UNDER PRESSURE: AGING OUTLET CONDUITS

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Abstract

The Federal Emergency Management Agency's (FEMA) *Technical Manual: Conduits through Embankment Dams (FEMA 484)* describes four potential failure modes (PFM) associated with nonpressurized and pressurized conduits through embankment dams. The first part of this paper identifies the four PFMs described in *FEMA 484*; discusses factors that contribute to failure along conduits; and reviews the erosion process of soils by flow from a pressurized conduit, which is designated as Potential Failure Mode Number Two (PFM 2). Older water supply dams were often constructed without upstream control, resulting in conduits that are constantly pressurized, and given the period in which these aging dams were constructed, many of these conduits are made of cast iron. Since PFM 2 results from high pressure flow exiting from a defect in a conduit, the mechanisms and contributing factors that lead to the corrosion and potential failure of iron pipes are discussed. Two methods to identify potentially corrosive conditions and data related to corrosion rates of cast iron pipe are also presented.

The second part of this paper focuses on issues related with the inspection and assessment of pressurized conduits through existing embankment dams. Some regulatory agencies require owners to inspect their conduits by dewatering and/or providing upstream control; however, owners understandably resist given the difficult-to-quantify risk. The prospect of dewatering an aging conduit that is normally pressurized to facilitate inspection and/or rehabilitation presents significant concerns, primary of which is collapse of the pipe by the unbalanced loading. Since reservoir drawdown would result in loss of water supply, inspection of conduits under full reservoir head is often required and sometimes difficult to achieve. Typical bulkhead and plug configurations used to dewater conduits will be presented. Effective inspection of the pipe requires that the pipe walls be cleaned by pigging, scraping, or jetting. The interior walls of pipes, specifically cast iron pipe, may be covered with several inches of tuberculation. While the tuberculation is a byproduct of corrosion, it also acts as a protective layer that reduces the rate of corrosion. Pipe cleaning methods may remove the protective layer, and can accelerate the corrosion process unless the pipe is lined. Possible non-destructive testing to estimate pipe section loss is also explored.

The final section of this paper presents several means to reduce the risk of failure associated with pressurized conduits through existing embankment dams. Since project teams are challenged with balancing technical and regulatory requirements to improve the

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safety of existing dams while reducing the risk of damage to achieve those goals, recommendations are presented for a risk-based decision-making process to evaluate the need for inspection and/or rehabilitation of pressurized conduits.

Review of FEMA 484

Outlet conduits are typically installed through embankment dams to allow the conveyance of reservoir water through the site in a controlled manner. In the United States, tens of thousands of these conduits are aging and deteriorating, which, if left unaddressed, pose a significant risk of developing defects that could ultimately lead to catastrophic dam failure (FEMA 2005a). To address this concern, FEMA developed a technical manual in conjunction with several other federal agencies, including the Association of State Dam Safety Officials (ASDSO), entitled *Technical Manual: Conduits through Embankment Dams*, or *FEMA 484*. This comprehensive document provides procedures and guidance for best practices related to design, construction, inspection, evaluation, maintenance, and rehabilitation of conduits through embankment dams. One objective of this paper is to discuss the failure mode associated with *Erosion of Soils by Flow from a Pressurized Conduit* identified as PFM 2 in *FEMA 484*. However, several introductory topics will be discussed/defined first to provide a common understanding of the terminology used in this paper.

Nonpressurized vs. Pressurized Conduits

Since the second part of this paper focuses on the inspection and assessment of pressurized conduits through earthen dams, a distinction must be made between pressurized and nonpressurized conduits. Nonpressurized flow can be characterized as open channel (or free flow) discharge at atmospheric pressure through either a portion, or the entire, conduit length (FEMA 2005b). This type of flow occurs when regulating gates or valves are located at the intake structure on the upstream side of an embankment as illustrated in Figure 1.

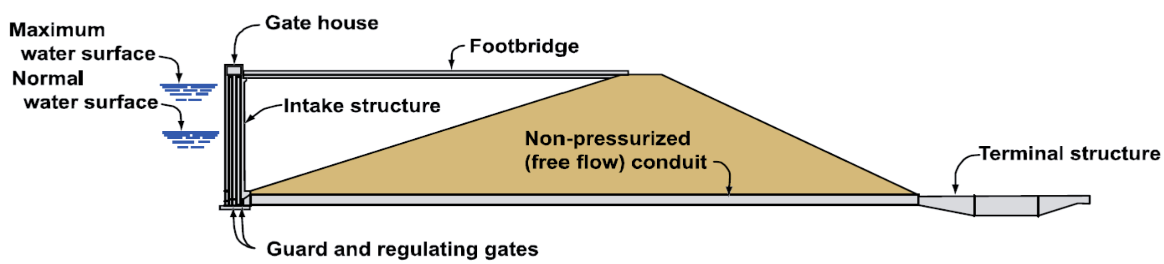

Figure 1. Upstream Control (Figure from FEMA 2005b).

This configuration is often referred to as 'Upstream Control.' Due to the potential for large external hydrostatic pressures acting on the conduit, the conduit must be kept watertight to avoid leakage through joints and cracks, which could allow embankment materials to be carried into the conduit (FEMA 2005b). Because the conduit can be dewatered by operating the upstream gates, access for inspection and maintenance along the entire conduit length can be relatively straight forward. While there are risks associated with Upstream Control, there is typically more concern with pressurized flow and Downstream Control.

When gates/valves are located at the terminal structure on the downstream side of the embankment, pressure flow exists through the entire length of conduit. This configuration is illustrated in Figure 2 and is commonly referred to as 'Downstream Control.'

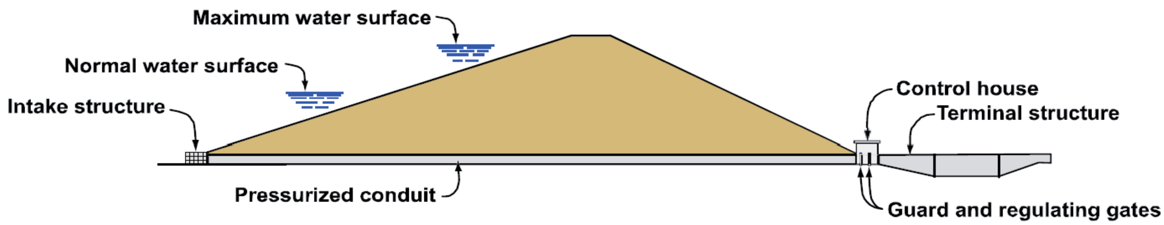

Figure 2. Downstream Control (Figure from FEMA 2005b).

Due to the gate configuration, access for inspection and maintenance is often difficult. Either the reservoir must be drained or the conduit dewatered by means of installing an upstream bulkhead from the reservoir side with divers. This arrangement typically presents more risk than Upstream Control. When full hydrostatic pressure exists on the interior of the conduit, a defect could allow high pressure flow to exit into, and subsequently erode, the surrounding fill (FEMA 2005b).

Internal Erosion and Backward Piping Erosion

Water leaking into or out of defects in conduits can contribute to excessive seepage pressures as compared to ordinary steady state embankment seepage. If preferential flow paths develop, the excessive seepage pressures can cause erosion in the surrounding fill and may compromise the safety of the dam. 'Internal erosion' and 'backward piping erosion' are two distinctly different terms used to describe erosional failure mechanisms of embankment dams.

Internal erosion is a general term used to describe various erosional processes, such as scour, concentrated leak piping, suffusion, etc., where water moves through cracks, discontinuities or other preferential seepage paths in embankment dams and foundation materials. Concentrated seepage typically results from internal erosion (FEMA 2005a).

Backward erosion piping applies to conditions where water flows through the pore structure of a saturated soil (i.e., intergranular seepage), not along concentrated seepage paths. In order to initiate backward erosion piping, there must be a high hydraulic gradient acting on soils that are susceptible to this phenomenon. Erosion becomes evident in the form of a boil or particle detachment at an exit face that is not properly filtered. As the soil particles are removed, erosion progresses backwards toward the seepage source. For backward erosion piping to progress to failure, soils susceptible to erosion must be present along the entire flow path. The material being eroded must also be able to support a 'pipe' or 'tunnel,' or be adjacent to a feature such as an overlying clay layer or concrete structure (FEMA 2005b).

PFMs Associated with Conduits and Contributing Factors

FEMA's *Federal Guidelines for Dam Safety* (FEMA, 2004) define a PFM as a "physically plausible process for an embankment dam failure, resulting from an inadequacy or defect related to a natural foundation condition, the dam or appurtenant structure's design, the construction, the materials incorporated, the operation and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir." The four PFMs associated with conduits through embankment dams identified in *FEMA 484* include:

1. PFM 1: Backward Erosion Piping or Internal Erosion of Soils into a Nonpressurized Conduit

2. PFM 2: Backward Erosion Piping or Internal Erosion of Soils by Flow from a Pressurized Conduit
3. PFM 3: Backward Erosion Piping or Internal Erosion of Soil Along the Outside of Conduit Caused by Hydraulic Forces from the Reservoir
4. PFM 4: Internal Erosion of Hydraulic Fracture Cracks in the Earthfill Above, Below or Adjacent to the Conduit

In addition to understanding the basic PFMs, it is also essential to recognize the following factors that can affect the timing and severity of failure so that appropriate responses and/or remediation measures can be implemented (FEMA 2005b):

1. Type of material of the conduit
2. Dimensions of the conduit defect (crack, hole, etc.) compared to the gradation of the surrounding soil
3. Susceptibility of the surrounding soil to internal erosion and/or backward erosion piping
4. Cracks in surrounding soil that are directly connected to water sources
5. Seepage gradient
6. Presence of pressurized or non-pressurized flow
7. Ability of surrounding soil to support an erosion tunnel or pipe

This paper is focused pressurized conduits through dams; therefore, discussion is focused on the failure mode associated with PFM 2: *Erosion of Soils by Flow from Pressurized Conduits*. Refer to *FEMA 484* for more details related to the other three PFMs.

PFM 2 – Erosion of Soils by Flow from a Pressurized Conduit

For this PFM to occur, high pressure flow exits the pressurized conduit through defects and erodes surrounding soils. This often occurs if the conduit has collapsed, has open joints, or is completely deteriorated. The sequence for this PFM is illustrated in Figure 3 and may include the following (FEMA 2005b):

1. Water flowing out of a pressurized conduit begins seeping through the embankment and emerges at an exit face. Particles can be carried by the seepage if the exit face is not protected by a properly designed filter.
2. Seepage forces detach soil particles from the exit face and backward erosion piping occurs if the soils are susceptible to erosion and are able to support a tunnel or pipe. Internal erosion can occur if a preferential seepage path (hydraulic fracture) develops that is directly connected to a conduit defect and the internal conduit pressure is high enough.
3. A dam breach can occur if the erosion feature extends from the conduit defect to the exit face.

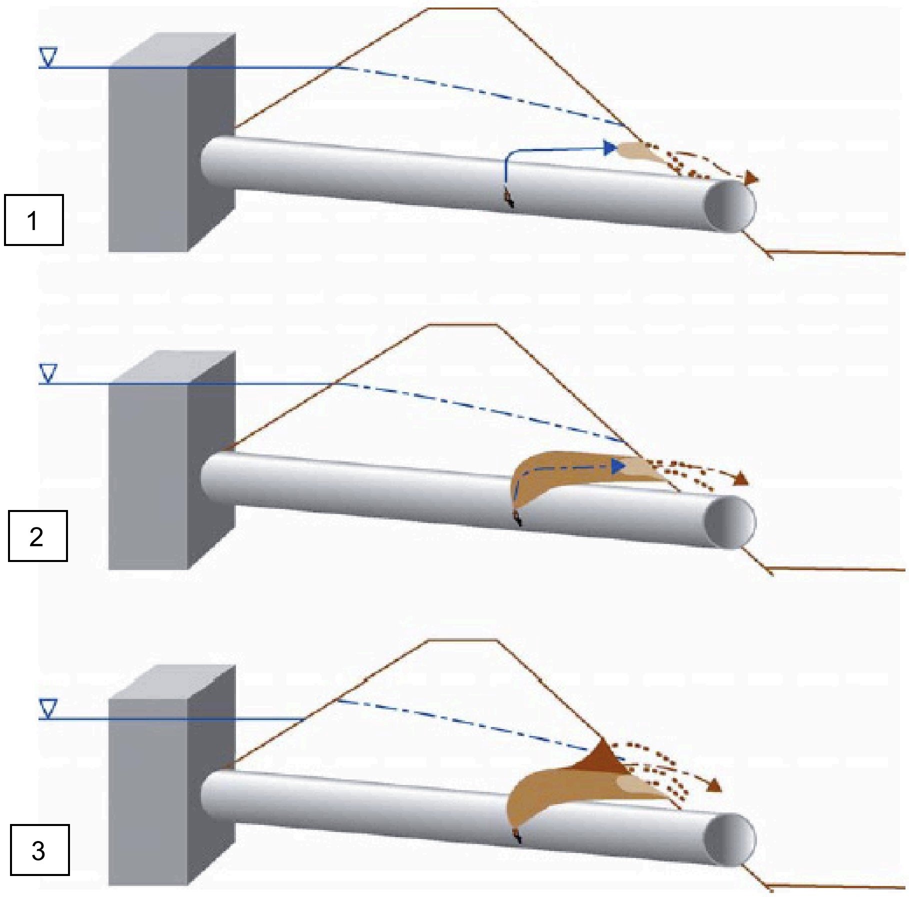

Figure 3. PFM 2 – Sequence of Backward Erosion Piping or Internal Erosion of Soils Surrounding a Pressurized Conduit with a Defect (Figure from FEMA 2005b).

For new dams, pressurized conduits are avoided where possible. However, when pressurized conduits are utilized, several design measures are typically selected to eliminate or reduce the likelihood of developing this failure mode, including using conduit materials that are resistant to deterioration, ensuring watertight joints for pressure flow conditions, and designing conduits to resist cracking from applied loads and foundation movements. Pressurized conduits could also be constructed in a rock trench, in a concrete encasement or installed in a non-pressurized 'carrier pipe'. For existing dams, other means are required to reduce risk and are discussed later in this paper.

Iron Pipes

PFMs Associated with Iron Pipes and Contributing Factors

Since the PFM described above hinges on high pressure flow exiting from a defect in a conduit, it is important to recognize the mechanisms and contributing factors that lead to the corrosion and potential failure of cast iron pipe (CIP) and ductile iron pipe (DIP). At the most basic level, pipe failures are caused by applied forces exceeding the residual strength of the metal. The applied forces can be divided into five groups: those produced by internal water pressure; bending forces; external pressure and crushing forces; soil movement-induced tensile forces; and temperature-induced expansive forces (Makar et al. 2001). PFMs associated with iron pipes tend to vary depending on the diameter of the pipe. Smaller diameter pipes have smaller moments of inertia, which make them more susceptible to bending failures. Larger pipes have higher moments of inertia, producing a tendency to longitudinal cracking and shearing at the bell (Makar et al. 2001). Listed below are common PFMs of CIP, along with the most likely cause of the failure:

1. Blowout holes (from corrosion pitting and loss of resistance to pressure)
2. Circumferential cracking (from bending forces; most common in small diameter pipes)
3. Bell splitting (from differential thermal expansion of “leadite” sulfur-based joint compound)
4. Longitudinal cracking (from internal water pressure, crushing forces, or longitudinal compression; more common in large diameter pipes)
5. Bell shearing (from bending at a joint and lever action of adjacent pipe)
6. Spiral cracking (believed to be from combination of internal pressure surge and bending forces)

Contributing factors leading to the development of these PFMs include corrosion, manufacturing defects, excessive applied forces, and human error. Corrosion often takes the form of pitting, where there is visible loss of material from the pipe’s surface. Corrosion likely plays a part in all of the above PFMs. For example, where chains have been used to lift a pipe, the abrasion and removal of the pipe’s protective coating can lead to pitting and eventual circumferential cracking failure of the pipe.

Corrosion can also take the form of graphitization: the selective dissolution of the iron matrix in the alloy, leaving behind only graphite flakes or nodules and corrosion products (Spickelmire 2012). The graphite flakes are held together in part by iron oxide, forming a solid substance on the pipe, and giving the appearance of undamaged material. Graphitic corrosion occurs over time to yield a structure that is weaker and more brittle than the original structure. Although little dimensional change occurs, the strength and other metallic properties, such as hardness, electrical, and thermal properties of buried pipe, can be significantly altered (NRC 2009). However, it has also been shown that graphitized pipe can have enough mechanical strength to withstand minimum pressure requirements in service. Melvin Romanoff of the National Bureau of Standards demonstrated that graphitized CIP could withstand pressures up to 500 pounds per square inch for 1.5-inch (3.8-cm) Class 150 pipe even if completely penetrated by graphitization (NRC 2009).

Manufacturing defects can also lead to the ultimate failure of CIP. Defects can take the form of porosity (air bubbles), which is the most common defect in pit-cast pipe. Inclusions, unintentional objects created in the casting process, are found in both pit-cast and spin-cast pipe. For example, undissolved ferrosilicon (added to the iron to lower the melting point) can create a disruption in the fabric of the pipe and act as a crack former (Makar et al. 2001). For spin-cast pipe, certain longitudinal flaws can be created during the spin casting process and lead to longitudinal type failures. However, the pit-casting method can also result in longitudinal flaws such as variable wall thickness, which can sometimes result in thickness variations of up to fifty percent between opposite sides of the pipe (Makar et al. 2001).

Identifying Potentially Corrosive Conditions

A 10-point corrosion rating system was originally developed by the Cast Iron Pipe Research Association (CIPRA, now DIPRA) in 1964 to serve as a guide for identifying potentially corrosive conditions to iron pipe. It is also currently contained in Appendix A of Standard C105/A21.5 (ANSI/AWWA) and ASTM A674. The 10-point system uses information drawn from five tests and observations: soil resistivity, pH, oxidation-reduction potential, sulfides, and moisture. For a given soil sample, each parameter is assigned points according to its relative contribution to corrosivity. Resistivity has the widest range of values and potentially has the greatest impact on the rating of a soil, with 2000 ohm-cm as the break point between higher and lower ratings. If the sum of all scores is 10 or more, the soil is considered potentially corrosive.

The US Bureau of Reclamation (Reclamation) uses the primary criterion of resistivity to identify corrosive soil conditions. Resistivity values less than 2000 ohm-cm are considered to be extremely corrosive, warranting the highest level of corrosion protection measures. Resistivity values between 2000 and 3000 ohm-cm are considered very corrosive, and values above 3000 ohm-cm range from corrosive to mildly corrosive. (Reclamation does not differentiate above 3000 ohm-cm and specifies polyethylene encasement as a minimum standard for this third corrosion classification.) Other researchers identify up to six categories of resistivity vs. corrosion potential ranging up to 25,000 ohm-cm (Spickelmire 2012). For soils with high resistivity (lowest but widest range of apparent corrosion potential), Reclamation recommends additional soil testing to identify the presence of other corrosion factors such as pH, sulfates, chlorides, and stray current interference that could warrant additional protection measures. Note that the 2000 ohm-cm threshold is also the break between high and low ratings in the DIPRA 10-point corrosion rating system.

Corrosion Rates

Initially, the rate of corrosion is controlled by the rate of diffusion of oxygen to the surface of the iron from the surrounding environment, which is dependent on the permeability of the soil adjacent to the pipe, the moisture content, and the depth of burial (Peterson and Melchers 2012). In the next phase, the rate of corrosion declines due to a buildup of rust products on the external surfaces and an increasing depth of graphitized zone, which provides an obstruction to the inward diffusion of oxygen to the surface of the metal (Peterson and Melchers 2012). At low moisture content, protective rust layers form quickly, close to the metal surface, and the corrosion rate is controlled by the anodic process. As the water content increases, the corrosion rate also increases up to a maximum value. However, under saturated soil conditions, oxygen is typically absent and corrosion rates are typically slower.

The Ductile Iron Pipe Research Association (DIPRA) has developed a database of more than 60,000 entries of cast iron and ductile iron pipe that includes research on more than 2,000 specimens extending over a 75-year period. Of the 2,000 specimens, 260 were bare or sandblasted gray iron pipe, and 423 were bare or sandblasted DIP. Exposure times ranged from 1 to 103 years for gray iron pipe and 1 to 35 years for DIP. Attempts at developing corrosion rates as a function of time have been elusive to researchers, since corrosion varies with soil type, moisture conditions, oxygen content, and bacterial counts, all of which can fluctuate over time. Thus, although corrosion rates tend to decrease over time as shown in Figure 4, DIPRA used a simplified approach of average values to present the research results. According to DIPRA, the mean deepest pitting rate for ductile and bare-iron specimens ranged from 0.01 to 0.05 in/yr for soils having scores of 10 or greater in the 10-point rating system, with average rates at 0.02 to 0.03 in/yr. The 10-point rating system is described in later sections of this paper. No corrosion rate data was available for uncoated pipe in soils having scores less than 10.

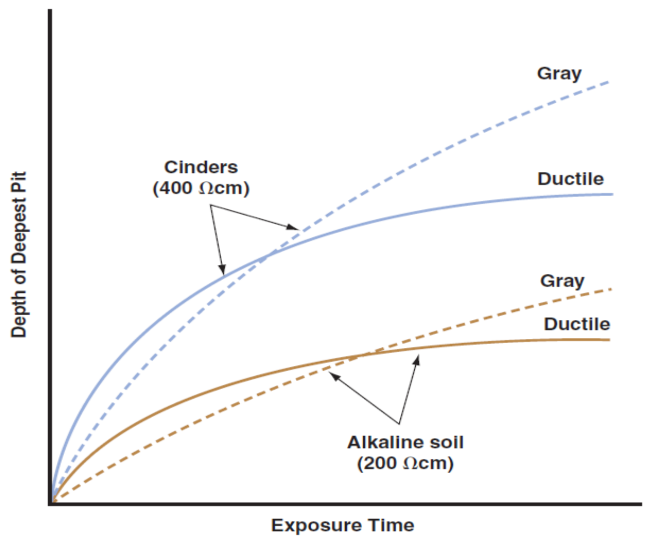

Figure 4. Increases of Maximum Pit Depth with Time for Ductile and Gray Pipes Buried in Two US Sites (Figure from Bonds et al. 2005).

Estimated lifespan for asphaltic coated pipe was available from DIPRA research. For soils that rated less than 10 when analyzed in accordance with the 10-point system, the total estimated years to penetration were 375 for asphaltic coated iron pipe. For soils that rated greater than 10 points, the total estimated years to penetration were only 24 for asphaltic coated iron pipe. For “uniquely severe environments,” tests showed an average of only 9 years to penetration for asphaltic coated iron pipe. Data was not available for uncoated pipe.

Corrosion of ductile iron pipe without surface coatings is comparable to that of CIP, thus allowing a greater database of samples for analysis. The extra thickness of CIP provides more metal for corrosion to attack (sacrificial thickness). As shown in Figure 5, the historical wall thickness difference in some cases can be as much as 75 percent thinner for a similar pressure and diameter pipe. Ductile iron relies on exterior and interior coatings for its corrosion resistance. However, if the wall thickness of ductile iron is only one fifth of the cast iron wall thickness, and if the ductile iron coatings have become compromised by mishandling, then the expected life of ductile iron will be substantially less than for cast iron in similar corrosive environments (Spickelmire 2012).

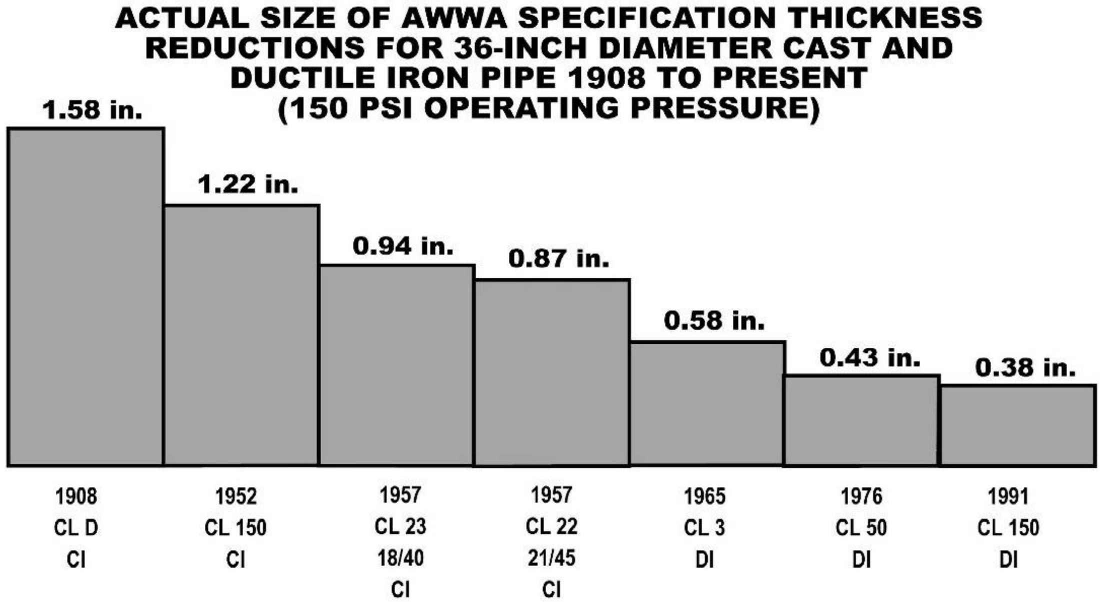

Figure 5. (Figure from Spickelmire 2012).

Inspection and Assessment of Pressurized Conduits

Introduction

Older water supply dams were often constructed without upstream control, resulting in conduits that are constantly pressurized. Consequently, these owners must address issues associated with pressurized conduits to protect their dam(s) from PFM 2 as discussed above and to comply with dam safety regulations.

Regulations regarding conduit inspection and evaluation vary greatly from agency to agency. It is necessary to develop an inspection plan or evaluation that is tailored to the guidance or regulations governing the dam. Some agencies require visual inspections of conduits during routine dam inspections and only perform detailed inspections if the visual inspection indicates the conduit is in a state of distress. Other agencies require detailed inspections on a routine basis that augment the routine visual inspections. These inspections may be required on a regular interval ranging from 2 to 10 years and include inspection of all components of the outlet system, including those on the reservoir side of the dam. Consequently, project teams must identify ways of performing these inspections in the wet, or dewater the outlet works.

Some state dam safety programs require owners to inspect their conduits by dewatering and/or providing upstream control; however, owners of these older dams with downstream control understandably resist given the difficult-to-quantify risk of performing the state-mandated work. The prospect of dewatering an aging conduit that is normally pressurized to facilitate inspection and/or rehabilitation is often difficult and presents significant concerns, primary of which is collapse of the pipe by the unbalanced loading.

Issues with Inspection/Dewatering

As discussed above, outlet inspections are recommended and sometimes required by law to assess the interior condition of conduits. Pipes with diameters of 36-inches or larger can be inspected by manned-entry, assuming proper OSHA precautions are taken. For smaller pipes, specialized inspection services are required and often utilize video equipment mounted on remotely operated vehicles (ROV). In either case, a comprehensive inspection of the interior may be hindered by flowing and/or murky water unless the conduit can be dewatered. This can be very difficult and sometimes costly to achieve in pressurized conduits that are not equipped with upstream control. If possible, the reservoir should be drained to facilitate inspection of the conduit in the dry; however, this is not very practical for most dam owners, particularly for water suppliers who would lose their water supply as a result of the drawdown.

A common means of dewatering is to have a commercial diving contractor install a temporary bulkhead or plug on the upstream opening of the conduit under full reservoir head. Typical configurations may include:

1. Installing a steel plate on the upstream end of a conduit. Depending on the configuration and condition of the conduit, a plate and gasket may be placed directly against the upstream headwall or pipe end to achieve a tight seal. If the conduit has a flanged end, the plate can be bolted to it. The plate will incorporate a valve to allow pressure equalization for plate removal at the completion of the inspection. Installation of additional pipe fittings and accessories on the existing conduit may be required to facilitate installation of the bulkhead. Manifolded intakes would require special attention.
2. Inserting an inflatable plug inside the existing conduit. A plug should be tethered to a bracing system in the event there is inadequate side friction to hold the plug in place. Additionally, the pressure required to inflate the bladder and seal off inflow should be closely evaluated to avoid rupturing the conduit. This is particularly important for applications with deeper reservoirs and potentially brittle conduit materials.
3. In some cases, equipping the intake structure at the conduit with slots, which will allow for installation of stoplogs or bulkheads.

Reliable record information related to the configuration of the conduit entrance may not be available for some existing structures. Therefore, a scoping mobilization may be required by the diving contractor to assess the conduit entrance and to provide detail required for design and fabrication of the bulkhead. If possible, provisions (flanges, slots, etc.) should be incorporated onto the conduit entrance during the initial outlet inspection to allow for easier installation of bulkheads during subsequent inspections.

In addition to the difficult nature of dewatering a pressurized conduit, access to the interior of the conduit for inspection may also be difficult. For water supply dams, pressurized conduits are commonly directly connected to a treatment facility some distance downstream from the dam. Access may be provided through blind flanges or access vaults that may be located at the toe of the dam. If an unused gate valve exists along the conduit at the downstream toe, its bonnet could potentially be removed and converted to an access port to the conduit interior. As a final resort, removal or tapping of a section of the conduit may be required to provide access. In this case, a tee and blind flange or access vault should be installed to simplify access for future inspections. Similar to the dewatering, addressing these accessibility issues would likely require a contractor and add to the owner’s costs.

While a dewatered conduit will facilitate a clearly visible inspection of the conduit. A dewatered conduit also presents a condition of unbalanced loading that may cause the conduit to collapse. External pressures acting on the conduit may be high enough to damage the dewatered conduit. This concern can be exacerbated with aging, deteriorated conduits. Consequently, the structural adequacy of the conduit should be closely evaluated prior to dewatering. When encased in concrete, the concern over conduit collapse is greatly reduced. These consequences could be reduced by lowering the reservoir prior to an inspection and by notifying local emergency management agencies. Hammer (2002) discusses a case history where a corroded corrugated metal pipe (CMP) collapsed and sinkholes began to form in the embankment after the conduit was permanently dewatered by installing upstream closure.

Tuberculation, Pipe Cleaning and Lining

Even when dewatering of a conduit can be achieved, tuberculation can obscure the pipe walls from inspection. Tuberculation is an encrustation of corrosion byproduct and mineral deposits consisting predominantly of iron oxide that forms on the inside of pipes (Elison and Duranceau 2003). The interior of a CIP may be covered with up to several inches of tuberculation, which can significantly reduce the effective flow area and hydraulic capacity of the conduit. This can be the primary justification for removal of the tuberculation buildup. Additionally, an effective inspection of an outlet conduit will require that the pipe walls be cleaned and tuberculation removed by pigging (aka scraping) or jetting.

A “pig” is a cylindrical device inserted into a conduit to perform cleaning or internal inspection (FEMA 2005b). The pig often has wire brushes to scrape the walls of the conduit. Normally the pig would be inserted into the upstream end of the conduit with reservoir pressure used to advance the pig through the dam. The process requires a pig retrieval station to recover the pig and collect debris at the downstream end of the dam. After the pig is inserted, pressure flow drives the pig through the pipe, scraping the sidewalls and pushing debris ahead. Multiple passes of increasingly larger pigs may be needed if there is significant buildup to be removed.

If pigging is not feasible or practical, jetting may be an acceptable alternative to clean the interior of the conduit. Jetting involves the use of a flexible hose attached to a nozzle that jets water ahead of it to loosen debris and sediment. The nozzle is propelled forward by reverse angle jets, which also push debris and sediment backwards toward the end of the conduit. The pressure selected for cleaning should consider the condition, age, and type of conduit to avoid further damage to the conduit (FEMA 2005b). Conduit cleaning should only be performed after the pipe interior is video inspected. Careful consideration should be given to cleaning before proceeding to avoid causing additional damage to the conduit. For instance, some minor cracks or defects in conduits may have sealed themselves by calcite deposition, which could be inadvertently removed by the cleaning process and cause previously sealed defects to open. Other more aggressive means of pipe cleaning may be possible, such as spinning chains adjusted to remove corrosion to bare metal or some small tolerance from the pipe surface. However, due to potential damage to the conduit and resulting dam safety concerns, this method should only be performed where the reservoir has been completely drawn down and the existing pipe will be slip lined.

While the tuberculation is a byproduct of corrosion, it also acts as a protective layer that reduces the rate of corrosion. As shown in Figure 4 above, corrosion of bare metal is initially rapid, decreasing with time after buildup of corrosion byproducts. The cleaning methods presented above will remove the protective layer, and unless the pipe is lined, can accelerate the corrosion process (Elison and Duranceau 2003). A common method to protect existing CIPs from accelerated corrosion is slip lining. Slip lining involves inserting a pipe of smaller diameter into an existing conduit and grouting the annulus. Slip lining has been used with high density polyethylene (HDPE) liners to repair conduits in embankment dams since the 1990s, and is widely accepted by many state dam safety agencies. Since slip lining is considered a ‘trenchless technology’ and does not require costly and intrusive excavations, it is often preferred over traditional removal and replacement methods. Slip lining can also be performed without draining the reservoir, assuming the conduit can be safely dewatered. The authors are unaware of any applications where a conduit has been slip lined in submerged conditions. Severely corroded, collapsed, offset and misaligned sections of pipe should not be slip lined, but should be entirely removed and replaced. Furthermore, slip lining is not appropriate in areas where the surrounding soil has been damaged by internal erosion or backward erosion piping.

Another method to protect existing CIPs from continued corrosion is cured-in-place pipe (CIPP) lining, which involves application of a plastic membrane into an existing conduit which is allowed to cure in place. CIPP liners are typically used within inaccessible conduits that are not severely damaged or deformed. CIPP liners may be installed by either the "inversion" method or the "pulled-in-place" method. The inversion method uses air or water to push the CIPP liner inside-out as it advances along the conduit. The pulled-in-place method uses a winch and cable system to pull the liner into position; the liner is then inflated. While spray lining has been widely used on small diameter water mains, it is not recommended for critical dam applications.

Non-Destructive Testing

Numerous methods are available for geophysical and non-destructive testing (NDT), and performance evaluation of conduits within embankment dams. *FEMA 484* details approximately 10 methods that have varying degrees of accuracy and application. Several methods are useful in assessing whether voids may exist along the outside of a conduit (self-potential, resistivity, seismic tomography, and ground penetrating radar). Sonar is a useful method in remote assessments of conduit interior dimensions and visible defects. Ultrasonic methods are useful for the assessment of concrete quality and thickness, and can be performed using a "smart pig" device passing through the pipe.

Ultrasonic thickness measurement of metallic pipe can be performed using a pulse-echo ultrasonic thickness gauge. An ultrasonic gauge measures the time required for a short ultrasonic pulse to travel through the pipe wall, which can be correlated to a thickness. Typically the sensor requires contact with bare metal; however, some gauges are capable of measurement through paint coatings. Surface corrosion must be removed for accurate thickness measurement. According to discussions with inspection contractors, traditional ultrasonic thickness sensors have difficulty with cast iron because of material composition. Typically a unit specific to cast iron is required and a small sample of the pipe wall (i.e., coupon) is required to calibrate the sensor. This method only records thickness measurement at a single point. Since cast iron is subject to localized pitting, readings may not be indicative of more corroded sections of pipe. Multiple readings should be performed to obtain a representative average thickness.

Magnetic flux leakage is another means of measuring wall thickness of metallic pipe; however, it must maintain a constant lift off distance between the pipe surface and the device. Additionally, this technology can only read a maximum wall thickness of about 0.6 inch. Therefore, this technology is not applicable to cast iron, which typically has much greater wall thickness.

Broadband electromagnetics is a technology that can map material thickness and pitting over a short section of pipe. A sensor is passed along and around the pipe on a closely spaced grid pattern and the material thickness, pitting, and other defects are mapped for visual evaluation. The survey is typically performed along a 6-foot length of pipe at one time. Therefore, judicious selection of pipe section is recommended to identify likely areas of significant corrosion. If soil resistivity is relatively constant along the pipe length, it is possible that the most significant corrosion is occurring at the downstream toe of the dam where moisture content is high but the pipe also has exposure to oxygen.

Various new leak technologies, consisting of a sensor that passes through the pipe, show promise and may eventually prove useful in identifying potential leaks from pressurized conduits in dams.

Reducing Risk of Failure

Typical Measures

Several means of reducing the risk of failure associated with pressurized conduits through existing embankment dams are presented below.

1. The existing conduit material should be assessed relative to the loads imposed on it. Inspections should be performed to identify defects in the pipe that could lead to failure. Additional discussion related to inspection and assessment of pressurized conduits have been presented in a previous section of this paper.
2. For existing dams with deteriorated conduits, it is often cost prohibitive to remove and replace the damaged conduit; therefore, conduit re-lining is often recommended. Relining may consist of slip-lining or CIPP lining. Slip lining involves inserting a pipe of smaller diameter into an existing conduit and grouting the annulus. CIPP lining involves inverting and curing a resin-saturated tube by water or air in an existing conduit. Of the two technologies, slip lining is more common in dam applications.
3. Identify whether soils susceptible to internal erosion and/or backward erosion piping (such as non-plastic silts, broadly graded silty coarse grained soils and dispersive clays) surround the existing conduit. If so, construct a filter diaphragm around the conduit in accordance with current practice, such as Chapter 26 of NRCS's *National Engineering Handbook*.
4. If additional load is placed on the embankment over the conduit (e.g., roller compacted concrete overtopping protection or slope flattening), settlement of the embankment in the vicinity of the conduit should be evaluated during design. Incorporate measures to mitigate possible differential settlement and the formation of cracks in the embankment materials, and include a filter diaphragm. Consider replacement pipe where compressible foundations and settlement may impart high stresses on existing pipe beneath the slope improvements.
5. If conduits are being extended as part of an upgrade, concrete cradles or encasements should be considered as a means to protect conduits from deterioration and stress concentrations. Cradles and encasements also allow for better compaction of earthfill adjacent to the conduits. Thorough earthfill compaction is required to avoid the formation of cracks and preferential seepage paths. Additionally, include a filter diaphragm around the conduit if one does not already exist.
6. If embankment upgrades are planned to address seepage or stability concerns, incorporate a properly designed chimney filter to intercept embankment seepage.
7. For existing dams with seepage problems near conduits, grouting may be considered to treat the seepage zone, but only in conjunction with additional drain/filters. Note that if internal erosion is the cause of the problem, a filter blanket of limited dimensions constructed over the exit face may become clogged

over time, and the seepage will seek an alternate exit (FEMA 2005b). If the conduit itself is the source of the problem, conduit remediation is likely needed (replacement or slip lining).

8. When possible, retrofit conduits with upstream control to avoid pressurized flow, or to allow depressurization of conduits in an emergency.
9. Perform routine inspections and monitoring in an attempt to identify and address potential seepage issues before they significantly compromise the safety of the dam.

Risk Analysis Framework

It is evident that defects in pressurized conduits, if left undetected and/or unaddressed, pose significant risks of dam failure. However, while inspection and repair of pressurized conduits may be performed with the intent of improving dam safety, it is important to recognize that attempting these activities may present unsafe conditions and increase risk of failure. Also note that the risk of failure while dewatering a pressurized conduit could be higher than the risk of a 'do-nothing' alternative. As such, a set of 'one size fits all' inspection and repair requirements/ recommendations may not be appropriate. Each dam site should be evaluated independently and an appropriate plan to investigate and repair a pressurized conduit should be developed to balance the technical and regulatory requirements. Such an approach will take careful planning and coordination among the entire project team, including owner, engineer, regulatory agency and inspection/repair contractors. In an effort to evaluate the need for investigation and/or repair of a pressurized conduit, a risk-based decision-making process could be considered.

It is outside the scope of this paper to describe the risk analysis process, but project teams can refer to widely accepted approaches developed by the US Army Corps of Engineers or the Bureau of Reclamation. Contributing factors that influence the development of failure of iron pipes and embankment dams with pressurized pipes were discussed in previous sections of this paper. Those factors and their consequences should be considered during the risk analysis. Several driving factors, including those listed below, may also provide useful means of prioritizing investigation frequency and possible pipe repair at various dams.

1. Age of conduit, type of material, thickness, and encasement configuration
2. Dimensions of the conduit defect
3. Susceptibility of the surrounding soil to erosion
4. Potential for hydraulic fracture or cracks in surrounding soil
5. Seepage gradient (Differential head)
6. Resistivity of surrounding soil (corrosion rating based on DIPRA's or Reclamation's rating system may be useful)
7. Other backfill soil parameters (pH, sulfides, moisture condition and exposure to oxidation)
8. pH of reservoir water
9. Estimated pipe section loss
10. Interior and exterior pipe coatings

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