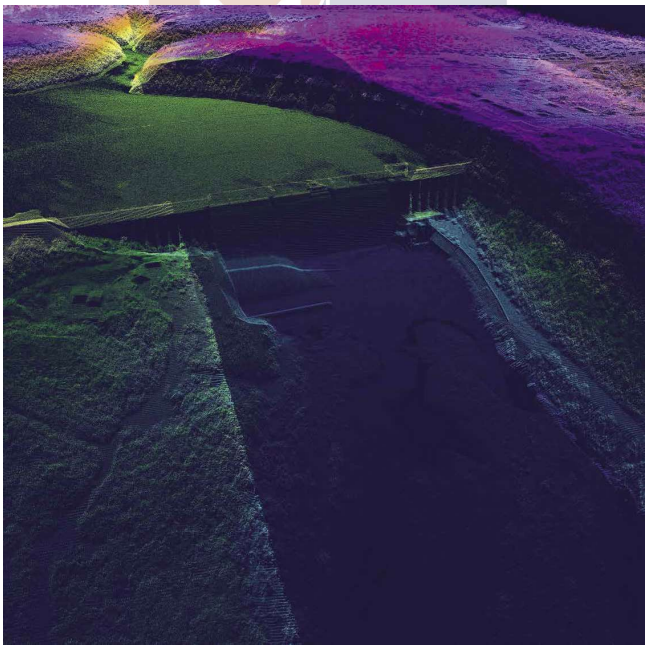

Fig. 6-7. LiDAR terrain model of Morris Sheppard Dam
Source: Texas Natural Resources Information System/Texas Water Development.

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CORS, which is a GPS antenna permanently attached to a deep drill-braced monument that transmits very accurate positions of a station. Many of these networks are currently in place and have been used by the geodetic/scientific community for several years. Advances in geodetic software, internet protocols, and communication systems have provided a very dense and accurate GPS network.

This new trend in detailed 3D intelligence, LiDAR/InSAR, and active GPS networks, along with modern geodetic analysis software, will help develop interesting strategies for future monitoring planning.

6.7.1 Interferometric Synthetic Aperture Radar

An emerging technology with possible application in dam monitoring is synthetic aperture radar (SAR). SAR is an electromagnetic imaging sensor often used in remote-sensing applications. The SAR sensor is mounted on an aircraft or a satellite and is used to make a high-resolution image of the earth's surface. Images of several passes are enlarged to obtain changes in elevation (Peltzer 1994). SAR uses a wavelength of 2.5 in. to 3 ft (1 cm to 1 m), whereas optical sensors use wavelengths near that of visible light, or 1 μm. These longer wavelengths enable SAR to see through clouds and storms, whereas optical sensors cannot because a SAR sensor carries its own illumination source in the form of radio waves transmitted by an antenna. SAR can be used at any time of the day or night. Methods are currently being developed that will allow for a dam and the surrounding area to be monitored for vertical movements using SAR.

SAR is a radar-based measurement technique used in geodesy and remote sensing. This method uses two SAR images to generate maps of surface movement or digital elevation models. This is done by determining differences in the phase of waves returned from the satellite or aircraft. Centimeter-scale changes in movement over spans of days to years can be detected for a time series. SAR is currently used in geophysical monitoring of natural hazards, such as earthquake fault zones, landslide areas, volcanic, and subsidence areas.

SAR can be used to supplement current monitoring methods used on large dam projects or to provide a more regional view of the terrain surrounding a monitoring project.

Fig. 6-8 (Mazzanti et al. 2015) illustrates SAR identifying elevation changes at Three Gorges Dam in China.

Continuous measurement and movement detection can be done by the same technology using a terrestrial-based system, a device for which is shown in Fig. 6-9. Day-and-night, all-weather observations can be conducted utilizing radar signals toward the face of a dam or structure and

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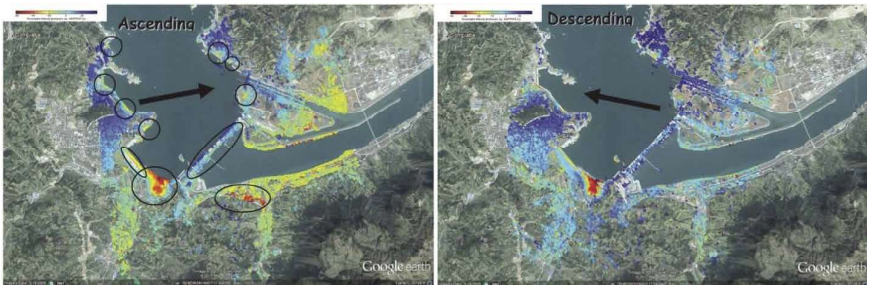

Fig. 6-8. Airborne SAR
Source: Courtesy of NAHZCA, Google Earth, reproduced with permission.

Fig. 6-9. Terrestrial SAR scanner
Source: Courtesy of Olson Instruments, reproduced with permission.

provide 2D displacement intensity maps that show back-scattered radar images.

6.7.2 Unmanned Aerial Vehicles

Unmanned aerial vehicles (UAVs), an example of which is shown in Fig. 6-10, are commonly referred to as drones and are remotely piloted aircraft. Other types of UAVs are unmanned air systems (UASs) and remotely piloted aircraft systems (RAPSs). The UAV is flown autonomously using an onboard computer system and flight software, or it is piloted using remote control. This technology is emerging, and payloads of special cameras and optics are bringing new monitoring opportunities as the accuracies and techniques are improved. The UAV can cover large areas that are inaccessible, unsafe, or too expensive for ground survey. Large dams and reservoirs can be measured quickly using a UAV. This capability is useful for emergency inspections and mapping and emerging technology to perform safer dam, spill gate, and transmission line condition inspections currently, requiring specialized high-angle access. UAVs provide high-resolution photographs and video for future comparison.

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Fig. 6-10. Unmanned aerial vehicle (UAV)

6.7.3 Real-Time Networks

On a much larger scale, plate tectonics and volcanic movements are monitored using real-time GPS networks. These networks are based on CORS equipped with a GPS antenna permanently attached to a stable monument. CORS continuously transmit very accurate positions of the stations, as shown in Fig. 6-11. Many of these networks are currently in place and have been used by the geodetic and scientific communities for several years, and their utility is likely to improve with time.

6.8 PLANNING AND IMPLEMENTING

This section provides suggestions for creating a new monitoring plan or evaluating an existing plan. With aging dams and advances in technology, the demand to maintain and/or expand a monitoring plan requires thought. A monitoring program that includes surveying to measure performance indicators requires an easily understood plan that is portable to the next generation. Every dam is different, and there is no single answer or solution to planning and designing an effective program. Lessons learned from experience are helpful for planning and implementing a geodetic monitoring plan.

Selection of the survey method will be proposed by the surveyor to measure those performance indicators identified in the review of failure modes. The surveyor provides the dam owner and engineer with survey means and methods to accomplish the required measurements and assists in selecting a preferred alternative. The comparative accuracies, reliability, and costs of competing alternatives must be balanced within the overall dam-monitoring program. Allowing the surveyor to recommend a preferred survey alternative has benefits because it is the surveyor who must do the work and obtain the measurements.

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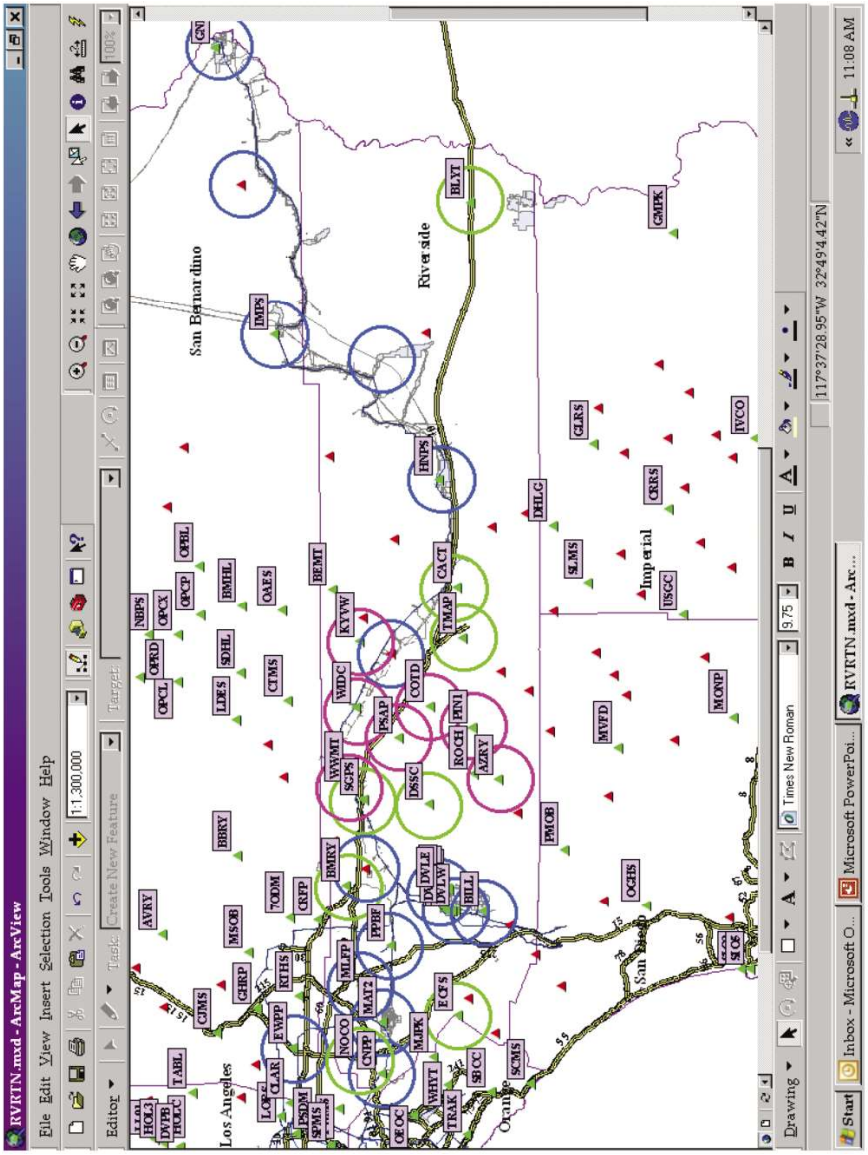

Fig. 6-11. CORS network

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When designing and implementing a geodetic movement-monitoring plan for a new project or when evaluating an existing plan, there are several aspects to be considered. A monitoring plan for new projects should be done in coordination with the dam owner, engineers, and design staff. There is a positive benefit to planning and designing before project design is advanced. The locations of monuments, sensors, instruments, and power sources are better managed if they are part of the overall design rather than being added as an afterthought. Many projects will require surveying during construction, which becomes an important planning factor for monitoring movement because the surveyor must handle both tasks until construction is complete.

Some of the main factors to carefully consider and evaluate are (1) performance indicators to be measured, (2) type of structure to be monitored, (3) accuracy requirements, (4) frequency of monitoring, (5) expected products, and (6) the schedule for performance.

6.8.1. Arrangements for Different Types of Dams

6.8.1.1 Multiple-Arch and Buttress Dams. For multiple-arch and buttress dams, monitoring points are usually located at the nose and toe of each buttress. In the case of massive buttresses and large multiple arches, special attention is required for the foundations of the buttresses. If buttresses have contraction joints, joint movement requires measurement (Chrzanowski et al. 1992).

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6.8.1.2 Gravity and Arch Dams. The requirements for measuring movement at the toe and along the abutments vary with the dam. The points to be measured are distributed as needed to address the need for measurements of performance indicators, as shown in Fig. 6-12. It is common practice to fit each monolith with monuments that allow for measuring movement of the crest.

6.8.1.3 Embankment Dams. Lines of monuments are located along the crest and on the downstream slope, as needed, to measure movement, as shown in Fig. 6-13. Monument spacing may consider loss of a monument so that the remaining spacing between monuments is small enough to reliably detect movement.

6.8.2 Accuracy Requirements

Required accuracy is a function of the expected behavior of a dam. The surveyor consults with the designer to learn the bounds of expected movements and then chooses the means and methods required to produce accurate measurements.

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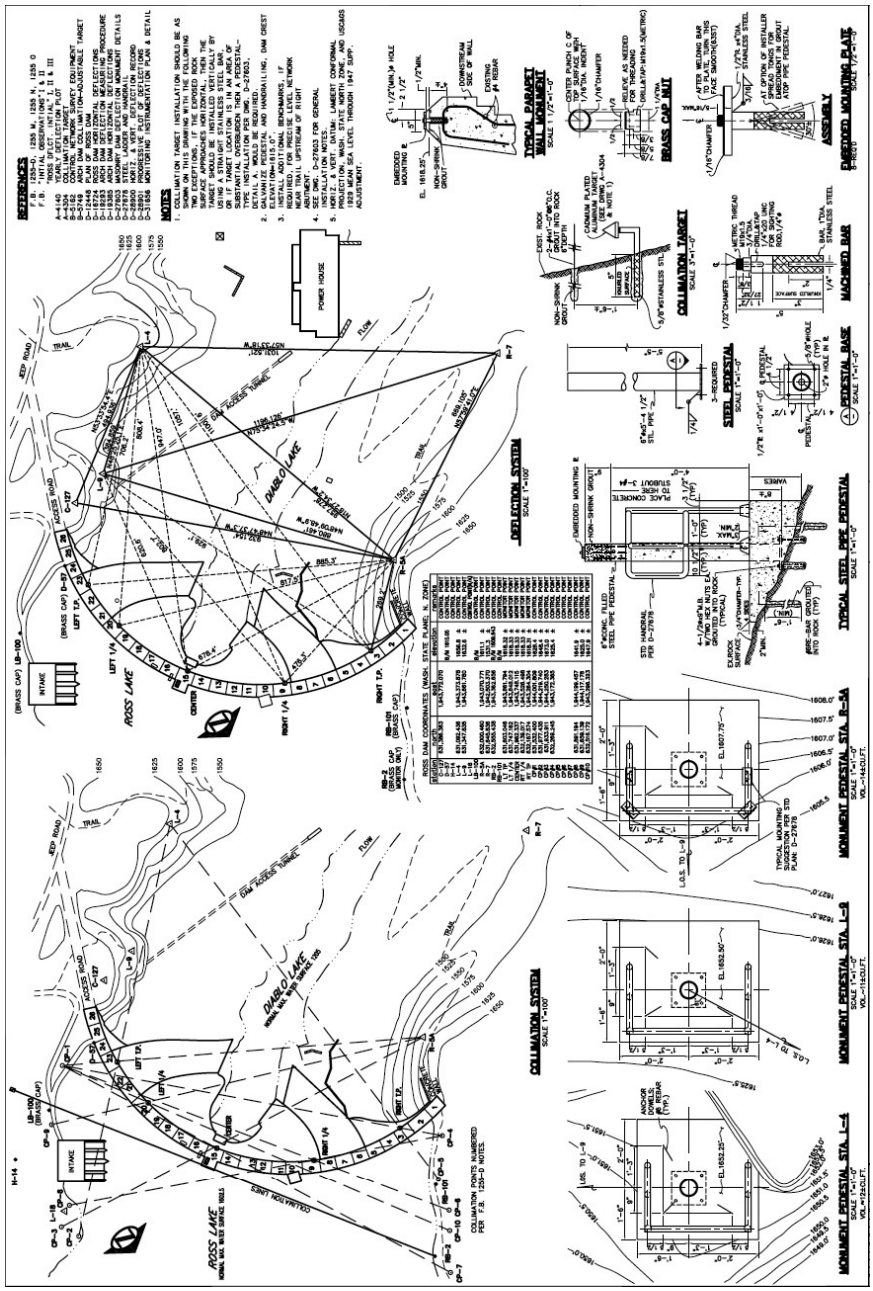

Fig. 6-12. Arch dam survey layout example.

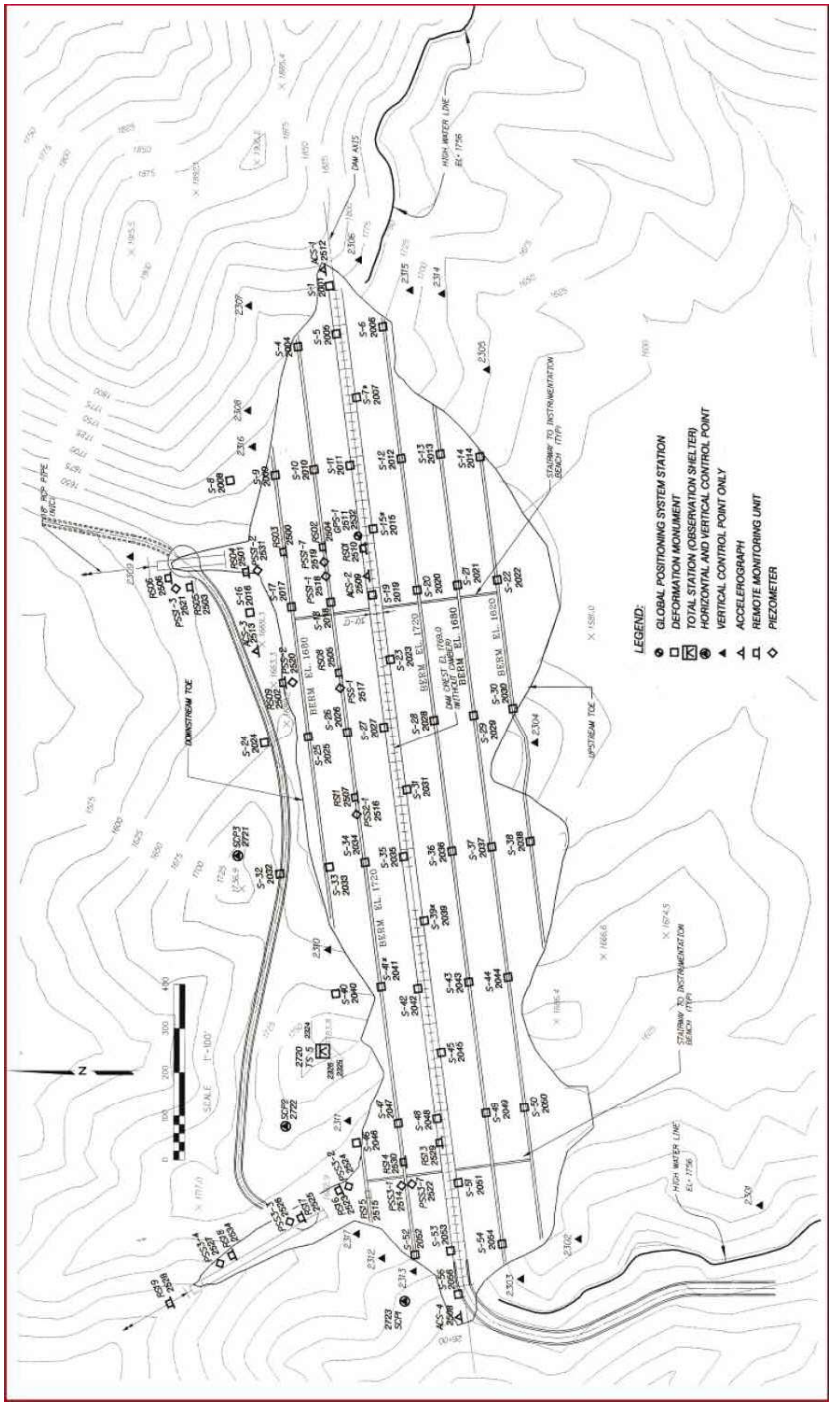

Fig. 6-13. Embankment dam survey layout example

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6.8.3 Monitoring Frequency

Frequency may depend on design specification, stage of construction, regulatory requirement, expected movements (a failing slope, high wall monitoring, first filling), and time of year (seasonal movement of concrete structures). Time of year affects the deformation readings owing to thermoelastic effects on a structure in different seasons. It is important for the geodetic engineer/land surveyor to understand the duration of the monitoring for the project and the frequency of measurements that are expected. These two aspects are important in how the plan will be designed and implemented as they affect project labor and material costs and the type of geodetic monitoring to be used.

The surveyor works with the owner to understand the limitations of program costs (if any) and engineer to establish monitoring schedules.

The frequency of measurements (or observation schedule) varies depending on the stage of the life of the dam:

- Preconstruction stage—geodetic positions are established and measured to establish baseline positions of reference points for later comparison;
- During construction—geodetic positions are measured to identify problems or to verify that structural behavior is compatible with expectations;
- During first filling—monitoring frequency is greatest during this stage. Measurements at this stage provide a means to evaluate design assumptions, construction adequacy, and overall performance; and
- During service operation—geodetic positions are measured less frequently.

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Whenever practicable, planning a monitoring system with digital data collection will provide greatest accuracy at the least cost. This eliminates errors related to handwritten notes and provides a backup system for data. Data-collection systems require review for flexibility of methods of collection and output formats.

Site conditions need to be considered when designing a survey system. The ability to automate a remote site or a site that is difficult or unsafe for personnel may determine whether it is better to use a conventional total station or a robotic system. The site conditions may also lend themselves to using GPS to monitor horizontal positions instead of a total station. This is especially true in areas where extensive heat waves make it nearly impossible to get good total station measurements. Steep valleys may interfere with signal reception from satellites. Otherwise, areas with line-of-sight problems may be better suited for GPS.

6.9 MONUMENTATION

All movement-monitoring plans require stable points that can be measured in three dimensions. Monuments of various types achieve this function. Monuments are described in this section for different monitoring surveys and for different structure types. A discussion on active versus passive monumentation is provided, along with monument diagrams. Factors to consider for monitoring plans are discussed along with suggestions for mapping and tracking of monuments for the duration of a project. Suggestions are included for proper measuring, acquisition, analysis, and reporting movement measurements.

Typical monuments are permanent devices such as concrete pedestals and embedded metal plaques. Once surveyed and marked, these monuments are observed repeatedly to measure movement. Each should have a unique identification name stamped on the monument itself. Computer-aided drafting (CAD) or geographic information system (GIS) mapping can be used to show the relative locations of both the monitoring points and the control monuments in relationship to the structure being monitored. A comprehensive map that accurately represents monument locations is useful for the duration of the project for all involved with the monitoring plan.

The durability of surface monuments is important. These devices may be located on spillways, embankment dams, concrete dams, reservoir slopes, abutments, supporting fills, dikes, and appurtenant structures such as penstocks. Failure to locate in both stable and accessible locations will result in loss of monitoring accuracy, as well as a lack of confidence in the results. Monuments used on a structure must also be located for durability, taking into consideration ground conditions.

RE-SOLUTIONS 40-50

6.9.1 Selection Criteria

Care is needed in considering

- Spacing interval of monitoring points,
- Efficiency and economy,
- Accessibility (crew safety),
- Durability,
- Type of monument,
- Terrain (stable ground, line of sight),
- Network design,
- Geometry of network, and
- Type of structure.

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6.9.2 Monument Types

The type of monument to be used at a given site is a function of the soil or rock type encountered. Setting monuments that have the possibility of losing their foundation support will result in loss of data. Reference monuments are located in natural ground or in cut areas where they are used as benchmarks or primary survey control points. Reference monuments are stable and durable away from areas of interference.

As well as being marked or stamped with a unique identification name, a monument will have a measuring point near the center that is easily discernible and will not be lost or misinterpreted over time. This mark, known as the "punch mark," allows for repeat measurement because a rod or prism tip can be placed in the same location every time a measurement is taken. The measuring point is best marked in brass or aluminum cap-type monuments whenever possible. Brass caps facilitate leveling operations. The attachment of the brass cap to the concrete foundation should be made at the time of the concrete pour whenever possible. Installation of brass caps into existing structures should be made with strong epoxy. The brass cap should be set flush or slightly recessed to avoid traffic damage and deter vandalism.

Monuments in large existing concrete structures or set in extensive constructed concrete foundations are the most commonly used. The larger the structure, the more likely the monitoring monument will not be affected by local ground disturbances such as vehicle traffic, rain runoff, or soil expansion.

SOLUTIONS 4.0

The monuments shown below are examples of robust design. Variations on these basic designs also are used.

These monuments can also serve as observation points.

Monument Type A-1, shown in Fig. 6-14, is best suited for embankment dams and as a reference monument when there is no bedrock for its foundation. It is the most economical of the monuments listed here.

Monument Type D-1, shown in Fig. 6-15, is used on an embankment dam crest where protection is required from motor vehicles. This monument can also be used to protect reference monuments that are located in natural ground that need protection from off-road vehicles.

Monument Type D-2, shown in Fig. 6-16, is used for reference monuments that must be located in areas with substantial permafrost activity or where the soil consists primarily of sand or other granular soil.

Monument Types D-4 and D-5, both shown in Fig. 6-17, are installed in embankment and concrete dams, respectively, where semi-automatic or robotic systems are utilized. These monuments can also be used for references at any site designed for semi-automatic or robotic instrumentation.

Another type of monument, shown in Fig. 6-18, consisting of a steel stud with a threaded end that is drilled and placed in concrete and fixed

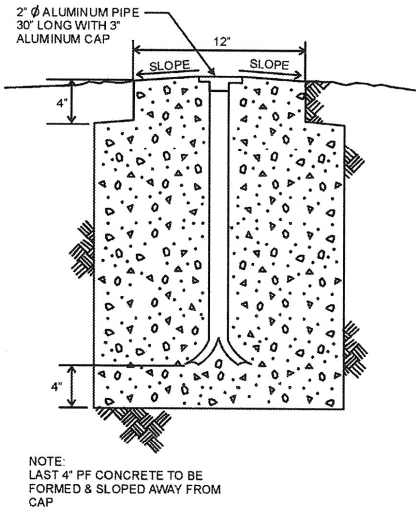

Fig. 6-14. Monument type A-1

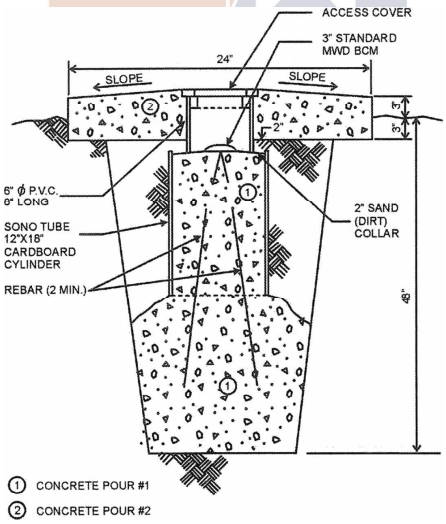

Fig. 6-15. Monument type D-1

with epoxy, can be used on the crest of concrete dams in lieu of those previously listed. A retro-reflector can then be attached and left in place if measurement frequency justifies the investment. Devices left in place are vulnerable to severe weather and vandalism, and they may cause tripping hazards.

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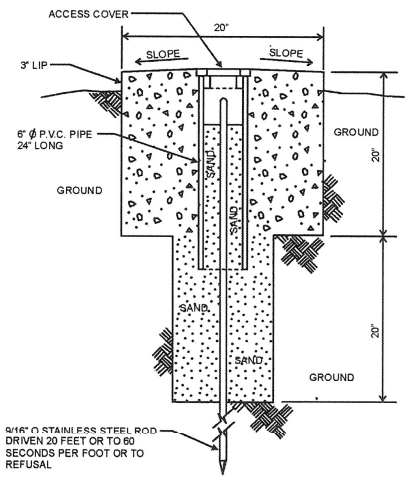

Fig. 6-16. Monument type D-2

The superior monument is one that really may not appear to be a monument, at least in the classical sense. CORS monuments, shown in Fig. 6-19, eliminate the effect of slight surface movement and weathering of the top soil. Collaboration among scientific agencies and organizations suggest a best-practice monument, which is five-legged, stainless-steel piping filled with pumped grout and driven at least 30 ft into the ground and welded at the apex where the GPS antenna resides. CORS monuments are designed to last more than 50 years with little or no movement owing to any factors other than earthquakes.

6.10 DATA COLLECTION

Data-collection methods are an important consideration when planning a monitoring system. The use of equipment that digitally collects and stores data, as shown in Fig. 6-20, improves the overall accuracy and provides a record of the fieldwork and measurements made. Labor efficiency is also improved with data-collection systems because they can replace handwritten note-taking typically done in the field. One potential disadvantage is that digital collection excludes the opportunity to look for visible clues to explain the data.

Total stations typically collect data with a handheld data collector or onboard data-collection software. The data is then usually stored on a digital memory card or similar device that is inserted into a PC or small peripheral for downloading.

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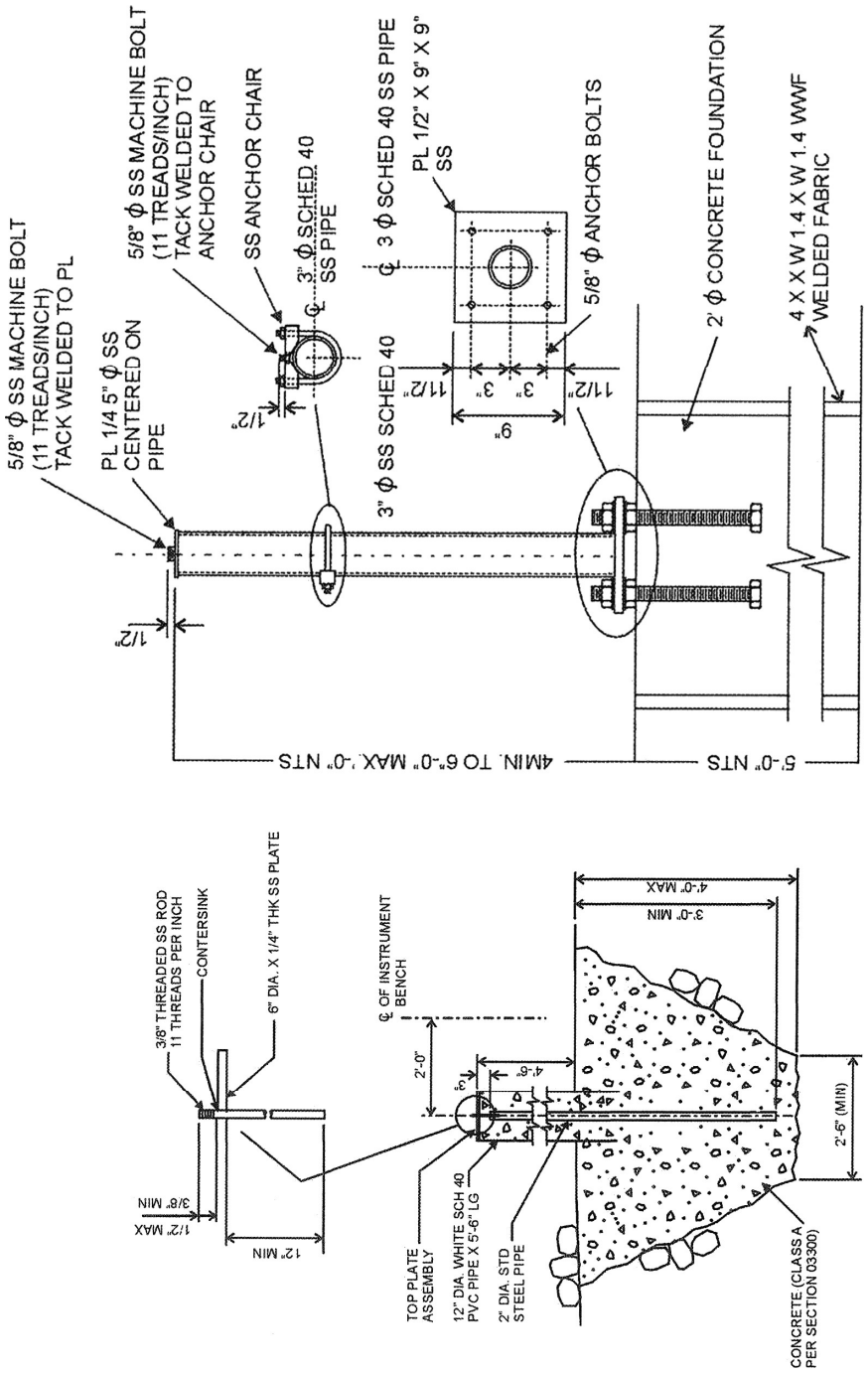

Fig. 6-17. Monuments type D-4 and D-5.

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Fig. 6-18. Stationary reflector

Fig. 6-19. CORS monument

The accompanying software allows the data to be downloaded and formatted for further processing or evaluation. Most equipment manufacturers sell proprietary software programs that are designed specifically for their equipment. It is important to consider the functionality of the software for data collection when considering the purchase of a specific surveying instrument as not all software programs have the routines that are best suited for movement survey methods, such as set collection. Electronic levels collect and store data on an onboard recording module. This module is then downloaded through a small peripheral utilizing the proprietary software that formats the data for further analysis. GPS receivers collect

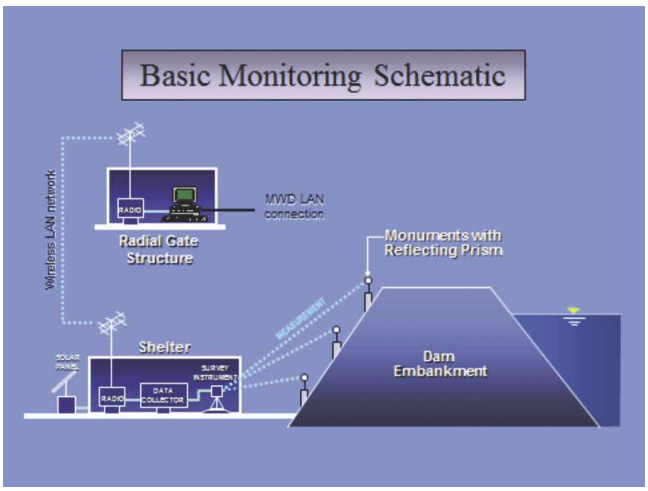

Fig. 6-20. Basic monitoring schematic

and store the data onboard, which may be downloaded through a serial connection to a PC. Each receiver manufacturer has proprietary software for downloading and processing of the raw data. Further analysis is then done using a least-squares adjustment program.

All three types of equipment need additional data collected by the field personnel. In all cases, measurements of the instrument and object heights need to be recorded. As a general rule, it is best to have the field person measure the height twice, once in meters and once in feet, to provide a check. Incorrectly measured or written-down height measurements are one of the most frequent avoidable sources of errors in survey field work. Recently, several equipment manufacturers have started selling fixed-height tripods. These tripods are designed to reduce errors in height by only allowing for a fixed height of the object (prism, GPS antenna, and target) and are usually in heights of 1.5 or 2 m.

Other data to be recorded include the point name or number. Leveling equipment and GPS equipment require a four-digit name or number of a monument. It is best to assign a four-digit number (versus a name with letters in it) to identify each monitoring point because not all equipment accepts alphanumeric input, and by assigning a number it gives greater flexibility for future methodology. Other data to collect manually include the usual survey information such as crew names, weather conditions, and visual observations.

ADASs are a cost-effective method to collect survey data on large projects. The Eastside Reservoir in Hemet, California, a very large project encompassing three dams, has an ADAS for all the geotechnical instrumen-

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tation and an automated data-collection system for the survey data. The data are collected by remotely operated robotic total stations directed by a PC-based monitoring application that directs the functions of the total stations. This system is automated to collect the data and then transfer the data to a remote location for analysis (Duffy 1998).

6.11 DATA ANALYSIS

Even the most precise monitoring surveys will not fully serve their purpose if they are not properly evaluated and utilized in a global integrated analysis as a cooperative interdisciplinary effort. This interdisciplinary effort includes visual inspections as well as geotechnical and surveying instrumentation.

The analysis of survey data has become much more advanced with the advent of computer software programs capable of least-squares adjustments. These types of analysis tools have allowed practitioners to use methods found in the field of mathematics to communicate statistical confidence in the position of monitoring points. With the advent of GPS technology, this type of tool has become essential. Positional tolerances can now be expressed in terms of the length and azimuth in the major and minor axes of an error ellipse figure. This can be calculated with different statistical probability criteria such as 39% probability when the standard error ellipse is used in defining the positional accuracy or 95% probability when the axes of the standard error ellipse are multiplied by 2.447. An engineer can express confidence, or lack thereof, in the absolute movement of each monitored point with some mathematical certainty. The output of many of these adjustment programs have a graphical display that can visually show the magnitude and directional movement trends of all the monitoring points together and individually.

It is important to understand that although geodetic networks and least-squares adjustment procedures are excellent analysis tools for understanding the integrity of control monuments, they are deficient, in some ways, to understanding the performance indicator movement associated with actual monitoring points in a geodetic scheme. The purest method of analyzing monitoring points for true movement comes about by simplifying the measurement vectors associated with each point. This can be restated by saying the best way to measure monitoring points is with an accurate independent measurement to each point accomplished directly from a stable reference monument. Any kind of adjustment performed at the monitoring point itself dilutes the ability to distinguish movement associated with adjustment and that associated with true movement.

Eventually, geodetic coordinates and elevations collected at monitoring points need to be analyzed together with other data such as seepage,

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pressure, and stress. This can be accomplished by comparing both types of data and trying to find a geographic connection or pattern to the data. Also, one may design a monitoring system so that most or all the instrumentation has a geodetic element to it, thus incorporating absolute capabilities to an otherwise relative measurement system. The monitoring system can also be organized or programmed to get readings from both types of instruments at approximately the same time intervals, thus allowing for better correlation of the data.

The technical term for this kind of evaluation process is "integrated movement analysis" (Chrzanowski et al. 1992). The expression "integrated analysis" means a determination of the movement by combining all types of measurements, geodetic and geotechnical, even if scattered in time and space, in the simultaneous geometrical analysis of the movement, comparing it with the prediction models, and enhancing the prediction models, which in turn, may be used in enhancing the monitoring scheme (Chrzanowski et al. 1992).

Several software packages for geometrical analysis have been developed, such as DEFNAN, PANDA, and LOCAL. Some of these packages, such as DEFNAN, are applicable not only to the identification of unexpected movement but also to the integrated analysis of any type of movement, whereas others are limited to the analysis of reference geodetic networks only.

6.12 REPORTING

SOLUTIONS 4.0

The owner or dam safety engineer who will use a movement report will also determine what type of plan to use. The surveyor may need to choose between automation systems versus conventional survey systems and determine the best data-collection method to use. Either way, the product must be usable for the dam safety engineer and it must be produced in an efficient and timely manner; it will be more critical during an emergency or under special operating conditions. This may be especially true in cases of problems associated with structures during filling operations and in earthquake-prone areas.

An efficient and well-thought-out monitoring plan loses value if the results are delayed because of lack of personnel, equipment, or other factors that may occur in an emergency. An early detection or early warning is an important factor in planning. Software applications delivering real-time alarms when a position tolerance is exceeded on a structure can deliver a movement report. The format for a movement depends on how it will be used. Reports that are simple, well thought-out, and flexible enough to allow the surveyor to relay information quickly are the best (Fig. 6-21).

Methods of reporting movement vary among the surveyors. Written reports describe the method used at the time of a survey and are supplemented with

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Porter Ranch Dam

Comparison PE1006.xls

Horizontal and Vertical Displacement Monitoring

NAD83 1991.35 Epoch, CCS Zone 5, Grid Coordinates & NAVD88 Elevation Comparisons

	INITIAL VALUES June 1998			June 2009 Survey			June 2010 Survey			CURRENT MINUS INITIAL YEAR			CURRENT MINUS PREVIOUS YEAR		
PCID NO.	NORTHING (MTRS)	EASTING (MTRS)	ELEV. (MTRS)	NORTHING (MTRS)	EASTING (MTRS)	ELEV. (MTRS)	NORTHING (MTRS)	EASTING (MTRS)	ELEV. (MTRS)	DELTA N	DELTA E	DELTA ELEV.	DELTA N	DELTA E	DELTA ELEV.
*North, East & Up offsets are positive and South, West & Down offsets are negative															
1001	584881.217	1948115.506	324.322												
1002	584797.712	1947987.474	310.238			310.232			310.234			-0.003			0.002
1006	584819.800	1948040.275	326.857			326.849			326.849			-0.008			0.001
1007	584831.964	1948025.588	326.815			326.806			326.806			-0.008			0.000
1008	584841.761	1948014.122	326.747			326.735			326.737			-0.011			0.001
1009	584851.490	1948002.395	326.662			326.654			326.655			-0.006			0.001
1010	584861.221	1947990.674	326.699			326.695			326.696			-0.003			0.001
1012	584817.724	1948019.483	318.086			318.083			318.082			-0.004			-0.001
1013	584810.021	1948007.161	312.095			312.094			312.095			0.000			0.001

	INITIAL VALUES June 1998			December 2009 Survey			June 2010 Survey			CURRENT MINUS INITIAL YEAR			CURRENT MINUS PREVIOUS YEAR		
PCID NO.	NORTHING (MTRS)	EASTING (MTRS)	ELEV. (MTRS)	NORTHING (MTRS)	EASTING (MTRS)	ELEV. (MTRS)	NORTHING (MTRS)	EASTING (MTRS)	ELEV. (MTRS)	DELTA N	DELTA E	DELTA ELEV.	DELTA N	DELTA E	DELTA ELEV.
*North, East & Up offsets are positive and South, West & Down offsets are negative															
1001	584881.217	1948115.506	324.322												
1002	584797.712	1947987.474	310.238			310.234			310.234			-0.003			0.000
1006	584819.800	1948040.275	326.857			326.849			326.849			-0.008			0.000
1007	584831.964	1948025.588	326.815			326.806			326.806			-0.008			0.001
1008	584841.761	1948014.122	326.747			326.735			326.737			-0.011			0.002
1009	584851.490	1948002.395	326.662			326.654			326.655			-0.006			0.001
1010	584861.221	1947990.674	326.699			326.696			326.696			-0.003			0.000
1012	584817.724	1948019.483	318.086			318.084			318.082			-0.004			-0.002
1013	584810.021	1948007.161	312.095			312.095			312.095			0.000			0.000

Page 1 of 1

Fig. 6-21. Horizontal and vertical displacement monitoring

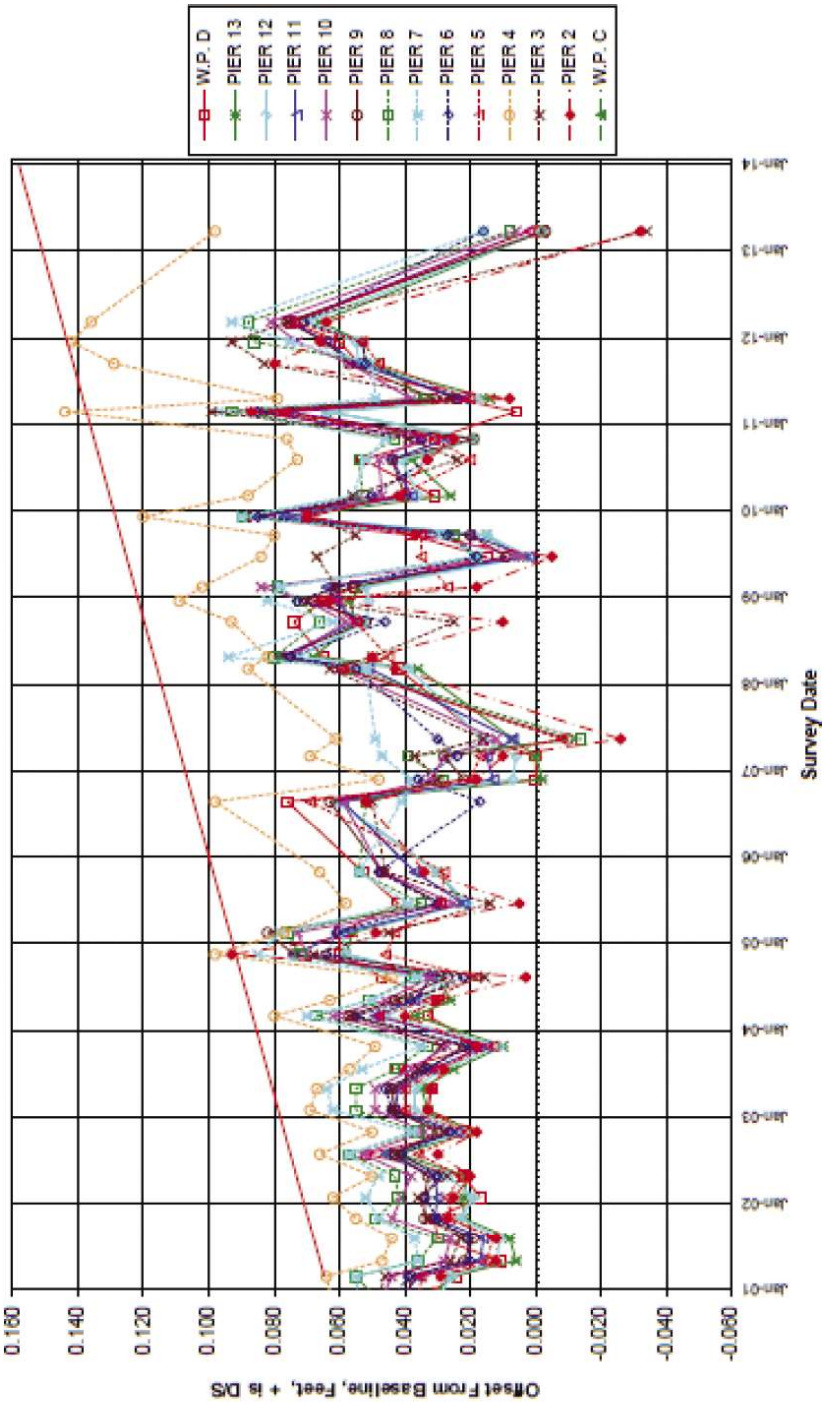

Fig. 6-22. Typical time versus reading crest movement graph.
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maps of the project area showing where measurements were taken. Survey reports are archived regularly. Maintaining the historical data on previous surveys is important when analyzing trends and problems in monitoring of dams or structures and for preserving the information when considering improving a monitoring plan. Typical report entries include

- General condition of the structure;
- Data formats and file locations;
- Equipment and instruments used;
- Horizontal measurement method;
- Vertical measurement method;
- Project notes such as changes to monuments;
- Reference drawings and monument maps;
- Point coordinates, number, and name;
- Date monitored;
- Time versus reading movement measurement (horizontal, vertical, or both); and
- Station name and monument description.

Field notes—A typical report includes original field notes such as leveling notes and traverse and GPS observation sheets, along with remarks made by personnel in the field. Although in raw form, field notes are included so that the survey used is documented.

Maps—Point maps that show monument locations in relation to the dam or structure are useful to add to a written report and aid in discussing particular areas of concern. More modern technologies in 3D surveying can provide not only a comprehensive map of a movement survey, but also color hue maps can be generated to show movements on structures by using color intensity.

Results—The purpose of the movement-monitoring exercise is to measure and report the measured movements in comparison to (1) expected movement and (2) Threshold and Action Levels that suggest a movement be explained. Time versus movement graphs (Fig. 6-22) can illustrate movement data for easy interpretation.

A valuable method of reporting is the use of an electronic real-time alerting system that has the ability to communicate between the dam safety engineer and surveyor in charge of the monitoring for a particular structure. Movement reports and alarms of exceeded threshold tolerances can be helpful to understand a problem with a structure or its system.

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CHAPTER 7
DATA ACQUISITION

> You can have data without information, but you cannot have information without data.
>
> Daniel Keys Moran

Data are measurements of performance indicators. Data are acquired manually or with data-logging methods. Data logging may employ handheld devices or data loggers, or they may be fully automated in a system termed an Automated Data-Acquisition System (ADAS).

SOLUTIONS 4.0

7.1 MANUAL ACQUISITION

Manual data acquisition involves using a variety of different tools such as water-level indicators for piezometers and observation wells, staff gauges for reservoir or water-level monitoring, surveying equipment, and specialized probes such as an inclinometer probe to measure inclination. Measurements are manually recorded on paper in the field or stored in the memory of a handheld readout and later transferred into a project data management system.

Checklists are valuable to manual data collection for preserving data integrity. Readily available checklists containing several previous readings can help the instrument reader discern an unexpected reading. Whenever an unexpected reading is noted, the measurement is repeated. For example, small-diameter standpipe piezometers may cause a false reading when the water-level probe reacts to humidity along the riser pipe rather than at the actual water level. Unexpected data may not be in error but require repeating a measurement. All field technicians are trained on the expected

behavior of an instrument so that the reader can make an immediate judgment if additional readings are needed. Errors may occur when an instrument malfunctions or during reading and recording the data.

Metadata such as the name of the instrument reader, instrument serial number, and the date and time of the reading are recorded and stored in the database. Where an instrument reading is suspect, metadata can assist in troubleshooting. Instruments that develop a calibration issue or an intermittent fault may be problematic. An inclinometer probe cable that has been fatigued, for instance, can give some incorrect readings. Where the data problems are subtle, it may take several readings before the problem is noticed.

Manual methods have lower initial costs, require less maintenance, reduce the level of expertise required to operate and maintain, are less susceptible to damage by weather and vandalism, and allow for concurrent visual surveillance to observe signs of distress at a dam.

> You can observe a lot by just watching.
>
> Yogi Berra

Cameras (digital or video) are useful tools for electronically recording visual observations that can later be transferred to data management applications for use as supplemental data to instrumentation data. For specific features of concern, cameras can be mounted at various vantage points and set to record continuously or at regular intervals. Coupled with the use of historical images, cameras can be a useful tool to identify and evaluate new safety concerns. Cameras can be included in a monitoring system to allow remote visual surveillance of the site for confirmation of conditions indicated by automatically collected data. Infrared or regular cameras supplemented with lighting for night use are used on many projects.

7.2 AUTOMATED ACQUISITION

Visual surveillance is the backbone of dam-performance monitoring. ADASs augment but do not replace visual inspection of a dam.

ADASs can include cameras to allow for rapid, preliminary visual surveillance from remote locations. If instruments report measurements exceeding alarm values, cameras can identify visual signs of distress to aid in deciding whether action is needed.

7.2.1 System Configurations

System-level models represent the most common current practice for monitoring dams. Choosing the appropriate model requires consideration of several factors that underlie the choice of a model:

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- Data may be acquired from many points of geotechnical and structural instrumentation or just one or two points of hydrological data;
- Instrumentation may be deployed over a large structure and benefit from a distributed system of multiple field measurement units, with collection units close to the instruments providing data; and
- The system not only records the measurements but also provides a mechanism to transport data to a computer where it can be recorded and viewed by an operator for evaluation.

Best practice is to scale a system to the monitoring needs of the site.

One model is a simple data logger, for example, one that reads only vibrating-wire sensors (Fig. 7-1), which are the most common sensor used in dam monitoring. One step above is a data logger that can measure multiple electrical signals (voltage, resistance, current) over extended periods

Fig. 7-1. Simple 8-channel data logger for vibrating-wire sensors only (left) and simple 1-channel data logger for MEMS/electro-level discrete or serial sensors only (slope indicator, right)
Source: Courtesy of DG-Slope Indicator, reproduced with permission.

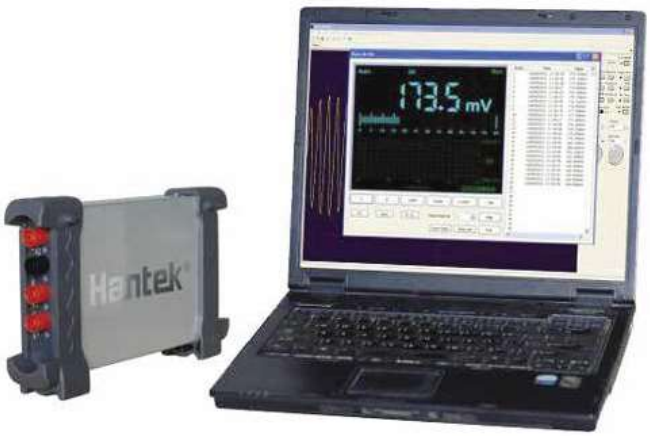

Fig. 7-2. Multisensor-type data logger and memory storage
Source: Quingdao Hantek Electronic Co.

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of time (Fig. 7-2). Measured data are converted into a digital format and stored, along with the date and time of measurement, on a local or internal mass storage device. The key aspect of a data logger system is that data are stored within the logger's memory.

The simplest method of data transfer is to either connect a PC to the logger using a serial or USB cable or use a combination of flash memory drive and data logger, also shown in Fig. 7-2. Data are retrieved from the data logger using the flash drive, which is the removable storage media. The recorded media is retrieved from the data logger and then taken to a computer to load the data into a database. The database is accessible to one or more software programs for display, analysis, reporting, and archiving.

The term "SneakerNet" is a concise way of referring to a network of one or more personnel who collect and bring data from remote data loggers to upload for evaluation. SneakerNet has some advantages compared with strategies requiring communication connections for automatic transport of data to computers. There is a potential capital cost advantage because the additional equipment or communications services associated with automatic data transport are not required. Another potential advantage is that there is no restriction on the location of the data logger imposed by the requirement for accessibility to a communication link or associated power demands of telemetry equipment. The person collecting the data can also make visual observations while visiting the logger locations.

There are also some disadvantages to SneakerNet. First, the requirement for routine physical accessibility may require installing the data logger in a vulnerable location requiring longer connections to instruments or more exposure to potential vandalism. Secondly, timeliness of data observations may be affected by inaccessibility to remote sites during bad weather.

Changes or new trends in measurements will not be recognized until the data are transferred to the computer and analyzed. Another disadvantage of protracted delays between human observations is that equipment or instrument malfunctions may not be detected for extended periods of time, which may conflict with the monitoring objectives. There is also an ongoing personnel cost associated with data retrieval. The disadvantages of SneakerNet can be overcome by accessing the data logger over the telephone network. Data loggers are typically equipped with a serial communications channel for connection to a serial RS232 or USB port on a personal computer. This allows programming the data logger with configuration software usually provided by the manufacturer and extracting data from the logger memory or data storage device. Along with the serial communication channel, data loggers usually provide a communications protocol for modem connection control over telephone networks and a terminal protocol for transferring data from the onboard data storage to the computer. This allows the same configuration and data transfer functions between the computer and the data logger over the telephone network that can be done with

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a local serial cable connection. Connections may also be made with radio frequency, cellular telephones, and communication satellites. A second model is a host-driven network, where the host computer controls the time and frequency of measurements and the flow of data from remote terminal units (RTUs) to the host. Fig. 7-3 shows an illustration of an ADAS network. Note that the number of RTUs or number of instruments is tailored to the dam and the associated monitoring needs. Because of its centralized role as arbitrator for all system communications and I/O operations, the host is often referred to as a central computer.

The sequence of interrogating data from RTUs is referred to as polling the RTUs. This network architecture is referred to as master–slave, where the host computer is the master and the RTUs are slaves. Supervisory Control and Data Acquisition (SCADA) systems, for example, almost always employ host-driven networks because the primary purpose of a SCADA system is to provide data to a human operator in the process of operator-supervised command and control of remote I/O. In other words, SCADA is designed primarily to be operator-interactive with a fast response time over remote communication links, and these objectives are usually best served with centralized system architecture.

Host-driven networks are simpler, at least in concept, than node-driven networks described in the next section. A host-driven network distributes essential functions required for logging data at the user-prescribed intervals across the network. Therefore, if a communication link fails or an unattended central computer fails or becomes unstable (for example, it must be rebooted, as often happens with PCs), data records will be missed during these periods of equipment outage. Note that the host computer itself is the data logger in a host-driven ADAS. All data-logging functions, logic, and data storage reside in the host computer.

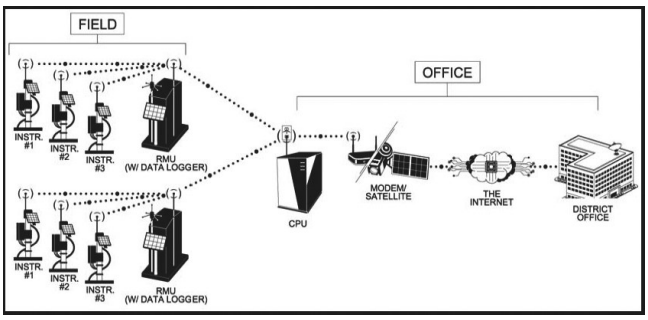

Fig. 7-3. ADAS host-driven network
Source: U.S. Army Corps of Engineers.

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Host-driven networks are expensive, requiring investment in the central computer and the communication links to achieve across-network reliability.

A local field-bus network of intelligent instruments polled by a data logger or motor control unit (MCU) is a host-driven network. A field-bus network with one or more sub-networks is not burdened by the expenses of remote SCADA host-driven networks. Field-bus networks often benefit from industry-standard communication protocols and are quite reliable. Unlike PCs, the data logger or MCU host controller is designed to be a hardened unit, that is, to run unattended in remote areas with high reliability. The communication links between the master controller and slave intelligent instruments are local area networks secured within the confines of the project with high-reliability connections.

Node-driven networks are commonly referred to as peer-to-peer networks. As implied by the peer-to-peer terminology, nodes share communications capabilities equally without a master controller, and each node can initiate access to a shared communications medium.

Node-driven networks are employed in instrumentation systems to allow critical functions at the node to operate autonomously. In data-acquisition systems, intelligent nodes can often perform their automatic data-acquisition functions more reliably without requiring communications with a distant host computer. In normal operations, the remote nodes initiate the communication with the operator interface computer rather than the other way around. This way, the measurement node retains the data in a temporary queue until a reliable communication link is established with the remote computer. In addition, measurement nodes can report to the computer not only on a scheduled periodic basis but also upon detecting an alarm condition. Furthermore, node-driven remote equipment consumes far less power because communication resources do not need to be continually active, as they would need to be to respond to commands from a host computer.

To summarize, the beneficial characteristics of MCUs operating as peers in node-driven networks are

- The remote units will perform data acquisition even if the communication link with the operator interface computer is unavailable;
- The power consumption of the remote equipment can be managed effectively when nodes control access to communication links, which are often the highest power-consuming components of the remote equipment; and
- Nodes can be designed to bridge between different communication media, such as wire line, radio, telephone, and satellite, thus increasing flexibility and redundancy and reducing overall system deployment cost.

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ADAS telemetry is defined as any system for monitoring the performance of a dam that includes components for data collection that are permanently installed and programmed to operate without human intervention. The definition is not limited to systems that include all potential aspects of ADASs (i.e., automated collection of data, transmission of the data to a remote site, processing data, and plotting of data).

For example, a simple system that included a data logger or computer located at the dam and programmed to automatically record measurement data would be included under this definition of ADAS, even if the data were subsequently retrieved and processed by personnel visiting the site and uploading the data manually. Use of ADAS tools has significantly improved what was once a labor-intensive and time-consuming exercise. Methods that rely on a data logger system are capable of performing continuous unattended data collection, but they require manual data transfer. Methods that rely on ADASs are capable of continuous unattended data collection, remote automated data transfer, and real-time display.

The advantages of investing in an automated system are

- Frequent collection of data, capturing performance data under varying loading conditions;
- Collection of data when manual collection would be difficult or impossible, for example, when the dam is inaccessible in the winter because of snow or when site access is difficult because of heavy rain and swollen rivers. During floods, staff can focus on data analysis and visual monitoring without spending time on data collection;
- Reduction of reader-error in data collection and transcription errors in data entry; and
- Rapid processing and plotting of data, allowing easier and timelier analysis.

ADASs have been designed to include early warning features. False alarms are likely to occur in any ADAS system. An alarm suggesting a developing dangerous situation requires visual verification before declaring an emergency.

There are typical aspects of ADAS installations, but most have unique aspects that are tailored to the monitoring needs for the dam and monitoring environment. Some typical components are shown in Fig. 7-4.

Typical components include a power source, a base station consisting of a desktop computer and monitor or just a stand-alone server, a main data logger, and means of remote communication using a software package. The base station may be installed within a project office or at a dam.

The number and type of instruments can be expanded to add more instrument connections at a later date.

Radios may be utilized to transmit data between data loggers and base stations. Spread-spectrum radios spread the normally narrow-band

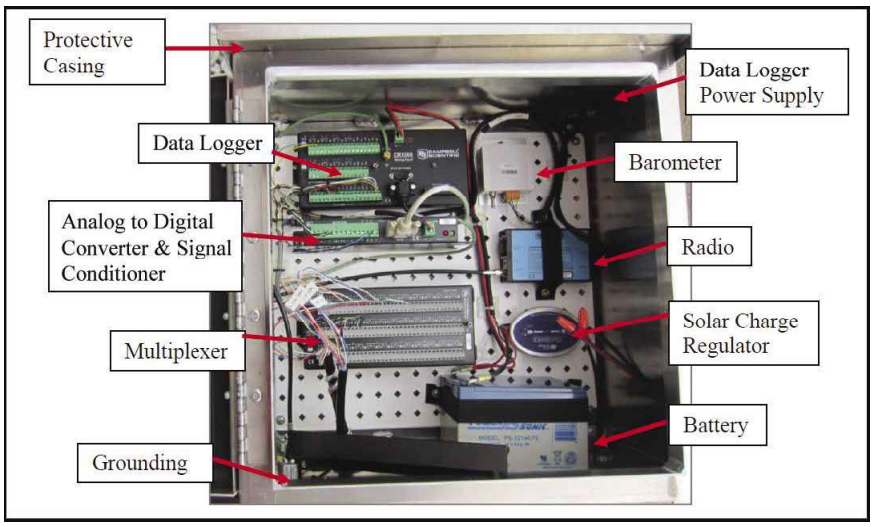

Fig. 7-4. ADAS installation
Source: U.S. Army Corps of Engineers.

information signal over a relatively wide band of frequencies. This allows the communications to be less susceptible to noise and interference from RF sources such as pagers, cellular phones, and other radios. Spread-spectrum radios do not require an individual license or frequency assignment through a regulatory agency.

7.2.2 ADAS Performance

Early systems had mixed results ranging from substantial success to outright failure. Some of the significant difficulties included contractors hampered by inadequate expertise, equipment that performed poorly or required excessive maintenance, and ADAS manufacturers that either went out of business or dropped out of the dam-monitoring business because of inadequate market potential. Sometimes installations were corrected by installing new ADAS equipment using instruments and sensors that were more reliable for automated measurements. With rapid advances in technology, ADAS equipment is continually becoming more reliable and more affordable, and there is an observable trend for increased use of ADASs for dam-performance monitoring.

Instrumentation only collects data from point measurements of performance indicators and cannot be relied upon to provide a complete picture of structural behavior. The instrumentation system can only collect the information that the instruments were designed to collect. For example,

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ADASs would not identify the occurrence of seepage at a new location or the occurrence of settlement or horizontal movement at locations that were not instrumented. ADASs provide more opportunities for the extent and timeliness of analysis without curtailing opportunities for effective visual surveillance.

ADAS installations are capable of collecting more data than can be practically collected without automation. However, the collection of more data in and of itself does not provide value unless the data are regularly processed and evaluated. So, an important aspect of a successful ADAS is the allocation of resources to evaluate the collected data. There are applications that help with real-time collection, archiving, processing, and reporting of data.

It is also important that data collected from the ADAS are periodically verified through manual interrogation of the instruments. Hardware and software malfunctions can and do occur, so periodic manual verification is included in any ADAS program to ensure that judgments concerning performance of the dam are based on accurate information.

Finally, an ADAS will require periodic maintenance, calibration, and repair, and appropriate resources must be allocated for these functions. Sensors, computer hardware, and communication equipment will malfunction and require maintenance, repairs, and sometimes replacement. In addition, ADASs are subject to external influences such as construction activity, lightning strikes, vandalism, extreme weather conditions, fire, and water damage. Maintenance, repair, or replacement may be required.

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Most remote data-acquisition equipment used for dam monitoring falls into one of four categories—single data logger, host-driven network, fieldbus network, or node-driven network. Equipment often is battery operated and designed for minimal power consumption. This allows for the possibility of installing the equipment near instrument locations where there is often no availability of AC power. The equipment is operated from a battery, and an online battery charger is used to maintain the battery in a fully charged condition. The normal battery operation has the added benefit of allowing the equipment to continue operation (non-interruptible power) even in the event of intermittent interruptions of the battery charging power source.

The battery chargers for remote ADAS equipment are typically designed to use either AC power or solar power for inputs to the charger system.

If reliable AC power is conveniently available at the equipment location, this source is used for online charging. However, in many locations on and around dams, AC power may not be available; in such cases, battery charging is typically accomplished with a solar panel (Fig. 7-5) because of its low cost and good reliability.

Small 1-, 4-, and 8-channel loggers (Fig. 7-1) use nonrechargeable lithium batteries that last 3 to 6 years, depending on the amount of data recorded. Special extra-capacity batteries can last up to 10 years.

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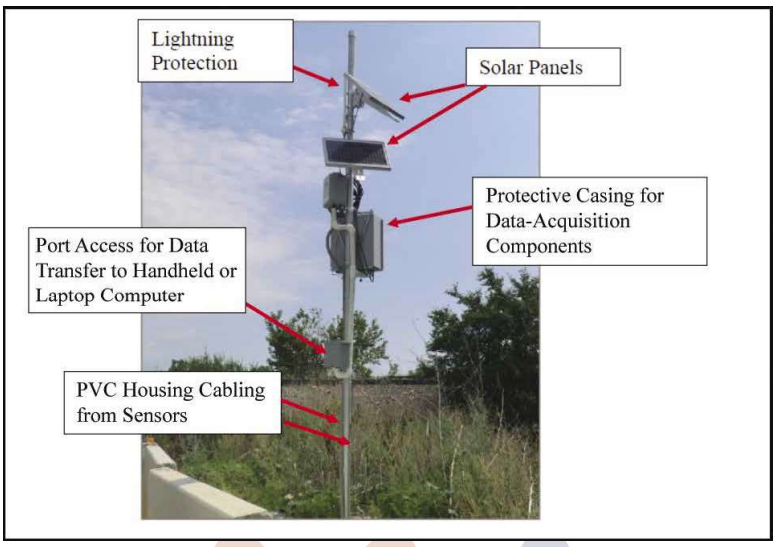

Fig. 7-5. ADAS setup using solar power
Source: U.S. Army Corps of Engineers.

When using rechargeable batteries, reliability problems may occur when the battery, the solar panel, or both are sized inadequately or marginally for the installation. Because power consumption of the remote equipment can be highly variable, depending on installed options, communication links, and programming, a degradation of power resources can occur over time if equipment configurations or programming are changed. When changes do occur from the original plan, more is usually demanded of the equipment rather than less by way of additional instruments requiring additional power-consuming signal conditioning and the increased duty-cycle of the radio transmitter.

ADAS designs require care when sizing batteries and solar panels for remote installations in order to evaluate the worst-case anticipated load, the equivalent sunshine days (ESD) for the installation site, and the lowest ambient temperature that a battery will endure. Battery technology and charging characteristics, particularly as they relate to temperature, must also be considered. Applications engineering data and assistance are available from most equipment manufacturers and systems installation contractors and integrators.

There are beneficial aspects to keeping the system as simple as possible. Whether data are manually or remotely entered, it is desirable that the number of steps and people involved between collection and entry is minimized to reduce opportunities for error.

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When maintenance occurs or other suspect sources of erroneous/biasing instrumentation data, the cause(s) is documented on manual data gathering sheets and on generated plots. Example error sources include personnel unfamiliar with instrument reading, new equipment, excessive moisture in the readout device, and faulty batteries.

The reliability of the electronic sensors selected for inclusion in an ADAS is an important practical consideration. The reliability of the sensors must match the expected lifetime of the required data collection, and the ADAS system design and installation must include consideration of the potential for sensor failure. Means used to address the potential for sensor failure include redundancy and replacement. Redundancy requires designing the sensor array with redundant locations, so that some number of sensors can fail without compromising the data-collection objectives.

Designs are made to allow failed sensors to be replaced. For example, when installing vibrating-wire piezometers, the piezometers could be installed in PVC casings (standpipes) extending into the ground surface instead of in permanently backfilled boreholes. With the casing installation, a failed vibrating-wire instrument can be removed and replaced. With this installation, the response time for the piezometer readings will be that of the PVC casing (standpipe) and not that of the vibrating-wire piezometer. The piezometer readings will change only as water flows into and out of the casing.

Electronic equipment will not operate properly and will be seriously damaged from water or moisture intrusion due to condensation. Therefore, particular attention must be given to outdoor installations of ADAS equipment. Bringing multiple instrument cables into a weatherproof enclosure that also provides easy access to the equipment can present difficulties if the field conditions are not fully anticipated when the equipment is purchased.

The variations in quantity and sizes of instrument cables, appropriate space and mounting considerations for transient protection and communication options, and climatic conditions must be considered in selecting appropriate field enclosures. Resistance to vandalism must also be considered for many locations. The variations in these requirements from site to site can present some challenges for equipment manufacturers whose objective is to offer standard weatherproof enclosures that are suitable for most situations. There is usually less expense and less risk involved in purchasing properly engineered enclosures from the ADAS equipment manufacturer. However, this is true only if the manufacturer has a standard offering that meets all the site-specific requirements. This is not always the case, and custom solutions are sometimes required.

There are basically two approaches to environmental protection for outdoor installations of electronic equipment. One approach is to try to keep the dry air in and the moist air out with an appropriately sealed enclosure. The other approach is to design the enclosure to naturally aspirate, or

breathe, to eliminate a significant temperature differential between the inside air and the outside air. Natural aspiration (convection) is assumed because forced aspiration, such as used in traffic signal control boxes, is not practical for solar-powered sites.

It is generally easy to keep the rain out of a weatherproof enclosure conforming to NEMA 4 (U.S.) or IP67 (international) standards. However, problems arise when large temperature differences occur between the captive air and the ambient air.

Most ADAS equipment for dams is installed in enclosures that meet the NEMA 4 or IP67 standards. Holes are punched in the enclosures for cable feed through connectors, which often violates the enclosure rating but which in and of itself does not necessarily cause a water intrusion problem.

The following scenario illustrates the main problem with low-differential pressure-sealed enclosures: The enclosure is secured with a desiccant package that slowly absorbs internal moisture up to the point that the package becomes saturated, with no more moisture-absorbing capacity. The desiccant is required to lower the dew point of the captive air. This prevents condensation on the equipment electronics as the air temperature lowers during the night or as a result of an advancing cold front. Now assume that following sunshine and hot weather, during which the enclosed air becomes quite hot, a cold front advances with heavy rain. The air is rapidly cooled inside the enclosure, resulting in a substantial drop in internal pressure. The pressure differential sucks moist air into the enclosure from the outside; the low-pressure seals required to meet NEMA 4 or IP67 do not prevent the leaks, not to mention all the cable entry seals. If water happens to pool around the weakest seals where the leaking occurs, the enclosure will suck in water directly, not just moist air. In the best case, the desiccant eventually becomes saturated with moisture and ineffective. In the worst case, vulnerable parts of the equipment become submerged in water, and failure occurs. This reality encourages the practice of making sealed enclosures as compact as possible, to minimize and better control locations that might leak, and to minimize the volume of air that must be kept dry.

There are several best practices that flow from the above scenario:

- Orient enclosures and gland panels so that water cannot pool around seals and cable entry glands and connectors;
- Use rain shields along top door seals, and use radiation shields to minimize internal air heating from sunlight; and
- Replace desiccant packages as needed. The replacement interval can vary dramatically depending on climatic conditions. Color changes of silica-gel desiccant make it easy to determine when replacement is needed. Only replace the desiccant during dry weather, because the cabinet will be closed up with the prevailing moisture content of the ambient air.

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Avoid locating enclosures in underground vaults unless the vault will never fill with water during a rainstorm or water-main break. Otherwise, the enclosure must be NEMA 6-rated and -pressurized to prevent the type of leaking described above.

Aspirated enclosures are designed to keep out rainfall while preventing the entrapment of moist air within the enclosure. The aspiration keeps air moving through the enclosure to prevent condensation on internal equipment. This works most successfully when there is AC power available to run a motor and fan to force the air circulation. With power available, the air can also be heated slightly at the intake, preventing any possibility of condensation. Air intake and exhaust ports must be filtered to keep out insects and dust. Convective aspiration is not as effective because air flow is impeded by the requirement for filtering. However, successful installations with natural aspiration are possible using larger enclosures to develop adequate convective pressure differentials to turn over the air.

Successful environmental installations for dam monitoring have been implemented by installing a NEMA 4-rated enclosure inside of a larger convective enclosure with natural aspiration and minimal filtering. This configuration prevents the possibility of water pooling around enclosure seals and buffers temperature changes between the captive air and the ambient air.

Surge voltages or electrical transients are induced from many types of sources into the wires and metallic cables connected to electronic equipment. Common sources of these surges are the switching of large inductive electrical loads, such as motors, switching disturbances on the electric power grid, electrostatic discharges from human contact with connection terminals, and lightning discharges. These transients pose a threat to all ADAS equipment used for dam monitoring.

Electronic instrumentation is particularly susceptible because extended signal cables are often connected between sensing devices and the measuring equipment. The earth ground potential difference between spatially separated points is often driven to momentary extremes. In addition, nearby atmospheric discharges or the more violent ground strikes induce high-voltage transients into the cable itself, acting as an antenna. Without effective transient protection, a high-voltage pulse may be generated between the equipment terminals and the chassis ground to which the electronic components in the equipment are connected. Unprotected electronic components are likely to be damaged by high-voltage pulses.

For transient protection networks to perform, the ADAS equipment must be located where an effective earth ground connection can be made. This may require special attention for embankment dams as effective ground connections may be difficult.

The circuits in electronic measuring equipment are especially susceptible to damage from transients because they employ highly integrated

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components with a low dielectric breakdown voltage. In addition, a low-impedance direct electrical connection from the instrument must usually be made for the measurement circuits to work properly. The most troublesome aspect of measurement circuits is that most approaches to transient protection tend to interfere with the measurement itself conducted between the sensing device in the instrument and the measuring unit. Therefore, designers must ensure that transient protection devices are used that have the appropriate characteristics. Because measurement circuits are unique to the type of instrument being measured, the instrument and ADAS equipment manufacturers can provide information for transient protection devices that do not interfere with the intended measurements.

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CHAPTER 8

DATA MANAGEMENT AND PRESENTATION

It is a capital mistake to theorize before one has data.

Arthur Conan Doyle

Up to this point in the manual, failure modes were evaluated to identify questions about a dam's behavior, monitoring programs and instrumentation to collect data to answer those questions were described, and data-acquisition techniques were discussed. This chapter describes how to manage those data and present them in an organized fashion to allow the exercise of engineering judgment about a dam's performance.

SOLUTIONS 4.0

8.1 DATA ARE MEASUREMENTS. MEASUREMENTS ARE DATA.

Data management includes the procedures used after measurements are made to record the measurements for subsequent processing or evaluation, organize the readings so that the data can be easily located, process the raw data into meaningful engineering units, validate the measurements to eliminate faulty data or correct obvious errors, and archive the data to maintain a historical record. Data presentation refers to the display or reporting of the instrument data.

8.1.1 Data Organization

For each instrument or survey measurement, two types of information must be managed properly to permit interpretation of the data: instrument attributes and their measurements. Instrument attributes are the characteristics of a fixed instrument. For example, the attributes of an open hydraulic

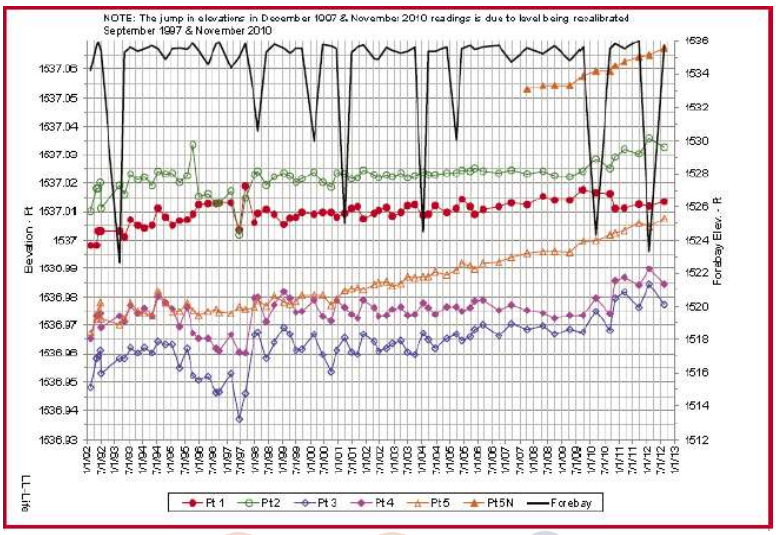

Fig. 8-1. Understanding data

piezometer installed within a sand filter would include location (x–y coordinates indicating its horizontal location), surveyed elevation, reference elevation, ground elevation, elevations of the top and bottom of the piezometer tip, and the installation date.

Attributes are often recorded when an instrument is installed, usually in a field logbook documenting the details of the instrument installation. The attributes may also be recorded in summary tables in paper or electronic files, but best practice is to retain the original logbooks as the data source. Most instrument attributes do not change over the life of the instrument. Some do change. Attributes may change as the result of instrument maintenance, repair, or recalibration. A new reference point may be established requiring a data adjustment. Whenever an instrument attribute changes and affects the processing of the raw data, the date of the change is recorded so that the field readings can be processed properly. For example, a damaged piezometer riser pipe may be replaced, requiring a new surveyed elevation. Historic data would remain the same, but future data reduction would utilize the new elevation. When this is not done, data become difficult to interpret, as illustrated in the unadjusted data shown in Fig. 8-1. The discrete jumps in Pt3 and Pt4 are at least partly caused by level recalibrations in December 1997 and November 2011, not by actual response.

One instrument attribute of particular importance is the instrument status code, which reflects the condition of the instrument itself; this is distinct from a reading status code, which conveys information on a specific read-

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ing. Typical instrument status codes might include **A**ctive for instruments operating normally, **M**aintenance for instruments that need maintenance but still produce accurate instrument readings, **R**epair for instruments that do not produce accurate instrument readings and require repair, and **X** for instruments that have been destroyed or abandoned. Instrument readings are periodic measurements. An open hydraulic piezometer measurement is the depth from the reference elevation to the water surface in the riser tube. The instrument reading should be recorded with the date and time of the reading.

Instrument readings may be recorded manually in field logbooks or on standardized forms or may be downloaded directly as electronic data. The original paper or electronic record is often retained as the original data source in case there are any questions about the data.

8.1.2 Data Recording

Each instrument type yields a raw measurement that is the primary piece of information that is being recorded and preserved. Raw data are the direct output from the instrument and may or may not be in meaningful engineering units. Examples of raw data include the measured depth to water in an open hydraulic piezometer, the frequency from a vibrating-wire piezometer, the voltage from the accelerometer within an inclinometer probe, the height of water in a flow measurement weir, the vertical offset of a settlement point from an established datum, or the spacing between reference points of a crack monitor. All may have different units.

For many modern electronic instruments, the value displayed on the readout unit may have already been converted into meaningful engineering units. The displayed data value is typically converted from the raw data using a formula that may include user-defined calibration factors. If readings are recorded manually, the displayed data value is recorded. If the readings are downloaded from the readout unit, the downloaded data may include both the raw data value and the displayed value. In both cases, it is important that the calibration factors are recorded with the data or that they can be calculated from the raw data and displayed data pairs.

The familiarity of the field technician with the normal and expected ranges of the instrument readings is very valuable because it can help identify suspect readings while still in the field, allowing an instrument to be reread to confirm or correct the original reading. Field reading forms for manual data collection can be printed and carried into the field to show the previous reading or the range of recent readings, facilitating detection of any significant variation.

Standard reading status codes can be developed to indicate the conditions associated with an instrument reading. For example, for one dam project, the reading status codes for open hydraulic piezometers included

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Normal, **D**ry, **O**bstructed, **C**ontaminated, and **Q**uestionable. Note that reading status codes convey information on a specific reading and are distinct from instrument status codes, which reflect the condition of the instrument itself. In all cases, the depth measured by the sensor—even if a piezometer was dry or obstructed—was recorded, together with the status code. The **N**ormal status code was applied when the water level measured was at the expected depth. The **D**ry status code was applied when the sensor reached the bottom of the instrument without detecting water. The **O**bstructed status code was applied when the sensor did not detect water and could not be lowered farther in the standpipe, but comparison with the installation or maintenance records indicated that the sensor had not reached the elevation of the bottom of the instrument. The **C**ontaminated status code indicated that oil or other hydrocarbons were detected on the sensor probe and wire. The **C**ontaminated status code not only indicated potential leakage from the reservoir but also alerted the data user that the field reading did not accurately reflect the total head. The **Q**uestionable status code was used when the readings that appeared to indicate the presence of water in the standpipe were repeatable but were outside the normal expected range. The **Q**uestionable status code alerted the data user that the reading merited extra scrutiny before being accepted as accurate.

Whether written into a field book, entered into a field data collection form or electronic device, or acquired electronically, field data is placed in a permanent, consistent, retrievable, and traceable manner. Recording of data in field books, field reading sheets, or electronic forms allows for comparison of current readings with previous readings at the time the readings were collected. That comparison may be the linchpin that resolves a question about a performance indicator (e.g., has total seepage exceeded a Threshold Level)? This early comparison of the data aids in assuring the correctness of the readings and also allows for early detection of problems with instruments. The instrumentation monitoring plan specifies the actions required by the data collector if the field readings are outside of the expected range, such as obtain a second reading, inspect the instrument and readout device for damage, observe the area for signs of disturbance or distress, or alert the dam safety engineer to assess whether any action is required to ensure safety.

Project-specific field reading forms are developed to record both visual observations and instrumented measurements. Examples are provided in Chapter 13. Good practice includes columns for the current readings, as well as for the high and low limits of expected readings (threshold values).

Many owners find it beneficial to use dedicated software for the purpose of automating some of the processes around data management and presentation. Such data visualization, management, reporting, and alarming software is now available from several providers. The software is installed

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in an on-site or remote-site computer that is interfaced by telemetry or direct interface to the data loggers installed on the dam that are collecting readings automatically from instruments, as described in Chapter 7. Among its main features, the software typically allows the display of readings from all instruments in real time, graphs of readings in relation to time, and a comparison of readings to predetermined alarm thresholds. When alarms are detected, the software can be configured to generate actions, such as sending a text message or email, or to initiate a visual alarm or siren. Combined graphs such as piezometric levels in relation to reservoir level or seepage flows can be displayed or on another graph that enables better understanding of the behaviors and their evolution. Reporting functions are usually available to facilitate periodic reporting of instrument readings in tabular and graphical form.

The screens shown in Fig. 8-2 are typical outputs from typical data management and visualization software. The first two screens show real-time readings of concrete pressure cells (CPCs), embedment strain gauges (SG), uplift piezometer pressures, and temperatures in a concrete gravity dam. As can be seen at the bottom left of the figures, similar screens are available for pendulums, extensometers, seepage weirs, joint meters, open standpipes, and weather stations. The third screen shows historical plots of radial and tangential CPCs in the concrete lining of a powerhouse.

SOLUTIONS 4.0

8.1.3 Data Reduction

Data reduction is the conversion of the raw field readings into meaningful measurements such as total head or displacement. Data reduction usually involves the application of an algebraic formula, either manually or through programming, to the raw field readings to convert them to meaningful engineering values.

8.1.4 Data Validation

Data validation is the process of reviewing the instrument readings and checking them for reasonableness. Data validation may be performed either on the raw readings or on the readings after they are converted to meaningful engineering units, but it is done as soon as practicable. Checking both the instrument and the measurement are required to validate data.

8.1.5 Instrument Validation

To ensure that the readings obtained from dam instrumentation are reliable, the instrumentation itself must be evaluated periodically. Readings

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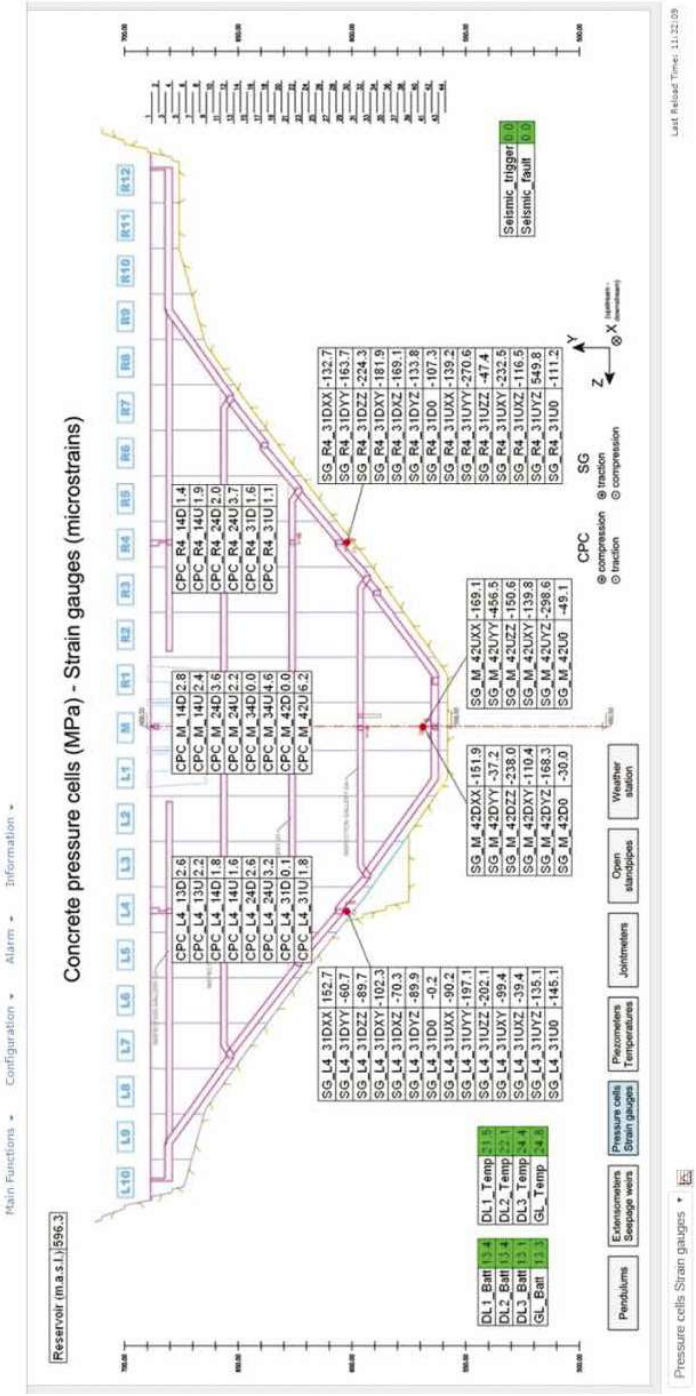

Fig. 8-2. Real-time screens and historical plots

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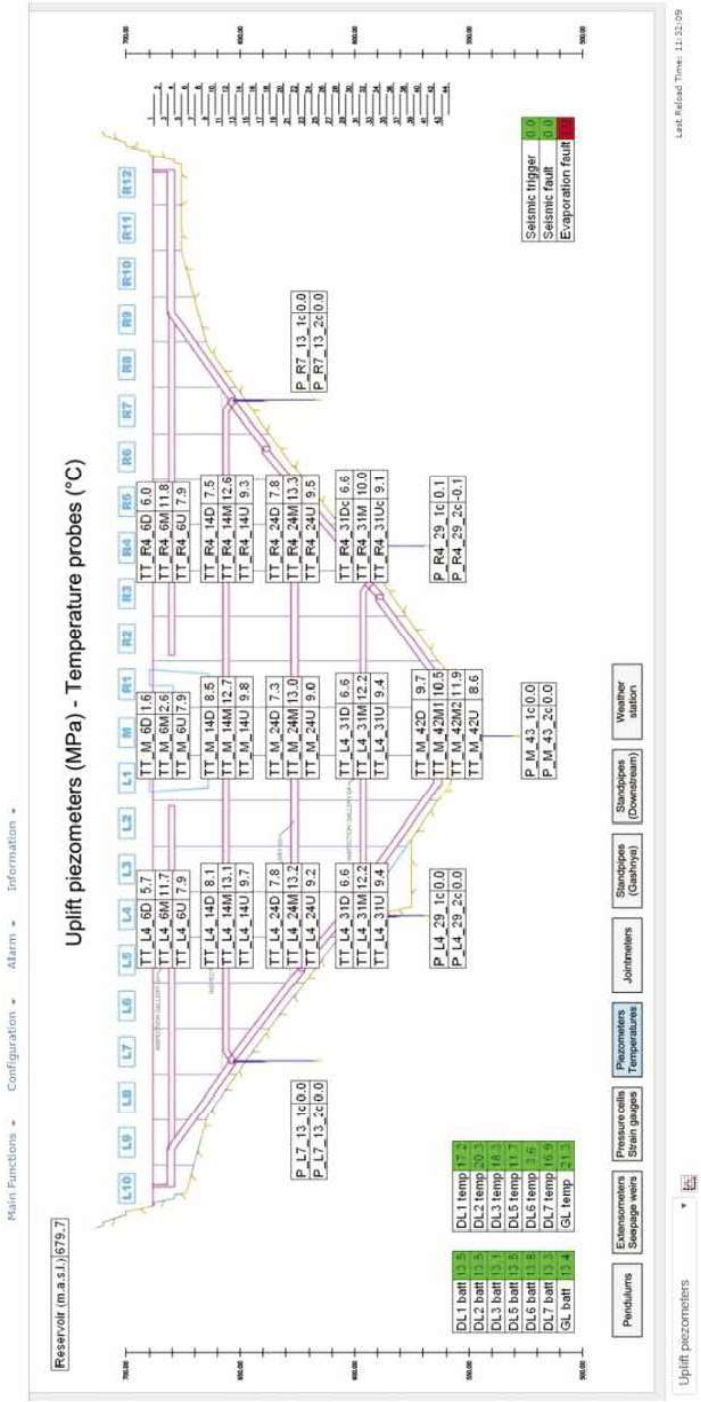

Fig. 8-2. (Continued) Real-time screens and historical plots

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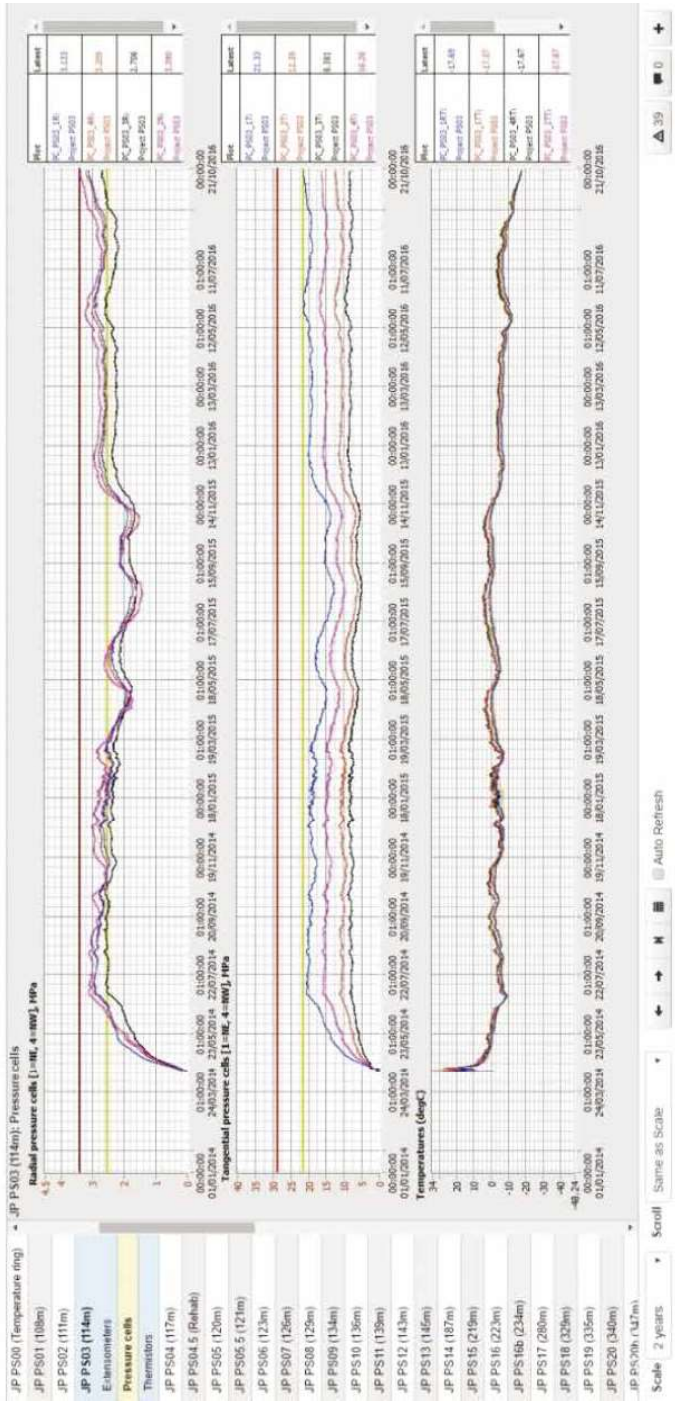

Fig. 8-2. (Continued) Real-time screens and historical plots

may be acquired, reduced, displayed, and reported correctly yet be of limited value because of instrument malfunction, rendering evaluation of dam behavior impossible.

Instruments are calibrated regularly to avoid bad measurements. Instruments are evaluated by checking measurable properties and by careful assessment of the instrument readings. Functional parameters of the instrument are checked on a scheduled basis and whenever instrument readings suggest the possibility of questionable reliability.

For example, in an open piezometer, the reference elevation from which the water depth is measured is periodically checked against a reference elevation. The standpipe is checked for obstructions by sounding to the tip elevation and checking the result against the installation records. The tip may need to be flushed to dislodge sediment. The response of the piezometer may need to be checked by dewatering or adding water to the standpipe. In some instances, the influence zone seals may need to be checked by adding water to the annulus between the surface protective casing and the piezometer standpipe or to another existing piezometer in the same hole.

For electrical piezometer transducers, the input and output voltages or frequencies and the steadiness of the reading can be checked. If the transducer is removable, its response and calibration can be checked by submerging it in various depths of water or applying known pressures. If removed, it is imperative that its elevation is accurately recorded upon its replacement. Whenever possible, replacing an instrument at the same location is good practice to allow consistency of measurements.

In many cases, the manufacturer has established procedures that prescribe methods for testing its instruments. The manufacturer's operation manuals are retained as references on operation, calibration, and troubleshooting. Most manufacturers offer technical support, and they may be needed to help with testing more sophisticated electronic instruments.

8.1.6 Reading Validation

The second element in assessing instrument reliability is a careful review of the instrument readings. The easiest cases to deal with are those in which the readings yield values that are impossible or as expected. Be aware that anomalous readings can be deceiving if they fall within the expected range. A reading that is within the realm of possibility but indicates unexpected behavior must be carefully investigated. The first step is to repeat the reading to determine if the instrument is faulty or if the dam performance is outside of the expected range. Any unusual instrument readings require explanation. If data collection and processing have been ruled out as causes of the anomaly, the instrument function must be investigated.

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An investigation of instrument function will usually reveal why a reading does not seem plausible. If needed, the instrument can be abandoned, repaired, or replaced. An investigation may yield inconclusive results, and the decision to rely on the instrument data will require judgment. Dam behavior can be enigmatic. Restraint is needed when classifying data as erroneous. The confidence placed in the data may make the difference between timely notification of an emergency, late notification of an emergency, or the issuance of a false alarm.

Computer or data logger entry permits rapid checking of a reading against expected or historic values. Data obtained automatically by data-acquisition systems can be immediately validated as readings are recorded. In actual practice where computers do the graphing, proofreading the data displays or data plots is often the most efficient means of checking the data.

Validating data requires a technical background and experience to understand how the dam was designed and behaves, its performance indicators, how various measurements are made, and access to information on the external geometry, internal geometry, surrounding geology, and material properties of the dam.

In some cases, questionable readings can be corrected if the cause of the error is clear. For example, during manual data collection, it may be obvious that an instrument reading was entered in a form field for the wrong instrument or that digits were transposed. Any corrections are documented with the original data, preferably in the field logbook or on the field reading form containing the original data. Questionable data either are not used or flagged to document the uncertainty of the readings.

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8.1.7 Data Archiving

Archives may be either paper or electronic records that include both the raw and the reduced data, as appropriate. Projects with many instruments or long-term monitoring programs can benefit greatly by archiving the instrument data in an electronic database, but for smaller projects with few instruments, paper records may be an acceptable choice.

The length of time to store archived records will depend on the nature of the project and the type of data, but many dam projects have a full dataset that covers the entire life of the project. This can prove useful in the event of performance assessment against new criteria, structure modifications, litigation, or dam failure. Important instrument data may be backed up and stored in multiple locations to protect against loss from accidental misplacement or physical damage. Periodic review is needed to ensure compatibility with current software and hardware.

The value of archiving historic instrument data can greatly outweigh the storage costs. The following quotation from the U.S. Army Corps of Engineer's Engineering Manual is worth noting:

Valid instrumentation data can be valuable for potential litigation relative to construction claims. It can also be valuable for evaluation of later claims relative to changed groundwater conditions downstream of a dam or landward of a levee project. In many cases, damage claims arising from adverse events can be of such great monetary value that the cost of providing instrumentation can be justified on this basis alone. Instrumentation data can be utilized as an aid in determining causes or extent of adverse events so that various legal claims can be evaluated. (USACE 1995)

8.2 DATA PRESENTATION

Data presentation encompasses the portrayal of the reduced data in tabular or graphical form. Graphs of time versus readings are generally recognized as one of the most powerful visual means of communicating information (Williams 1985). When necessary, graphs can show the data set, give a summary of behavior, and illuminate detail all at once.

Instrumentation monitoring is worth little if the results are not evaluated and communicated to the appropriate decision makers in an understandable and timely manner. The monitoring presentation or report easily allows an engineer, even one not intimately familiar with the dam, not only to understand the findings but also to develop conclusions without having to refer to a great deal of other documentation for key information.

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8.2.1 Defining the Objective

The form of data presentation depends upon the intended purpose. Data may be presented in one form for engineering evaluation but in a different form for a public presentation or summary report. Each format may include different data subsets, instrument attribute information to aid interpretation, and different scales. When the choice of format is suitable for the intended purpose, the objective of the data presentation is clearly defined.

Some typical objectives include confirming design estimates, monitoring historical or long-term trends, comparing actual values to predicted values, detecting changes in the data values, or consolidating data from multiple instruments to improve the understanding of the dam behavior.

8.2.2 Example Formats

One of the most common forms of graphical presentation is the historic trend or time series plot. The values of the data collected are seldom as important as trends. In tabular form, the presentation could simply be a

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two-column list of dates and instrument readings. In graphical form, the most common format plots time on the horizontal axis and the engineering parameter on the vertical axis. Historical trend plots often include multiple instruments on a single page to show how changes in one instrument compare to changes in some other instrument.

8.2.3 Synoptic Presentations

Another common form of data presentation shows the data from multiple instruments acquired at approximately the same time and presented to show the variation in the measured parameter across an area or along a path. Examples would include total head contour plots or settlement along the crest of a dam. Graphical forms are generally better for this type of presentation because both the values and the locations can be easily portrayed, but tabular forms can also present useful information such as the range, minimum, maximum, and average of the values.

8.2.4 Comparison to Predicted Values

Perhaps the most informative format for presenting the data involves comparing the instrument readings to the predicted values for the measured parameters. This allows the engineer to evaluate whether the dam is performing as expected, whether any of the engineering assumptions may be questionable, whether physical phenomena not considered in the design may be affecting the dam's behavior, or whether the instrument is providing erroneous data.

In tabular form, instrument readings that fall outside of the predicted range can be easily highlighted to focus the reviewer's attention on those values. Including minimum and maximum predicted values in the table provides more context with which to assess the deviation from the predicted values. In graphical form, the predicted range can be visually represented. For example, on a historical trend plot, the minimum and maximum predicted values can be shown on the plot as a shaded band, minimum and maximum lines, or low and high bands on individual data points.

8.2.5 Changes from Past Values

A similar type of presentation compares current instrument readings to historical instrument readings. An increase in seepage flow, turbidity, or crest settlement can indicate that the physical condition of the dam has changed. It is important for the engineer to understand these changes in context to properly evaluate the performance and safety of the dam. As with the comparisons to predicted values, historical comparisons can be presented in either tabular or graphical form.

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8.2.6 Hysteresis Plots

Hysteresis plots are often an informative way to plot the correlation between two variables and to illustrate how the correlation changes with time or with the direction of change. Hysteresis plots are useful, for example, in displaying the response of piezometers to changes in reservoir level or the patterns of movement of a concrete dam with changes in temperature.

8.3 REPORTING INSTRUMENTATION DATA

The objectives of the instrumentation data report are to clearly present the current field readings, highlight any deviations from the normal or expected readings, document historical performance, and preserve performance history. It provides information to the dam safety engineer to evaluate the performance of a dam along with other information such as geological data, design data, construction records, and visual inspections.

8.3.1 Reporting Instrument Reading Results

To ensure that data are evaluated in a timely manner, a routine process to reduce, validate, archive, and report the instrument reading results is required (Terzaghi and Peck 1968). The process need not be elaborate but should include the following elements:

- The data management process is a written document. It explicitly defines the steps in the process, the person responsible for each step, the inputs and outputs from each step, and the schedule for performance;
- Field readings are required within an appropriate time frame to alert operators and owners of any problems;
- A review is made of the field readings to document that the readings have been received, to indicate whether the data are complete, and to note any omitted, unexpected, questionable, or out-of-bounds readings. If warranted, the review may suggest that unusual readings be retaken; and
- A report of the instrument reading results is prepared for the engineer who will evaluate the dam performance. This report would include the reduced readings and may include supporting information such as the raw data or historical trend plots of past readings. The report may present the data in tabular or graphical form. Having the capability to view the data in both formats can provide a clearer interpretation of the data. Access to an online database that can present the data in several formats provides the greatest flexibility.

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Dam size and complexity and organizational preferences produce different approaches to preparing data for evaluation. Personnel who collect the data and produce the data reports and the engineers who evaluate the dam performance may be different. At other projects, these tasks may be performed by a single individual. The details of the data management and presentation plan reflect the staff organization and organizational preferences. Having a periodic independent review of the instrumentation system and data can help protect against complacency or oversight, even in small organizations. If the tasks are distributed among several parties, it is important that a single individual has a lead role to assess whether data collection and evaluation are occurring according to schedule and to acceptable levels of quality.

8.3.2 Report Content

Performance indicators are likely to include

- Seepage quantity and quality,
- Reservoir levels and piezometric pore pressures, and
- Movement.

The introduction of the data report explains which measurements are being reported. For example, small dams may have only reservoir level and crest monuments. For each performance indicator, the information may be divided into three parts:

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- Instrumentation description,
- Instrument readings, and
- Data validation notes.

Each subsection contains a description of the instrumentation involved. For example, a discussion of seepage performance would begin with a description of the weirs, flumes, samplers, or other devices used to obtain seepage data.

Instrument types and locations are included so that the report becomes the primary documentation of the instrumentation. The presentation of reading data that follows the instrumentation description is organized according to the performance indicator measured.

Complete reports contain drawings and cross sections of instruments. It may not be necessary to go to any document other than the report on instrumented performance for information on the layout, location, type, and operating condition of the instrumentation. Previously measured but abandoned instruments are identified.

The report includes performance indicators and their measurements in tabular or graphical form. Both current data and historical results are reported, preferably graphically. Time-versus-measurement graphs are

the easiest to evaluate. In some cases, it may be neither desirable nor practical to display all data for a given installation (e.g., an observation well with a 20-year record of weekly readings). In some cases, all data are presented.

Data validation notes discuss the characteristics and quality of the data. Gaps in the data record, questionable readings, instrument reliability, and other facts that affect the data quality are described. A summary of the most significant aspects of the recorded behavior is required.

8.3.3 Reporting Instrumentation Data

This section presents a sample format for a periodic instrumentation data report. Many other formats are equally valid, and, of course, the sections would be customized to the specific project. Consistency in the report format improves efficiency, facilitates locating relevant data, and facilitates comparisons with different periods.

Identification of the dam site

Example: "This Instrumentation Data Report covers the XYZ Dam site. The site instrumentation covers the dam itself, the dam abutments, the upstream water level, and downstream area."

Identification of the monitoring period

Example: "The report includes new instrument readings from 1 March 2015 through 31 March 2015, as well as historical readings required for trend analysis."

Identification of the installed instruments

Example: "Instrumentation at the XYZ Dam site includes headwater and tailwater gauges, weirs, piezometers, inclinometers, and surface settlement points."

Data presentation (repeated for each performance indicator)

Performance Indicator (Seepage and flow quantity)
Measurements
Data plots or tables

- Headwater and tailwater levels,
- Observations and recommendations,
- Significant performance aspects,

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- Adequacy of instrumentation, and
- Adequacy of reading and reporting schedule.

If measured, the seepage flow rate is a very important performance indicator. Most dams are constructed to retain water, and the seepage rate is a primary indicator of the ability of a dam to fulfill this primary function. More important, changes in the seepage rate can provide an early indication of physical changes in the structure of a dam.

Seepage quantity and quality must be correlated with headwater level and precipitation. Other influencing variables may include ambient and concrete temperature, reservoir water quality, tailwater level, groundwater level, and groundwater quality. The following sections provide examples of how data may be reduced and presented.

8.3.4 Reduction and Display of Seepage Quality

Water-quality data related to a performance indicator is generally limited to turbidity. Turbidity may be reported in simple terms such as clear, cloudy, muddy, or carrying particles.

If measured, water quality can be reported as turbidity or as total suspended solids (TSS). Turbidity can be measured in the field with direct reading instruments or by visual comparison to prepared standard samples prepared in a laboratory.

Water-quality data on the dissolved salts or TDS may come from direct reading meters or from laboratory analyses. In either case, the data are most likely to be received in meaningful engineering units, not as raw data. However, the reviewer must be involved with determining and understanding where, when, and how the samples are obtained and analyzed. The measurement of most interest is that of the mass of dissolved material per unit volume of seepage water. Measuring the dissolved concentrations of particular compounds may also help identify the dissolution of foundation bedrock or grout curtain.

Water-quality data are displayed in a variety of ways. Because the reviewer is most often interested in the rate of mass loss in the foundation or embankment, a simple plot of turbidity, TSS, or dissolved concentrations versus time may be useful. Such plots may also indicate useful correlations.

For chemical analysis, a quick comparison of concentration and constituents can be made by comparing the size and shape of graphical representations such as Stiff, Piper, or Schoeller diagrams. These are different methods of graphically displaying water-quality data, and details may be found in any groundwater or hydrogeology text.

A Stiff diagram, shown in Fig. 8-3, portrays the equivalent concentrations of the major ions in a water sample along a series of parallel horizon-

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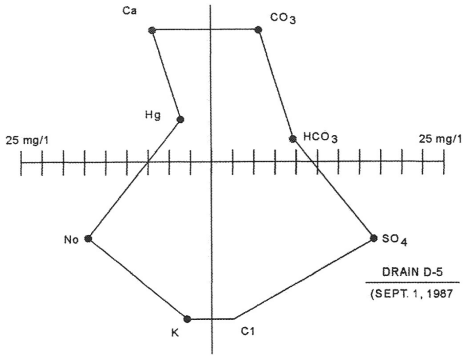

Fig. 8-3. Stiff diagram
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

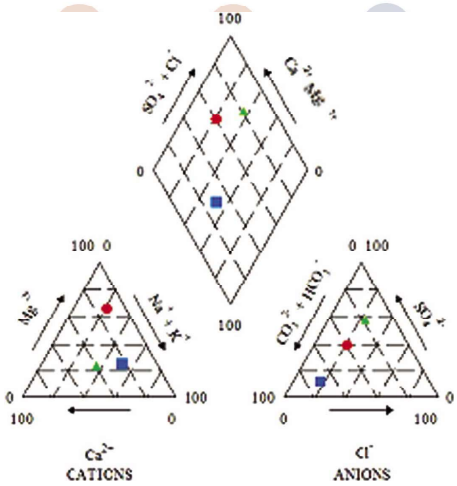

Fig. 8-4. Piper diagram

tal axes. Traditionally, cations (positively charged ions) are plotted on the left and anions (negatively charged ions) are plotted on the right.

In a Piper diagram, also known as a trilinear diagram, shown in Fig. 8-4, the relative ion concentrations in milliequivalents per liter (meq/L) are plotted in two triangles, one for cations and one for anions, with each point indicating the relative percentages of the total cation or anion concentrations. Projecting the cation and anion relative percentages onto a gridded quadrilateral allows a visual comparison of the geochemical properties among different water samples.

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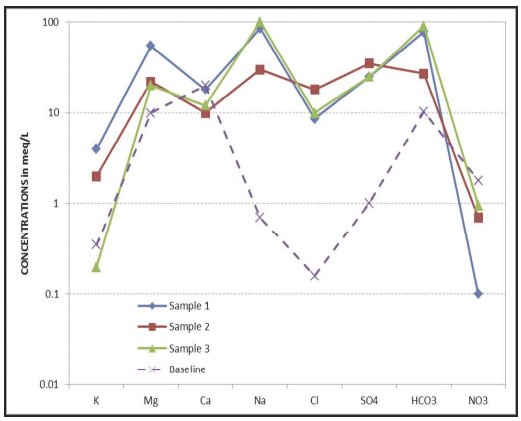

Fig. 8-5. Schoeller diagram
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

A Schoeller diagram, shown in Fig. 8-5, presents the individual ions spaced evenly along the horizontal axis and plots the ion concentrations in milliequivalents per liter against a logarithmic vertical axis. It is particularly useful in identifying water samples with similar patterns of concentrations.

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8.3.5 Reduction and Display of Hydrostatic and Piezometric Data

Hydrostatic data refer to the reservoir headwater and tailwater levels. Piezometric data refers to pore water pressures within a dam, its foundation, and its abutments.

The piezometric level or total head is the elevation to which water from a given pressurized location would tend to rise in a tube vented to atmospheric pressure. Generally, this form of pressure expression is used because of the ease of relating it to the reservoir surface elevation. It can be measured directly by actually allowing water to rise in a tube, as is done in open piezometers, or indirectly, as is done in closed piezometers or by pressure transducers by measuring the force exerted on a calibrated diaphragm or a closed tube. The latter method determines the pressure head that can be converted into an equivalent height of water, which in turn can be used to calculate total head by adding the piezometer tip elevation (also known as the elevation head). For groundwater flow, the velocity head is generally ignored.

$$\text{Total head} = \text{Pressure head} + \text{Elevation head}$$

Measurement of total head may come in raw form as depth to water. Thus, the elevation from which the depth is measured must be known.

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Usually, the depth is subtracted from the top of pipe elevation. If the pressure head is needed, the tip elevation of the piezometer can be subtracted from the total head to yield a height of water that can be converted to an equivalent pressure. In a properly installed and functioning piezometer, the pressure head corresponds to the pore pressure at the location of the piezometer tip. When stability analysis is the concern, it is most appropriate to express pressure in the same units that the material strengths are expressed in, usually force per unit area.

Raw data from closed piezometers may come in various forms. In some cases, such as with pneumatic and hydraulic sensors, the pressure is measured directly, and the readings can be used as they are or converted to total heads. In others, such as circuit strain or vibrating-wire sensors, the readout is electrical resistance or period of vibration, respectively, and requires conversion according to the data reduction formula and instrument calibration factors.

Caution is required to be certain that data are reduced with the correct equations and associated with the correct elevations. For example, it may not become evident that readings of depth to water are being associated with the wrong standpipe until a depth measurement indicates the impossible situation of a hydrostatic level below the tip elevation.

Because of the flow characteristics of open piezometer systems, there are trade-offs between the length of the collection zone and response time. The total heads measured by a piezometer are taken as the midpoint elevation of the collection zone.

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Common methods of displaying hydrostatic-level data consist of hydrographs (water level versus time), hysteresis plots (water level versus reservoir head), pressure diagrams (maps of the pressure distribution), and total head contours.

Graphs of water level or pressure versus time, shown in Fig. 8-6, are plotted at a scale that allows deviations of significance to be easily identified. Reservoir and tailwater levels are graphed on the same page and, if practical, to the same scale. This allows a visual estimation of the piezometer's response to fluctuations. Several piezometers can be shown on one page, and it is often convenient to do so if several piezometers have a common feature.

Examples of common features would be all piezometers at a given elevation in a given zone, perhaps all piezometers in a zone if there are only a few, or all left abutment piezometers. Tailwater level versus time is also graphed because the driving variable is really "reservoir head," which is the difference between reservoir level and tailwater level. In some cases, graphing the reservoir head may be more informative than graphing the reservoir level.

To show the relationship between piezometric heads and the reservoir level, a hysteresis plot may be helpful. An example hysteresis plot is shown in Fig. 8-7.

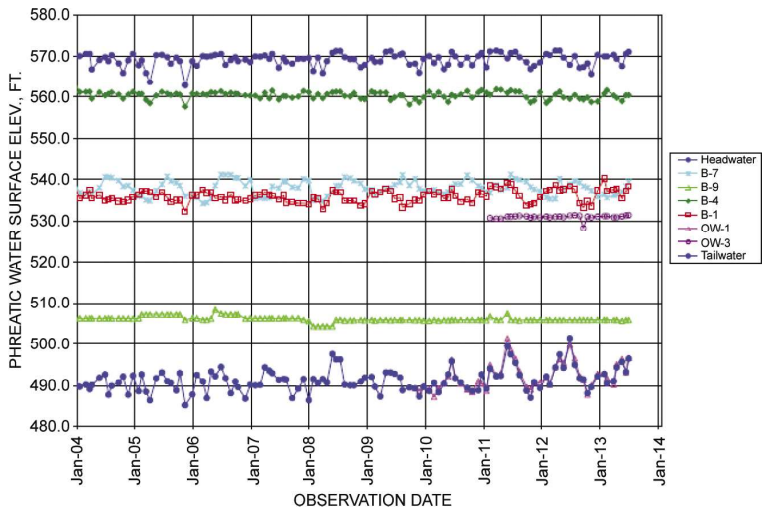

Fig. 8-6. Graph of reservoir and piezometer levels versus time
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

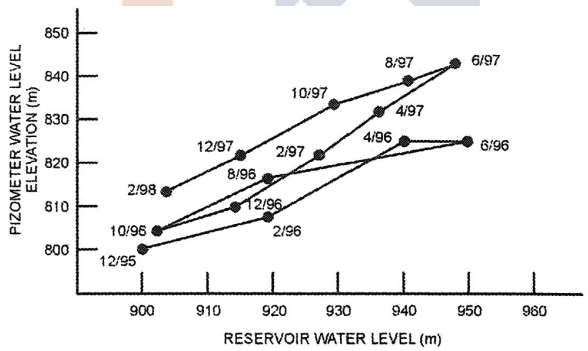

Fig. 8-7. Hysteresis plot
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

If the sensor location is such that tailwater level has little effect, then a plot of piezometer reading (dependent variable) versus reservoir level (independent variable) will suffice. With such a plot, it can easily be determined if there are factors other than reservoir level that influence the piezometer and, more important, if their relationship is changing with time. To get a clear picture of what is happening with time when several

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cycles are graphed, it may be necessary to differentiate the data in different time periods by color, symbol, or annotation. It is possible that because of the location of the instrument that tailwater, groundwater, or river stage is the prime influence, and those independent variables are plotted against the instrument reading. Hysteresis plots can also clearly demonstrate any critical levels (levels at which the dependent variable response changes) for the independent variable.

Fig. 8-8 illustrates pressure distribution within an embankment. Lines are drawn to connect points of equal pressure. Using elevation information, the pressure data may be used to also produce lines of equal potential energy (pressure head plus elevation).

A plan view of the pressure distribution is a horizontal slice through the distribution at a given elevation. To do this, the data used to draw pressure contours or equipotential lines must be from the same or nearly the same elevation within the dam or foundation.

Pressure contours are perhaps most valuable when embankment stability analysis is the concern. Pressure values for any point on the diagram can be determined by interpolation between the pressure contours. The equal potential diagram on the other hand is best used to understand the direction of seepage flow along with gradient in the direction of flow.

For concrete dams, the hydraulic grade line, shown in Fig. 8-9, indicates the uplift pressure beneath the foundation contact or at other surfaces.

8.3.6 Reduction and Display of Movement Data

Movement data encompasses surface, crack and joint, internal, and appurtenant structures. Movement may be horizontal, vertical, or a combination of both.

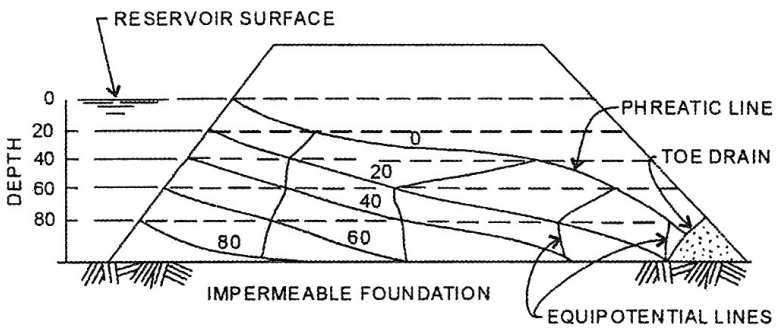

Fig. 8-8. Embankment cross-section pressure diagram
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

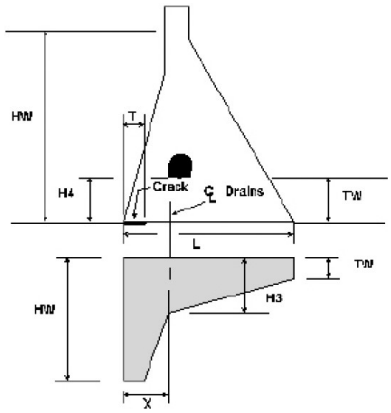

Fig. 8-9. Hydrostatic grade line
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Raw data for displacement measurements can be of several forms: direct measurements, angular measurement, measurements relative to some reference point, pressure, stress, voltage, resistance, or vibration period.

All data except the direct measurement must be reduced to show magnitude and direction. Chapter 6 described the method of surveying measurement points.

Data from each type of instrument are reduced to coordinates to provide a means of visualizing the nature and significance of movement. For some instruments, the measurement is referenced to a line such as a centerline showing changes in horizontal and vertical position related to the line.

Display, however, can sometimes be more effective if actual measurements are not shown but rather a calculated value such as change expressed as a percent of the original value. An example of this could be internal vertical settlement. The reviewer would have to be aware of actual settlement and where the maximum occurred, but it may well be that it is desirable to communicate the embankment settlement to others as percent compression or vertical strain. For movement plots, it is sometimes helpful to use a logarithmic scale for time because the slope of the line after initial settlement (immediately after construction) will be constant. For example, normal compression, consolidation, and lateral spreading will yield a straight line on semi-log paper and rate changes are magnified (Sherard et al. 1983).

One important note about presenting movement data is that the sign convention used must be clearly identified (i.e., the data plots and tables must indicate whether positive data values indicate compression or expansion, upstream or downstream).

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8.3.6.1 Horizontal Movement. Fig. 8-10 illustrates how horizontal movement may be presented. With such displays, the reviewer can evaluate total displacement for excessive values and look for significant differentials between adjacent points that may signify embankment instability, cracking, or internal erosion. When there are indications of a problem, net head (headwater minus tailwater) and temperature may be included along with displacement versus time on a graph to determine if the rate of displacement is sensitive to reservoir level or temperature. Data from additional lines of measurement points would allow for areal mapping of the movement and identification of patterns of movement.

In Fig. 8-11, a graph of four sets of settlement profile data for seven measurement points is shown. On such a graph, the reviewer looks at the total settlement to determine if the freeboard is adequate and if the pattern of settlement is as expected. Again, differentials between points are examined to determine if cracking or internal erosion may be a problem. Under normal conditions, the rate of settlement will generally diminish with time, although reservoir operation may affect the rate. With a regular reading schedule, the interval between lines tends to decrease with time, as shown. Determination of the elevations on additional rows of measurement points will aid in delineating any potential slope stability problems.

8.3.6.2 Internal Movement. Various instruments such as settlement plates, cross-arm devices, extensometers, settlement sensors, and slip-joint inclinometer casings are used to determine internal settlement within dams and foundations. With these instruments, compression and vertical

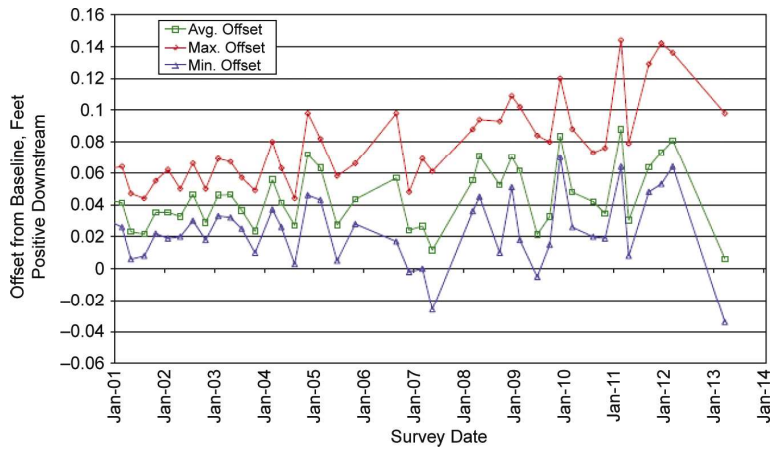

Fig. 8-10. Horizontal deflections
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

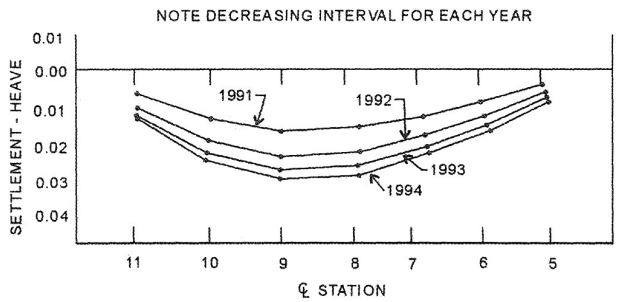

Fig. 8-11. Settlement versus time
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

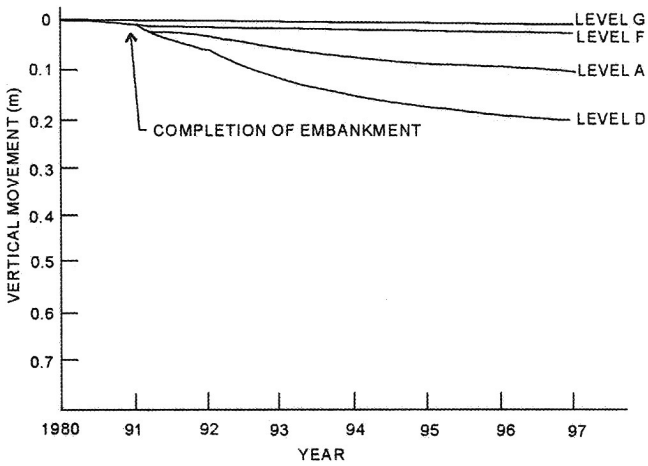

Fig. 8-12. Internal settlement versus time
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

displacements of foundations and embankments can be determined at any depth. Data records can begin during construction.

A typical plot of internal settlement or compression is shown in Fig. 8-12, and it is similar to the vertical settlement plots discussed earlier. Settlement of each level was anticipated by the designers, and compression data are compared to the anticipated values. Again, note how rate decreases with time.

Internal movements, especially with extensometers, may be measured in directions other than vertical or horizontal. The principles for effective

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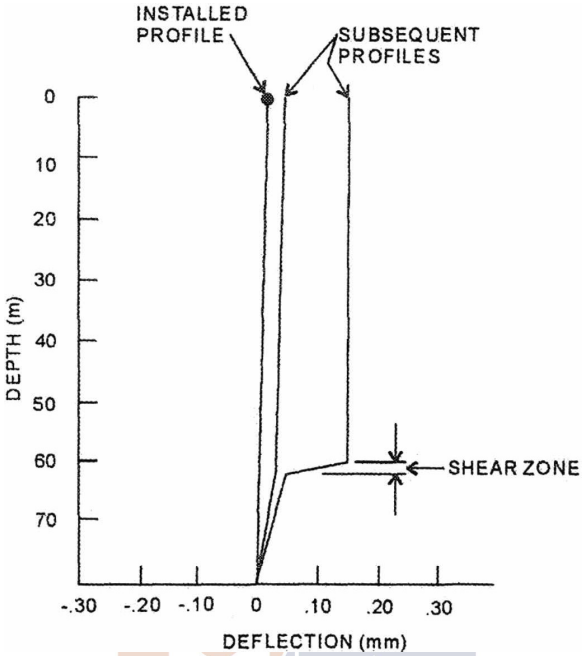

Fig. 8-13. Plot of inclinometer data
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

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display remain the same, but the plots must clearly indicate the location of the instrument and the direction of movement.

The principal purpose of an inclinometer is measuring horizontal deflection of the casing along a vertical profile. Deflection can be measured in two planes, one parallel to the line of expected movement and the other perpendicular to it. If the casing moves horizontally, the inclinometer will measure the magnitude of movement. Readings are typically plotted as shown in Fig. 8-13. The series of readings on the same plot illustrate that progressive movement is occurring. Shear-zone elevations can be shown on a cross section to identify a failure surface. Usually the bottom of the inclinometer casing is considered as a fixed reference point. The reviewer must be familiar with the foundation to know if the bottom is fixed. If it is not, the top of the casing must be surveyed each time data are taken. All displacements from a set of readings are then referenced to the verified top of casing elevation.

Embankment construction is a special case for inclinometers because nearly every time the casing is read, there is a new, longer casing length as sections are added as the embankment height increases. Each profile

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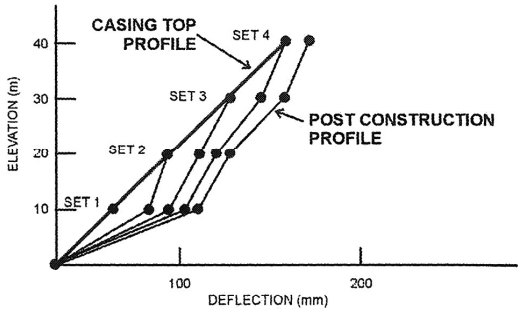

Fig. 8-14. Construction-stage inclinometer data
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

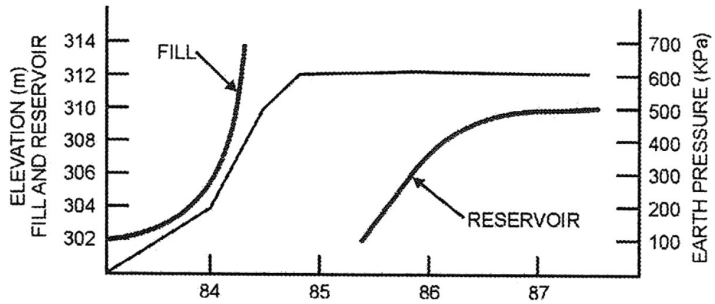

Fig. 8-15. Earth pressures response to fill and reservoir level
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

represents a new initial point. A good way to get an overall picture of what is happening during construction is to make a profile consisting of initial top of casing locations, as shown in Fig. 8-14. Profiles can be compared to the initial top of casing profiles as if it was an initial profile of casing.

8.3.7 Reduction and Display of Earth Pressure Data

Readings from earth pressure cells are reduced to units of stress. The data are usually plotted versus time but may also be plotted versus reservoir level or construction fill height to produce a hysteresis plot (Fig. 8-15). If the information is being used in an effective stress analysis, then the pore water pressure, measured by a nearby piezometer, is plotted along with the cell readings or subtracted from the cell readings before plotting.

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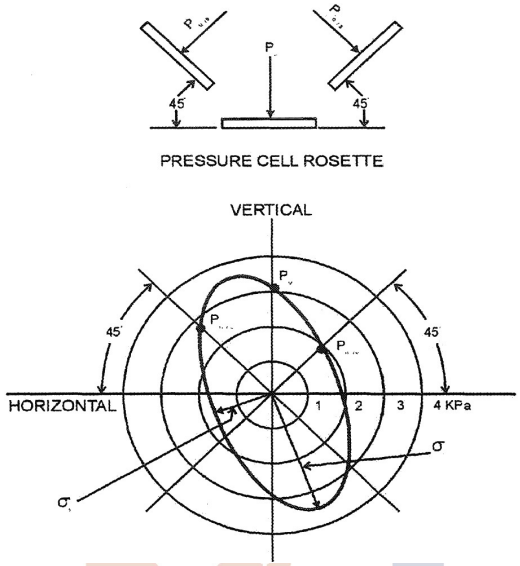

Fig. 8-16. Data from a stress rosette
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

If the data come from a rosette, then a stress ellipse, shown in Fig. 8-16, can be constructed to show the direction and magnitude of principal stresses. If principal stresses are calculated for each set of readings, then it is advantageous to plot principal stress, major, minor, or both, versus time, reservoir level, or fill height.

Chapter 13 contains sample data forms and plots that may be helpful in preparing a performance-monitoring report. Data management and presentation prepare the dam safety engineer to evaluate and make decisions about dam performance—the subject of Chapter 9.

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CHAPTER 9
EVALUATION, DECISION, AND ACTION

> Monitoring programs have failed, because the data generated were never used. If there is a clear sense of purpose for a monitoring program, the method of data interpretation will be guided by that sense of purpose. Without a purpose there can be no interpretation.
>
> John Dunnicliff

Up to this point in the manual, ways and means were presented to address a single question: "Is this dam performing as expected?"

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Failure modes and their associated performance indicators were identified. Instruments and a monitoring scheme to answer those questions were integrated into a dam-performance monitoring plan. The plan was implemented. Both visual observations and instrumented measurements produced data. Data were validated and their quality assessed for each performance indicator. The instrumented data were compared with the visual observations. Reports were written and data were presented.

The next step is to evaluate the data in the context of answering a single question about a dam's safe performance: "Is this dam behaving as expected?" This chapter is intended to provide a foundation for evaluating, deciding, and acting on the products of the dam-performance monitoring program.

9.1 EVALUATION

Data gathered for the identified performance indicators are meant to provide a basis to judge whether or not a dam is performing as expected.

Some examples of measurements of key performance indicators may be similar to these examples:

- Does the record of seepage volume and quality support the conclusion that an internal erosion failure mode is not developing?
- Is the measured rising trend in joint water pressure in the left abutment indicative of the development of a privileged path of leakage that might lead to loss of foundation support, potentially destabilizing the arch dam?
- Are measurements along the embankment crest indicative of foundation settlement or piping or simple consolidation?
- Do plunge pool survey measurements suggest that the toe is likely to be undercut, causing a loss of support and potentially allowing the gravity dam to slide?

As discussed in Chapter 2, experience has shown that there are vulnerabilities common to all dams, but each dam has its unique set of vulnerabilities that could provide a path to initiate a sequence of events leading to a loss of reservoir control. Evaluation of performance indicator data from a monitoring program in the context of the common failure modes and any additional failure modes unique to a particular dam requires skill and judgment. Analyses may be required to reach a conclusion about a dam's safety.

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9.2 DECISION

> We cannot solve our problems with the same thinking we used when we created them.
>
> Albert Einstein

Two questions must be answered before deciding what, if any, action to take:

1. Are there sufficient reliable performance indicator data to judge whether this dam is performing as expected?
2. Have I thought of everything?

The decision process leading to appropriate action will benefit from setting limits for a measured performance indicator beyond which additional measurements must be taken or analyses performed to judge whether a dam's performance is acceptable.

Threshold and Action Levels are part of FERC's *Engineering Guidelines* (FERC 2005) for monitoring dam performance. Other organizations and

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agencies may use different terms, but the intent is to provide a basis to support safety decisions. As defined by FERC,

- A Threshold Level is a value used in the analysis or design or a value established from the historic record. Measurements that exceed a Threshold Level require further inquiry.
- An Action Level is a value that requires increased surveillance or the need for intervention.

To the degree practical, Threshold and Action Levels are established for each instrument, taking into account the expected performance of the dam, location of each instrument, and measurement characteristics of the readings. All data are compared with design and analysis estimates. For example, measured pore pressures and uplift pressures are compared against those used in design stability analyses and prior measurements.

Numerical limit values may be based on theoretical or analytical studies (e.g., uplift pressure readings above which acceptance criteria are no longer met). In other cases, limits may need to be developed based on historically observed behavior (e.g., seepage from an embankment dam). The assigned limit values are those that are judged to require further evaluation to determine whether a potential failure is developing or whether there is a problem with the data. Limits for both magnitude and rate of change may need to be established. In some cases, a value may be a lower limit (e.g., a decreasing trend of piezometric level may indicate the opening of a flow path to the downstream side of the dam). The limit levels reflect a careful consideration of failure modes, and more than two limit levels may be appropriate in some cases.

The established values are periodically reevaluated to determine if the values need to be changed to address daily, seasonal, or other cyclic relationships, new information, or changes to the dam. Values may be set by the designer based on his or her understanding of how the dam will perform. During actual operation, the dam may perform differently, with some of the instruments showing readings exceeding the originally set levels. Additional conscientious evaluation of the construction experience and overall performance of the dam may indicate that these readings do not indicate unacceptable performance. The values could then be revised based on the more complete picture of how the dam is performing. The reverse is also true, where undesirable performance occurs at levels below the limit levels, and the values are reduced.

The limit levels are evaluated periodically during operation to verify that they remain consistent with dam performance. Considerable care and thought must be given before revising Action Levels. It is important to verify that proposed revisions are compatible with safe performance.

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Periodically, the appropriateness and adequacy of the instrumentation and monitoring program are evaluated. The evaluation includes answers to the following four questions:

- Is the instrumentation and monitoring program appropriate for the potential failure modes of concern at the dam?
- Are the type, number, and location of instruments appropriate for the behavior being monitored?
- Is the frequency of readings appropriate?
- Are the data being collected, processed, and evaluated in a timely and correct manner?

If the performance indicators for failure modes are not being appropriately monitored, they should be. Additional instrumentation or monitoring may be required. If there is a discrepancy between the measured and expected behavior of the dam, it may indicate that data do not adequately represent the behavior of the dam or that conditions exist that were not accounted for in the expected behavior. In either case, after detailed evaluation and interpretation, it may be necessary to make new analyses, perform field investigations, or install additional instrumentation.

Best practice limits measurements to potential failure modes. If there is no question related to a performance indicator identifying a developing sequence that could progress to a failure, then no instrumented measurement is required.

If trends or interrelationships between data are not clear, it may be appropriate to take more frequent measurements or collect additional, complementary data.

9.3 ACTION

> I never worry about action, but only inaction.
>
> Winston Churchill

A convenient way to decide if action is required is to think of limits as a traffic signal, shown in Fig. 9-1. Measurements less than a Threshold Level would be GREEN and signal GO. Measurements exceeding the Threshold Level but less than the Action Level would be YELLOW and signal CAUTION. Measurements exceeding an Action Level would be RED and signal STOP.

Although measurements usually fall within the expected ranges (the GREEN or GO state), there are actions that can be considered, including

- Continuing data collection unchanged,
- Reducing reading for instruments with a long unchanging record, and
- Abandoning or deactivating instruments that no longer measure a performance indicator related to a failure mode.

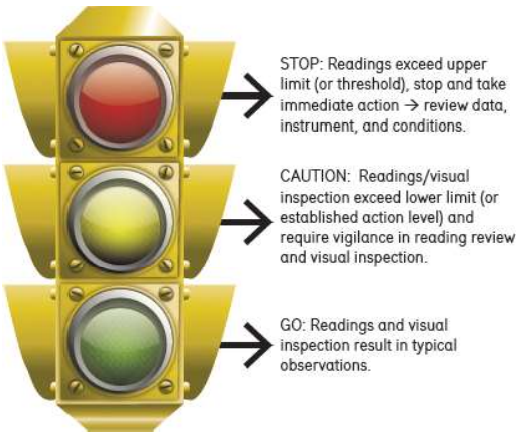

Fig. 9-1. Stop–Caution–Go
Source: ASCE Task Committee on Instrumentation and Monitoring Dam Performance (2000).

Measurements may fall within the range of threshold values (YELLOW) or CAUTION zone. Measurements within threshold boundaries are unlikely to jeopardize reservoir control. The signal has not turned RED. However, evaluation is required.

For example, a high reading of one piezometer in an embankment may exceed the piezometric level estimated in the stability analysis for that location at the same time other piezometers along the same cross section could indicate the overall piezometric line is lower than estimated in the design stability calculations. The same logic holds for piezometers used to measure uplift pressure beneath a concrete gravity dam. For these cases, a single instrument indicating values above design level does not necessarily indicate a process headed toward instability.

Measurements outside expected ranges are supplemented as quickly as possible by a visual check of conditions and the instrument of concern in an attempt to determine the likely cause of the unexpected measurement. If needed, an additional instrument may be strategically located to provide independent data for evaluation of an unusual condition. For example, one might be placed along a cross section between existing instruments to interpolate the behavior along the cross section. Or a more appropriate instrument that better responds to varying rates of change may be added.

Data outside expected ranges may lead to additional engineering investigations or analyses. Analyses may be undertaken to evaluate the margin of safety associated with a particular failure mode based on measurements. Alternatively, analyses may be undertaken to try to determine why a measured performance indicator is outside of the expected range. Depending

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on circumstances and the need to resolve uncertainty about a dam's behavior, additional field investigations may be needed to better define conditions. A thorough review may lead to the conclusion that widening threshold limits is justified because the margin of safety is greater than previously estimated. Again, sound engineering judgment is required.

When the signal turns RED, it is time to STOP and take immediate action to either quickly resolve why a measurement exceeds the upper bound of the threshold limit or prepare to initiate emergency procedures. It would be unusual to implement the emergency action plan (EAP) solely on the basis of monitoring data. There is little evidence of loss of reservoir control without some physical manifestation of trouble evident to visual observation.

The instrument returning the worrisome measurement may have failed; if so, its failure must be discovered quickly. A review may reveal that the action limits are too low. In any event, the review of monitoring data is intended to trigger a thorough visual inspection to judge whether a rapidly developing situation exists that requires initiation of the EAP. For remote unmanned projects, it may not be possible to physically observe the situation quickly enough to delay the initiation of emergency procedures. The exercise of good judgment is essential in deciding when to implement an EAP.

Lowering the reservoir or placing stabilizing fill is among the actions that may be appropriate, depending on the situation.

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CHAPTER 10
EMBANKMENT DAMS

> True stability results when presumed order and presumed disorder are balanced. A truly stable system expects the unexpected, is prepared to be disrupted, waits to be transformed.
>
> Tom Robbins

Chapter 3 introduced monitoring considerations for embankment dams from the perspective of their potential failure modes. This chapter discusses embankment dam vulnerabilities and behavior and provides guidance about means and methods to measure the performance indicators that answer the question, "Is the dam behaving as expected?"

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10.1 DESIGN

Embankment dam designs vary widely in terms of size, purpose, and type of construction materials. Common varieties are zoned earthfill dams, zoned rockfill dams, homogeneous dams, and membrane dams. Each relies on its mass to resist the imposed loads. Proper design demands that an embankment dam remain stable and retain the reservoir under all anticipated loading conditions.

Embankment dams are constructed with soil and rock and are supported by foundations and abutments consisting of soil and rock. Engineers characterize soil, rockfill, and bedrock properties by some or all the following material properties: strength, stiffness, consolidation, compressibility, density, plasticity, void ratio, permeability, and moisture content. The properties of embankment materials govern their response to the loads of the dam

itself, water, and earthquakes. Materials are selected to provide sufficient stable mass to resist those loads.

An embankment dam must maintain stable upstream and downstream slopes and be compatible with the materials and geometries of its abutments. The design must meet acceptance criteria requiring margins of safety for normal, flood, and earthquake loads.

Abutment geometry, foundation stratigraphy, and character influence abutment shaping, requiring an understanding of

- Rock properties such as permeability and presence of discontinuities with marginal stability,
- Soil properties such as strength, seepage resistance, and susceptibility to liquefaction,
- Weak zones,
- Stress history, and
- Groundwater conditions.

Chapter 3 introduced three principal modes of embankment dam failure—uncontrolled seepage, overtopping, and slope instability. This chapter describes effective monitoring measures to reduce the risk of the loss of reservoir control and to answer the question, "Is this dam behaving as expected?"

10.2 PERFORMANCE

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Performance depends on an embankment dam's ability to respond to physical processes experienced during its service life.

10.2.1 Settlement

Settlement results in general or local decreases in the elevation of the crest and slopes of a dam. The decreases in dam surface elevations resulting from settlement can vary gradually across the dam or occur as distinct differential movement, which can result in surface cracking. Settlement of the general embankment results from a reduction in the void volume (consolidation) within the soil or rockfill of the embankment or foundation. An undesirable consequence of general settlement of the embankment is that freeboard decreases, increasing the risk of overtopping and possible breach. Settlement can also occur owing to exterior loading, such as the weight of an appurtenant structure on a compressible soil foundation.

Transverse cracking can occur where there are abrupt changes in abutment contact geometry, such as at abrupt changes in the height of the dam over near-vertical faces in the foundation or abutment rock or over concrete structures such as outlet works conduits. Abrupt slope changes produce a

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sudden change in stress that can cause differential settlement resulting in cracking and damage to cores and filters and the subsequent loss of resistance to internal erosion. Differential settlement along conduits through embankments can result in joint separation or cracks in the conduits. Settlement, longitudinal cracking, and slope displacement can also be a sign of slope movement or earthquake-induced deformations. Localized settlement such as sinkholes or depressions along retaining walls can be signs of internal erosion. Dam contacts with foundation soil, bedrock, and concrete structures are particularly susceptible to seepage and potentially to internal erosion, as are contacts between the embankment and concrete structures.

10.2.2 Slope Stability

Embankment dam materials consist of discrete soil and rock particles rather than a continuous solid such as concrete. As such, these materials are dependent on friction and cohesion (shear strength properties) for stability. They must be contained by abutments and have adequately proportioned slopes to remain stable. Embankment slope stability depends on the slope angle, the strength of the embankment and foundation materials, and the phreatic surface through the embankment. A defect in one or more of those factors may trigger slope failure resulting in rotation or lateral translation of the slope that could cause a loss of freeboard or cause seepage failure through resulting cracks in the embankment. Slope instability also can occur if stresses from ground shaking during an earthquake exceed the strength of the soil.

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Instability of the upstream slope can be caused by rapid drawdown of the reservoir. If the reservoir is drawn down faster than the seepage within the embankment can drain, the slope experiences rapid, undrained loading. If the undrained strengths of the soil materials are not sufficient to resist the driving forces during undrained loading, slope failure will result. Upstream filters and drains can reduce the potential for upstream slope failure, and they have become common in current practice but are seldom found at older dams.

Instability of the downstream slope may initiate during intense precipitation, causing unusually high and sustained reservoir levels. As the reservoir level rises, pore pressure in the downstream slope may rise, reducing effective stress, shear strength, and stability. Slumping may result, as shown in Fig. 10-1.

Another potential initiator is a blocked toe drainage system.

10.2.3 Freeboard

Freeboard is the difference between the embankment crest elevation and the elevation of the reservoir water surface, and thus maintenance of

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Fig. 10-1. Scarp in downstream slope indicative of instability

adequate freeboard is essential to embankment stability. Embankment materials are susceptible to erosion from flowing water. As the depth and duration of water over the crest increases, the probability of loss of freeboard increases. The crest elevation of the core is an important design consideration because once the core is overtopped, breaching of the dam owing to progressive internal erosion and erosion of the embankment is likely with loss of reservoir control. Failure by overtopping is the second most common cause of embankment dam failures, uncontrolled seepage being the most common. Prudent designs provide for adequate freeboard for all design conditions, considering settlement, reservoir level rise during floods, predicted wave amplitudes, and wave run-up on the upstream slope of the dam.

10.2.4 Seepage and Leakage

Seepage is the movement of water through the voids of soil and rock of an embankment, abutment, and foundation. Water seeps through, around, and under embankment dams, controlled by the permeability of the embankment, abutments, and foundations. The volume and location of seepage depends on the seepage gradient, design, and construction. Embankment dams are often zoned, using materials of varying permeability in different parts of the cross section to keep the phreatic surface as low as possible in the downstream slope.

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All embankment dams exhibit some seepage at or under the toe. The potential for higher rates of seepage exists along the contacts of embankment materials with rock foundations, concrete structures, or pipes. Leakage is water that moves through preexisting openings such as an open joint in the foundation, a crack in the concrete facing of a concrete-face rockfill dam, a deteriorated grout curtain, a tear or bad seam in an impermeable liner, or through a crack in a slurry cutoff wall.

Seepage and leakage cause problems if flow velocity rises to the point of initiating internal erosion by carrying away soil grains at the toe or at the contact between the embankment and foundations or structures. This concern is addressed by providing properly designed filters and a drain at all potential seepage flow locations to reduce the probability that uncontrolled seepage or leakage will occur.

Leakage that does not threaten the safety of the dam may still be unacceptable because of the economic loss of water.

10.2.5 Stress

Changes in stress can be caused by differential settlement between core and shell material in a zoned dam. If the core is very compressible and consolidates more than the shell, the core can "hang up" on the shell, reducing the overburden pressure and, consequently, the lateral pressure, which is lower within the core. Steep abutments may exacerbate differential settlement. The sharp change in stress at an abrupt change in slope can crack the core and initiate internal erosion.

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Stresses imposed by the embankment overburden on buried conduits and structures or retaining walls may be a concern. If stresses exceed the conduit strength, cracking could occur and provide a source of water under pressure to initiate erosion of embankment material into a conduit. Conversely, a leaky conduit through an embankment may be a source of water under pressure that initiates internal erosion along a conduit.

10.2.6 Earthquake Response

As the seismic waves from an earthquake pass through the foundation and abutments of an embankment, the embankment shakes in response. Its response is dynamic oscillation and the initiation of shear stresses and deformation in the embankment and foundation materials. The shear stresses may also reduce strength in the embankment and foundation materials and lead to post-earthquake instability. A dramatic example of such strength loss was the liquefaction of cohesionless soils that resulted in failure of the upstream slope of the Lower San Fernando Dam during the 1971 San Fernando, California, earthquake (Fig. 10-2).

Fig. 10-2. Lower San Fernando post-earthquake
Source: Courtesy of EERI, reproduced with permission.

10.2.7 Construction

An understanding of how an embankment was constructed is essential to judging performance.

The embankment and its foundation require the greatest attention to detail during construction. Other features such as the provisions for seepage control, filters, and drainage vary widely with the particular design; however, performance depends on how well the foundation is prepared, how well the embankment is placed and compacted, and the care taken to provide for seepage control, filters, and drainage.

Rock foundations require preparation to receive fill. Removal of weathered and loose rock is essential. Seepage past a cofferdam or springs is troublesome because it makes compaction difficult owing to difficulty with moisture control in the fill. Care must be exercised to keep flowing water away from active fill zones, especially the core contact area. Special treatment such as slush grouting and dental concrete work may be required for fractures and weak zones to inhibit seepage and to avoid stress concentration. Proper shaping of the foundation and abutments is essential because abrupt changes in the rock surface may make proper compaction difficult and may concentrate stress that could lead to cracking of the overlying fill.

Soil foundations also require preparation to receive fill. Weak or compressible soils must be removed. Pockets of coarse soils that might concentrate seepage along the contact with the overlying fill must be removed or cut off. Control of groundwater is important, as noted previously, because

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