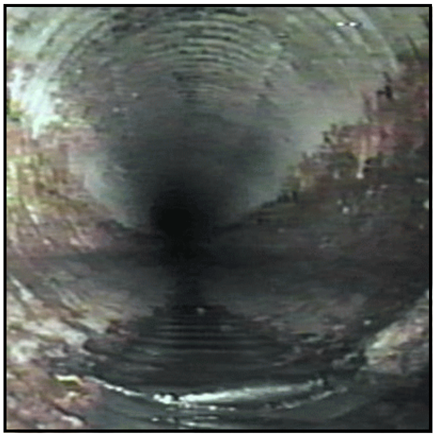

Figure 110.—CMP corrosion within an outlet works conduit.

Figure 111.—CMP corrosion on the invert of an outlet works conduit.

Figure 112.—CMP corrosion within an outlet works conduit caused by a leaking pipe joint.

Figure 113.—An outlet works conduit that has experienced corrosion and failure.

Figure 114.—Spalled concrete and exposed reinforcement in an outlet works conduit.

and have differing products of corrosion. Soil-related bacterial corrosion produces oxidation scale, which is active in organic, poorly drained soils of nearly neutral pH. This scale is usually black, but upon being exposed to aerated conditions in conduits, becomes rust colored. Water-related bacterial corrosion produces nodular oxidation, which exists on pipe surfaces associated with a water source of nutrients. Local perforations on the pipe invert characterize nodular oxidation. Nodular oxidation results from sulfate-reducing bacteria activity.

Polyethlene plastic pipe is not subject to galvanic action and will not corrode. Naturally occurring water and soil conditions will not affect the pipe.

8.2 Poor design and construction

Good design and construction practice can extend the service life of a conduit. However, poor design and construction practice can greatly shorten it. Much of the following discussion was adapted from USACE's *Evaluation and Repair of Concrete Structures* (1995b, pp. 3-1 to 3-14) for reinforced cast-in-place concrete. Some of the most common areas where poor design and construction practice can affect conduits are:

- *Poor design practice.*—Design errors may be divided into two general types: those resulting from inadequate structural design and those resulting from lack of attention to relatively minor design details. Common design errors include:

  1. *Inadequate structural design.*—Inadequate structural design exposes the concrete to greater stress than it is capable of carrying, or greater strain than its strain capacity. This may result in excessively high compressive stresses and appear as spalling. Similarly, high torsion or shear stresses may also result in spalling or cracking. Also, high tensile stresses will result in cracking. To prevent this from occurring, the designer must complete a thorough and careful review of all design calculations. Any renovation that makes use of existing conduit must be carefully reviewed.

  2. *Poor design details.*—While a conduit may be adequately designed to meet loadings and other overall requirements, poor detailing may result in localized concentrations of high stresses in otherwise satisfactory concrete. These high stresses may result in cracking that allows water to access the interior of the concrete. In general, poor detailing does not lead directly to concrete failure; rather, it contributes to the action of one of the other causes of concrete deterioration described in this chapter. A frequent cause of cracking in conduits is improperly spaced joints. Thermal cracking can also result in conduits where joint spacings are too long or are not provided in the conduit to accommodate for changes of length. In general, all of these problems can be prevented by a thorough and careful

review of plans and specifications for the project. In the case of existing conduits, problems resulting from poor detailing should be handled by correcting the detailing and not by simply responding to the symptoms.

- *Poor construction practice.*—Not following specified procedures and techniques may result in construction errors. While individually these errors may not lead directly to failure, when grouped together they could lead to the development of defects that could adversely affect a conduit's integrity. Construction errors can occur during new construction, renovation, and repairs. In concrete, cracking and spalling can be a symptom of poor construction practice. Common construction errors include:

    1. *Improperly located reinforcement.*—Reinforcement that is improperly located or is not adequately secured in the proper location may lead to two general types of problems. First, the reinforcement may not function structurally as intended, resulting in structural cracking or failure. The second type of problem stemming from improperly located or tied reinforcement is one of durability. This involves reinforcement that is improperly located near the surface of the concrete. As the concrete cover over the reinforcement is reduced by wear, it is much easier for corrosion to begin.

    2. *Improper alignment of formwork.*—Improper alignment of the formwork leads to discontinuities on the surface of the concrete. This occurrence is critical in areas that are subjected to high velocity flow of water, such as where cavitation-erosion may be induced.

    3. *Adding water to concrete.*—Water is usually added to concrete at the delivery truck to increase slump and decrease emplacement effort. This practice generally leads to concrete with lowered strength and reduced durability. As the water/cement ratio of the concrete increases, the strength and durability decreases.

    4. *Improper consolidation.*—Improper consolidation of concrete may result in a variety of defects, the most common being surface air voids (also known as bugholes), honeycombing, and cold joints. Surface air voids are formed when small pockets of air or water are trapped against the forms. A change in the mixture to make it less "sticky" or the use of small vibrators worked near the form has been used to help eliminate surface air voids. Honeycombing can be reduced by inserting the vibrator more frequently, inserting the vibrator as closely as possible to the form face without touching the form, and slower withdrawal of the vibrator. Obviously, any or all of these defects make it much easier for any damage-causing mechanism to initiate deterioration of the concrete. Frequently, a fear of "overconsolidation" is used to justify a lack of effort in consolidating

concrete. Overconsolidation is usually defined as a situation in which the consolidation effort causes all of the coarse aggregate to settle to the bottom while the paste rises to the surface. If this situation occurs, it is reasonable to conclude that there is a problem of a poorly proportioned concrete rather than too much consolidation.

5. *Movement of formwork*.—Movement of formwork during the period while the concrete is going from a fluid to a rigid material may induce cracking and separation within the concrete. Cracks open to the surface allow access of water to the interior of the concrete. An internal void may give rise to corrosion problems if the void becomes saturated.

6. *Settling of the subgrade*.—Poor foundation support can impart tensile stresses, resulting in cracking of the concrete conduit. This often occurs during the period after the concrete begins to become rigid, but before it gains enough strength to support its own weight; cracking may also occur.

7. *Settling of the concrete*.—During the period between placing and initial setting of the concrete, the heavier components of the concrete settle under the influence of gravity. This situation may be aggravated by the use of highly fluid concretes. If any restraint tends to prevent this settling, cracking or separations may result. These cracks or separations may also develop problems of corrosion, if saturated.

8. *Vibration of freshly placed concrete*.— Most construction sites are subjected to vibration from various sources, such as blasting and from the operation of construction equipment. Freshly placed concrete is vulnerable to weakening of its properties if subjected to forces that disrupt the concrete matrix during setting.

9. *Premature removal of shores or reshores*.—If shores or reshores are removed too soon, the concrete affected may become overstressed and cracked. In extreme cases, there may be major failures.

10. *Improper curing*.—Curing is probably the most abused aspect of the concrete construction process. Unless concrete is given adequate time to cure at a proper humidity and temperature, it will not develop the characteristics that are expected and that are necessary to provide durability. Symptoms of improperly cured concrete can include various types of cracking and surface disintegration. In extreme cases, where poor curing leads to failure to achieve anticipated concrete strengths, structural cracking may occur.

Figure 115 shows an example of poor construction practice (improper consolidation of concrete). For an example of how poor design and construction practice can lead to the failure of a concrete conduit, see the Olufson Dam case history in appendix B.

Poor design and construction practices particular to reinforced cast-in-place conduits were discussed in the previous paragraphs. However, poor design and construction practices affect all types of conduits. The following paragraphs briefly discuss effects of poor design and construction practices affecting other types of conduits, such as precast concrete, or CMP. The appearance of these defects can lead to preferential seepage paths and the development of potential failure modes for conduits. Some of these include:

- *Deformation.*—Deformation occurs when load or force changes the shape of the conduit. Deformation is typically caused by the application of excessive external load (e.g., improper selection of design loadings), loads from heavy construction equipment, or seismic activity. Figure 116 shows an example of where heavy construction equipment likely caused deformation of a CMP conduit. CMP is flexible and is designed to deform some as it transfers load into the surrounding backfill. The surrounding backfill provides stiffness and load carrying capacity. Improperly designed backfill or inadequately compacted backfill under the CMP haunches does not provide the needed lateral stiffness to the CMP. This can result in excessive deformations and structural failure or collapse of the CMP (Kula, Zamensky, and King, 2000, p. 3).

- *Differential settlement.*—Differential settlement occurs when the embankment materials next to the conduit are improperly or inadequately compacted or when the conduit is placed on a foundation of varying density. The conduit location and the resultant embankment loading can result in differential

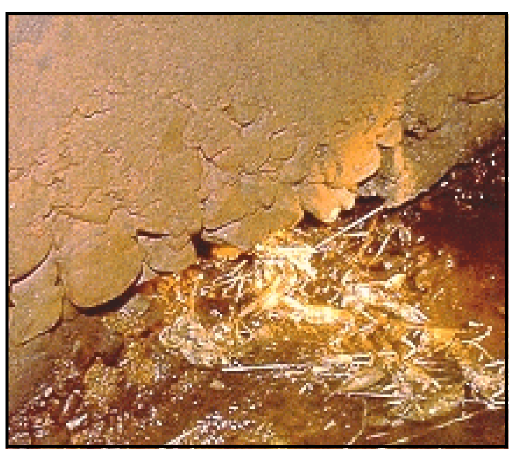

Figure 115.—A rock pocket at the bottom of a conduit side wall.

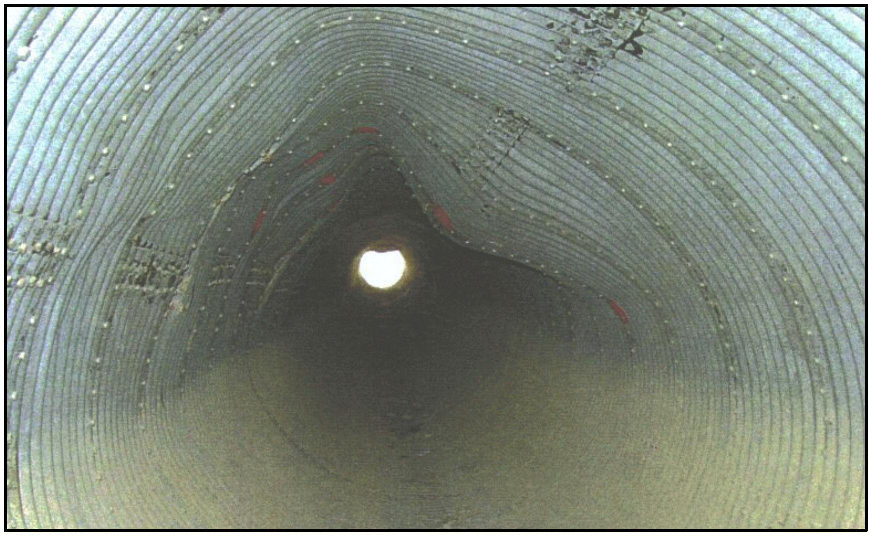

Figure 116.—Deformed CMP conduit. Deformation likely occurred during original construction, possibly from construction equipment traveling over the conduit with inadequate earthfill cover.

settlement problems. Differential settlement affects the structural integrity of the conduit by causing distress to the conduit in the form of misalignment (vertical or horizontal), shape distortion, joint offsets/separations, cracks, or spalls. Differential settlement occurs when one section of conduit settles more than the rest. This typically occurs at joints in the conduit (figure 117). The settling process can open these joints and provide a path for water either into or out of the conduit. Examples of differential settlement and the resulting damage are:

1. Spreading of the embankment dam, causing separations in the conduit joints. As compressible soils under the embankment dam consolidate, some spreading is inevitable. As soils spread laterally, sections of the conduit may separate, leaving joint openings through which water can then move.

2. Differential settlement due to foundation discontinuity, causing offsetting of joints.

3. Differential settlement of the embankment dam, causing loads greater than the conduit can accommodate, resulting in cracking and excessive deformation of the conduit.

- *Misalignment*.—Misalignment occurs when poor construction practice allows for alignment deviation or from improper or inadequate compaction of

Figure 117.—This conduit was severely damaged after the foundation settled more than 2 feet.

embankment materials next to the conduit. Misalignment can also be caused by compression of the foundation allowing rotation at the conduit sections.

- *Separation of joints*.—Separation of pipe joints occurs when the conduit experiences deformation, differential settlement, misalignment, or shear strains as a result of a weak foundation. Joint separation can result in a loss of conduit watertightness by allowing seepage to exit through the joint. The lack of joint gaskets being installed, or installation of the incorrect type of gasket, or the use of incorrect joint-connecting bands also affects watertightness. Seepage can lead to internal erosion or backward erosion piping of surrounding embankment materials and loss of support around the conduit.

Chapter 9

Inspection and Assessment of Conduit-Related Problems

Inspection of embankment dams, including their conduits and foundations, will detect many developing problems before they can affect the safety and reliable operation of the facility. Inspection should also assess the adequacy and quality of maintenance and operation procedures. Periodic inspection may reveal trends that indicate more serious problems are developing. The conduit is typically inspected as part of an overall inspection of the embankment dam and its appurtenant features. Typically, structural defects and deterioration develop progressively over time. A trained and experienced inspector can identify defects and potential problems before existing conditions in the embankment dam and conduit become serious. However, some situations can suddenly arise and cause serious damage in a short period of time. Examples of these situations are operations at full discharge capacity, seismic activity, or other special conditions. The need for special inspections should be evaluated after occurrence of any of these situations. The main focus of this chapter is on the inspection of conduits. However, reference is made to certain aspects of embankment dam inspection, since they have relevance to problems associated with conduits.

In 1986, 14 federal and State agencies developed a comprehensive training program (Training Aids for Dam Safety [TADS]) designed to train individuals involved with, or having responsibility for the safety of dams. The TADS program consists of modules that can be tailored to meet individual or organizational needs. The TADS program is widely used and recognized by the dam safety community. Further details on the TADS program are available from the Bureau of Reclamation. Additionally, training courses on dam safety inspection are available from various sources. Interested parties should consult the ASDSO website for a listing of available training opportunities. For information concerning inspection of penstocks see the American Society of Civil Engineers (ASCE) *Guidelines for Evaluating Aging Penstocks* (1995).

9.1 Types of inspections

Inspection intervals may vary, depending on the overall conditions determined from previous inspections and the existence of any dam safety concerns. Periodic inspections can vary in scope and purpose and by the organization or personnel (damtender, agency/district level, etc.) performing the inspection.

Dam safety organizations and embankment dam owners may employ a variety of inspections during the life of a conduit (figure 118). These inspections may include the following types (Reclamation, 1988, p. I-2):

- *Initial or formal*.—Initial or formal inspections include an in-depth review of all pertinent data available for the conduit to be inspected. Design and construction data are evaluated relative to the current state-of-the-art to identify potential dam safety problems or areas requiring particular attention. A thorough onsite inspection of all features is conducted, and an attempt is made to operate all mechanical equipment through their full operating range, if possible. Many State and federal agencies require formal inspections on a set frequency (e.g., every 6 years).

  The first time the reservoir behind an embankment dam is filled is critical to its integrity. The embankment dam will experience the hydraulic loading for the first time and will begin to adjust to this loading. During first filling, the wetting front begins to penetrate the embankment dam. History has shown that a much higher frequency of incidents occur at this time. Also, the conduit through the embankment dam will be tested for the first time.

  Good practice dictates that the embankment dam be monitored by frequent inspections during this crucial period. Round-the-clock surveillance is not uncommon for high hazard facilities. Special lighting provisions may be installed to permit adequate nighttime visibility.

  There may be several "hold" periods during initial fill to allow stresses in the embankment dam to partially stabilize and instrumentation to level off prior to the continuation of filling. The rate of reservoir rise may be limited to allow for the wetting front to slowly penetrate the embankment dam. A rate of reservoir rise in the range of 0.5 to 2 feet per day is a common. Limiting the rate of rise for small reservoirs that do not usually have large outlet systems may not be feasible. If the outlet conduit has a small capacity and large inflows follow a high precipitation event, no method for controlling the rate of rise exists.

  The first fill monitoring may be staggered to accommodate the amount of water available to fill the reservoir. For some embankment dams, many years may be required to reach their fully operational reservoir level. Often, an embankment

Figure 118.—Visual inspection for seepage on the downstream face of an embankment dam.

dam reaching a new record reservoir elevation during a flood is also considered to be in first fill status, necessitating heightened inspections. This is because portions of the embankment dam may have never received hydraulic loading until the flood stage was entered.

Following a major modification to an embankment dam, the dam may also be placed in a first fill monitoring situation, if the modifications were extensive. For example, if an existing conduit were completely removed and replaced, this would likely require first fill monitoring status. Complete removal and replacement of the conduit would require a section of the embankment to be excavated and replaced. For guidance on the removal and replacement of conduits, see chapter 13.

- *Periodic or intermediate.*—Periodic or intermediate inspections are conducted between formal inspections. An in depth review is made of all pertinent data available on the conduit to be inspected. However, the data review focuses on the current status of the conduit, and the data are not evaluated relative to current state-of-the-art criteria. A thorough onsite inspection of all features is conducted. All mechanical equipment may not be tested during any one inspection. Some equipment may be operated at another time or during the next inspection.

- *Routine.*—Routine inspections are typically conducted by field or operating personnel. The primary focus is on the current condition of the conduit.

Available data may not be reviewed and evaluated prior to the inspection, depending on the inspector's familiarity with the conduit. Inspections may be scheduled regularly or performed in conjunction with other routine tasks.

- *Special.*—A special inspection is conducted when a unique opportunity exists for inspection. For example, if low water conditions exist in a reservoir exposing a normally inundated structure, a special inspection may be arranged.

- *Emergency.*—An emergency inspection is performed when an immediate dam safety concern is present or in the event of an unusual or potentially adverse condition (i.e., immediately following an earthquake).

The actual terms and meanings used to define the types of inspection may vary between dam safety organizations and embankment dam owners.

The operating personnel responsible for daily operation and maintenance of the facility should also participate as inspection team members. Where applicable, water user organization representatives should also participate in the inspection. Additionally, the applicable State water resource agency may need to be advised for their possible participation in the inspection.

To the extent possible, inspections should be scheduled in different seasons. This will enable the structure or facility to be examined under differing reservoir levels, water delivery, and site conditions.

Before beginning inspection of a facility, the inspection team should discuss the order in which features are to be examined, to accommodate operations, as well as to ensure that time for the inspection team is appropriately allotted. In addition, the team should conduct a job hazard analysis (JHA) prior to the inspection, whereby procedures and equipment necessary to minimize or avoid potential safety and health hazards are discussed. Of primary importance is the need for detailed clearance (particularly if there are confined spaces), and lockout or "tag-out" procedures when accessing areas affected by equipment or gate/valve operations. For guidance on preparing a JHA, see section 9.4.

9.2 Factors influencing scheduling of inspections

Scheduling of periodic conduit inspections may be influenced by (Reclamation, 1988, p. III-7):

- *Sufficient notice* .—Embankment dam owners and operators may need sufficient time to make necessary arrangements, such as preinspections associated with lockout/tagout and confined space entry, or special equipment or approval for unwatering conduits, terminal structures, or pools. This process could require several weeks or months, depending on the facility.

- *Scheduling access*.—Access for the inspection should be scheduled when most or all of the major components of the conduit can be examined. Some features, such as intake structures and upstream conduits, are usually submerged and not accessible. Downstream conduits and terminal structures may or may not be able to be unwatered and made accessible for inspection. The embankment dam owner or operator may be requested to provide notification when reservoir conditions permit or when the reservoir can be drawn down to allow the inspection to be performed.

  If the feature to be inspected is normally inundated and inaccessible, certain factors (Reclamation, 1985, p. 4) should be considered in determining the extent and frequency for inspection, such as:

  1. Results of previous "hands on" inspection or evidence from the inspection of the normally accessible portions of the feature. Inspection of the normally accessible portion of a feature may provide information on the probable condition of the inaccessible portion. This information may include:

     a. *Condition of the feature*.—Cracking, joint separation, or significant deterioration.

     b. *Condition of the embankment dam and foundation*.—Excessive postconstruction settlement or alignment distortion of the downstream conduit; excessive embankment dam settlement or the existence of sinkholes on the upstream face along the alignment of the conduit.

     c. *Observed seepage*.—Seepage or wet areas observed at the downstream toe of the embankment dam.

     d. *Flow conditions*.—Changes in the discharge capacity of the conduit.

     e. *Damage and deterioration*.—Damage or deterioration of gates/valves and metalwork.

     f. *Water quality*.—Water quality known to be detrimental to concrete, conduit linings, or waterstops. Excessive amounts of sand or other material transported by the discharge.

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2. Operational history and performance of the feature, since its previous inspection.

3. Relative costs for providing access for inspection of the feature, including costs associated with lost water and power revenues.

4. Age of the feature.

5. Design and construction considerations, such as:

   a. *Changes in standards or guidelines*.—Design criteria, construction techniques, and/or quality of material at the time of construction fail to meet current standards or guidelines.

   b. *Foundation conditions*.—The conduit was constructed on foundation of varying compressibility, where there is a potential for differential settlement. This may result in cracking of the conduit or excessive opening of joints. Differential settlement is also possible between the conduit and gate chamber due to different pressures being exerted on them.

   c. *Foundation faults*.—The conduit crosses a foundation fault where there is the potential for movement or disruption of the conduit.

   d. *Unfavorable stresses*.—The conduit is located where conditions are conducive to arching, resulting in unfavorable stresses in the embankment dam and/or conduit. These stresses could be conducive to hydraulic fracture of the embankment dam or stress concentrations on the conduit.

   e. *Conduit within the core of the embankment dam*.—A significant portion of the conduit upstream from the gate chamber lies within the core of the embankment dam, so that any cracks in the conduit create the potential for water to be injected under pressure into the core. If erodible material is used to construct the impervious core, the potential for adverse consequences is increased.

   f. *Inadequate conduit joints*.—Inadequately sealed or encased conduit joints, which could lead to the escape of water under pressure, which creates the potential for water to be injected under pressure into the surrounding embankment.

   g. *Filters*.—Lack of adequate filters and drainage material around the conduit downstream from the im pervious zone of the embankment dam to safely convey seepage or leakage along the conduit to an exit point.

6. Critical function of the feature.

7. Any existing site conditions that may compromise the safety of the feature.

The appropriate frequency and extent to which the normally inundated features are examined will vary based on available information. The review personnel and decisionmakers will need to determine the appropriate frequency and extent based on the above factors. As an example, Reclamation has identified about 6 years as an appropriate frequency for a "hands-on or equivalent inspection frequency" for inaccessible features, such as conduit.

- *Operation*.—Certain problems may not normally appear when the feature is dry that appear when the feature is being operated. Also, when a feature is operating during a period of higher than normal releases, additional information may be gathered that may not have been available during normal operations.

The opportunity to optimize both access and operation during a single inspection typically is not possible. Inspection objectives may have to alternate from one inspection to the next. This may necessitate the need for scheduling "special" inspections during unusual conditions, in addition to regular inspections to provide a comprehensive understanding of the conduit safety. Special inspections may be required after floods, seismic activity, or other unusual or extreme events.

9.3 Periodic inspections by selected organizations

The frequency of periodic inspections varies among organization and embankment dam owners. Emergency situations may require much more frequent inspections, such as daily or hourly. Situations can arise suddenly that cause serious damage in a short period of time. Examples of these problems are operations at full discharge capacity, seismic activity, or other special conditions. The need for special inspections should be evaluated after occurrence of any of these situations.

A sampling of periodic inspections as required by selected organizations:

- *Reclamation*.—Reclamation employs the following process (Reclamation, 1998c, pp. 2-11) to monitor its significant and high hazard dams and attempt to detect any potential dam safety deficiencies:

  1. *Annually*.—Annual inspections are performed by inspectors who are generalist (as opposed to specialist) engineers very familiar with the

embankment dam and its operations, and can readily distinguish changes from year to year. All inspectors attend regular training in dam safety inspections.

2. *Periodic.*—On a 6-year cycle (alternating with the comprehensive facility review (CFR), each embankment dam is examined by a team originating in a Reclamation Regional Office, including the regional examination specialist. This examination is referred to as a periodic facility review (PFR) and includes a rather thorough review and reporting of all past dam safety and operation and maintenance (O&M) recommendations.

3. *Comprehensive.*—On a 6-year cycle (alternating with the PFR; the CFR and PFR are offset by 3 years), each embankment dam is examined/evaluated by a team of specialists from Reclamation's Technical Service Center that includes an examination specialist, mechanical engineer, and a senior dam engineer (either geotechnical or civil/structural specialist). This examination is referred to as a CFR and includes not only the PFR activities, but also technical evaluation of all design, construction, and analysis of the dam.

- *Federal Energy Regulatory Commission (FERC).*—Significant and high hazard embankment dams are inspected annually by FERC engineers and every 5 years for a Part 12D inspection by an independent consultant (FERC, 2005, pp. 14-43 to 14-45). FERC engineers inspect low hazard embankment dams at least every 3 years. An independent consultant also inspects some low hazard embankment dams every 5 years, if the dam is 30 or more feet high or the reservoir is 2,000 acre-feet or larger and the licensee or exemptee has not requested and received approval for an exemption from the Part 12D independent consultant inspection.

- *NRCS.*—The NRCS requires the sponsor/owner to be responsible for making inspections after they are turned over to the sponsors/owners (NRCS, 2003, pp. 1-2). Personnel trained in conducting the inspections perform special, annual, and formal (once every 5 years) inspections. If requested by the sponsor/owner, NRCS may participate in inspections; provide training to ensure that the sponsor/owner understands inspection techniques and the importance of completing corrective action; and provide technical assistance to address specific O&M needs. If an inspection reveals an imminent threat to life or property, the sponsor/owner shall immediately notify all emergency management authorities.

- *USACE.*—The USACE performs periodic, intermediate, and informal inspections on the basis of project size, importance, or potential hazard (USACE, 2004b, pp. 6-3 and 6-4):

1. *Initial periodic inspection*.—The first periodic inspection and evaluation of a new embankment dam is carried out immediately after topping out of the dam prior to impoundment of the pool.

2. *Second periodic inspection*.—The second periodic inspection for new embankment dams is performed no later than 1 year after impoundment is initiated.

3. *Subsequent periodic inspection*.—Subsequent periodic inspections are performed at 1-year intervals for the next 2 years. The next two inspections are performed at 2-year intervals and then extended to a maximum interval of 5 years. More frequent inspection intervals are scheduled, if conditions warrant.

4. *Intermediate inspection*.—For projects on a 5-year inspection cycle, an intermediate inspection of all or some of the features may be scheduled, if warranted. Selection is based on consequences of failure, age, degree of routine observation, a natural event (i.e., earthquake), performance record and history of remedial measures. Intermediate inspections are also made of any portion of a project exposed during unwatering that could not be accomplished during scheduled periodic inspection.

5. *Informal inspection*.—Appropriate employees at the project perform frequent informal inspections. The purpose of informal inspection is to identify and report abnormal conditions and evidence of distress.

9.4 Preparing for an inspection

The success of a conduit inspection depends upon good planning and preparation. Any inspection should consider:

- *Selection of the inspection team*.—The members of the inspection team will vary, depending on the needs and resources of the organization or embankment dam owner, type of the inspection, results of the data review, and any special requirements.

- *Review of project data*.—The amount of available data may vary greatly. The extent of project data review and evaluation depends on the type of inspection to be conducted.

- *Preparation of an inspection plan*.—A detailed inspection plan should be prepared to identify all features to be inspected, problem areas, and areas of potential problems. The inspection plan will also identify special logistics, access, or equipment requirements. An inspection checklist is typically prepared as part of an inspection plan. The checklist is used to identify specific inspection objectives and is also useful in developing the final inspection report.

Prior to any inspection, inspection personnel should review all pertinent and available design and as-built drawings, design criteria, geology, operational history, previous inspection and maintenance reports, and safety information. Typical documents that should be reviewed prior to an inspection are:

1. Technical record of design and construction
2. Design summary
3. Laboratory reports
4. Stress model reports
5. Geology reports
6. Site seismicity reports
7. Plans and specifications
8. As-built drawings
9. Final construction report
10. Construction progress reports
11. Travel reports
12. Correspondence files
13. Operation and maintenance records
14. Examination reports
15. Designers' operating criteria
16. Standing operating procedures
17. Reservoir operation records
18. Data books

After reviewing available documentation, a list of important and significant concerns should be prepared for use during the inspection.

A log should be established at the embankment dam that records the date, type of inspection performed, name of the inspectors, and the results. All inspections should be documented in the form of an inspection report with photographs, reservoir water levels, discharges from the conduit, and relevant instrumentation data, such as from nearby piezometers, and forwarded to the engineering staff or personnel responsible for technical review and evaluation. An ongoing visual inspection checklist should be developed to provide guidance and consistency in looking for signs of distress. If information is found that suggests the embankment dam, foundation, or conduit was not designed to current standards, specific items should be added to the inspection checklist to address specific deficiencies. All inspection reports should be maintained in a secure location for future reference. Good recordkeeping of inspection reports, technical reports, etc. will ensure that development of any adverse trends are identified and proper actions are taken to correct any problems.

For further guidance on inspection programs and checklists for inspection, see Reclamation's *Review of Operation and Maintenance Program Field Examination Guidelines* (1991).

A job hazard analysis should be prepared for embankment dam and conduit inspections, following approved safety guidelines. The basic elements of a JHA are outlined in Reclamation's *Operation and Maintenance Safety Standards* (1989b, pp. 65-66). Note: Other agencies and organizations may utilize their own set of standards for safety guidance. All personnel involved in the inspection should receive and review a copy of the JHA. As a minimum, a JHA should include:

1. Names of all participants and the agency, organization, or group they are representing.

2. Operations to be performed.

3. Special considerations, such as monitoring of atmospheric conditions prior to entry into confined spaces. Detection of adverse atmospheric conditions at any location requires that the confined space be mechanically ventilated or the examination be abandoned. Entry should only proceed upon confirmation of acceptable atmospheric conditions. All entrants into confined spaces are to have lockout/tagout and confined entry space

training and are required to wear an approved body harness to facilitate extraction of personnel should they become incapacitated.

4. Potential hazards associated with the confined spaces defined previously are engulfment by water; oxygen deficiency; walking/working surfaces; electrical hazards; lighting; molds, mildews, and spores capable of irritating the respiratory system; and other hazards (e.g., rodents, snakes, spiders and/or insects, or crayfish).

5. Mitigating measures.

6. Hazards and solutions.

7. Safety-related equipment, such as hard hats, safety boots, proper clothing, gloves, communication equipment, oxygen/gas detection meter, mechanical ventilation equipment, flashlights, first aid kit, rubber boots, safety lines and harnesses, extraction/hoist equipment, and eye protection.

8. Safety standards requirements.

9. Emergency services.

10. Signatures of the inspection team members indicating that they have reviewed the JHA and have been instructed in and understand the requirements and hazards associated with the entry into confined spaces for the purpose of conducting this examination.

Upon completion of the inspection, all participants should discuss the inspection to identify what could be improved in the JHA for the next time. Any findings or recommendations should be documented for inclusion in future JHAs. Any mishaps or near misses should be identified during the postinspection discussion.

A dive plan or dive hazard assessment should be prepared prior to any dive inspection. Most commercial diving companies have their own dive plans. Guidance on dive safety can be found in Occupational Safety and Health Administration (OSHA) Standards 29 CFR, Subpart T, *Commercial Diving Operations—General Industry* (2004), and the Association of Diving Contractors International's (ADCI), *Consensus Standards for Commercial Diving and Underwater Operations* (2004). Various government agencies have guidance on dive safety, such as Reclamation's Safety and Health Standards Section 29—*Marine and Diving Operations* (2002).

9.5 Performing the inspection.

Methods used for the inspection of the various features of a conduit mainly depend upon accessibility. Factors influencing accessibility include:

- *Inundation*.—Reservoir operations and water levels may make some features unavailable for normal inspection and require specialized inspection services (e.g., dive team, remotely operated vehicles).

- *Confined space*.—Certain features may require OSHA confined space permitting for man-entry, lockout/tagout procedures, and preparation of a JHA. An alternative to man-entry is the use of specialized inspection services (i.e., closed circuit television).

- *Size constraints*.—Limitations in size may prevent man-entry and require specialized inspection services (i.e., closed circuit television).

9.5.1 Inspection of entrance structures

In most cases, due to the entrance structure's location in the reservoir, it is either partially or fully inundated. If the entrance structure is partially inundated, inspection of the structure above the water level will be fairly straightforward. However, inspection of the portion of the structure below the water level, such as the intake or inlet, trashracks, fish screens, ice prevention systems, gates/valves, stoplogs, and bulkheads, will require specialized inspection services.

If the intake structure is a tower, it may have a wet well or some other access to the control mechanism. Closure of a guard gate or bulkhead may provide the ability for inspection of the interior of the tower. Problems common to entrance structures include deterioration, damage, and misalignment.

Descriptions of more specific problems related to trashracks, fish screens, ice prevention systems, gates/valves, stoplogs, bulkeads, and bridges are beyond the scope of this document. The TADS program as discussed earlier in this chapter should be referred to for more detailed information concerning the inspection of entrance structures.

9.5.2 Inspection of conduits

Generally, conduits with diameters 36 inches or larger can be inspected by man-entry, if proper OSHA precautions are taken. Conduits with diameters smaller than 36 inches are generally inaccessible for man-entry and require specialized inspection services.

9.5.2.1 Exterior inspection

Exterior inspection of the areas above and surrounding the conduit can provide many clues concerning the condition of the conduit. Items to look for include:

- Look for signs of infiltration of soil into the conduit. Depressions, sinkholes (figures 119 and 120), or cavities that exit onto the surface of the embankment dam along the centerline conduit alignment are usually an indication that internal erosion or backward erosion piping is occurring. These features often appear as holes that line up with one another. Such features should be marked with reference points and monitored to determine whether they are expanding with time. Sinkholes should be probed to determine the extent of the void, which may be dome shaped and enlarge with depth. The seepage and flow conditions on the downstream slope and through the conduit, should be examined for evidence of association with the sinkhole. Sinkholes are a cause for immediate concern and further investigation. Beware that some animals may take over these areas, and they may not be recognizable as sinkholes or cavities.

- Look for signs of seepage or indications that seepage is sometimes present. The best time to look for seepage may be when the conduit is operating in a pressurized condition or at full discharge capacity. Evaluate the following:

    1. If an area on the surface of the embankment dam is wet, the area should be marked or staked, and photographed, to see if it is expanding over time. If the seepage is flowing, measures should be taken, such as the installation of a weir, to collect and measure the quantity of flow. A seepage rate that is increasing faster than expected, relative to the reservoir level, may be an indication of internal erosion or backward erosion piping. Seepage in these areas may be characterized by increased vegetative growth or the presence of plants that thrive in wet areas. If instrumentation is available, measurements of seepage should be compared to previous measurements to reveal changes in flow rates. Piezometers should also be monitored.

    2. The quantity of seepage along the conduit or through the conduit's backfill may indicate that adequate compaction around the conduit was not achieved or internal erosion or backward erosion piping is occurring. The area where water outlets from a seepage diaphragm should be closely monitored. Seepage areas may be indicated by changes in vegetation or color. The limits of a newly wet area should be marked to determine whether the area is increasing in size. When possible, the seepage should be channeled away from the embankment dam and directed through a pipe, weir, or other device that will allow the quantity to be measured.

Figure 119.—Sinkhole in the crest of an embankment dam.

Figure 120.—Sinkhole around a spillway riser. Photo courtesy of Schnabel Engineering.

Measurement of flow by a stopwatch and bucket is a simple way to collect flow information. Installation of a weir and staff gauge is preferred for more uniform data collection under longer term conditions.

3. The quality of any seepage, especially whether it is carrying soil particles should be analyzed. Water seeping into, out of, or along a conduit can cause problems by carrying particles with the flow. If the quality and quantity of the water flowing into the conduit is different from the water flowing out of the conduit, then it is likely that open joints or cracks are allowing additional seepage flow to enter the conduit, or normal discharge to leak out. The appearance of the flow at the area where water outlets from a seepage diaphragm is of particular concern. Any water flowing in the vicinity of the conduit should be observed for evidence of fines being transported, such as cloudiness or discoloration. The internal erosion and backward erosion piping processes can occur intermittently, with fines being transported sporadically. Evidence of fines being carried in seepage is cause for concern, further investigation, and prompt action.

The monitoring of any condition involving seepage or discharge should also include the corresponding reservoir pool level. Any sudden change, or unusual trend over time, which does not correspond to changes in the reservoir level, could indicate a seepage problem. For example, an increase in the seepage rate while the pool level is constant could be an indication of internal erosion. Pool levels may be measured by a staff gauge, by calibrations placed on a fixed structure in the reservoir, or by water-level sensing devices.

- Look for signs of internal erosion or backward erosion piping where the conduit exits the downstream slope of the embankment dam near the terminal structure. Water flowing through cracks in the earthfill or along the conduit may erode soils and cause a cloudy effluent with turbulent flow. Deposits of sand may form at the exit point of seepage. Water escaping from intergranular seepage in granular soils may create sand boils, and the flow is less likely to be turbid. Other indicators of developing problems include deposits of sediment not associated with runoff, sinkholes, and signs of settlement, such as depressions on the surface of the embankment dam or its foundation.

- Any changes in the embankment dam or foundation in the vicinity of the conduit. Since the location of a conduit represents a unique condition in the embankment dam, and a potential seepage path through the dam, any changes in the vicinity of the conduit should be investigated. Such changes might include slope movement, changes in vegetation, areas of new or unexpected wetness or seepage, unusual piezometric readings, etc.

- Check the exposed areas of the conduit for cracking, weathering, and/or chemical deterioration.

- Look for any whirlpools in the reservoir in the vicinity of the conduit.

- During operation of the conduit, additional items of concern include:

    1. Any unusual noises, such as popping, banging, or vibrations should be investigated. Vibrations may occur, if the conduit is not properly supported. Vibrations could adversely affect the conduit and surrounding backfill.

    2. Color changes or fines observed in the discharge water coming out of the conduit.

    3. Pulsating or unstable flow.

    4. Unexplained reductions in discharge capacity.

9.5.2.2 Interior inspection.

Typical problems within the interior of conduits include deterioration, obstructions, joint offsets and separations, defective joints, cracking, and mechanical equipment misoperation (figures 121 and 122).

If the conduit is accessible, the inspector should use a measuring tape or pace off the locations of all damaged or questionable areas within the conduit. Damage or questionable areas should be documented using still, digital, or video camera equipment. If the conduit is inaccessible, CCTV inspection equipment should be utilized.

The interior inspection should look for:

- Water ponding on the invert of the conduit, which could be an indication of settlement-related problems in certain reaches of the conduit, especially if the conduit as-built drawings show a constant invert slope.

- The locations of cracks should be documented using a crack map or similar reporting method. Be aware of any previously reported cracks, and note any new cracks. The length and width of the crack should be measured. To get an indication of the continuity of cracks through a concrete structure, use a geologist's pick or similar hammer to tap the concrete and listen for changes of pitch that give clues to the condition of the concrete. At some selected sites where accessible conduits are constructed on compressible or nonuniform foundations, strain gauges, total stress cells, and crack meters have been used to monitor changing conditions. For guidance on performing a crack survey, see USACE's *Evaluation and Repair of Concrete Structures* (1995b, pp. 2-1 to 2-13). For

Figure 121.—Inspection of a CMP conduit looking for signs of deterioration.

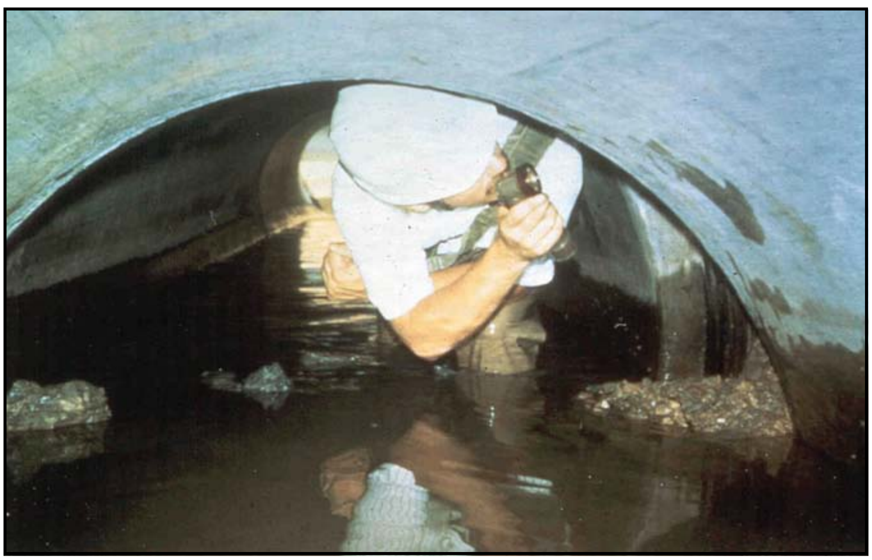

Figure 122.—Inspection being performed in difficult conditions. The joints of this 48-in concrete pipe separated when foundation movement occurred during construction of the embankment dam. For details, see the case history for Little Chippewa Creek Dam in app. B. Photo courtesy of Ohio Dam Safety Division.

an example of a how a crack survey was used within a conduit, see the Beltzville Dam case history in appendix B.

- Joint separations between conduit sections and at connections to entrance and terminal structures. In accessible conduits, joint meters have been used to monitor the opening and closing of joints in conduits. For additional guidance on crack and joint measuring devices, see USACE's *Instrumentation for Concrete Structures* (1987, pp. 5-1 to 5-24).

- Metallic corrosion of pipe or exposed reinforcement.

- Discoloration or staining of concrete surfaces.

- Damaged protective coatings.

- Deformation of the conduit circumference.

- Chemical deterioration of concrete.

- Leakage into or out of the conduit.

- Misalignment of conduit sections.

- Plugged drain holes.

- Voids behind the concrete near any observed cracks, joint separations, or misalignments. The ideal time to look for seepage through these areas is when the conduit has been recently unwatered and water may be draining into the conduit from the surrounding embankment.

- Spalled concrete from compression or reinforcement corrosion.

- Drummy or hollow-sounding concrete. The extent of deterioration may be difficult to determine. Sampling (coring) and testing of the material may be required. Samples taken from areas of deterioration are often compared with samples taken from good quality concrete. Testing may include determining the strength properties and use of petrographic examination.

- Erosion, abrasion, or damage in concrete downstream of gates/valves, offsets, and/or changes in slope.

- Cavitation damage.

- Binding of mechanical equipment.

- Blockages at the conduit entrance (i.e., trash or debris) or at the exit (i.e., vegetation, backed up water).

In attempting to inspect the interior of any conduit, there may be difficulties to overcome, such as:

- *Unwatering.*—A comprehensive inspection may be hindered, unless the conduit can be unwatered. Proper precautions should be considered prior to any unwatering situation. The possibility exists of external pressures being high enough to damage the unwatered conduit or vents being plugged, causing negative internal pressures to develop and collapse the conduit. This is a concern when pressurized conduits are unwatered. Unwatering a conduit may be impractical or impossible for one or more of the following reasons:

    1. Lack of a bulkhead or closure device.

    2. The need to limit reservoir drawdown. Lowering of the water surface may be restricted, which would prevent exposure of the conduit or entrance structure.

    3. Structural adequacy of the conduit to withstand external hydrostatic pressures in a unwatered condition.

- *Poor air quality.*—Poor air quality may exist within conduits. Poor air quality conditions may include lack of oxygen and the existence of hydrogen sulfide.

- *Inaccessibility.*—The conduit may be too small or too dangerous for man-entry inspection. The use of CCTV inspection equipment should be considered for inaccessible conduits. If this is not feasible, the inspection must then be based solely on the condition of the exposed and/or accessible portions of the conduit. Some details of the interior may be obtained by use of a bright light and the zoom feature of a camera.

For an examples of a man-entry inspections of a conduits, see the Dalewood Shores and Salmon Lake Dam case histories in appendix B.

9.5.3 Inspection of terminal structures

The terminal structure may be dry or partially inundated, depending on the time of year and the schedule of releases through the conduit. If the terminal structure is partially inundated, inspection of the structure above the water level will be fairly straightforward. However, inspection of the portion of the structure below the water level, such as the basin, chute blocks, baffle blocks, or end sill, will require specialized inspection services.

Problems common to terminal structures include deterioration, damage, obstructions, misalignment, backfill and foundation deficiencies.

Descriptions of more specific problems related to basin, chute blocks, baffle blocks, or end sills are beyond the scope of this document. The TADS program, as discussed earlier in this chapter, should be referred to for more detailed information concerning the inspection of terminal structures.

9.5.4 Specialized inspection

Specialized inspection includes the use of a dive team, climbing team, remotely operated vehicle (ROV), or closed circuit television.

9.5.4.1 Underwater inspections

Underwater inspection is typically accomplished by either scuba diving operations or surface-supplied air diving operations. Scuba diving equipment typically includes a breathing gas supply tank, which is carried by the diver. A scuba diver has more flexibility and maneuverability compared to surface-supplied diving operations. However, this method of inspection limits diver communication and should be limited to areas where the diver has an unobstructed path directly to the surface. Surface-supplied diving operations provide breathing gas to the diver via an umbilical and offer deeper dive capability, the potential for longer underwater stays, and communication between the diver and the surface, and should be utilized whenever the diver enters an overhead environment (diver does not have a direct vertical path to the surface).

Dive inspections are used for the examination of conduits, and entrance and terminal structures. However, the focus of this section will pertain only to dive inspections of conduits. The inspection of a conduit is often termed a "penetration dive."

Dive inspections are expensive, and the costs are greatly influenced by the depth of the dive, the elevation at which the dive is performed, and the temperature of the water. All specialized inspections involve a number of variables. As a general a rule of thumb, when comparing the costs involved with dive inspections to ROV inspections, dive inspections are about 3 to 5 times more expensive.

A dive inspection has the advantage of using a variety of instruments for testing the structural integrity of the conduit, such as a rebound hammer for providing data on concrete surface hardness, a magnetic reinforcing steel locator to locate and measure the amount of concrete cover or reinforcement, and an ultrasonic pulse velocity meter to determine the general condition of concrete based on sound measurements. Dive inspections also offer the potential for hands-on, tactile inspection of features in limited visibility or those covered with shallow layers of organics or sediments.

Some important considerations for any dive inspection are (Dulin and Crofton, 2004):

- *Certification*.—All divers and personnel associated with dive inspection should be certified commercial divers trained to meet the minimum requirements of ADCI's *Consensus Standards for Commercial Diving and Underwater Operations* (2004) through the training standard of an accredited Association of Commercial Diving Schools program. They should be compliant with all commercial diving training standards, have onsite documentation of first aid training, cardiopulmonary resuscitation (CPR), and meet other standards as applicable in compliance with OSHA and ADCI standards.

- *Dive team*.—The dive team should include the diving supervisor, a lead diver, and a backup diver for relief or emergencies. The diving team should have a Dive Master, whose primary talents are coordination of his crew and a solid understanding of what needs to be accomplished. Another member of the dive team should have a good understanding of mechanical equipment, what functions have to be maintained, and what has little importance to the equipment. Another member of the dive team should have solid experience with electronic equipment, such as ultrasonic thickness gauges, underwater still cameras, and communication equipment. All divers on the team should have the strength to accomplish the physically demanding tasks involved with the inspection.

- *Communication*.—Communication with a diver underwater is difficult. Everyone involved with the project needs to know the chain of command and what role each individual plays. The means of contact, both primary and secondary, should be fully understood by all parties who may be involved with any portion of the diving inspection.

- *Safety*.—A specific job hazard analysis should be performed to address all aspects of the diving operation. All parties who may be involved with any portion of the diving inspection should hold a kickoff meeting. Discussion should include the lockout tag-out (LOTO) procedure. A draft copy of the procedure should be provided to all attendees. The procedure should be finalized prior to commencement of any diving. No diving activity should start until the LOTO is finalized and accepted by all parties involved.

Diving in an environment where the diver does not have a direct route to the surface is a very specialized area of diving. No clear-cut criteria exist for defining conduits that can or cannot reasonably be inspected by divers. Many conduits that are large enough for a diver to enter may have factors that preclude them from being inspected. Certain factors must be weighed against one another and a judgment made as to the viability of a dive inspection. Factors that must be considered include:

- *Depth*.—As the depth of the conduit below the water surface increases, the difficulty of performing a dive increases. Divers have a limited amount of time on a given dive, and that time decreases with the increased pressures on deeper dives. Also, as the dive becomes deeper, more of the allowable dive time is spent descending to the conduit. Allowable dive times can be increased by means, such as using mixed gas, or diving in a pressurized “newt suit.” This increased dive time at depth comes at an increased cost due to requirements for items like larger dive crews, more specialized equipment, and a limited numbers of companies that can actually do the work. As an example, a 25-foot deep dive at sea level using air would not have a no-decompression limit (NDL), an amount of allowable dive time before decompression is required, while an 80-foot deep dive under the same conditions would have a NDL of 40 minutes. Decompression diving can be utilized to increase the work time available to the diver, but would likely come at an increase in the costs associated with the dive.

- *Altitude*.—The altitude at which the conduit is located can greatly affect the viability of a dive inspection. This could really be considered a subfactor of the depth factor. Due to the lower atmospheric pressure at higher altitudes, the diver has an even more limited bottom time associated with a given depth of dive. For example, comparing the 80-foot deep dive previously discussed:

    1. At sea level, NDL of 40 minutes

    2. At 2500 feet, NDL of 30 minutes and would be treated as a 90-foot dive

    3. At 5000 feet, NDL of 25 minutes and would be treated as a 100-foot dive

  Using decompression diving is an option for addressing the impact of altitude on dive time, but once again this would likely come with an increased cost.

- *Water temperature*.—As the water temperature decreases, it can have the effect of decreasing the dive time available to a diver. This is not necessarily a quantifiable variable as it relates to dive time. Often the temperature effect can be mitigated to some degree by the level of thermal protection worn by the diver. Care should be exercised with decompression diving in extremely cold water, because a failure in the thermal protection measures (leak in suit, hot water heater shutdown, etc.) after the diver has passed the NDL will necessitate what could be a long, cold decompression stop with the risk of severe hypothermia.

- *Length*.—As with depth, the conduit length becomes a factor relating to the amount of time the diver has available at depth. If the conduit is extremely long, it can take much more time to inspect than the diver has available. The available dive time for a long conduit can be increased, but this can be costly. Safety also must be considered. Because the diver does not have a direct path to the surface, the farther the diver must penetrate into the confined space, the farther the diver is from a direct path to the surface.

- *Access*.—Often the entrances to conduits are equipped with trashracks on the inlet side. The ability to remove enough of the trashrack bars to allow easy entry and egress is important. Since divers in such an overhead environment will be utilizing some type of surface-supplied breathing gas, it is important that the access point be such that the hoses will be able to be fed into the conduit without hanging up. A second diver is required to be stationed underwater at the confined space entry point to tend the primary diver's umbilical.

- *Leakage and currents*.—The leakage of downstream gates or valves in a conduit is a safety factor that can affect whether a dive inspection can be safely performed. Currents can be unpredictable. Any inspection of this type should be performed, such that the diver enters the conduit against any current and then returns and exits with the current. In the case of an inverted siphon, this can be accomplished by entering from the downstream end, but in the case of an outlet works, a submerged conduit will more than likely need to be entered from the upstream end. Therefore, the condition of the gates or valves and how much leakage is exhibited is a big factor with respect to the viability of a dive inspection.

- *Conduit size*.—A conduit should really be large enough that the diver can turn around inside and exit head first. The size for this will obviously depend on the size of the individual diver and also the exact type of equipment required.

- *Visibility*.—The distance a diver can see is important to whether a dive inspection of a conduit is advisable. In poor visibility situations, the diver can use their sense of touch for inspection. Sometimes a diver can use a hand to probe areas that cannot be seen. In the event of zero visibility, there would likely be little reason to pursue a dive inspection, as the shear magnitude of the entire surface of a conduit would be extremely difficult to inspect by touch alone. Also, in a circular conduit, a diver does not have a real edge or other reference point to keep track of any findings. If a dive inspection (figure 123) is planned for a conduit, consideration should be given to making a large release prior to the inspection as a means of flushing sediments from the conduit and then allowing some amount of time for the water to settle out prior to diver entry. This time will depend on the type of sediments in the water, but could vary from a day to a week. If visibility is good, the diver may want to use a high resolution hand-held video camera to document conditions existing within the conduit. The video camera can be either self-contained or configured for topside viewing. A self-contained video camera is enclosed in a special waterproof case that allows for easy operation by the diver. For topside viewing, a cable is required from the camera to the monitor located on the top. Audio can be provided during the recording by the diver or topside personnel. Video cameras can also be mounted on the diver's helmet. However, no matter how good the video camera's resolution is, if visibility is poor, the camera will only be able to document a few square inches of surface at one time.

Figure 123.—Diver performing an underwater inspection.

Sometimes in pressurized conduits, it may be difficult for a diver to determine, if a defect is allowing water to leak through it. In these situations the diver may want to release colored dyes (e.g., food coloring) and observe if it gets sucked into the defect. Another option would be the use of a wand with a string or frayed rope attached to it. If water is leaking out of the conduit the string or frayed rope would be sucked into the defect (Stoessel, Dunkle, and Faulk, 2004, p. 2). Temporary repairs by the divers are possible by plugging these defects with Oakum or similar materials. However, a more permanent repair will need to be considered.

In certain situations, the combined use of divers and ROV or CCTV equipment may be required to complete the conduit inspection. The divers are used to gain access to the conduit and place the ROV or CCTV equipment in the proper location to begin the inspection.

For an example of an underwater conduit inspection, see the Salmon Lake Dam case history in appendix B.

9.5.4.2 Climb inspection

Although not often required for conduits, a climbing team may be utilized to perform inspection of the inaccessible portions of intake towers and the walls of terminal structures (figure 124).

9.5.4.3 Remotely operated vehicle

The ROV was first developed for industrial purposes to inspect oil and gas pipelines and offshore platforms. ROVs are now being utilized for underwater inspections of

Figure 124.—Climber performing an inspection on a terminal structure wall.

entrance and terminal structures and conduits. The focus of this section will pertain only to ROV inspections of conduits.

ROVs are normally linked to a surface power source, although untethered models are also available. However, untethered (autonomous) vehicles are typically larger and not used for inspection of conduits. ROVs that are linked to the surface have cables that carry electrical signals back and forth between the operator and the vehicle. Most ROVs are equipped with at least a video camera and lights. Additional equipment is commonly added to expand the vehicle's capabilities. These may include a still camera, a manipulator or cutting arm, water samplers, and instruments that measure water clarity, light penetration, and temperature.

An ROV consists of a video unit, a power source for propulsion, vehicle controllers (referred to as "joysticks"), and a display monitor. The ROV can provide real-time viewing. Most ROVs are either observation or working class vehicles. An observation class vehicle is small and compact and is used for visual inspection where nonintervention applications are required. Typically, observation class ROVs include a high resolution color video camera capable of zoom and manual or auto focus. Figure 125 shows an observation-class ROV entering the water. Precision color scanning sonar is an added option, but can be expensive. Some observation class ROVs may have a single function manipulator. Working class ROVs are typically capable of search, survey, inspection, and light intervention to depths of

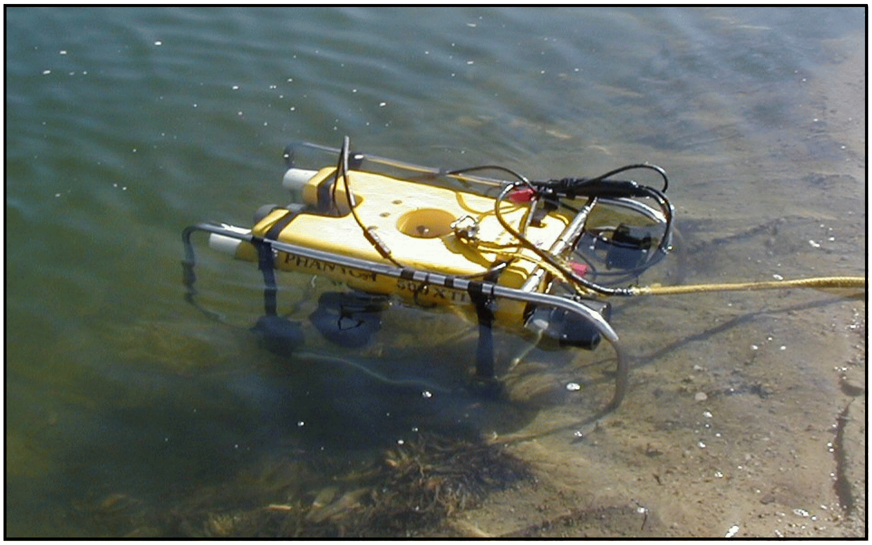

Figure 125.—An observation-class ROV entering the water to begin an inspection.

2,000 feet. Working class vehicles can typically support a payload capacity to allow for the attachment of sophisticated accessories. Most working class ROVs have multifunction manipulators.

An operator or "pilot" controls the vehicle from the surface. Using a joystick, a camera controller, and a video monitor, the operator moves the ROV to the desired location. The operator's eyes essentially "become" the camera lens. The vehicle's depth and heading can be recorded. A global positioning system (GPS) is generally not available on most ROVs and is an expensive and complicated added feature that cannot be used within the conduit. Joysticks are used to control the propulsion and manipulation of the ROV and any accessory equipment. ROVs typically have three thrusters, two horizontal and one vertical. The thrusters allow the vehicle to move forward and backward and to turn left and right. Some ROVs may have a fourth thruster mounted horizontally for lateral movement.

ROVs are capable of accommodating various attachments (i.e., a pincer claw) for grasping, cleaning, and performing other inspection tasks. However, the addition of attachments requires larger ROVs to accommodate the attachments. Specially designed ROVs can accommodate and operate non destructive testing equipment.

In the event that diving is prohibitive and dewatering of the conduit is not economically or technically practical, an ROV can be utilized. ROVs can compensate for the limitations inherent in underwater inspections performed by divers, since they can function at extreme depths and water temperatures, are not affected by altitude concerns, remain underwater for long durations, enter smaller diameter conduits, and repeatedly perform the same tasks without sacrifice in quality. Also, the costs involved for ROV inspection are considerably less than for dive inspection. Inspection by ROV may be preferable in certain situations prior to performing a dive inspection. This is especially important in regards to safety. An ROV that is damaged or destroyed can be replaced. However, this is not comparable to the loss encountered by a diver who is injured or killed.

Extreme caution is advised when performing an ROV inspection. The ROV operator should be qualified, experienced, and knowledgeable about the hazards involved. The potential exists for the ROV to become stuck in small diameter conduits due to offsets, sharp bends, or debris. The ROV can also become entangled in its umbilical cable (or the umbilical cable can become entangled with debris, such as tree branches). ROVs can be expensive depending upon the level of sophistication and costs involved with the retrieval of a stuck ROV can be very expensive and time consuming.

The ROV is typically inserted into the conduit from the upstream end. Depending on the entrance structure's configuration, assistance may be required from a diver to assist the ROV getting past trashracks. This approach can be used where the depth, length, and/or access limits a dive inspection's viability, but it is difficult to get the ROV into the conduit. The trashracks typically have a hatch cover that can be removed, or the ROV can also be lowered through a gate slot to access the conduit. If trashracks cannot be removed, a few of the bars may need to be cut and removed to allow insertion of the ROV. At some sites where the downstream conduit is located within a larger conduit, an ROV can be inserted from the downstream end of the conduit. For downstream end insertion, the ROV is placed within the unwatered section of conduit between the downstream guard and regulating gates/valves. The ROV cables are threaded through a special manhole in the pipe. Once the conduit section is rewatered and the guard gate opened, the ROV can proceed upstream and inspect the conduit. This method may be difficult, especially if umbilical cable needs to be continually fed through the opening, and should only be attempted by qualified and experience personnel.

Some of the limitations using an ROV for conduit inspection include (USACE, 1995b, p. 2-15):

- *Two-dimensional.*—The ROV inspection provides only a two-dimensional view and does not project the full extent of any defect. If the conduit diameter is large, the ROV inspection is much more likely to be limited to one small path along the conduit, whereas a diver can cover a much larger path or wider swath as the diver moves down the conduit.

- *Visibility.*—Murky water limits the effectiveness of an ROV inspection. With an ROV in a limited visibility situation, the only area inspected is the small area directly in front of the camera. A diver can use their sense of feel, in a limited visibility situation and focus in on any problem areas.

- *Orientation*.—In some situations, it may be difficult to determine the exact orientation or position of the ROV. This can impede accurate identification of the area being observed. Also, since ROVs often rely upon a compass, the steel in the conduit lining and/or concrete reinforcement can affect the navigation. If a CCTV camera-crawler is used in lieu of an ROV, the length of cable tether can be measured to determine the location within the conduit.

- *Maneuverability*.—In some "tight" areas the ROV may have more difficulty with maneuverability than divers would have in the same situation. Water currents can also affect maneuverability by causing the tether to become entangled.

The technology associated with ROVs is continually evolving. Continued advancements will allow the operator to overcome some of the existing ROV limitations by utilizing more sophisticated attachments and instruments to improve diagnostic capabilities.

9.5.4.4 Closed circuit television

The use of CCTV as an inspection method has undergone significant technological advancements. The introduction of robotic and automated systems, such as smart pigs, camera-crawlers, and other remotely controlled vehicles has allowed previously inaccessible conduits to be inspected. CCTV and man-entry are the most widely used methods of conduit inspection.

CCTV is a very useful method for examining small or inaccessible conduits (figures 126, 127, and 128). CCTV inspection provides significant improvements over other methods of inspection, such as man-entry inspection where an inspector crawls through the conduit (36 inches or larger) and documents the conditions, manual inspection where a sled with a camera is pushed through the conduit using long push rods, and mechanical inspection where a camera tethered to a wire rope is pulled through the conduit. CCTV inspection has the advantages of being able to examine conduits regardless of size limitations, has complete mobility, and provides real time video images.

CCTV inspection also can be used in conduits where confined space entry issues may require permitting prior to man-entry. OSHA regulations define a confined space as having limited access and egress, and not being designed for continuous human habitation. This would include not only small conduits, but also larger diameter conduits, where risks, costs, or system complexity may make remote inspection more advantageous.

Figure 126.—Seepage entering a CMP conduit through a defect.

Figure 127.—Corrosion within a 24-inch-diameter CMP outlet works conduit.

Generally, a CCTV inspection consists of a video camera attached to a self-propelled transport vehicle (crawler). Some crawlers utilize tracks, and others use wheels. The transport vehicle and camera are commonly referred to as a camera-crawler (figure 129). An operator remotely controls both the transport vehicle and camera. The camera can provide both longitudinal and circumferential views of the interior

Figure 128.—A CCTV inspection camera-crawler entering the downstream discharge portal of an outlet works conduit.

of the conduit surfaces. Video images are transmitted from the camera to a television monitor, from which the operator can view the conditions within the conduit. The video images are recorded onto videotape (VHS) or DVD for future evaluation and documentation. The operator can add voice narrative and text captions or notations as the inspection progresses.

Figure 129.—Camera-crawler used for CCTV inspection of conduits. Photo courtesy of Inuktun Services, Ltd.

CCTV inspection equipment was initially used for gas/oil and sewer pipelines. Over the last 10 to 15 years, CCTV inspection has expanded into many applications, such as conduits. In that time period, the robotic equipment used for CCTV inspection has changed significantly. The latest trend for equipment used in CCTV is for modular efficiency (interchangeable components), allowing greater versatility and a wider range of applications. The benefit of modular design is the reduction of added costs required for "application-specific" equipment and "custom designs."

Depending on the model, camera-crawlers used in conduits with very small diameters (about 4 to 14 inches) have cameras with some pan, tilt, and zoom capabilities, a wide range of tether pulling capacity (200 to 1,000 feet), and some steering capabilities. Camera-crawlers used in conduits with diameters of 15 inches or larger are steerable, have a greater cable tether-pulling capacity (500 to 1,500 feet), and have cameras that can provide a wider array of optical capabilities, including pan, tilt, and zoom. As the technology of CCTV inspection equipment advances, greater tether lengths and optical capabilities will become available. Actual tether limits obtainable in the field, vary greatly, depending upon a number of factors, such as conduit diameter, bends, invert slopes, and existing invert conditions, such as sediments, mineral encrustations, and bacterial growths.

In large diameter conduits, the video camera can be attached to a scissor mechanism mounted to the transport vehicle. The scissor mechanism, controlled by the operator, can raise or lower the video camera as needed for inspection. In addition, the video camera usually has a high powered zoom, which can be used to provide closeup views of areas that might be difficult for the transport vehicle to get near. These features allow examination of very large conduits with diameters as large as 40 or 50 feet.

If required, some models of camera-crawlers allow for the attachment of retrieval tools, such as alligator clamps, grippers, and magnets. These tools can be used to remove light debris or damage. The attachment of any type of retrieval tool will require additional clearance within the conduit to operate the retrieval tool. Some models of crawlers have robotic cutters attached to them. These cutters can be used to remove debris or protrusions in concrete, steel, or reinforcement. Most camera-crawler systems are portable and can be carried to conduit access locations (figure 130). The use of an all-terrain vehicle (ATV) may be beneficial for transport of equipment in difficult access areas.

Sometimes the conduit is too small and a transport vehicle cannot be used, or obstructions/invert conditions exist that prevent the transport vehicle from traversing the conduit. For these types of situations, a small color video camera (1.5 to 3 inches in diameter) with maximum pressure depth ratings up to 1,000 feet of water can be used. Figure 131 shows an example of this type of video camera. This video camera can be attached to metal or PVC poles (commonly referred to as push poles) and manually pushed up the conduit. Push poles are normally used for straight sections of conduit. The use of push poles for advancement is generally limited to about 400 feet of conduit length. If bends exist in the conduit, a flexible snake device (spring steel wire, coiled wire, or flexible polypropylene-jacketed fiberglass push rod) can be used instead of the push poles. A coaxial cable connects the video camera to a video cassette recorder and television monitor. Snake devices are generally limited to about 75 to 200 feet of conduit length.

Figure 130.—Most CCTV inspection equipment is portable and can be carried to conduit access locations.

The quality and adaptability of CCTV inspection equipment can vary greatly, depending on the requirements of the inspection. Any company or contractor selected to perform a CCTV inspection should have a wide range of available equipment for differing site conditions. No CCTV inspection equipment exists that is fully adaptable for all conditions, and a variety of crawler configurations and cameras may be required.

Figure 131.—A small color video camera used for CCTV inspection.

Camera-crawler inspection equipment is expensive to purchase, operate, and maintain. The environment being inspected is typically harsh and can pose many hazards and obstructions. Although rare, camera-crawler inspection equipment can become lodged in small diameter conduits if adverse offsets or obstructions exist. If camera-crawler inspection equipment becomes lodged within a conduit, it can partially block the conduit, reducing its discharge capacity. Also, due to the harsh environment, this type of inspection equipment can experience breakdown while operating within the conduit. The retrieval process for removing a lodged camera-crawler can be expensive and time consuming. If the camera-crawler inspection equipment becomes stuck in totally inaccessible portions of a conduit, complete abandonment and loss of the equipment is possible. For this reason, the operator of any inspection equipment must be very experienced and have a clear understanding of the capabilities and limitations of the equipment. The operator must be very cautious and should not push the equipment beyond retrievable limits. The ability to recognize inspection limitations is based largely on the operator's skill and prior experience. The operator must have a thorough understanding of potential dam safety defects, conduit materials, and obstructions within the conduit. Operators must understand that conduits within embankment dams are not like sewers, where only a limited amount of overburden typically exists and where excavation could facilitate camera-crawler retrieval. A conservative approach to inspection is best advised.

Experience with CCTV inspection has shown that past conduit design practices did not always allow for accommodation of equipment used for CCTV inspection. Also, certain configuration of entrance and terminal structures may not allow access for CCTV inspection due to existing trashracks, bends, baffles, etc. The design of any new conduit or the modification of an existing conduit should incorporate features to allow for complete inspection using CCTV inspection equipment. For an example of a conduit inspection using CCTV equipment, see the Pasture Canyon Dam case history in appendix B.

The success of performing a CCTV inspection depends upon the quality of the equipment and the experience of the operator. A CCTV inspection usually requires a two-person crew consisting of an operator and cable reel handler. Additional crew members may be required in difficult access locations. Guidance to consider in performing a CCTV inspection includes (Cooper, 2000, pp. 4-5):

- *Light*.—The amount of light is critical to the success of the inspection. Without the proper amount, areas of concern cannot be observed clearly enough. Lack of clarity hinders making definitive conclusions as to the integrity of the conduit. Also, the larger the diameter of the conduit, the more light that is needed. A trial-and-error procedure may be required to obtain sufficient light intensity. The ability to vary light intensity and control glare is an important feature to consider.

- *Camera*.—The video camera should be able to pan and tilt and also be capable of looking straight ahead. Zoom capabilities allow for close up viewing. Not all inspections involve horizontal conduits. Inspections of vertical drops are sometimes required. The video camera should be able to accommodate different conduit diameters, shapes, and orientations.

- *Footage meter*.—A footage meter should be superimposed on the videotape. This meter makes identifying specific locations within the conduit much easier. In lieu of a footage meter, the operator should verbally record on the videotape the location of the camera-crawler by measuring the length of cable tether.

- *Compass*.—A compass unit will provide azimuth and inclination readings superimposed on the videotape. This will assist in determining conduit alignment. However, a compass unit likely will not work in a steel conduit.

- *Narration*.—All inspection videotapes should include narration by the operator. The operator should describe in detail what is being seen. Narration should note any deposits, changes in the slope of the invert, condition of conduit joints, areas of deterioration, changes in shape, etc.

- *Drawings and photographs*.—Copies of all available design and/or as-built drawings of the embankment dam and conduit should be onsite during the CCTV inspection for immediate reference and confirmation of details and features observed during the inspection.

- *Measurements and data collection*.—The inspection and the technical evaluation will be greatly enhanced if the following data are collected at the time the CCTV inspection is performed: reservoir water level, any relevant data on nearby piezometer levels, history of past operations, and time/date.

- *Videotape library*.—The operator and other inspection personnel should review all previous inspection videotapes (if available) prior to doing the CCTV inspection. This will provide a baseline reference, so the rate of any continuing deterioration can be evaluated.

An important part of any CCTV inspection is the technical evaluation of the conditions observed during the inspection. A qualified professional engineer experienced in the design and construction of conduits should perform this evaluation. Interpretation of the results of the CCTV inspection should not be left to inexperienced personnel. The correct determination of conditions within the conduit is crucial in understanding potential failure modes involved. Many years may pass before the opportunity to perform another CCTV inspection is available. The engineer should prepare a report of findings (ROF), which documents all problem areas observed and recommends future actions. The ROF should also include pictures captured off the videotape or DVD showing areas of concern, a drawing or sketch showing the limits of the CCTV inspection, additional informational drawings if needed, and a detailed summary or log of observations that corresponds with time and linear footage on the videotape. Figure 132 shows a picture captured from videotape.

Other innovations in inspection systems are under development for sewers and for the oil and gas industry. These systems may eventually prove applicable to conduit inspection. These systems involve state-of-the-art laser scanners (digital imaging), and gyroscope technology. Laser scanner systems allow the operator to see the total conduit surface with color coding of conduit defects on a digital computer image.

Figure 132.—A joint has separated in the steel pipe of this outlet works.

Data processing and report preparation are completed using a manufacturer's proprietary software. Currently, laser scanners are not readily adaptable for conduit inspection, since they have some difficulties identifying infiltration, corrosion, and conduit ovality. Laser scanners also are limited to conduits in the range of 8 to 24 inches in diameter. Inspections utilizing laser scanners generally cost 50 to 75 percent more than for CCTV. However, the major benefit of laser scanners is the ability to produce a digital record, which reduces the subjective interpretation of results. Computerized evaluation will gain wider acceptance as a reliable inspection and evaluation tool as further technological advancements are made (Civil Engineering Research Foundation, 2001).

9.6 Cleaning of conduits

Small, inaccessible conduits are especially vulnerable to plugging issues. Cleaning is usually only an issue where man-entry is not possible. If a conduit requires cleaning, it should only be done after careful consideration of the potential effects on known or suspected deterioration within the conduit. The basic philosophy used in the cleaning of conduits should be to "do no harm." This means a very cautious approach is required for cleaning of conduits.

9.6.1 Reasons for cleaning

- *Inspection*.—Cleaning may be required to allow for operation of CCTV inspection equipment within the conduit.

- *Construction.*—Cleaning of the existing conduit may be required as part of the selected renovation method; see chapter 12 for renovation methods requiring cleaning of the existing conduit.

- *Maintenance.*—Cleaning may be required to improve the flow capacity within the conduit due to hard deposits, bacterial growths, sediments, or debris that may have collected in the conduit. Periodic operation of the conduit will flush out many of these types of collections. However, infrequent operation or nonoperation may allow for continued buildup of these collections.

    1. *Hard deposits.*—If a conduit has not been periodically operated, certain mechanisms may develop within the conduit. In conduits experiencing seepage into the conduit through a joint, solid deposits may develop where the seepage water evaporates. These deposits often contain calcium carbonate, which precipitates out of solution as the mineral calcite. Calcite will form deposits when the calcium ion and bicarbonate ion concentrations in the water increase to the point where they exceed the capacity to dissolve in water. Hard deposits of calcium carbonate precipitate may develop when the seepage water evaporates.

    2. *Bacterial growths.*—If a conduit has not been periodically operated, certain bacterial growths may develop within the conduit. Bacterial growths are common and can develop under a variety of conditions. Bacterial growth can occur anaerobically (without oxygen) and aerobically (with oxygen). Most of the time, bacterial growths are soft and easy to remove, but in some situations, these growths can become hard and mineralized. Aerobic bacterial growth can also create hazardous conditions by depleting the oxygen in the air of a confined space.

    3. *Sediments and debris.*—If a conduit does not discharge water completely out of the system or if the discharge channel is adversely sloped, water may partially or completely submerge the exit portal. If this occurs, sediments and debris can back up into the conduit, resulting in sediment deposits or debris accumulation.

9.6.2 Cleaning methods

The improper use or the selection of incorrect cleaning equipment may cause additional damage to a deteriorating conduit and further degrade its structural integrity. The type of conduit material (i.e., concrete, plastic, or metal) must be considered in selecting the appropriate cleaning method. Some conduit materials (such as CMP) are much more prone to defects. Cleaning of inaccessible conduits should only be considered after CCTV thoroughly inspects the conduit. If a deteriorating conduit is cleaned without the benefit of CCTV inspection, the conduit may become unknowingly damaged.

Indications of obstructions within the conduit may include reduced outlet flow capacity, etc. If obstructions are found during the CCTV inspection, the method of cleaning can be evaluated and a preferred method selected. Sometimes, CCTV inspection and cleaning are done on the same day. Some cleaning services have limited CCTV inspection equipment. Any cleaning should be attempted only in the presence of qualified and experienced staff representing the agency/owner of the embankment dam. Complete documentation (including photographs) of all activities at the site is highly recommended.

The success of any conduit cleaning depends upon accessibility, type of cleaning required, and the cleaning method used. A variety of cleaning methods are available:

- *Flushing.*—If debris and sediments are not significant, adequate cleaning may be obtained by merely flushing the conduit with water. Flushing can be accomplished by opening a gate or valve and allowing water to flow through the conduit or by inserting a flexible hose and pumping water into the conduit. In many cases, volume and low pressure is all that is needed to adequately clean the conduit.

- *Pressure washing.*—Pressure washing (figure 133) involves the use of a flexible hose attached to a metal nozzle that directs jets of water out in front of it to loosen debris and sediments in the conduit. The jet is created by a shaped restriction in the flow channel that forces water to accelerate and converts potential energy (pressure) into kinetic energy (velocity). The nozzle is propelled forward by reverse angle jets. The reverse angle jets also push debris and sediments backwards toward the end of the conduit, where the flexible hose exits. Pressure washing is best suited where biomasses or mineral encrustation are to be removed. The pressure selected for cleaning should fully consider the condition of the types of conduit material, age, and type of joints. The lowest possible pressure that effectively cleans the conduits should be used. The jets on the nozzle should be angled no more than about 30 degrees, so the jets are not aimed directly at the conduit wall. The nozzle should be kept rotating and moving and should not be allowed to remain in one spot during jetting.

- *Mechanical.*—Mechanical cleaning utilizes rotating brushes.

- *Cleaning pig.*—Cleaning pigs have wire brushes to scrape the walls of the conduit. A variety of brushes are available, depending on the type of cleaning required and the existence of any coatings on the interior surface of the conduit. Cleaning pigs are generally available in diameters up to 48 inches.

Figure 133.—Pressure washing cleaning head.

Again, it should be strongly emphasized that any cleaning should be given considerable thought before proceeding, to avoid causing any damage, or worsening existing defects within the conduit.

In some situations, minor cracks or joints experiencing seepage may eventually seal themselves by calcite deposition. This process occurs when calcite precipitates out of solution and forms a deposit. Deposition may occur as the seepage evaporates, leaving the calcite behind. Calcite deposits typically mineralize and harden over time. Figure 134 shows a conduit joint where calcite deposition has sealed a minor leak. If inspection shows locations within a conduit where this has occurred, cleaning with high pressure could remove enough of the calcite deposition to cause seepage to begin again. This possibility needs to be carefully considered prior to performing any cleaning operations within the conduit.

9.7 Forensic investigation

To better understand and to provide further knowledge concerning the failure mechanisms resulting from the internal erosion or backward erosion piping within an embankment dam, forensic investigation should be considered. Although traditionally a forensic investigation is conducted to establish the failure mechanism for legal cases, a detailed investigation can be very helpful in determining the causes of failures and to provide insight into design changes to reduce failures in the future.

For projects where a failed conduit is being removed and replaced, close coordination between designers, embankment dam owner, and the contractor will be required to preserve the soil adjacent to the conduit. The investigation team should

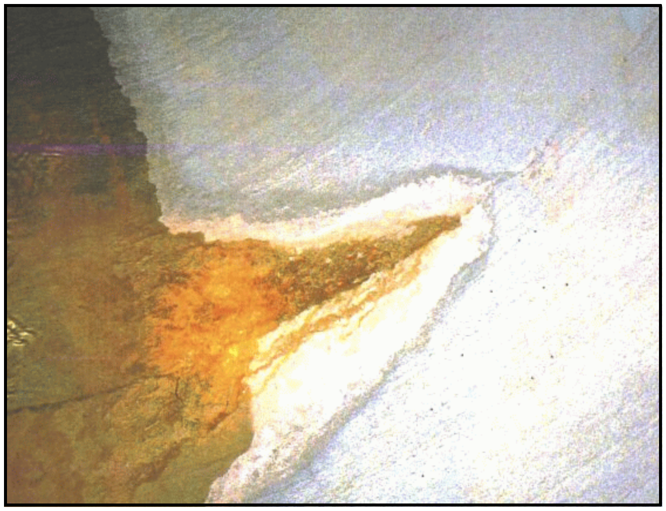

Figure 134.—Calcite deposition has sealed this leak at a conduit joint.

consist of experienced geotechnical and civil engineers, geologists, surveyors, and construction personnel. All anticipated items of interest (e.g., voids) should be clearly communicated to all parties involved prior to the commencement of embankment excavation. Test pits are usually excavated along the conduit, extending a specified depth below the bottom of the conduit. The contractor must take care to prevent damage to in-situ conditions before the investigation team can document them. Figure 135 shows an outlet works conduit excavation during a forensic investigation. Figure 136 shows how polyurethane grout flowed through the backfill surrounding an outlet works conduit during joint sealing operations. Close coordination between the forensic team and contractor were required in order to preserve this information for study.

Documentation of the conditions encountered is essential to be able to recreate the events leading to the failure. A surveyor with a transit, theodolite or total station, and one or more assistants with survey rod or reflector target should be available to precisely document the location (position and elevation) of items of interest. Numerous photographs should be taken, even of items that do not appear to have contributed to the failure in case they are needed later, since the soil structure surrounding the conduit will likely be destroyed by the investigation and the information will be forever lost, if not carefully documented.

A JHA should be prepared for all onsite forensic investigations. See section 9.4 for details on preparing a JHA. For details of a forensic investigation, see the Annapolis Mall Dam case history in appendix B.

Figure 135.—An outlet works conduit is being excavated during a forensic investigation. The top of an antiseep collar is exposed on the left side of the figure.

Figure 136.—Close coordination between the forensic team and contractor allowed for careful study of how polyurethane grout injected into the deteriorated joints of a conduit flows through surrounding backfill. In this case, the forensic investigation showed the injection of grout was relatively successful in sealing the joints of the conduit.

9.8 Instrumentation and monitoring

Instrumentation and monitoring are performed for three distinct reasons:

1. To aid in the evaluation of water pressure conditions surrounding a conduit and detect signs of a problem (i.e., first identification). Key detection elements include:

    a. Visual monitoring for unusual settlements or deformations above the conduit

    b. Visual monitoring for seepage emerging in or near the downstream end of the conduit

    c. Inspection of the interior of the conduit

    d. Structural measurement points in the conduit (where possible)

    e. Embankment measurement points in the vicinity of the conduit alignment

2. To gain a better understanding of an already detected problem for use in evaluation and design of a remediation

3. To monitor embankment and foundation water pressures during and following conduit remediation

Instrumentation in a conduit or embankment dam furnishes data to determine if the structure is functioning as intended and to provide a continuing surveillance of the structure to warn of developments that could endanger the safety of the embankment dam facility. Conduits are not normally instrumented unless there is a specific concern due to known adverse foundation conditions or other unusual circumstances. The means and methods available to monitor an emergency event or condition that could lead to a embankment dam failure include a wide spectrum of instruments and procedures from very simple to very complex. The need for instrumentation designed for monitoring potential and/or existing deficiencies at existing embankment dams must take into account the threat to human life and property downstream of the dam. Thus, the extent and nature of the instrumentation depends not only on the complexity of the conduit and embankment dam, and the extent of the deficiency being monitored and the size of the reservoir, but also on the potential for loss of life and property damage downstream of the dam (FEMA, 1987, p. 51; Reclamation, 1987b, pp. 1-3).

An instrumentation program should involve instruments and evaluation methods that are as simple and straightforward as the project and situation will allow. Instruments selected for use should be accurate, precise, and provide for repeatability of measurements. Beyond that, the designer and embankment dam owner should make a definite commitment to an ongoing monitoring program. If not, the installation of instruments will probably be wasted. Increased knowledge of any deficiency and emergency condition of the embankment dam acquired through an instrumentation and monitoring program is extremely useful in determining the cause of the deficiency, the necessary or probable remedy, and monitoring during and following corrective actions. Involvement of qualified personnel in the design, installation, monitoring, and evaluation of an instrumentation system is of prime importance to developing and achieving a successful and meaningful instrumentation and monitoring program.

A wide variety of devices and procedures are available for use in monitoring the behavior of and deficiencies along a conduit and at an embankment dam. Table 9.1 provides a listing of potential deficiencies and conditions and their causes that could be encountered along the alignment of a conduit. The table also provides a brief description of where the condition could be encountered and the instrumentation that could be used to monitor the condition. Additional discussion of each measurement is provided in the following sections. Most of these measurements are typically done for embankment dam concerns. However, there is some applicability to conduits. Further information or instrumentation and monitoring is available on ASCE's *Guidelines for Instrumentation and Measurements for Monitoring Dam Performance* (2000).

9.8.1 Structural deformation

Structural deformation of a conduit could lead to crack development or joints opening up along the alignment of the conduit. These deficiencies could result in the potential for internal erosion or backward erosion piping of embankment dam materials into or along the exterior of the outlet conduit. In the case of water seeping into the conduit through open joints or cracks, an unprotected exit point for the seepage exists, which could allow for the internal erosion or backward erosion piping of embankment dam materials into the conduit. For pressurized conduits, open joints or cracks in the conduit could allow for the saturation of the embankment dam materials around the conduit under a high seepage gradient condition, which could also lead to the internal erosion or backward erosion piping of embankment materials. Structural deformations may result from foundation settlement, lateral deformation of the embankment slopes above or below the conduit, or a collapse of the conduit due to a structural defect in the conduit or growth processes within concrete, usually resulting from alkali-aggregate reaction.

Table 9.1.—Instruments used for monitoring of conduits (ASCE, 2000)

Property measured	Cause	Measurement location	Typical instruments
Structural deformation	Vertical-settlement	Joints, alignment	Strain gauges, extensometer, joint meter, survey profiles
	Lateral-slope movement	Joints, alignment	Strain gauges, extensometer, joint meter, survey profiles
	Expansion-autogenous growth (alkali-aggregate reaction)	Any location of interest	Strain gauges, extensometer
Uplift pressures	Shallow structure and high groundwater	Within embankment dam	Piezometers, observation wells
		Within foundation	Piezometers, observation wells
Seepage quantity	Internal erosion or backward erosion piping	Any location of interest	Calibrated container, weir, flume, flow meter
Horiz. and vert. movements	Internal erosion or backward erosion piping	Any location of interest	Survey, staking, probing
Water quality	Internal erosion or backward erosion piping	Any location of interest	Turbidity meter, jar samples
Reservoir water level and flows	-	Reservoir or outlet channel	Elevation gauge

Structural deformation of the conduit can sometimes be first detected by defects noted on the surface of the embankment dam in the form of depressions, bulges, and cracks. For guidance on horizontal and vertical movement of embankment dams, see section 9.8.4.

9.8.2 Uplift pressures

Where the conduit is shallow and groundwater is high, uplift pressures on the conduit may be sufficient to the push the conduit or associated structures upward.

This movement could cause cracks to develop or joints to open up in the conduit similarly as discussed for structural deformations of conduits. Conduits in sandy and silty soils also could be susceptible to damage, if the soils are liquefiable.

If this condition is suspected along the alignment of a conduit, instrumentation, such as observation wells, could be placed near the conduit alignment. Installation of instruments to measure uplift pressures cannot be relied upon as the sole means of detection of these problems. Rather, instruments to measure pore pressure should only be placed as a means of providing information on the general water pressure conditions at the location of interest. If piezometers are installed after the conduit and embankment dam have been constructed, caution should be used in considering drilling close to a conduit, as low stress zones with the potential to hydraulically fracture often exist as a result of the structure. In a zoned embankment dam, locating the instrument in a zone other than the core should be considered.

Installation of instruments to measure pore pressure resulting from internal erosion or backward erosion piping cannot be relied upon as the sole means of detection of these problems. Rather, instruments to measure pore pressure should only be placed as a means of providing information on the general water pressure conditions within the embankment dam.

Designers should note that a trend is growing in the industry to eliminate the installation of instrumentation within the cores of embankment dams during construction. The performance of embankment materials is well understood, so there is little need to repeat past research. Also, it is very unlikely that the instrument will be placed in the correct place to detect a chance problem. Furthermore, it is recognized that the mere act of installing the instrument can adversely affect the quality of the embankment dam. Vertical risers associated with cables and tubing can disrupt the proper flow of compaction equipment. Instrumentation trenches can potentially introduce flaws that could lead to concentrated leakage.

Installing instruments in the cores of existing embankment dams to detect particular problems should still be considered. The instrument can be placed within the embankment dam by drilling techniques, but specific techniques that limit the potential for fracturing the embankment dam should be employed. Drilling into the embankment dam with techniques that use water or air to remove cuttings should be avoided, because blockages within the drill holes have been known to cause the buildup of high fluid pressures leading to fractures in the earthfill. For guidance on drilling within embankment dams, see section 14.3.1.

9.8.3 Seepage quantity

Seepage along a conduit or through an embankment dam is a valuable indicator of the condition and continuing level of performance of an embankment dam.

Particular attention should be given to seepage exiting ground conduits and the quantity of seepage flowing out of conduits. The quantity of seepage entering a seepage collection system is normally directly related to the level of the water in the reservoir. Any sudden change in the quantity of seepage collected without apparent cause, such as a corresponding change in the reservoir level or a heavy rainfall, could indicate a seepage problem. Similarly, when the seepage becomes cloudy or discolored, contains increased quantities of sediment or changes radically in chemical content, a serious internal erosion or backward erosion piping problem may be developing. Moisture or seepage at new or unplanned locations on the downstream slope or below the embankment dam also may indicate a seepage problem. Seepage should be monitored regularly to determine if it is increasing, decreasing, or remaining constant as the reservoir level fluctuates. A flow rate not changing relative to a reservoir water level can be an indication of a clogged drain, internal erosion or backward erosion piping, or internal cracking of the embankment dam.

Seepage may be measured with weirs of any shape, such as a V-notch, rectangular, or trapezoidal; flumes, such as the Parshall flume; water exiting a pipe measured with a stopwatch and bucket; and flowmeters. When a new seepage area that produces measurable flow is identified at an embankment dam, the seepage should be monitored and, in some cases, measured. A qualified engineer should promptly evaluate each new seepage area. In some situations, a change in the seepage regime precedes failures. The flow should first be confined and directed away from the embankment dam by excavating drainage channels or ditches. Then, the quantity of seepage can be measured by creating a large enough drop in the drainage channel to install a pipe, weir or flume or to facilitate the measurement of the flow by means of a stopwatch and bucket. The integrity of the seepage measurement devices should be maintained so that seepage does not bypass the device and the device is kept clear of obstructions.

Points where seepage measurement devices are added are often a good location to measure the amount of sediment that may be carried in the seepage. Sediment transport is often a sign of internal erosion or backward erosion piping failure modes. Providing an area adjacent to a weir where water flow is stilled can allow some of the sediment in the water to fall out and collect with time.

Seepage into conduits should also be monitored where it is determined to be important. Note that if the seepage into a conduit is transporting material, operations of the conduit may be transporting material out of the conduit. Frequently, the highest seepage gradient at a site is associated with seepage into a nonpressurized conduit. For this reason, inspection of the conduit is important. The internal erosion and backward erosion piping processes are frequently intermittent, and in many cases, the transport of materials in the seepage is sporadic. Inspection should look for signs of deposits, as well as clarity of the seepage.

9.8.4 Horizontal or vertical movements

Movements in the embankment dam or foundation have been known to damage conduits and create potential internal erosion backward erosion piping conditions. On soft, stiff, or weak foundations, it is important to realize that the conduit will be deformed over its length as it follows the deformations of the foundation. Conduits within large embankment dams have also experienced distress on rock foundations over areas where the foundation stiffness varies greatly due to the presence of shears, faults, or soft zones. Designs should account for these conditions, and consideration should be given to the possibility of distress in monitoring for horizontal and vertical movement. When monitoring a crack in the conduit, crack meters are also used to determine if the crack is formed due to temperature and shrinkage, or due to slope movement in the embankment dam.

Movements of embankment dams are generally caused by stresses induced by reservoir water pressure, unstable slopes (low strength), low foundation strength, settlement, thrust due to arching action, expansion resulting from temperature change, and heave resulting from hydrostatic uplift pressures. Monitoring displacements can be helpful in understanding the normal behavior of an embankment dam and in determining if a potentially hazardous condition is developing. The displacements, both horizontal and vertical, are more commonly measured on the surface of the embankment dam. Measuring displacements of points on the surface is usually accomplished by conventional surveying methods and the installation of permanent surveying points/monuments.

External vertical and horizontal movements are measured on the surface of embankment dams through the use of level and position surveys of reference points. Reference points may be monuments or designated permanent points on the embankment dam crest, slopes, or toe of the embankment dam or on an appurtenant structure.

For saturated areas on the downstream slope of an embankment dam, the perimeter of the hole or wet area should be surveyed to determine the extent of the area. As a minimum, the perimeter of the hole or wet area can be staked out with metal fence posts or wooden stakes (figure 137) and the length, width and location of the wet area recorded and photographed for future reference. For saturated areas on the embankment dam face, the degree of wetness should also be estimated and recorded, such as "boggy," or "surface moist but firm underfoot." Any flow of water from the wet area or into a sinkhole should be measured, if possible, and/or estimated and recorded. See section 11.3 for guidance on actions involving sinkholes.

Detecting surface evidence of slope instability is of primary importance. Such evidence includes slope bulging, sagging crests, foundation heave at or beyond the toe, and lateral spreading of foundations and embankments. During the operation of

Figure 137.—The perimeter of a wet area at the downstream toe of an embankment dam located with wooden stakes.

the embankment dam, measurements of lateral transitional movements from forces caused by pool loading, reservoir drawdown, gravity, and the effects of seepage pressures are required to help evaluate safe performance of the embankment dam.

The measured internal movements of embankment dams consist principally of vertical movements and relative horizontal movements caused mainly by the low shearing strength or the long term creep strain of the foundation or embankment materials. Internal movements generally result in external movement of the embankment dam's crest or side slopes. Internal displacement-monitoring plans can be very complex and expensive. Internal movement-monitoring devices consist of baseplates, inclinometers, tiltmeters, extensometers, and shear strips.

In the event of an emergency situation at a damsite, some relatively simple devices can be installed to monitor embankment dam movement, such as cracks and slides. If a small crack is observed on the embankment dam, it may be very important to know if the crack enlarges. An easy method of monitoring the crack is to drive steel rebar or wooden stakes on both sides of the crack to monitor additional separation and vertical displacement on one side of the crack relative to the other side. Also, the ends of the crack should be staked to determine if the crack is lengthening. This scheme can be used to monitor both longitudinal and transverse cracking.

Another special situation, which would require immediate attention, is the development of a slide on one of the embankment dam slopes. A simple yet reliable method to measure movement of the slide area would be an alignment method. A strong wire is stretched across the slide and tied to pins outside of the slide area. At intervals along the wire, pins are driven into the slide mass. If additional movement occurs, the amount is directly determined by measuring the distance between the pins and wire.

If a defect is suspected in a conduit, an inspection using man-entry or CCTV methods is required.

9.8.5 Water quality

Seepage comes into contact with various minerals within the soil and rock in and around the embankment dam and its foundation. This can cause two problems: the chemical dissolution of a natural rock, such as gypsum, or the internal erosion of soil. Dissolution of minerals can often be detected by comparing chemical analyses of reservoir water and seepage water. Such tests are site specific; for example, in a limestone area, one would look for calcium and carbonates, and in a gypsum area, calcium and sulfates. Other tests, such as pH, might provide useful information on chemical dissolution.

Internal erosion and backward erosion piping can be detected by comparing the turbidity of reservoir water with that of seepage water. An increase in turbidity may indicate internal erosion and backward erosion piping of the materials. A method of comparing observations is to collect a sample of the water in a large glass jar, which is marked with the date and location the sample was collected and retained for future comparison. Another jar should be used for the next water sampling. Glass jars should be filled periodically with the seepage flow and set aside to allow for any material to settle out. By comparing jars, one can determine if material is moving and if it is increasing. However, this method does have some limitations, since material transport is not usually continuous and can be episodic. For certain tests, such as iron bacteria, the sample must be kept refrigerated until tested.

The frequency of instrument readings or making observations at an embankment dam depends on several factors and could include the following items:

- Relative hazard to life and downstream property damage that the failure of the embankment dam represents
- The importance of the instrument in detecting a failure mode
- The nature and urgency of an emergency condition being investigated and monitored at the damsite

- Height or size of the embankment dam
- Volume of water impounded by the embankment dam
- Age of the embankment dam
- History of the performance of an instrument
- Frequency and amount of water level fluctuation in the reservoir
- Frequency of staff visits for other reasons, such as operations

In general, as each of the above factors increases, the frequency of the monitoring should also increase. For example, very frequent (even daily) readings should be taken during the first filling of a reservoir and more frequent readings should be taken during emergency events and high water levels in the reservoir under storm and seismic events. As a rule of thumb, simple visual observations should be made during each visit to the damsite. In the event of an emergency at the damsite under potential dam failure, and/or imminent dam failure, the frequency of the instrumentation monitoring and visual observation could vary from weekly to daily to hourly or less, depending on the nature and urgency of the situation. Lights are frequently employed during critical times to facilitate nighttime observations. In almost all cases, the consequences would be greatest if failure occurred at night.

Documentation and recording of the instrumentation readings and data and visual observations are very important in the monitoring and evaluation of an emergency situation at a damsite. The documentation should include tabulations of the instrumentation readings and data, written documentation of the visual observations and findings, and photographs of key elements or features of the investigation at the site during the occurrence of an emergency. The documentation should include the instrumentation description, location and readings, the date and time of the readings and observations, the reservoir water surface and tail water levels, the releases being made from the embankment dam, weather conditions, evaluation of the present condition of the embankment dam and comparison of previous information, and the recommendation for monitoring and/or remedial measures to correct the deficiency.

Proper training of those who are to inspect and take readings at the embankment dam is very important. Training will ensure that the inspection staff are familiar with the proper method to read the instruments, what other data and information from the site is necessary, what anomalous behavior might look like, how to report normal and unusual conditions, and what steps need to be taken in an emergency.

9.8.6 Reservoir water level and flows

The reservoir water surface level is a key item to record when measuring other instrumentation at a damsite and should be measured and recorded each time the embankment dam is visually inspected, and when other instrumentation is observed or read. The reservoir water level is also used when evaluating the information provided by the other instruments at the site. For instance, the amount of seepage exiting the embankment dam as it relates to reservoir water level is often crucial. A pattern of increasing seepage at the same reservoir level is cause for concern. Water levels may be measured by simple elevation gauges, such as a staff gauge or numbers painted on permanent, fixed structures in the reservoir, or by complex water-sensing devices. Reservoir flow release quantities are often computed from the depth of flow in the conduit or exit channel or by predetermined conduit discharge rating tables/curves. During an emergency, it is important to monitor the water level in the reservoir and the downstream pool regularly, along with the quantity of water being released from the embankment dam's outlet works and spillway.

Chapter 10

Evaluation by Geophysical and Nondestructive Testing

Geophysical and nondestructive testing (NDT) techniques can be used to investigate the condition of a conduit directly or indirectly by providing data on the condition of the conduit and the surrounding embankment dam. These techniques are used to detect flaws, defects, deterioration, and other anomalies that could lead to a failure and do not disturb the feature being evaluated or tested. The most common techniques used include:

- Seismic tomography
- Self potential (SP)
- Electrical resistivity
- Ground-penetrating radar (GPR)
- Sonar
- Ultrasonic pulse echo and ultrasonic velocity
- Mechanical and sonic caliper
- Radiography
- Surface hardness

Depending on the particular situation, some techniques are more effective than others. The selection of the applicable technique(s) requires evaluation of the type of information needed, the size and the nature of the project, the conditions existing at the site, and any impacts that may result to the structure from performing the technique. These techniques require trained and experienced personnel to perform and interpret the results. The various applications for these techniques are summarized in table 10.1. The following sections briefly discuss these techniques.

Table 10.1.—Geophysical and NDT techniques

Investigation methods	Problem identification	Comments
Seismic tomography	Voids along outside of the conduit	Best results when inside of conduit is accessible. Good results may or may not be obtained, if sources and receivers are on outside. Target resolution is very frequency-dependent, and will strongly depend on composition of zones in a zoned embankment. Air-filled voids easier to detect than water-filled voids.
Self-potential	Seepage along outside of the conduit	Provides direct detection of seepage. Data interpretation may be difficult. Data are generally acquired at high- and low-pool conditions, for comparison.
Electrical resistivity	Locations of large buried metallic objects, possibly indicating seepage zones	Available equipment can acquire large volumes of data, interpretation and nonuniqueness may be an issue. Independent ground truthing is advisable.
Ground-penetrating radar	Locations of suspected voids, and delaminations	Depth of penetration limited in clay soils; good technique for concrete structures; can be used to image from inside of the conduit outwards. Air-filled voids easier to detect than water-filled voids. Independent ground truthing is advisable.
Sonar	Displacement and delaminations within conduit	Provides a direct measure of the interior condition of the conduit.
Ultrasonic pulse velocity	Concrete quality, thickness, and/or delamination	Limited to about 1.5 ft of thickness when access is limited to one side. With access on both sides, concrete quality can be evaluated for much thicker sections.
Ultrasonic pulse echo		Depth of investigation limited to 1 ft. Requires access to only one side of surface to be investigated. Can be used underwater (with waterproof transducers). Considerable judgement/experience required.
Ultrasonic pulse echo	Steel pipe wall thickness	Requires access to only one side of surface to be investigated. Can be used underwater (with waterproof transducers).
Mechanical caliper, sonic caliper	Inside dimensions of conduit	Typically used in conduits 18 inches or larger to detect changes or defects within the conduit.
Radiography (x-ray)	Steel weld integrity	Access to both sides of conduit wall is required.
Surface hardness	Concrete quality	Imprecise measurements of concrete strength.

Additional information on nondestructive testing is available in Molhotra and Carino (2004), USACE's *Evaluation and Repair of Concrete Structures* (1995b), and ACI (1998a).

10.1 Seismic tomography

The seismic tomography method (figure 138) is a noninvasive geophysical method similar to methods applied in medicine, such as ultrasound, computerized axial tomography (CAT) scans, and magnetic resonance imaging (MRI). Seismic tomography uses elastic waves produced by seismic sources implanted around or within boreholes in the embankment dam. Receivers (geophones or accelerometers) installed at other locations on the structure record the generated waves.

Seismic tomography uses the same processing technique as in the medical field, but the image is not as detailed, since sources and receivers cannot be placed at all sides of the embankment dam, and because the frequencies propagated are much lower than those used in medical imaging. However, surface-mounted sources and receivers may be sufficient to discover potential problems within the structure of the embankment dam. Target detection depends strongly on the ability to transmit and receive high frequency seismic energy through the embankment dam, the dimensions of the suspected target, the location of the phreatic surface, and whether the

Figure 138.—Seismic tomography being used on an embankment dam. Photo courtesy of URS Corporation.

suspected voids or stopes are air- or water-filled. Placement of sources and receivers inside the conduit, when accessible, can improve the technique.

The parameters recorded can provide important information about different features that may damage the embankment dam's structure, such as fractures, low density regions, saturated zones, and high stress regions. The results may be presented as cross-section images (figures 139 and 140) of compression (P- [primary]) wave velocity, or of seismic wave attenuation. These properties may be correlated to other engineering parameters of interest, such as possible fractured zones, and potential void areas. For an embankment dam in Maryland (Schaub, 1996, p. 3), the tomographic investigation interpretations revealed that the relative compaction of the earthfill around a CMP spillway conduit ranged from 65 percent to nearly 100 percent. The areas with the lowest interpreted densities were found to be under, along, and above the conduit.

For concrete, high compression (P-) and shear (S- [secondary]) wave velocities indicate competent concrete. Lower velocity values may indicate cracking, deterioration caused by ice and other weathering, alkali reaction, or defects.

10.1.1 Spectral analysis of surface waves

Recently developed geophysical procedures called Spectral Analysis of Surface Waves (SASW) and Multichannel Analysis of Surface Waves (MASW) measure the "dispersion" of surface wave velocities to evaluate material properties. (Billington and Basinger, 2004, p. 4; Park et al., 2001; and Miller et al., 1999). These techniques, termed "indirect methods," since the measurements can be made from one side of a structure, provide estimates of material properties averaged over relatively large distances.

The SASW/MASW techniques can be used on a large scale to evaluate embankment dams, such as for locating possible voids or potential seepage zones along a conduit (Stokoe, 1999, p. 3). On a smaller scale, these techniques can be used to evaluate the quality of conduit materials, such as concrete deterioration and loss of wall thickness due to corrosion.

Use of surface wave data is a powerful technique that allows measurement of soft layers beneath harder layers. This means that SASW/MASW may be able to detect possible voids in the backfill adjacent to a conduit by making measurements from inside of the conduit. (In comparison, the seismic refraction technique generally cannot be used to locate softer layers under harder layers.)

The basis of the methods is measurement of the "dispersion" of Rayleigh type surface waves (USACE, 1995c, p. 3-24). Essentially, surface waves of different wave

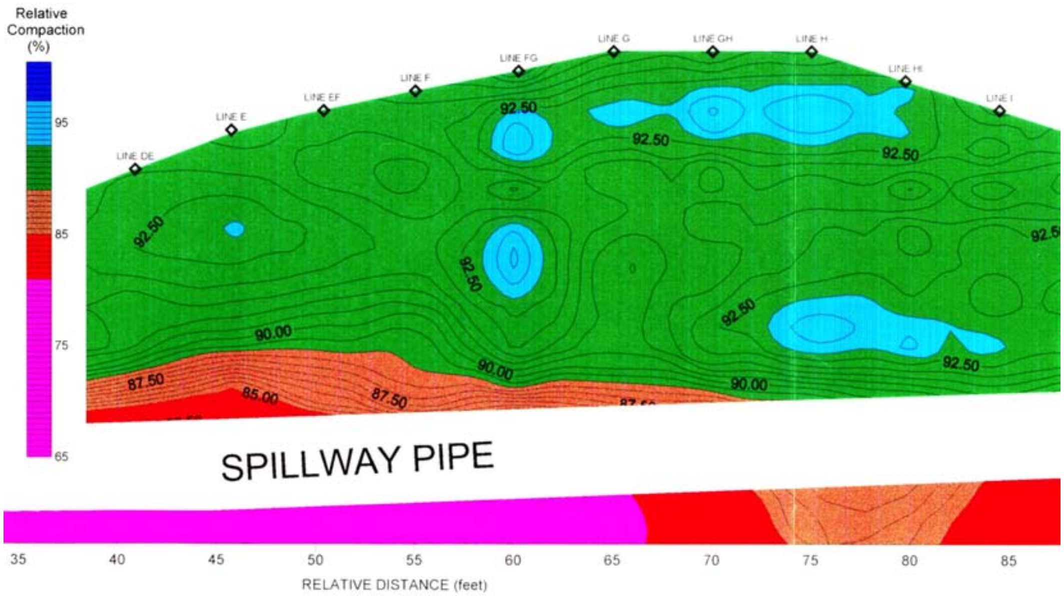

Figure 139.—Seismic tomography profile along failed CMP spillway conduit in an embankment dam.

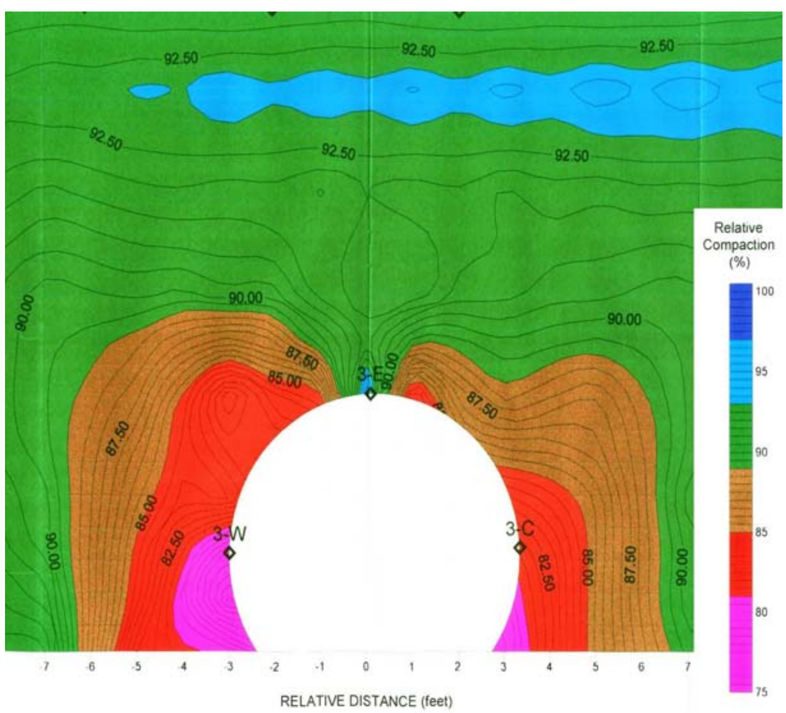

Figure 140.—Typical section from seismic tomography used to identify voids along the outside of a CMP spillway conduit in an embankment dam.

lengths (frequencies) propagate at different velocities through nonhomogeneous materials. This variation in velocity is related to the shear wave velocity and thus shear modulus (Shaw, 2003).

Different equipment is used depending on whether the SASW/MASW technique is to be used for geotechnical analysis of soil (to depths of 3 feet to 300 feet), or for structural evaluation of concrete. The equipment generally consists of two or more geophones, a hammer or other impact device for generating vibrations, and a seismograph or other data collection unit.

Higher wave frequencies and close geophone spacing are used for shallow investigations, and lower frequencies with wider spacing are used for deeper investigations. The field data are later processed with specialized software, such as WinSASW, developed by the Geotechnical Engineering Center of the University of Texas at Austin, or SurfSeis, developed by the Kansas Geological Survey.

10.2 Self potential

Self potential (sometimes referred to as streaming potential or SP) (figure 141), measures the electrical potentials (or voltages) that exist in the ground or within an embankment dam. Flowing water naturally generates these potentials as a consequence of the separation of ions in the seepage water itself. SP is considered to be the only geophysical method capable of direct detection of seepage (Corwin, 2002). Other geophysical methods, such as resistivity, infer the existence of seepage based on other measured parameters.

Theoretically, it is possible to measure these potentials and predict seepage anomalies, such as along a conduit within the embankment dam, up to several hundred feet deep. However, the technique is not widely applied, and few people or contractors can expertly interpret the data. In addition, the measured potential (usually on the order of tens of millivolts) in any area can vary with other in-situ parameters, and with man-induced voltages.

Existing procedures were developed for the USACE's Waterways Experiment Station and published in 1989 (USACE, 1989), and also for the Canadian Electricity Association Dam Safety Interest Group (Corwin, 2002). SP interpretation and modeling computer programs are beginning to be developed along the lines of existing programs available in other geophysical disciplines, such as resistivity and seismic methods.

Canadian Electricity Association Technology, Inc. has published a series of DOS program codes (Corwin, 2002) and the University of British Columbia has available a modeling procedure that runs under Visual ModFlow, and models the SP response

Figure 141.—Collecting self potential (SP) data on the crest of an embankment dam in Virginia to trace the source of observed seepage. The 75-ft high embankment dam had a sinkhole, a sand boil, and several seepage points on the downstream face. This information was used in complement with electrical resistivity imaging data. Photo courtesy Schnabel Engineering.

for a user input distribution of permeability and electrical resistivity parameters (Sheffer, 2002).

Self potential measurements are affected by soil moisture, resistivity, temperature, and other in situ parameters. Therefore, the SP technique should be combined with other methods, such as resistivity or temperature measurement.

10.3 Electrical resistivity

Electrical resistivity technology is relatively well developed and can be a very effective tool for locating large buried metal targets, and other highly electrically resistive or highly conductive targets (Ward, 1990) . The technique, involving an array of electrodes that measure the distribution of voltage applied to the ground, has been used to investigate some embankment dams. However, small changes in measured data can result in very different interpretations. Resistivity interpretations are nonunique, and should be constrained by independent data. Other field parameters (permeability, dissolved minerals, temperature) may need to be measured at the same time. The method is sensitive to interference from nearby metal objects (such as pipes and wires within the embankment dam, or overhead wires and fences).

One- or two-dimensional, or tomographic software can be used to process the data, which can be displayed as color plots of resistivity versus depth. Currently, available field equipment is capable of obtaining and automatically processing large numbers of resistivity measurements, regardless of data quality. Automatic processing can lead to misinterpretation of the data, if the operator does not recognize the problem, or is not familiar with nonuniqueness effects in conducting resistivity surveys.

10.4 Ground-penetrating radar

Ground-penetrating radar (GPR) uses high frequency electromagnetic energy to penetrate below the ground surface (figure 142). An antenna is used to transmit a short duration pulse, which travels through the air and the subsurface until it is reflected back by a change in the dielectrical properties of the material being imaged. The resulting reflections are displayed in sounding or section format, with sections being the far more common display mode. If the GPR profiles are conducted on a close spacing, the resulting data can be treated in a data volume manner, allowing arbitrary slices through a three-dimensional data mass. This three-dimensional technique can be labor intensive to acquire and process.

GPR can be used to locate possible void, stope, or incipient sinkhole areas. However, the depth of penetration of radar waves in soils and concrete depends strongly upon the electrical resistivity of the material in question. Saline pore water and clay-rich soils can severely limit this depth of penetration. Metals are opaque to radar energy, so complete radar wave reflection occurs at metal surfaces, such as steel conduit and rebar. Soils or concrete behind such metallic objects will have shadow zones or other absence of data.

Figure 142.—Conducting a ground-penetrating radar survey across dam crest to locate voids beneath roadway and spillway. Photo courtesy Schnabel Engineering.

Known void areas are extremely useful in "calibrating" a GPR survey at a particular site. Lacking known void areas, core drilling or other direct inspection methods are highly desirable to aid in the GPR data interpretation. GPR data profiles can be difficult to interpret properly, if no site "ground truth" is available. Figure 143 shows a core hole being drilled to reveal voids behind the concrete, and figure 144 shows an example of GPR profiles along a conduit invert.

Because the radar waves travel equally well in all directions, GPR may be used to image from the inside of a (nonmetallic) conduit outwards, along crown, springlines, and invert. Modern GPR equipment is commonly mounted on a cart or pole to allow imaging in the required direction. Note that steel well casings, communication cables, metal buildings, overhead wires, and other cultural features can cause anomalous-looking radar profiles. The GPR interpreter must be aware of the locations of such features at the site.

10.5 Sonar

For inundated conduits with a heavy suspended sediment load and very poor visibility, three-dimensional real-time imaging sonar is advantageous. A rotating sonar transducer mounted on a sled, crawler vehicle, or ROV can be used to scan and record the condition of a conduit (Sonex Corporation, 2002). Since the times

Figure 143.—A core hole is being drilled to reveal voids behind the concrete in this conduit.