FERC Engineering Guidelines
Risk-Informed Decision Making

Chapter R10

Internal Erosion and Piping

Draft

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Chapter R10 – Internal Erosion and Piping

Internal erosion is one of the leading causes of dam failures in the United States, and yet it remains one of the most difficult potential failure mechanisms to understand and predict. The Federal Energy Regulatory Commission (FERC) has been addressing internal erosion concerns during the course of developing Potential Failure Modes (PFMs) in our Potential Failure Mode Analysis (PFMA) program since 2002. As we move towards a Risk Informed Decision Making (RIDM) Process, it becomes even more important to understand the mechanisms behind internal erosion in as much detail as possible in order to fully understand the risk it poses to embankment dams.

Every embankment dam will develop seepage, which is simply the movement of water through soil. There are a multitude of paths the seepage can take, as will be discussed below in this chapter, but it is uncertain when the seepage will occur. Many of these paths may never be seen or detected during the life of an embankment. The real concern begins when the seepage begins to transport particles of soil from one location to another; called internal erosion. This chapter will further discuss why this can be a concern for the safety of an embankment dam, and at times, a concern for concrete dams or other concrete structures founded on soils.

One of the least understood aspects of internal erosion is that it can rapidly develop upon first filling, or alternatively, can slowly develop over the course of decades after the embankment has been in operation. Seepage plays a significant role in the performance of an embankment dam. Too often, the justification for not addressing a possible seepage concern with an embankment dam is that it has performed well for decades and there is nothing to indicate that it would not be expected to continue to perform in a similar manner, and therefore no action is required. Many geotechnical problems are difficult to identify with regards to critical seepage mechanisms within an embankment dam, regardless of the amount and type of subsurface information, instrumentation, and visual observations that are available. While not perfect, an understanding of how an embankment dam was designed, constructed, operated, and how it has performed since construction is very important in understanding internal erosion mechanisms. This understanding is best developed by a thorough compilation of the available information, which can entail a search of archived design geotechnical investigations and testing; design analysis reports; and plans, specifications, reports and photographs from construction. Also, reports and studies addressing how the dam has performed throughout its operational history often reveal important puzzle pieces.

As stated above, all embankment dams experience seepage and properly designed structures include modern filter criteria and/or a drain collection system that prevents the migration of finer grained material (internal erosion). If seepage exits on the downstream side of the dam, a properly filtered exit will provide security against piping. However, if seepage exits downstream of a dam through an inadequately filtered exit, embankment soils can be transported with the seepage, including seepage along conduits and structure interfaces, or locations where seepage daylights with elevated exit gradients at inadequately filtered or counter-weighted locations. These conditions can ultimately progress to piping, heave, and/or other processes that pose a risk of dam failure. The key to preventing detrimental internal erosion is an understanding of the potential seepage paths and the media and discontinuities through and along which seepage passes. Since seepage cannot be stopped, security against piping is best obtained by mitigating the potential for the development of an unfiltered and sometimes un-weighted exit.

Elevated exit gradients result when the seepage path through the embankment is of such high permeability that the seepage velocity easily carries soil out of the embankment or provides sufficient uplift force to displace or dislodge less permeable soil (blow out or heave). This can result in a very dangerous internal erosion and piping condition, as will be discussed in more detail below.

R10.1 Introduction and Purpose

The overall purpose of this chapter is to provide guidance for performing a risk analysis on internal erosion and piping potential failure modes (PFMs) for embankment dams in a manner that is in conformance with the FERC RIDM process. This chapter provides the information necessary to estimate the probability of failure of a PFM. There are also different levels of complexity when performing a risk analysis, depending upon the information available, the downstream consequences, and the intended use of the results of the risk analysis. Chapter R24, Risk Analysis contains more details regarding the different levels of risk analyses and how to estimate the probability of dam failure for each PFM. This chapter also does not discuss how the Licensee should use these probabilities of failure to assess the risk at the dam. Refer to Chapter R27, Risk Assessment, for this guidance.

This chapter also includes general concepts and descriptions of various mechanisms of internal erosion. Definitions can be found in Appendix 10-A. The general types of internal erosion are exemplified with case studies, detailed PFMs, and event trees developed for the specific event leading to the postulated failure. These examples are presented as aids in understanding actual cases of failure or near failure attributed to internal erosion. The case studies presented in Appendix 10-B should not be construed to be a definitive listing of all possible piping mechanisms.

This chapter provides general concepts of internal erosion for the wide and varied group of FERC users assessing dam safety, including regulators, licensees, and consultants. The intent is to provide a general understanding of the complexity involved with describing and assessing internal erosion, and emphasize the need to involve experts, as required, in evaluating embankment dams and soil foundations. To help the user obtain a more comprehensive understanding of internal erosion, this guideline provides references for more detailed information available on internal erosion and case studies of dam failures. Review of this chapter and information referenced should quickly convince the reader that it is critical to the safety of the embankment dam, and the success of the PFMA or risk analysis to include a geotechnical engineer who is experienced in evaluating internal erosion aspects of a dam.

R10.2 Overview of the Methodology of Assessing Internal Erosion and Piping Risk

This section contains a general overview of the methodology for assessing internal erosion and piping risk. Each step of the process will be discussed in more detail in the following sections.

The first step to assess the risk of piping or internal erosion is to develop a detailed understanding of the embankment dam. This includes reviewing all aspects of design and construction, including construction materials, foundation conditions and treatments, construction techniques, design decisions and rationale, and all other information available on the project.

The following discussion presents the general process for assessing the risk of an internal erosion and piping PFM. Many parts of this process are applicable to potential failure modes in general, but are included here because of the difficulty in developing internal erosion PFMs. Sufficient detail must be examined to determine the likely internal erosion initiation mechanism. This level of detail is crucial for properly determining and estimating risk.

Following comprehensive data compilation and review, the next step is to fully develop all potential PFMs unique to the project and the site. Depending upon the size and complexity of the project, this process could take a PFM team several days to a week or more to complete. In general, the more pertinent information available to review by the team before the PFMA, and the more prepared the team members are with all the information available, the more thoroughly and quickly detailed PFMs can be developed. It is essential that project operations personnel (Operators) are engaged with the team during PFM development because these individuals are intimately familiar with the performance history of the dam, and quite possibly the design and construction as well. Without a fully developed PFM, it will be impossible to accurately estimate the risk that the PFM poses. The initial development of each PFM, assumes that each PFM step will occur and the dam will fail, regardless of the likelihood of that ultimate outcome. The likelihood or unlikelihood of each portion of the PFM is discussed and ranked as either likely or unlikely factors.

Once a full PFM has been described in detail, an event tree can be developed for the progression of the PFM. The event tree is used to qualitatively evaluate the PFM, as discussed in Section 6.7 below. Much like an organizational chart, the event tree is developed such that a decision node is created at each step of the PFM progression where the likelihood of an event must be estimated.

After the event tree has been fully developed, each node of the tree is evaluated more closely and the probability of that event occurring is estimated. Probabilities are expressed as a fraction of 1.0, where 1.0 indicates complete certainty that the event will occur, and 0 indicates complete certainty that the event will not occur. Once probabilities are estimated for each node, the total risk is calculated by multiplying the risk at each node together to obtain one, final numeric risk value. It is essential that the team critically review the final "answer" using sound, engineering judgment before moving on to the next PFM. If node probabilities are estimated too conservatively or too aggressively, the end result is a failure probability that does not represent the true dam conditions. During the course of developing the PFM, the event tree, and the probability estimates, it is important that enough information is available about that PFM that engineers experienced with internal erosion and piping will be capable of using sound engineering judgment to determine if the assessed risk is reasonable. If it is the view of any member of the team that the final result does not make sense, the team should revisit each node of the event tree and reassess the estimates.

R10.3 Limitations of Methodology

Perhaps the greatest limitation of this methodology is the potential for the oversimplification of the steps leading to the ultimate outcome (e.g., breach of embankment) when estimating the risk of internal erosion. Referencing case studies and work done by others on similar embankment dams is a great learning tool, but carries the risk of preventing the unbiased consideration of site specific conditions unique to the actual embankment dam being reviewed. While internal erosion mechanisms are typically very similar for all embankment dams, and there are cases where there appear to be nearly identical PFMs for different dams, the actual site conditions are totally unique for each and every embankment dam and must be treated as such. A full understanding of the embankment under evaluation is the only way to develop credible PFMs and risk estimates appropriate for the project.

As with any decision-making process, the quality of the decision is based upon the information available when making the decision. The evaluation of internal erosion is particularly vulnerable to poor information since it is necessary to evaluate geological conditions of naturally deposited soils as well as mechanically placed soils. The best data available to evaluate this information typically consists of boring logs, geologic mapping, construction photographs, as-built design drawings, and personal experience of those present during the construction. With the growing age of many of the dams being evaluated, records, as-built drawings, and persons directly familiar with the design and construction are not often available.

Ultimately, it is crucial to have well-balanced, experienced, and preferably neutral (unbiased) team members for developing PFMs and risk estimates for internal erosion.

R10.4 Types of Dams and Appurtenant Structures Affected by Internal Erosion

Internal erosion can occur whenever soil is exposed to a potentiometric gradient. In addition to embankments and manmade soil structures, this also includes natural soil deposits, such as soil foundations under any manmade structure. Seepage may develop and stay within the same soil horizon, or it may pass into other horizons, to a free face downstream of the structure, depending upon the permeability of the soils and other subsurface features. Movement of soil by subsurface flow (internal erosion) is typically initiated by a new or elevated groundwater gradient and/or flow velocity. On a flood plain, the construction of an embankment may result in a reversal in the natural groundwater gradient exposing soil that may have had a natural filter to flow in a direction without filter protection. Therefore, any change in seepage conditions can result in the transportation of soil particles if the conditions are conducive to the movement of particles of soil. More details about the conditions susceptible to internal erosion and the likelihood of internal erosion developing are discussed below. Additional discussion is also included about other foundation conditions that can also be impacted by seepage. This section is intended only to discuss the types of structures that can be affected by internal erosion and piping.

Types of structures affected by internal erosion generally includes:

- earth and rock fill dams on an alluvial soil foundation
- earth and rock fill dams on a solution-prone, karstic, or highly weathered rock foundation
- earth and rock fill dams on steep rock abutments
- earth and rock fill dams on rock foundations with naturally occurring voids or discontinuities
- earth and rock fill dams with manmade conduits penetrating the embankment and/or through bedrock

- earth dams without a system of filters and drains to collect, control, and release seepage
- concrete dams on an unprepared rock foundation with erodible seams, joints, fractures, layer, or other flaws within the rock
- concrete dams abutting earth fill embankments
- concrete dams on soil foundations
- concrete lined spillways with soil foundation
- concrete guide walls penetrating embankments or separating aquifers and a groundwater gradient
- pump stations and forebays
- earthen levees
- levee T-walls
- lock walls on rock foundations with naturally occurring conduits or discontinuities
- lock walls

The key thing to keep in mind is that every foundation is unique to the geologic conditions of the structure foundation. Foundations are often altered during construction and it is critical to have a detailed understanding of the foundation conditions when evaluating PFMs and estimating risk.

The following sections provide general discussion about the more common structures that can be affected by internal erosion and piping. More details about these and other types of structures can be located in some of the references noted at the end of this chapter, as well as general design manuals for embankment dams. Prior to the evaluation of a specific project, more research should be performed to get a full understanding of the project design features.

R10.4.1 Earth and Rock Fill Dams

Modern earth and rock fill dams are designed to filter, collect, and convey seepage away from the downstream toe in a controlled and collected manner. This is typically done by placing one or more zones of a graded filter in the embankment that prevents the migration of soils from one zone of the embankment into another zone, or around a pipe that is intended to collect and covey seepage away from the dam. If the filter system is constructed incorrectly, becomes damaged by settlement or earthquake-induced deformations, erosion of one zone into adjacent downstream zones can lead to a potentially catastrophic consequence. Evidence of this erosion may be difficult to detect until piping of soil is observed, subsidence is noted, a sinkhole appears above the area of erosion, or the embankment dam fails catastrophically.

Embankment materials are often placed directly upon an alluvial soil foundation soils, although this is not as common in current practice in areas with liquefaction concerns. Since dams are typically constructed across existing stream channels, the foundation soils can range from clean sands and gravels to well-graded soils with clays. Modern design standards require a filter analysis between the foundation and the soils placed in direct contact with the foundation to ensure filter compatibility between the soil types. The analysis must evaluate the anticipated direction of flow whether it would be from the embankment into the foundation, or from the foundation into the embankment. This will dictate design criteria.

In older dams, small containment ponds or dams, or in long canals and levees, it may be typical that no filter is placed on the foundation below the embankment or in the embankment as a result of the size of the structure and the costs associated with constructing the filter system. Depending upon the development of the internal phreatic surface, the lack of a foundation filter may not be an issue. Typically, the gradient is downward from the reservoir through the embankment and into the foundation. However, it is not uncommon for upward seepage to develop from the foundation into the embankment or just downstream of the toe of the embankment. This can result in the development of a sand boil and a significant loss of effective stresses with an increased potential for piping to occur.

Another area of concern is where earth and rock fill dams are placed against a steep abutment, narrow trench, in and over a solution feature, or over a conduit with soil backfill or a portion of the conduit that extends above the foundation. In these instances, differential settlement can result in the development of transverse cracks or arching of the soil which results in a significant reduction in vertical and lateral stress. When the lateral stress drops below the seepage pressure, hydraulic fracturing can occur and a transverse crack can form in the cohesive embankment material or clay core. If this crack conveys unfiltered water or causes damage to the filter, internal erosion may commence.

Wherever a discontinuity is encountered, a potential flaw can exist in the embankment. This flaw could allow hydraulic fracturing to occur. Embankment loads will result in an arching effect from the low modulus material to the high modulus material. No matter how well compacted, the modulus of soil fill will always be much lower than rock or concrete, resulting in a reduction in vertical and lateral stress in the soil embankment. This could allow for internal erosion and piping to commence through this area.

R10.4.2 Penetrations through Dams

Embankment dams have historically been constructed with outlet conduits passing through the embankment. Seepage collar construction was one common method used to lengthen the seepage path along the conduits and reduce the potential for internal erosion and piping. The lesson learned from problems with the historical use of seepage collars is that because it is difficult to adequately compact the soil adjacent to the collars, internal erosion and piping is actually more likely. As compression of this poorly compacted soil occurs in contrast to the rigidity of the conduit and collar, the stress field in the soil arches onto the conduit and the collar, which reduces the minor principal stress and facilitates the development of hydrofracturing at the interface increasing the potential for internal erosion. With the well compacted soil above the conduit, and the conduit adjacent to the seepage path, an erosion feature can easily form along the length of the conduit resulting in the failure of the embankment. Contrary to the design intent, the use of seepage collars actually reduces the safety of a dam from seepage induced internal erosion. Current, modern design standards for conduits through embankments typically require the conduit to be encased in concrete with battered sides to allow for good compaction. In addition, filter diaphragms are also used to prevent internal erosion pathways along the conduit and dam or foundation fill contacts.

This same concern exists with any penetrating structure through an embankment dam. Any vertical wall, retaining wall counterforts, or other artificial penetration through an embankment must be closely evaluated and discussed when discussing the potential for internal erosion and piping.

R10.4.3 Concrete Dams

While concrete dams are not generally subject to internal erosion, the foundation may be susceptible if the dam is constructed on soil. Foundation internal erosion through the foundation may result in a significant change in uplift pressures that may affect the static stability of the structure. The concrete dam can easily form a roof over the erosion feature that may not collapse, but allows the erosion to continue unabated. Seepage gradients within the soil in contact with the base of the concrete dam may also increase. The erosion may not be evident until there is discolored water noted at the toe of the dam or there is a significant change in uplift pressure, which would be difficult to comprehensively monitor. The change in uplift pressure may be detected in serendipitously located piezometers, or is more often indicated by a significant change in measured seepage at the toe of the dam.

When a concrete dam abuts an earth fill embankment, differential settlement and arching of the soil stress field may occur. The interface between the concrete and the earth embankment is similar to the interface between an earth embankment and a steep rock abutment or along a penetration through an embankment. This allows for a higher potential for internal erosion and piping to occur along this interface.

R10.4.4 Spillways

Spillways founded on soil foundations can be particularly susceptible to internal erosion and piping. If not constructed with care on soil foundations, spillway chutes can easily crack, settle or otherwise experience movement that could create some type of an offset. Many spillways are also designed with weep or drain holes to prevent or mitigate excess pore pressure accumulation behind the slab or walls. If these are not properly designed to filter soils behind the spillway or become plugged and are not maintained, pore pressures can build up beneath the spillway leading to a greater risk of preferential flow path development. Erosion of soil and/or rock at the toe of the spillway may also be caused by subsurface discharge flows. If this continues undetected (toe of spillway is always submerged), this could result in an increased seepage gradient and greater potential for piping.

There are two primary concerns for spillways on soil:, slab-jacking and cavitation pressures. With gated structures, the spillway inlet is typically below water during many times of the year; this includes intake walls that typically become the spillway chute walls. As discussed above in penetrations through embankments, this situation raises concerns that should be evaluated as well. This provides the opportunity for seepage to develop and collect below the slab. Any open crack or drain hole provides a possible unfiltered exit.

A second and perhaps more significant concern with spillways is erosion or scour potential. Although not actually related to internal erosion, the magnitude and direction (upstream higher than downstream side of crack, or vice versa) of the offset, creates a potential for slab jacking or cavitation of the concrete slab. If a portion of the slab is lost while the spillway is operating, scour of the soil foundation of the spillway is inevitable and could result in an uncontrolled release of the reservoir. This makes it crucial to closely monitor the behavior of the spillway slab and evaluate the structure for PFMs during the PFMA.

R10.4.5 Ancillary Structures

Ancillary structures associated with dams may include intake structures, retaining structures, power houses, guide walls, etc. These structures may be susceptible to internal erosion when a seepage gradient is present along the side or below the structure. These solid structures can easily form a roof for the development of pipe along the structure. If there is no filter to control the erosion of fine grained materials at material interfaces, the embankment could fail along one of these structures.

R10.4.6 Locks and Dams

Locks and dams are subject to erosion hazards similar to these described above for ancillary structures. Unlike dams, the largest gradient occurs when the head differential between the upper and lower pool is the greatest and the embankment acts like a typical embankment dam. During high discharge or when the gates are being operated, the gradient across the structure may be low. With the fill and discharge of locks during operation, there are other considerations to take into account when discussion internal erosion PFMs. Any repeated charging and discharge of soil raises a concern of excessive movement of material with each cycle.

The operation of a lock is essentially the same as performing cycles of rapid fill and drawdown of a reservoir. Embankments are typically designed for such an operation by providing riprap and ripirap bedding, and in some instances, an upstream filter when it is known that the reservoir will go through multiple fill and drain cycles. As the reservoir is drained, bank storage in the soil will drain and seepage forces can increase significantly, resulting in a higher likelihood of soil transportation. After many cycles of this type of reservoir operation, it is possible to erode a sufficient amount of soil from the embankment that could either result in an upstream slope failure, or create a seepage path that could quickly develop a pipe through the embankment and cause the embankment to fail.

The construction and operation of a lock and dam should be reviewed in detail when developing PFMs to determine where any vulnerable weaknesses may exist in the embankments and/or foundations of the project.

R10.5 Considerations for the Development of Potential Failure Modes and Event Trees

Every dam is unique in its design, construction, operation, and performance. Earth and rock fill dams add a special component to this uniqueness by the complexity resulting from dealing with variable natural materials. As a result, a detailed potential failure modes analysis and the development of specific event trees should be developed for the site specific conditions of the project under review and evaluation. The foundation geology, design, construction methods, monitoring program, and historic performance of the structure affect the development of each detailed potential failure mode and the probability of each node on the event tree to progress to failure, or be stopped prior to progressing to failure. The project characteristics discussed below should be considered during the development of PFMs and the performance of a risk analysis of internal erosion and piping of an earth structure or soil foundation. It should be emphasized that this is a partial list of considerations that affect a PFM and the probability of nodes on the event tree. Also refer to Section R10.8.1 for a discussion on the uncertainties surrounding the information used to evaluate a PFM.

1. Zoned Embankment. Many existing FERC projects include embankments that are homogeneous rather than zoned earth with protective filters. Homogeneous embankments are susceptible to many potential failure modes. The following items are some of the things to consider when evaluating a homogeneous embankment, but also apply equally to any fine-grained embankment material: The soils in the foundation and the embankment are also a consideration. Here are some examples:

    a. Cohesive soils are less susceptible to erosion but more likely to support a roof over a pipe feature
    b. Residual soils are generally well-graded and more internally stable than alluvial soils
    c. Dispersive soils have a much higher probability of internal erosion.

2. Filters. Many FERC projects include embankments that were constructed before modern filter design procedures were established. The U.S. Bureau of Reclamation (Reclamation), and others, have established procedures for the evaluation of the probability of piping of base soils through a filter in this case. Gradation curves for both embankment and filter materials are needed to utilize this procedure. When evaluating filters within an embankment dam, the following items are a partial some items to consider:

    a. What method was used to develop the filter gradation?
    b. Was filter compatibility checked between all adjacent zones, including foundation and abutment soils?
    c. Are there gradations available of the as-built embankment to confirm filter compatibility calculations?

3. Drain Pipes. Piping along or into drain pipes or perforated/slotted pipes as well as old clay pipes that may have become separated over the years. The following items should be considered when developing PFMs for drain pipes in embankments.

    a. Was the filter designed appropriately for the size of perforations in the drain pipe?
    b. Is their ample thickness of filter surrounding the drain pipes?
    c. Was the slope of the pipes considered along with the hydraulic conductivity of the filter and surrounding material?
    d. Was the mineralogy of the filter material evaluated to prevent possible cementation of the filter? A cemented filter may crack, developing an unfiltered path for internal erosion, or block and divert seepage making the filter ineffective.
    e. The configuration of the drains can be a factor.
        i. For example, a thin horizontal sand blanket drain may become clogged and ineffective over time.
        ii. A horizontal blanket drain does not provide the same level of protection as a chimney drain.
        iii. A chimney drain that does not extend vertically above flood levels may leave the embankment susceptible to piping during corresponding hydrologic events.

4. Foundation Treatment. The proper treatment of a foundation, including up the abutments, is critical to prevent piping along the foundation or from the embankment into the foundation. The following should be considered:

    a. Was the foundation adequately prepared to received fill (remove weathered materials, organics, potential deleterious materials)?

b. Was the rock foundation properly grouted using appropriate methods?
c. Were all overhangs removed or grouted?
d. Were abutments sloped appropriately for good compaction connection between the abutment and the embankment soils?
e. Was the foundation filter compatibility checked for all embankment soils placed against the foundation soils?
f. Were the foundation soils checked for internal instability?
g. Were all geologic features properly addressed?

5. Construction Defects. Defects created during embankment construction that lead to internal erosion and piping are usually unknown until the failure mode is initiated. However, understanding how the embankment was constructed and how closely it was monitored during construction can significantly increase or decrease the estimated likelihood of a potential failure mode. Properly identifying and evaluating the risk of these failure modes is extremely challenging. When possible, construction photographs and records should be reviewed to attempt to identify defects that make the structure susceptible to piping. In general, the probability of defects in embankments constructed with formal quality control and quality assurance oversight is lower. The list of possible construction defects can generally be related to the embankment construction techniques. The following conditions could result in possible construction defects:

a. Segregation. Was construction procedures used that could result in segregation of filter materials during loading, hauling, and/or placement?
b. Contamination. Was careless construction techniques used that could result in contamination of filter materials with base soils or other adjacent filter zones? This can easily occur if improper techniques were used when placing the filter zones or when it may have been necessary for equipment to cross filter zones.
c. Damaged drain pipes. Was care used when installing drain pipes in embankments to prevent crushing, separation of joints, or careless installation? Was a video inspection of the pipe performed after the installation was completed and several feet of material was placed over the pipe?
d. Construction interruption. Was there an extended shutdown period, such as a winter shutdown, that left an exposed surface for a length of time? Was this surface properly prepared prior to resuming construction and placement of additional earth materials?
e. Were appropriate techniques used to prevent "Christmas tree" effects in the filter zones? Are the contacts between the filter zones relatively sharp or is there contamination and mixing of the contacts?
f. Compaction Techniques. Was compaction along abutments or along structures through the embankment performed in the upstream to downstream direction rather than parallel to the crest of the embankment, as appropriate? Was the

compaction of all embankment materials sufficiently monitored, observed, and tested for meeting design specifications?

6. <u>Piping along Structures/Penetrations through Embankments</u>. A large percentage of embankment dams were constructed with some type of penetration, which is one of the highest risk elements in potential failure mode consideration. In many of these dams, the penetration construction did not take the proper care to ensure that adequate bond was created between hard and soft structures or that flow restriction features were effective. This can include low-level outlet work pipes, spillway chute walls, powerhouse walls, and any structure passing through all or a portion of an embankment in an upstream to downstream direction. Specific penetration concerns are discussed in more detail below; however, the following items can apply to any penetration:

   a. Are the sides of the structure battered allowing better compaction against the structure?
   b. Is there a filter system along the penetration to prevent possible piping along the structure?
   c. Was the mineralogy of the filter material evaluated to avoid the use of materials that are subject to cementation. A cemented filter may crack, developing an unfiltered path for internal erosion, block and divert seepage making the filter ineffective.

7. <u>Conduits</u>. The initiation of internal erosion may typically proceed along several general paths at a conduit location, such as:
   a. Along the sides, top, or bottom of the conduit to a downstream exit
   b. Through conduit joints, into the conduit, then exiting with releases
   c. Cracks above the conduit in the embankment, caused by arching stresses.

   Also, seepage collars in historic dam construction were thought to lengthen the seepage path and decrease the likelihood of piping. However, the collars actually inhibit compaction, and low density zones of soil remained adjacent to the conduit, making it more susceptible to piping. Additionally, many dams constructed before the development of filter criteria, had either no filters, or inadequate filters at conduit penetrations, creating the opportunity for unfiltered exits. Oftentimes, conduits were constructed within narrow cuts in foundation soil or rock, creating an opportunity for arching to cause low density zones, or cracks, adjacent to the conduit.

   If conduit joints or joint waterstops are ineffective, gradients may push and pull soil into the conduit through open joints, which can be flushed out of the pipe unnoticed during normal scheduled releases throw the outlet works pipe. The amount of water released through the conduit may hide the loss of soil, so that progression of erosion may not be noticed for years. Conduits that experience pressurized flow, such as when high flows submerge the stilling basin, may push water out of the joints along the conduit, initiating erosion along the outside of the conduit.

The Natural Resource Conservation Service (NRCS, formerly SCS), has documented cases of dam failures where cracks formed above the conduit due to arching and settlement, providing a preferential path for the development of internal erosion leading to dam failure. This is especially a concern in dams constructed of dispersive soils, where erosion, once started, can accelerate rapidly.

For further guidance on the risk and risk mitigation measures regarding internal erosion at conduits, reference FEMA 484.

8. <u>Core Walls</u>. Core walls are typically constructed longitudinally within the embankment, parallel to the crest of the dam. However, improper construction and subsequent compaction of material along the core wall could result in differential settlement and cracking along the core wall. In addition, if a core wall extends into an abutment, or from a concrete section into an embankment section, proper compaction in these areas is critical.

9. <u>Historic Performance of Embankment</u>. Any assumption of the current state of the safety of a dam based upon the (apparent) satisfactory historical performance of the dam should be viewed critically. This is particularly relevant with respect to seepage and internal erosion since the piping process can easily progress at such a slow rate over the course of decades with no outward expression of its progress. A review of historical embankment dam failures reveals that embankment dams are most susceptible to failure within the first five years of construction or after operation for more than 50 years. Therefore, the historical performance of the embankment should be reviewed in detail prior to developing potential failure modes. This is also strong justification to be vigilant in maintaining a good monitoring program of any existing seepage and always be aware that an outward expression of ongoing seepage could develop at any time. The following is a partial list of conditions to review:

   a. Where are existing seepage areas?
   b. Has there been any changes in the quantity of seepage, either increases or decreases?
   c. Is there a well-designed toe drain collection and monitoring system in place?
   d. Do collection weirs have covers or other protective measures in place to prevent windblown dust from accumulating in the collection boxes?
   e. Has there ever been any sediment noted in seepage?

f. Is there any history of sinkholes, slumps, cracks, or any unusual deformation of the embankment?
g. What has been the maximum sustained and historic reservoir elevation experienced by the embankment?
h. What is the normal reservoir operation; e.g. rule curve or run of river?
i. Have there been any changes in the reservoir operation, outlet works, or other component of the dam that deviate from the original design criteria?
j. Has there always been a good vegetation management plan in place?
k. Has there ever been any deep-rooted vegetation removed from the embankment or near the toe of the embankment? Was the removal and repair performed appropriately?
l. Have there been any design modifications, additions, changes in configuration, or other type of change to the embankment since it was originally designed and constructed?
m. How frequent are visual inspections performed and are they of sufficient detail and frequency to note possible problems with the embankment, if a problem was beginning develop?

10. <u>Monitoring</u>. The type and frequency of monitoring is also critical to the detection and mitigation of a possible problem. As with most problems, the earlier an issue is detected, the more likely it is to prevent a catastrophic event. Instrumentation should be focused on the Dam Safety Surveillance and Monitoring Plan as well as general operational condition of the project.

a. Instrumentation. The types of instrumentation used to evaluate the performance can vary and should be customized to the project requirements. This can include piezometers, crack monitors, survey monuments, seepage collection weirs, staff gauges, inclinometers, and many other types of instrumentation.
b. Visual Monitoring. The frequency and completeness of visual monitoring of all portions of the project are critical to early detection and intervention of a potential failure mode.

R10.6 Developing an Internal Erosion Potential Failure Mode

Performing a proper risk analysis is critically dependent upon starting with a detailed, precise, step-by-step PFM. This is particularly true for piping, heave, and/or blowout in an embankment dam since a seepage path could take several different paths. The PFM must detail the progression of the failure mechanism from the exit point to the reservoir. Unfortunately, it is not uncommon that internal erosion and piping PFMs for FERC projects prepared by PFMA core teams do not contain sufficient details to conduct a risk analysis. An actual example of a piping failure mode (unedited) from a PFMA report that is inadequate for a PFM and risk analysis is as follows:

Description of the PFM: "Piping from the embankment into the foundation."

This PFM does not include a description of how it starts, continues through the embankment into the foundation, an exit point for the soils to pipe to, or any of the details required to develop an event tree to estimate the probability of the event.

In order to perform a risk analysis, a Potential Failure Mode (PFM) description needs to have a specific loading condition (e.g., reservoir elevation), a description of a flaw or condition that could, in combination with the loading condition, result in the initiation of a sequence of events leading to failure and uncontrolled release of reservoir. The PFM must be written as if every step of the process does exist and does progress to a catastrophic failure of the embankment or uncontrolled release of water.

When developing a PFM, it is very important that no consideration is given to the actual likelihood or probability of the different steps of the PFM. This should only be done once the PFM has been developed and a list of the likely and unlikely factors is developed. One exception to this rule is when a point is reached in the development of the PFM where the seepage could go more than one direction. At these junctions, the team should discuss the most likely path of seepage and progress from that location towards failure of the dam. A separate PFM should be developed for each path of seepage where there were other possibilities. The specific flaw or condition may or may not be known to exist, or have a credible or non-credible possibility of existing, but should be speculated in the PFM based upon the understanding of the project. The sequence of events should provide a roadmap for drawing an event tree, with each step representing a decision node, and conclude with an actual failure of the structure. The following figure illustrates general steps required to create adequate internal erosion PFMs. However, it must always be kept in mind that the step-by-step process is unique to the project and will vary between projects and PFMs, but must detail the exact steps required to result in a failure of the embankment.

- ⇘Reservoir loading condition
  - ⇘Flaw exists – Continuous crack, high permeability zone, etc.
    - ⇘Initiation – Particle detachment (erosion starts)
      - ⇘Continuation – Unfiltered or inadequately filtered exit exists
        - ⇘Progression – Continuous stable roof and/or sidewalls
          - ⇘Progression – Constriction or upstream zone fails to limit flows
            - ⇘Progression – No self-healing by upstream zone
              - ⇘Unsuccessful detection and intervention
                - ⇘ Dam breaches (uncontrolled release of reservoir)

An example of how the above inadequately described PFM could be rewritten is provided:

> **Revised Description of the PFM:** "During a period when the reservoir is above elevation 123 feet, internal erosion of the core initiates into the gravel foundation at the interface of the foundation with the cutoff trench near Station 2+35, where poor construction practices resulted in inadequate foundation treatment. Material passes through the foundation and exits at the toe of the dam through an unfiltered exit. Backward erosion occurs until a "pipe" forms through the core, continuing upstream through the embankment until reaching the reservoir. A portion of the embankment upstream face eventually collapses into the pipe greatly increasing the velocity of flow and enlarging the pipe until the crest of the dam collapses into the void, resulting in an uncontrolled release of the reservoir.

An alternative approach to writing a PFM in paragraph form is to use bullets. This could be done initially to help develop the event tree. For example, the revised PFM above could also be written as follows:

- ⇳Reservoir is above elevation 123 feet.
  - ⇳Internal erosion of core material begins into gravel foundation at Sta. 2+35 as a result of inadequate foundation treatment during construction.
    - ⇳Core material passes through foundation and exits unfiltered at dam toe.
      - ⇳Backward erosion creates a pipe through the core into the upstream shell.
        - ⇳High flows commence through core enlarging pipe and erode foundation material allowing upstream shell material through the pipe and out the toe of the dam, creating a void in the upstream shell.⇳The upstream void collapses allowing large flows through the pipe which erodes and results in an uncontrolled release of the reservoir.

The event tree, similar to the bullet items listed above, can now be developed from the detailed PFM, with each node of the event tree consisting of a decision point as to what will happen as a result of the next step in the failure sequence. The case studies contained in Appendix B includes detailed PFMs and event trees for the failure mechanism presented.

R10.7 Types of Internal Erosion and other Considerations

In order to develop a PFM with sufficient detail for use in risk assessment, the PFM author, or at least one member of the PFMA team, needs to be well-versed in the general scenarios for which piping could lead to a credible failure. It is critical to have an experienced geotechnical engineer on the PFMA and RIDM teams to aid in this process. Typical scenarios to consider when beginning your review of internal erosion can be listed as follows:

- Piping through the embankment;
- Piping through the foundation;
- Piping through the embankment into the foundation;
- Piping along a structure penetrating the embankment (conduit, concrete wall, etc.);
- Heave/Uplift (associated with "quick" conditions);
- Blowout (pressurized aquifer under a confining layer);
- Scour (erosion through a crack); and
- Inadequate understanding of foundation geologic conditions

These scenarios are the more typical starting places for internal erosion, but each project is unique and must be carefully evaluated for any potential failure mode. Each of these mechanisms are discussed in additional detail below followed by a list of some of the pathways that should be considered for PFMs under this mechanism; some of which are also contained in Section R10.5 above..

R10.7.1 Piping through the embankment

Piping through the embankment is defined in basic terms as the development of a pipe that begins within embankment material and terminates within embankment material. This pathway could take any route imaginable from the surface of the embankment to the contact with the abutments, with Figure 10-1 illustrating the general concept. For rock-faced dams, detecting seepage can often be difficult unless the embankment is in an arid climate and vegetation growth stands out during visual inspection. This could be confused with water retained from a storm event as well, so a clear understanding of the dam construction is crucial. Common exit points are along the groins and toe of the dam, which should be fully evaluated.

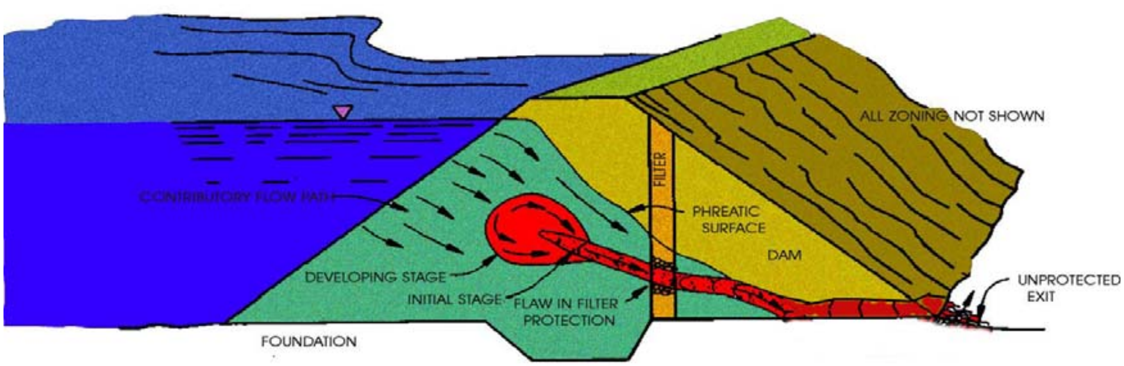

Figure 10-1 – Piping through the embankment.

The following considerations are a partial list of things to consider when developing PFMs for this condition.

- Improper compaction of a lift.
- Improper preparation of the embankment after a winter shutdown prior to placing additional embankment material.
- Incorporation of non- specified material within one or more of the zones.
- Compaction performed upstream to downstream.
- Flaws between embankment and foundation and abutments.
- Overhangs left in rock foundation abutments.

R10.7.2 Piping through the Foundation

Piping through the foundation is similar to failure through the embankment in that in basic terms, the pipe begins within the foundation upstream of the structure and terminates within the foundation downstream of the structure. This pathway could take any route imaginable from anywhere within the reservoir to anywhere downstream of the toe of the embankment. The exit point could be at the toe or hundreds of feet downstream of the embankment. The exit could occur into a body of water downstream of the embankment, such as the tail race, a canal, or into the original river channel. It can also be obscured by vegetation, rocks, or a multitude of other things, and therefore requires close scrutiny. Figure 10-2 illustrates the general concept.

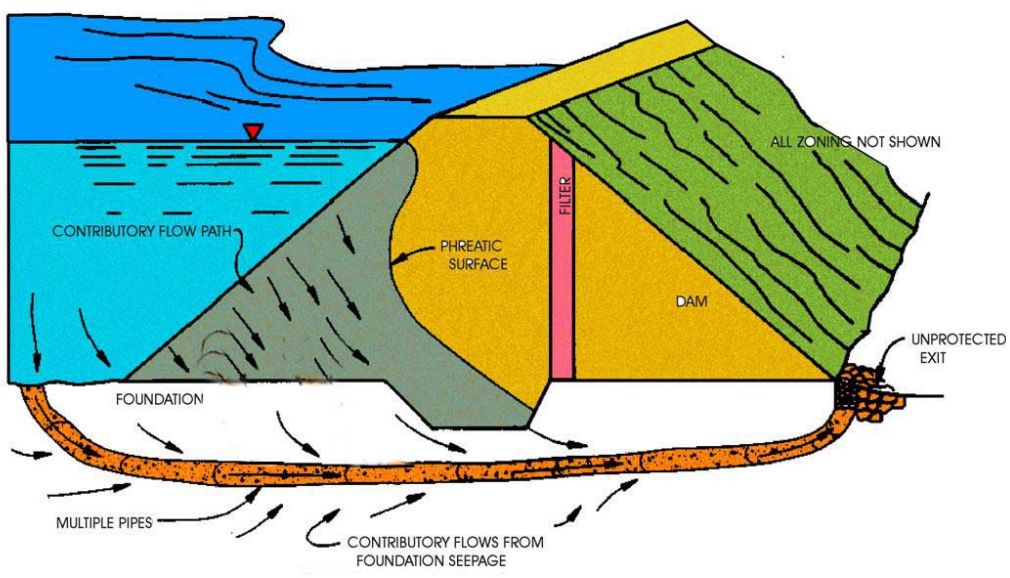

Figure 10-2. Piping through the foundation.

The actual failure of the embankment from this mechanism ranges from a restricted, yet full release of the reservoir to a catastrophic failure of the embankment as it collapses into the pipe through the foundation. The actual mechanism of failure must be evaluated during the development of the PFM and may require more than one PFM to address all potential scenarios.

The following considerations are a partial list of things to consider when developing PFMs for this condition.

- Filter compatibility of foundation, and adjoining embankment zones.
- Special treatment of foundation (slush grout, dental concrete, grout curtain, etc.
- Over-excavation and replacement of unsuitable portions of foundation.
- Recognition of foundation defects post-construction.

R10.7.3 Piping through the Embankment into the Foundation;

Piping through the embankment into the foundation is the development of a pipe that commences within the embankment and transports material into the foundation and out of an exit downstream of the toe of the dam. Obviously this is a combination of the two previous mechanisms. one typical pathway is shown in Figure 10-3 with core material being piped into the foundation at the contact between the fine-grained core and the cutoff trench into the foundation. The proper analysis and treatment of the foundation is critical to preventing the development of this PFM.

Also associated with this mechanism is the development of a sinkhole as shown in Figure 10-4. The embankment materials can enter a void or a gap-graded soil in the foundation and not progress further downstream. The piping continues until a sufficiently large void develops in the dam and collapses to form a sinkhole. The development of a sinkhole will not necessary result in a release of the reservoir. The location of the sinkhole will dictate whether the embankment will experience a catastrophic failure.

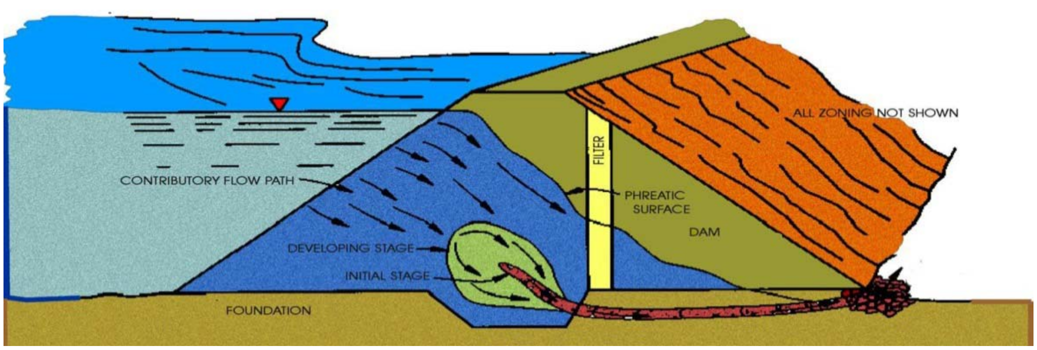

Figure 10-3. Piping from the embankment through the cutoff trench into the foundation.

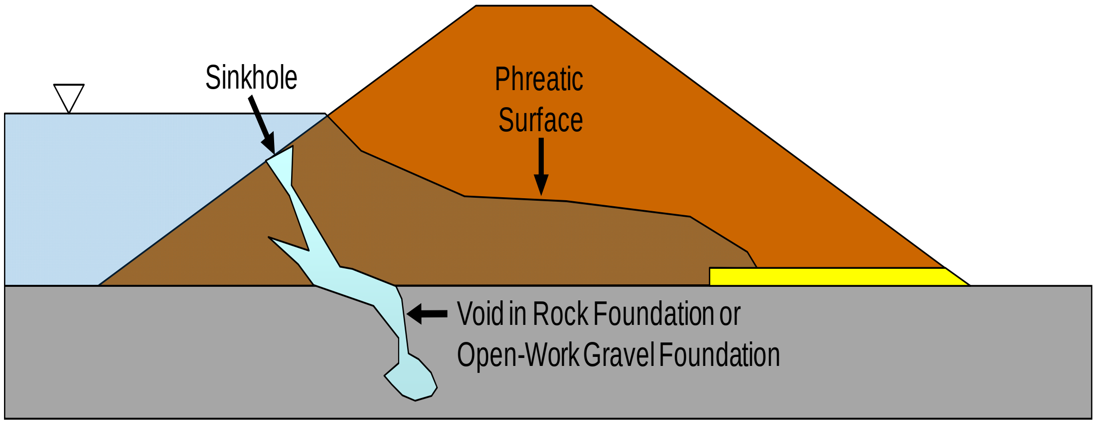

Figure 10-4. Piping from the embankment into the foundation.

The following considerations are a partial list of things to consider when developing PFMs for this condition.

- Filter compatibility of embankment materials and foundation soils.
- Treatment of joints in foundation.
- Gap-graded soil foundations.
- Lava tubes in the foundation.
- Karstic limestone in the foundation.

R10.7.4 Piping along a Structure Penetrating the Embankment (into, along, or out of a Conduit, Concrete Wall, etc.)

Piping along a structure that penetrates an embankment dam is one of the most common failure scenarios for an embankment dam. Any dam component that allows for an easy connection between the reservoir and the downstream face of a dam requires special design considerations.

The seepage can develop in many ways. One common method for old embankments constructed with corrugated metal pipe (CMP) conduits is for the pipe to corrode and develop a hole. This allows embankment material to pipe into the outlet works pipe and easily exit out through the CMP, as shown in Figure 10-5. If the outlet works conduit is used frequently, it may be difficult to observe the sediment being washed into the conduit. If the conduit is operated infrequently, it is likely that the discharge will be muddy when first opening the gate since sediment would likely have accumulated in the reservoir against the gate, making it impossible to determine if the sediment is from the reservoir or being piped into the conduit. A video inspection of the conduit would help make this determination.

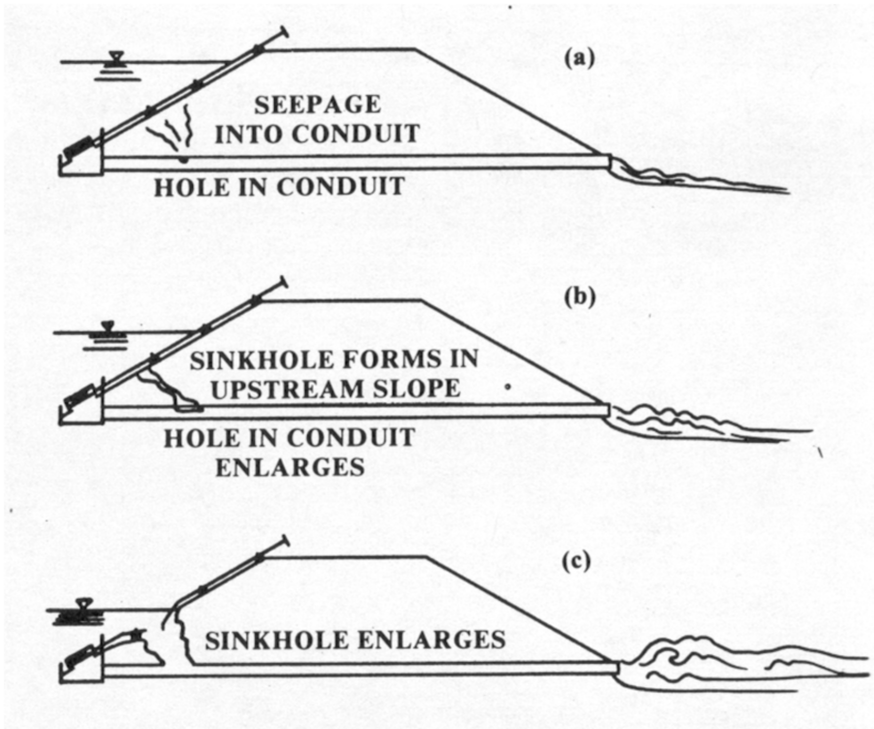

Figure 10-5. Piping into a flaw in an outlet works conduit.

Older CMP pipes may have been coated with asphalt, tar, or other anti-corrosion substance. However, it is not unusual to damage this coating during installation and corrosion can begin immediately resulting in the eventual formation of a hole in the pipe. If the control structure on the CMP is at the downstream end of the pipe, the pipe is always pressurized with the full head of the reservoir when the gate is closed. If a hole develops in the pipe, water could exit the pipe under pressure and act similar to a fire hose. This could eventually result in washing sufficient material from the downstream slope of the embankment and cause a catastrophic failure of the embankment as illustrated in Figure 10-6.

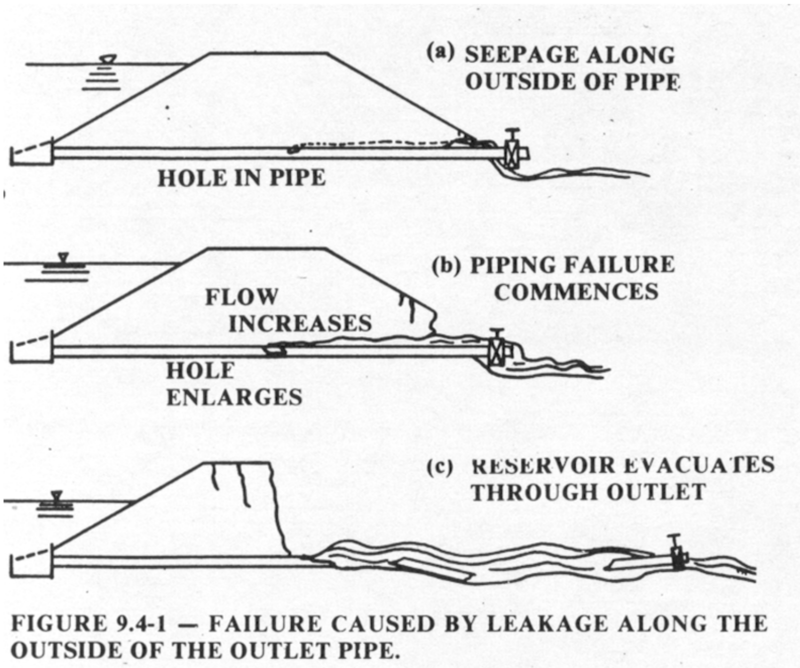

Figure 10-6. Piping from the conduit into the embankment.

Perhaps the most common seepage path associated with dam failures constructed with penetrations through the embankment is piping along the outside of the conduit. This is similar to piping through the embankment, but treated as a special case because it is so common and may be such a serious concern. This is often the result of improper design, poor compaction along the penetration, or poor compaction along seepage collars, which were originally intended to prevent the problem. Current design standards do not allow for the construction of seepage collars along pipes penetrating an embankment. Figure 10-7 shows a schematic of the general concept.

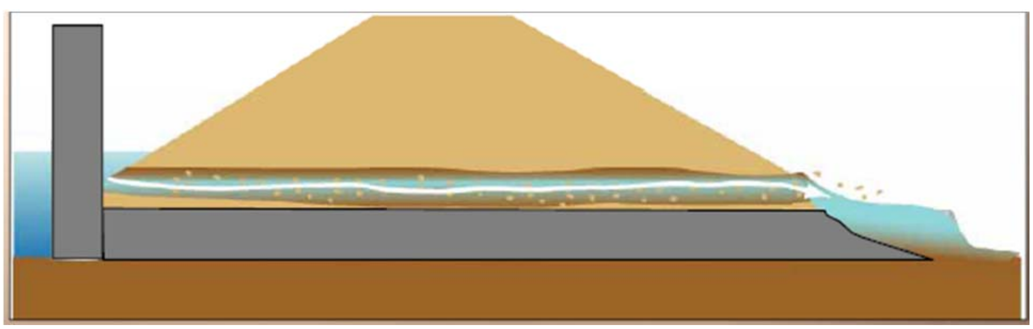

Figure 10-7. Piping along a conduit.

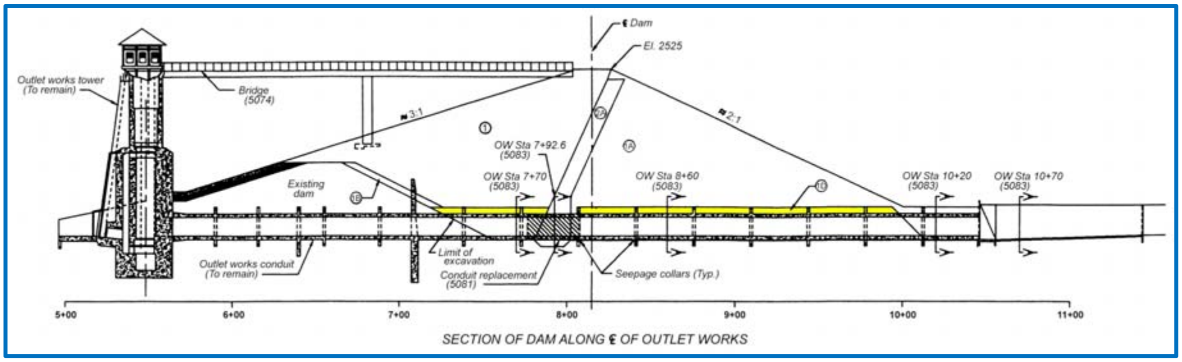

Figure 10-8. Piping along conduit with seepage collars.

The following considerations are a partial list of things to consider when developing PFMs for this condition.

- Seepage collars around outlet conduits.
- Soil placed in haunches under round pipes.
- Narrow zones of soil compacted between outlet pipe and rock trench excavation.
- Corrugated metal pipes in old embankments.
- Retaining walls through the embankment.
- Spillway chute walls.
- Integral powerhouse with an embankment dam.
- Morning glory spillway.

R10.7.5 Heave/Uplift

Heave and/or uplift will typically occur at the toe of a dam, or within a relatively short distance downstream of the dam. This type of piping can develop from seepage through the embankment or seepage from the embankment into the foundation. This results from a poor design that likely did not take into account the foundation conditions and provide measures that would allow sufficient reduction of the seepage gradient from the reservoir to the downstream area of the dam. The result is upward flow with sufficient velocities to carry soil particles, typically resulting in the creation of sand boils. Figure 10-9 presents different conditions driving the formation of sand boils and shows that boils may not automatically result in a dam safety concern. However, an immediate evaluation of flow conditions is necessary to rule out the possibility of failure and/or form the basis for remedial measures for the sand boils. During the PFMA, it is necessary to understand the seepage path and the soil conditions at the exit point to determine the level of concern of this PFM.

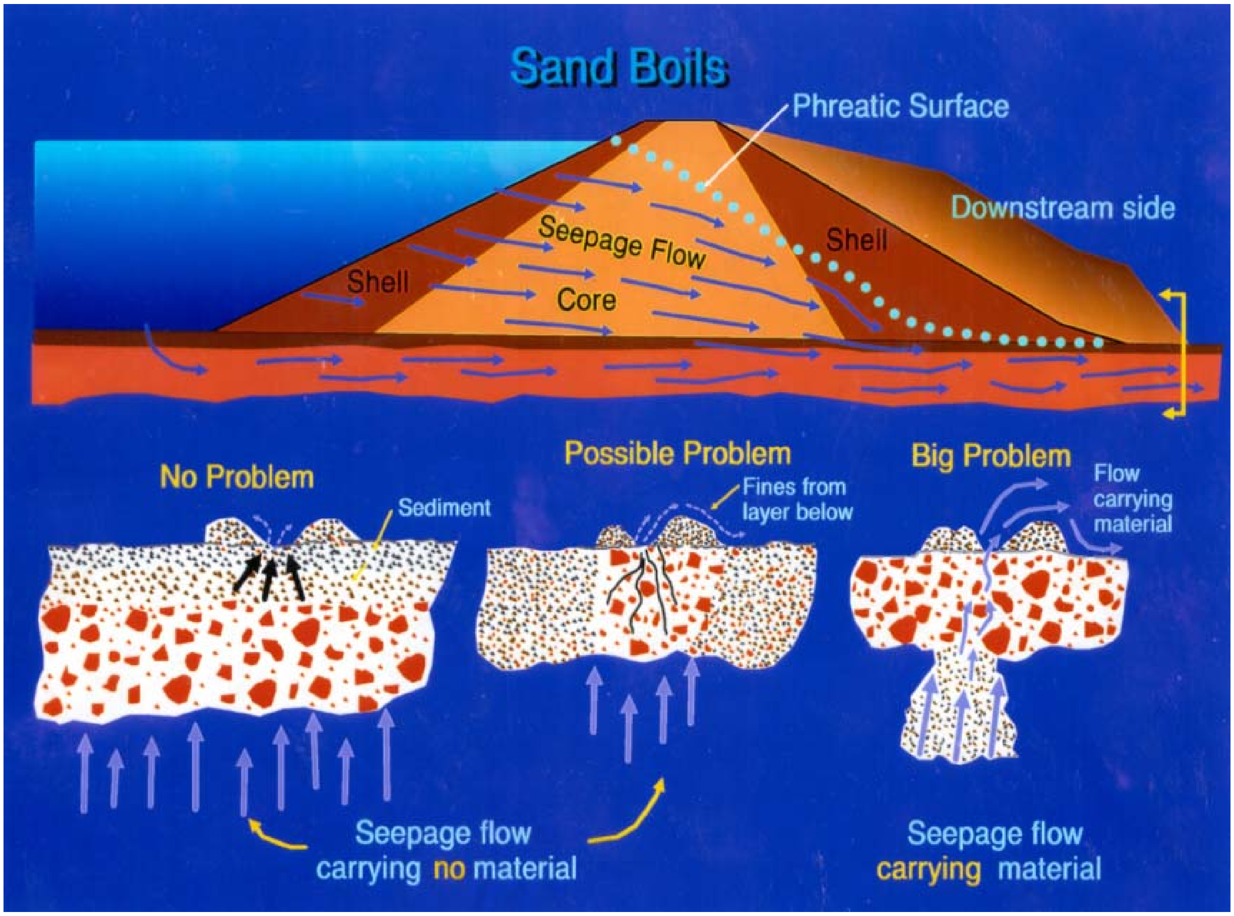

Figure 10-9. Mechanisms for the formation of sand boils.

The following considerations are a partial list of things to consider when developing PFMs for this condition.

- Hydraulic gradient across embankment or structures in embankment.
- Filter characteristics of the soils at the exit point and along the seepage path.
- Understanding of soil foundation conditions and the potential to develop preferred flow pathways.

R10.7.6 Blowout;

Blowout is a special case of heave and/or uplift. The upward forces are so great that it ruptures the surface at the exit point allowing soils to freely flow out of the foundation. Figure 10-8 illustrates sand boil conditions that do not pose an immediate threat to the dam. However, if these conditions develop into a blowout condition and the filtered exit condition was no longer present, then a catastrophic failure of the embankment could occur.

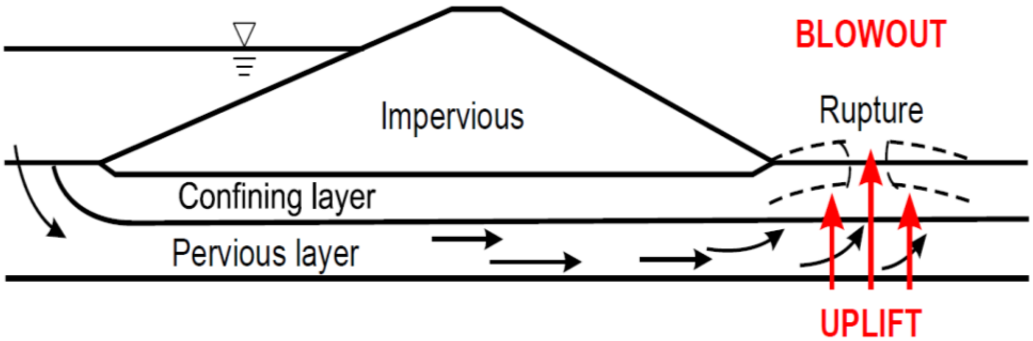

Figure 10-10. Illustration of blowout conditions.

The following considerations are a partial list of things to consider when developing PFMs for this condition.

- Hydraulic gradient across embankment or structures in embankment.
- Filter characteristics of the soils at the exit point and along the seepage path.
- Presence of a buttress with sufficient mass to resist uplift forces.
- Thorough knowledge of foundation geology and the potential for an underlying confining layer.

R10.7.7 Scour (Erosion through a Crack);

Scour is the erosion of soils through a crack or opening in an embankment. Embankment dams can experience transverse cracking in a multitude of ways. Similar to a pipe through an embankment, a structure such as a spillway wall could experience movement that allows the wall to pull away from the embankment soils, as illustrated in Figure 10-10. This opens a pathway for seepage to develop. If there is no filter or crack-stopper material along the pathway, the seepage could erode sufficient soils to allow a full breach of the embankment.

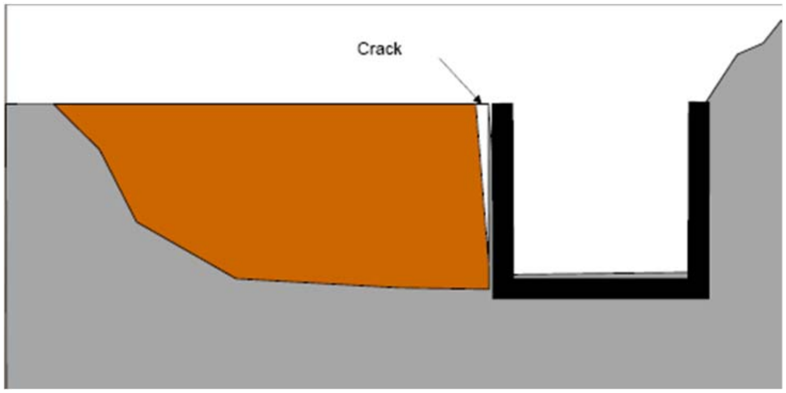

Figure 10-11. Illustration of a scour condition.

There are countless ways for cracking to develop in embankment dams. In arid climates, desiccation cracking could occur if the embankment contains medium to high plastic soils. Other cracks could develop by differential settlement of the embankment and a multitude of mechanisms. Figures 10-11 and 10-12 illustrate some of the ways cracks can develop in embankment dams.

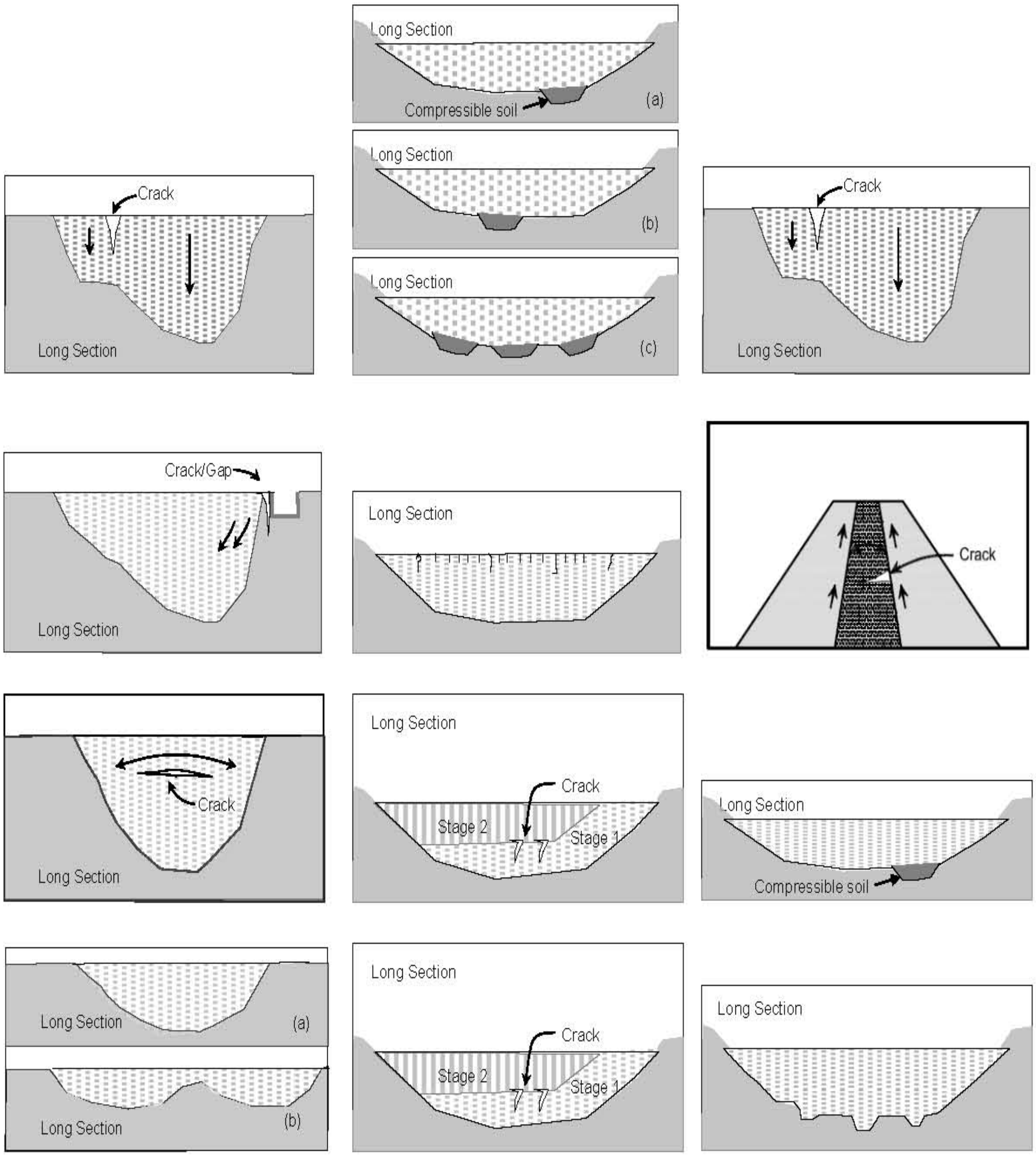

Figure 10-11. Illustration of mechanisms for the development of cracks in embankments.

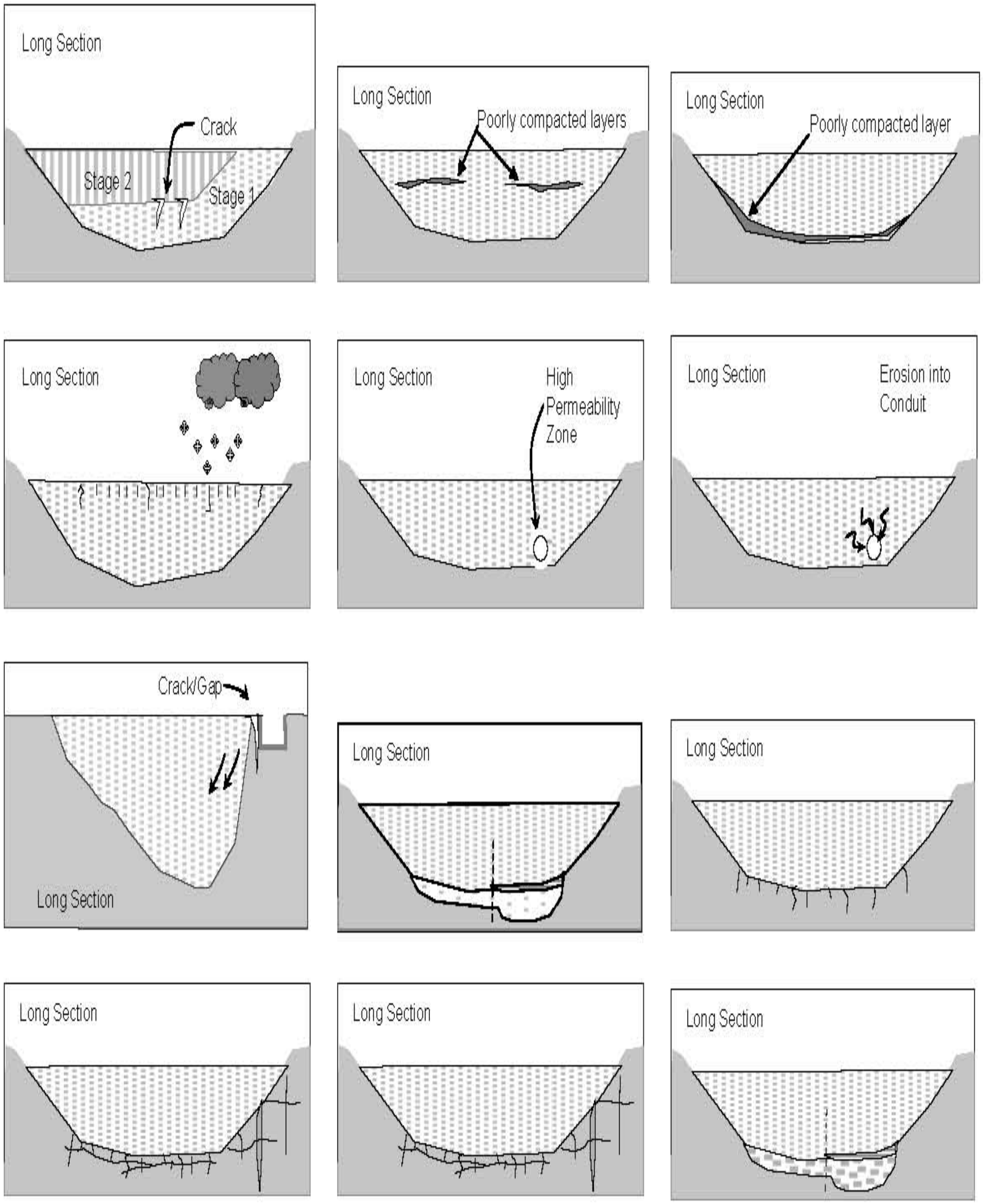

Figure 10-12. Illustration of mechanisms for the development of cracks in embankments.

R10.7.8 Inadequate Geologic Understanding of Foundation Conditions

An inadequate understanding of the geologic conditions of an embankment dam could result in the development of all of the mechanisms discussed above. It is critical to all aspects of a dam, not only internal erosion and piping, to fully understand the geologic conditions of the foundation of a dam before it is designed and constructed. Without this understanding, inadequate foundation treatment will surely result in an incident with the dam if not an entire catastrophic failure. It is crucial to have an experienced geologist or engineering geologist as part of the PFMA team when discussing foundation conditions and developing PFMs influenced by the foundation.

The following items are a small list of items that need to be considered when discussing foundation conditions for any of the internal erosion mechanisms:

- Compressibility of the soil.
- Presence of potentially dispersive clays in the foundation.
- Hydro collapse or subsidence potential in the foundation.
- Joints, fractures, fissures of bedrock.
- Filter compatibility of the foundation soil with embankment materials.
- Internal instability of foundation soils.
- Solubility of foundation soils and rock.
- Unrecognized foundation geomorphology
    - Relict landslides.
    - Lava Tubes
    - Karst limestone
    - Other soluble foundation rock.

R10.7.9 Other Considerations

R10.7.9.1 Animal burrows

Burrowing animals can result in problems that can result in the failure of an embankment. Muskrats, otters, and beavers can burrow into an embankment just at or below the water surface and create pipes that penetrate sufficient distance downstream that the seepage path is shortened and seepage commences on the downstream face of the embankment. The seepage does not have a filtered exit and the entire embankment could fail.

On the downstream side of an embankment, burrowing animals can penetrate the embankment and encounter the phreatic surface which is then free to exit the downstream face through the newly formed pipe.

These events typically occur on small embankment sections like power canals and levees but are noteworthy on near all water retaining structures.

R10.7.9.2

Open for other considerations to be added here….

R10.8 Internal Erosion Risk Estimating

Estimating the risk of internal erosion PFMs is very complicated if done with the extreme detail required to fully understand the mechanism of the potential failure mode. As with the development of the PFM, the risk estimated at each node of the event tree is fully dependent upon the level of the team's understanding for each particular node. It is often very difficult to get a good level of understanding for every internal erosion PFM.

For example, if a pipe begins to develop in the core of an embankment, questions that must be answered include whether the pipe will continue to grow and eventually extend through the entire core and reach the reservoir? Will the pipe develop in the downstream direction sufficiently to reach the unfiltered exit? Will the pipe collapse and prevent additional development of the pipe in either direction? Will a pipe develop downstream of the core allowing sufficient material to pass to allow the embankment to fail? Answering these and many other questions can be very difficult, but a decision must be made at each node before proceeding to the next node of the event tree.

When estimating hydraulic gradients, there are several things that must be considered to properly assess whether internal erosion is possible. These include things like the magnitude and distribution of the gradient, the grain size distribution of the soil subject to erosion, and the orientation of the seepage exit (vertical, horizontal or some combination). This information coupled with the questions noted in the paragraph above help aid in the evaluation of internal erosion potential. Early erosion studies have identified the "creep path" criteria (Bligh, 1910, and Lane, 1935) and the critical gradients (Terzaghi, 1929) for various grain size materials.

The following table provides some guidance for the piping resistance of fine-grained soils.

Table 10-1. Correlation between piping resistance, plasticity index and compaction

Greatest Piping Resistance Category (1)	**Plastic clay, (PI>15), Well compacted.**
	Plastic clay, PI>15), Poorly Compacted.
Intermediate Piping Resistance Category (2)	**Well-graded material with clay binder, (6<PI<15), Well compacted.**
	Well-graded material with clay binder, (6<PI<15), Poorly compacted.
	Well-graded, cohesionless material, (PI<6), Well compacted.
Least Piping Resistance Category (3)	**Well-graded, cohesionless material, (PI<6), Poorly compacted.**
	Very uniform, fine cohesionless sand, (PI<6), Well compacted.
	Very uniform, fine, cohesionless sand, (PI<6), Poorly compacted.

In addition to erodible soils in a foundation, there are other conditions that can pose a hazard to water-retaining structures. Minerals such as gypsum can be easily eroded or dissolved with the erosion continuing undetected until the problem becomes difficult, if not impossible, to control. In this case, seepage is not as much of an issue since static water conditions can result in soluble minerals entering into a solution resulting in the loss of soil support. Another condition to be aware of are clay-filled solution cavities in limestone which can be an issue if the clay erodes from the voids allowing other soil to fill the voids left behind and allow the development of preferential pathways. Water flowing along the boundary between a soil susceptible to internal erosion and a non-erodible material like bedrock can open new flow paths with the bedrock potentially providing a roof for piping to commence. Grouting joints below structures can prevent or reduce the possibility of soils transport but grouting is generally ineffective in a clay-filled joint environment. The construction of a continuous concrete cutoff wall is often the only effective means to address this issue. Recent examples of dams in the U.S. undergoing remediation for seepage in karstic, erodible foundations include Wolf Creek Dam, KY, and Clearwater Dam, MO.

Determining an actual quantitative value for internal erosion poses several problems because of the uncertainty associated with natural materials. The Joint Federal Best Practices Guidelines developed by the Bureau of Reclamation and U.S. Army Corps of Engineers, propose a very detailed procedure to estimate the probability of the event at each node. These procedures are based heavily upon Fell, et al. and are very familiar and experienced with the data being used since they were involved in developing the method. Very few individuals who use the FERC guidelines have the same expertise as those with other agencies who were also instrumental in developing that information. For the purpose of estimating the probability of the progression of the failure at each node for the FERC at this time, the following table will be used by the risk analysis facilitator to select the probability agreed upon by the risk team.

Table 10-2. Risk estimate descriptors

Descriptor	Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

The "Descriptor" plays the major role in selecting the "Probability". Most engineers and operators with a project have some sense of how likely or unlikely an event is based upon the information available when discussing a particular node of a PFM. Less understandable is a discussion of a numerical probability for the event, particularly for those not familiar with risk at all. Most people don't have a good feel for the different between 10^{-3} as compared to 10^{-6}. Until more people are familiar with internal erosion or for special cases where an extremely detailed risk analysis is required, the method proposed in Table 10-2 will be utilized by the FERC for internal erosion risk estimates. It remains critical for all team members to have a very thorough understanding of the dam when performing a risk analysis.

When discussing each node of an event tree, the Risk Team should discuss how likely the "yes" branch is to happen. In discussing and determining the most appropriate "Descriptor", it is helpful to carefully review the likely and unlikely factors developed during the development of the PFM. The facilitator will ask the Team which Descriptor is considered appropriate for each node of the event tree. During the discussion, it is not unusual to find that there is a lot of uncertainty regarding the internal erosion PFM. In fact, for internal erosion, it is unusual if there is a lot of certainty regarding the PFM. The next section of this chapter contains a discussion about addressing the uncertainty of a PFM. In addition, refer to the Chapter R24, Risk Analysis, for discussions about Expert Elicitation and Structured Expert Interaction.

Depending upon the level of uncertainty, it is typical that the Team will have varying ideas of which specific Descriptor is most appropriate. Team members could have ideas that range from one to several descriptors apart. In this case, the facilitator must lead additional discussions in an attempt to narrow the consensus between the outlying team members. With additional discussion, it is generally possible to bring the Team into an agreement relatively close to only one descriptor, or at least ranging between two adjacent descriptors. In this case, the team may reach an agreement that the risk lies somewhere between very unlikely and neutral. The facilitator must then try to bring the team slightly closer to an agreement to one value with a range of uncertainty. For example, if team members agree that it is unlikely, then the Probability for that node could be assigned a value of 0.01 with a band of uncertainty ranging from 0.01 to 0.5. If the team determines that it is closer to very unlikely but cannot agree that it is completely very unlikely, it is acceptable to estimate the risk at that node to be in between the two values, for example, 0.08 with an uncertainty range from 0.01 to 0.5.

When the "yes" branch of the node is decided upon, the probability of the "no" branch of the node is calculated by subtracting the probability from 1.0. The probability between the yes and no branches must always add to 1.0. In the above example where it was agreed by the Team that the "yes" branch has a probability of 0.08, the "no" branch would then be assigned a probability of 0.92 (0.08+0.02 = 1.00). This means that there is an 8% chance of the event happening and a 92% chance of it not happening.

Once all the nodes of the event tree have been completed, the final annual probability of failure for that particular PFM is the product of each "yes" node of the event tree. See Appendix 10-C for a specific example.

R10.8.1 Accounting for Uncertainty

Estimating the risk associated with an internal erosion potential failure mode must take into account how well the PFM team understands the dam, with a full appreciation of the complexity and variability of how soil and rock interacts with water. In evaluating an internal erosion potential failure mode, understanding the uncertainty of accurately describing material properties and behavior is essential and the team must also recognize and account for the limits of the models used to describe the power of water moving through soil and rock. Considering these aspects is essential to quantifying the range of risk.

Uncertainty in material properties and their behavior based upon design intent, construction quality, and current dam performance includes:

- Gradation
- Density
- Plasticity
- Erodibility
- Permeability and permeability ratio
- Unknown material types in undetermined locations within the dam or foundation

All sampling and testing of embankment dam materials is limited by the very small amount of material that is actually evaluated, and the inherent non-heterogeneity of soil and rock. This particularly applies to natural soil deposits that were not placed and compacted in a controlled manner.

To reduce the effects of material property uncertainty, design and pre-construction approaches could include a greater testing frequency of samples collected during the initial site investigation in order to better define expected value and variance in anticipated performance. A sensitivity analyses can also be performed by varying specific material properties that are determined to be a key to the issue being evaluated. A sensitivity study should be performed using a reasonable standard deviation and distribution, to evaluate the resulting effects on the value of the properties being tested. This information can be used to help predict the probability of failure using probabilistic methods, such as Monte Carlo analysis, or other methods to evaluate the variability. Once a full understanding of the critical elements has been established, it should be easier to make the case of which parameters should be used in the analysis.

Small variances in material properties also have the potential to make a substantial increase or decrease in risk. For example, if the uncertainty of the value is at a threshold level where a change permits erosion to initiate or continue, the selection of the value could significantly impact the results. This condition should be further evaluated to eliminate the amount of uncertainty or clearly expressed as a level of uncertainty in the final calculation of risk numbers and how it impacts the assessment of risk.

Examples of model uncertainty also include the tools used to assess the phreatic surface and pore pressure conditions in a dam and foundation. In increasing levels of complexity, pressure gradients at an exit face may be evaluated by Bligh's or Lane's creep ratio, hand drawn flow nets, or software such as Geo Studio's SeepW, which is capable of generating and computing pressures with finite element meshes.

By applying the ranges in Table 10-2 when evaluating the different nodes of an event tree, it is possible to influence the range of uncertainty in the estimated risk.

R10.8.2 Dam Failure and Consequences

Chapter R22, Estimation of Life Loss Consequences, should be referenced for more specific details regarding the estimation of downstream consequences resulting from a dam failure. However, the critical component of internal erosion and piping failures in estimating the consequences of a failure is the time between detection of a problem and the failure of the embankment.

Piping failures can occur rapidly once observation of a moving soil is found, possibly within hours of the initial observation, such as Teton Dam. If the potential life loss is significantly affected by the amount of time available for evacuation, estimating the time to failure can give a better evaluation of the true risk of the potential failure mode to the downstream population. This would be included in the warning time and subsequent calculated loss of life when evaluating consequences.

Evaluating the time to failure can be challenging. One possible resource to provide general guidance is the Fell, Wan, Cyganiewicz, and Foster, UNCIV Report R-399 (2001). Keep in mind that if this approach is selected, it should only be used by someone well aware of the source of the data and the implications of decisions based on this approach. Several case histories of both failures and near-miss incidents (erosion without breach) due to internal erosion mechanisms were analyzed, assessing or estimating the time from initiation to breach, and also from progression to breach. These studies noted that the first observation of the failure or accident was often not until the progression stage had been reached, i.e., the erosion mechanism had initiated and had continued for some time prior to human observation. This report provides a template that may guide a risk team to evaluate the relative time to failure of piping through an embankment, through the foundation, or along a conduit or wall. Their methodology brackets failure time into four categories: Slow, Medium, Rapid, and Very Rapid. The associated general failure times ranged from hours to years indicating the difficulty of failure estimates. Simply stated, the data must be used with caution and by someone who is well aware of the source of the data and its limitations.

R10.8.3 Levels of Risk – Scalability

The scalability of the different levels of risk for internal erosion is based upon all the factors discussed in this chapter. With the level of uncertainty that is associated with internal erosion, it is important to have a good feel for the consequences resulting from a piping failure. This will provide the opportunity to determine if additional field investigations and laboratory testing, document record searches, sensitivity analyses, etc., are required to better define the confidence in the risk estimate. If there is little or remote risk, then it becomes clear that there is no need to spend countless hours and dollars to further refine the estimate. As with all portions of risk, a unbiased, open-minded evaluation of the end result is required to help determine the level of effort required for estimating the risk of each PFM.

Appendix 10-A Definitions of Internal Erosion-Related Terms

The terms associated with internal erosion and piping used throughout this chapter are listed below. The terms are specifically associated with internal erosion and piping. Refer to the main Glossary in Chapter R2 for other risk-related definitions.

Seepage. Movement of water through a material typically considered to be pervious and which has a measurable value of permeability, such as soil.

Leakage. Movement of water through a material typically thought to be non-pervious such as concrete, steel, or similar material. Also applies to movement of water through mechanical items that are typically used to contain water, such as spillway gates, valves, locks, etc.

Internal erosion. Occurs when soil particles within an embankment dam or its foundation, are carried down-gradient by seepage flow. Internal erosion can initiate by concentrated leak erosion, backward erosion, suffusion and soil contact erosion.

Backward erosion. Backward erosion involves the detachment of soils particles at the downstream end of the seepage path and soil detachment progress upstream until reaching the source of water, such as a reservoir. For example, when seepage exits a free unfiltered surface, such as the ground surface downstream of a soil foundation, or the downstream face of an embankment, or a coarse rockfill zone immediately downstream of a fine grained core. The detached particles are carried down-gradient by the seepage flow and the process gradually works its way towards the upstream side of the embankment or its foundation until a continuous pipe is formed.

Reverse Erosion. See Backward Erosion.

Suffusion / internal instability. Suffusion is a form of internal erosion which involves selective erosion of fine particles from the matrix of coarser particles (coarse particles are not floating in the fine particles). The fine particles are removed through the constrictions between the larger particles by seepage flow, leaving behind an intact soil skeleton formed by the coarser particles. Soils which are susceptible to suffusion are internally unstable. Coarse graded and gap graded soils are susceptible to suffusion. In these soils the volume of fines is less than the volume of voids between the coarse particles.

Concentrated leak erosion. Erosion in a concentrated leak may occur in a crack in an embankment or its foundation, caused by differential settlement, desiccation, freezing and thawing, and by hydraulic fracture; or it may occur in a continuous permeable zone containing coarse and/or poorly compacted materials which form an interconnecting voids system. The concentration of flow causes erosion (sometimes called scour) of the walls of the crack or interconnected voids.

Piping. Piping initiates by backward erosion, or longitudinal erosion in a crack or high permeability zone, and resulting in a continuous tunnel called a ‘pipe’ between the upstream and the downstream side of the embankment or its foundation.

Flaw. Continuous crack, high permeability or poorly compacted layer in which a concentrated leak may form.

Arching. The soil property in which stresses distribute between a stiffer element, such as rock or concrete structure, and another stress plane or stiffer element, in such a way that the vertical stresses are less than the overburden pressure.

Hydraulic Fracture. A separation in a soil or rock mass that occurs if the applied water pressure exceeds the minor principal stress on the soil element. Hydraulic fracture may occur if differential foundation movement occurs. Soils compacted dry of optimum water content are more susceptible to hydraulic fracture.

Segregation–The tendency of particles of the same size in a given mass of aggregate to gather together whenever the material is being loaded, transported, or otherwise disturbed. Segregation of filters can cause pockets of coarse and fine zones that may not be filter compatible with the material being protected

Filter–A zone of material designed and installed to provide drainage, yet prevent the movement of soil particles due to flowing water. A material or constructed zone of earthfill that is designed to permit the passage of flowing water through it, but prevents the passage of significant amounts of suspended solids through it by the flowing water. Specific types of filters are further defined below:

> **Chimney**–A chimney filter is a vertical or near vertical element in an embankment dam that is placed immediately downstream of the dam’s core. In the case of a homogenous embankment dam, the chimney filter is typically placed in the central portion of the dam.
>
> **Collar**–A limited placement of filter material that completely surrounds a conduit for a specified length within the embankment dam. The filter collar is located near the conduit’s downstream end. The filter collar is usually included in embankment dam rehabilitation only when a filter diaphragm cannot be constructed. A filter collar is different from a filter diaphragm in that a filter diaphragm is usually located within the interior of the embankment dam.

Diaphragm–A filter diaphragm is a zone of filter material constructed as a diaphragm surrounding a conduit through an embankment. The filter diaphragm protects the embankment near the conduit from internal erosion by intercepting potential cracks in the earth fill near and surrounding the conduit. A filter diaphragm is intermediate in size between a chimney filter and a filter collar. The filter diaphragm is placed on all sides of the conduit and extends a specified distance into the embankment.

Filter Compatibility. This term refers to particle size distribution of zones in a multi-stage filter. The zones in contact with each other are considered compatible if they meet modern filter design criteria.

Christmas Tree Effect. This is a term typically used to describe the overlapping of adjacent filter or embankment zones causing contamination of adjacent zones. When viewed in a cross section, the resulting effect has the appearance of branches of a Christmas tree which, in a severe case, could result in a shortened filtered seepage path that could result in an unfiltered exit.

Unfiltered Exit. Seepage exit point that is not protected by a filter system. An unfiltered exit is needed for progression of piping and internal erosion failure modes.

Embankment. General term for earth or rock fill water retaining structure

Heave – The condition in soil when vertical seepage forces acting on soil grains result in an effective stress of zero, i.e., a quick condition. As vertical gradient increases, seepage forces increase, the effective stress goes to zero, and there is a volume increase in the soil mass. Heave is identified with pervious foundations, and boils often appear.

Uplift\Blowout – When a confining layer is present over a pervious layer, artesian pressures (aquifer pressure exceeds downstream ground surface elevation) may develop. When the artesian pressure on the bottom of the confining layer is larger than the weight of the layer, the confining soil may uplift. Often this pressure ruptures the layer, causing a blowout. Excessive seepage, boils, and movement of the pervious soils through the blowout in the confining layer may result.

Appendix 10-B Case Studies

Case studies will be forthcoming in a future version of the Internal Erosion Engineering Guidelines. The studies will present summary findings of dam failures and/or incidents and one postulated potential failure mode with an event tree as examples

Appendix 10-C Suggested Example Risk Analysis Report for Internal Erosion Risk

Scope
Participants
Risk Analysis Methodology
Description of Dam, Project, and Operations
- Description
- Operations
- Geology
  - Regional Geology
  - Site Geology

Past Performance
- Seepage
- Drain Holes
- Seepage Measuring Devices

Potential Failure Modes and Risk Analysis
- Static Potential Failure Modes
  - Seepage through Embankment
  - Seepage through the Foundation
  - Seepage from the Embankment into the Foundation
- Hydrologic Potential Failure Modes
  - Operational Considerations
  - Potential Failure Mode Analysis
- Seismic Potential Failure Modes
  - Assess Geology/SPT for Liquefaction Probability
  - Assume Distribution for Residual Strength
  - Assume relation between crest loss and residual shear strength
  - Post-earthquake Freeboard as a Function of Initial Freeboard and crest loss
  - Probability that a Dam Breach Will Result in a Given Post-Earthquake Freeboard
  - @Risk Analysis

Consequences of Failure
- Static Failure Consequences
- Hydrologic Failure Consequences
- Seismic Failure Consequences

Results
- Static Risk
- Hydrologic Risk
- Seismic Risk

Conclusions and Recommendations

Suggested Example Report

1. Scope

After performing a revised Potential Failure Modes Analysis (PFMA) as a result of the Seventh Part 12D inspection, the owner of Dam A determined the need to perform risk analyses of the project structures to more fully analyze the internal erosion PFMs developed during the PFMA. The owner gathered subject matter experts to perform the necessary evaluations, analyses and make recommendations regarding the safety of the dam following the procedures in Chapter R24 of the FERC Engineering Risk Guidelines.

The scope of work was defined in a meeting on November 15, 20XX and included defining the level of risk analysis and need for risk reduction measures.

- Add discussion here.

2. Participants

- List of participants

3. Risk Analysis Methodology

A Level 3 Risk Analysis was chosen to analyze risk at this dam, etc.

- Include definition of Risk
- Summarize requirements of FERC for a risk analysis
- Include the following table with a brief description of how it was use

Descriptor	Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

- State what software package, if any, was used for calculating risk numbers, loss of life, etc.

4. Description of Dam, Project, and Operations

- Include a brief, yet complete description of the project

- Focus on
  - Geology of project related to PFMs being analyzed
  - Discuss past performance, such as seepage, drainage measures, and other aspects related to the PFM.

a. Description

b. Operations

c. Geology

i. Regional Geology

ii. Site Geology

5. Past Performance

- Discuss past performance

6. Seepage

- Discuss sources of seepage, drainage at dam, and measurement systems

7. Potential Failure Mode Analysis

- Discuss PFMs by category, i.e., Static, Seismic, Hydrologic, and Operational. An example of a piping PFM follows.

a. PFM 3 – Piping Through West and East Embankment

- Provide an actual PFM description as well as the discussion below

The PFMs of concern involves the development of a piping failure caused by inadequate filters around the drain pipes embedded in the embankment, or collapse of the drains themselves, which allow soil transport into the drain pipes, development of a large void in the embankment, collapse of the void resulting in a breach through the crest which widens under flow from the reservoir, resulting in an uncontrolled release of the reservoir. The consequences of this PFM could be downstream incremental impacts (potential for loss of life and property damage), loss of water supply, loss of downstream control of minimum flow (waste water dilution), and loss of power generation capability).

It was discussed that the drain pipes are longitudinal to the embankment. The drains are layered vertically in the embankment; the top longitudinal pipe (elevation 510) is at least 20 feet downstream of the centerline of the crest; the middle longitudinal drain (elevation 490 feet) is 38 feet downstream of the crest, and the lowest drain (on the top of the native residual soil) is about 56 feet downstream of the centerline of the crest. The drain pipes are reportedly 6-inches in diameter, and an east retaining wall drawing indicates that the drains are clay (Drawing E40). The laterals from the longitudinal drains, which extend and daylight at the downstream slope are 100 feet on center. The pipes are indicated on the drawings to be encapsulated in "rock fragments". A plan view of the drains is shown on drawing H25, and H40 shows the drains in cross section.

It was also discussed that the foundation is a residual soil, so piping into the foundation is not anticipated since the embankment fill is also residual soil, and therefore, both have similar grain sizes. A wet area was observed at the downstream end of the east retaining wall during the site inspection (this is not necessarily a positive or negative factor). This PFM was classified as Category II since the clay tiles exist and potential future problems with piping through the drains could not be rule out, and to point out the need for continued surveillance to identify if any future problems are developing. The following presents the tabular development of this failure mode:

PFM 3 – Piping Through West and East Embankment	
Conditions making PFM Likely Or Unfavorable Factors	***Conditions making PFM Unlikely Or Favorable Factors***
- Rock fragments encapsulation material serving as drainage zone around pipes may not meet filter criteria of the surrounding residual fill soil. - Drains could possibly have been damaged during installation of piezometers/wells, although there is no evidence (settlement/sinkholes) that that occurred. - Drain laterals discharge into rockfill placed in 1985 on the downstream slope of the embankment, therefore flows from the lateral outlets cannot be monitored (completely covered by the rockfill). - Drains could be crushed or joints pulled apart, although no evidence (settlement/sinkholes) that this has occurred.	- PMF hydrograph exceeds elevation 522 feet for 48 hours (peak at 529.9 feet; embankment crest at 535 feet). The clayey residual embankment soils would not respond significantly to the elevated reservoir in such a short amount of time. - Piezometer cross section (MS1, 2 and 3) show suppressed phreatic surface. - The embankment fill generally has some plasticity (PI usually is 10 or more, with a few non-plastic samples, so embankment fill should be somewhat piping resistant). - No record of depressions since at least 1985. - No record of cloudy seepage flow at toe.
Category: **II** ***Rationale:*** **Since the clay tiles exist, the potential for future problems cannot be ruled out. Also to point out the need for continued surveillance to identify if any future problems are developing.**	

i. Potential Risk Reduction Measures, New Analyses or Other Actions:

The checklist used by the owner in his monitoring program could be modified to include checking the east and west embankments for new or cloudy seepage flows at the toe areas, watching for sinkholes and displacement in the plan area of the east and west embankment crest and downstream slope, or other signs of structural distress that could be a sign of piping development.

- Continue to periodically monitor and observe existing drain pipes (west dike weir and filter drain, located downstream of the left end of the left embankment).

- The owner could periodically observe the wet area at the toe of the east retaining wall; clear brush to improve surveillance of the area.

ii. Risk Team Evaluation of PFM 3.

During the review, the risk team determined that there were several different branches of the PFM event tree that should be further divided by location, loading condition and piping method. Through this process, the team identified the following, summarized, potential failure modes:

PFM 3A: Piping at East Embankment Station 20+50 under normal loading conditions

PFM 3B: Piping at East Embankment Station 20+50 under flood loading conditions

PFM 3C: Piping along the east retaining wall under normal loading conditions

PFM 3D: Piping along the east retaining wall under flood loading conditions

PFM 3E: Piping along the west retaining wall under normal loading conditions

PFM 3F: Piping along the west retaining wall under flood loading conditions

The team developed detailed step-by-step failure mode descriptions and event trees for each failure mode. The detailed description and event tree for PFM 3A is shown in the next section. After developing PFM 3A, the team added PFM 3G, for Piping at Station 20+50 after sinkhole doesn't collapse below the reservoir surface but internal erosion continues.

iii. PFM 3A – Piping at Station 20+50 Under Normal Loading Conditions

Under normal loading conditions, seepage water carrying fine embankment particles enters the clay longitudinal drain pipe at elevation 490 feet through an inadequate filter at a joint left between the clay pipes during construction. The rock fragments that surround the clay pipe do not provide adequate filter protection and moderate seepage quantities slowly carry fines through the opening in the clay pipe creating a small void through reverse erosion. The eroded particles are carried into the downstream rockfill. The seepage is filtered at a downstream toe drain, leaving the fine particles in the large rockfill section. The piping process continues undetected since the eroded particles cannot be seen at the surface and because monitored seepage flow downstream is clear. The silty clay embankment soils support the roof of the enlarging void while seepage flows gradually increase. No action is taken because the increase is not understood and the flow continues to be clear. There are small settlements in the embankment that are not detected. Subsidence cracks above the void are eventually detected in the pavement on the crest but before an investigation is initiated, the void collapses exposing the downstream slope to the reservoir. Heroic intervention is unsuccessful and overtopping flows quickly erode the embankment, releasing the impoundment.

The next step in the process was to assign probabilities for each node. A summary of the team's rationale for selection of values is shown below.

Node 1 – Normal pool loading (1.00) – Normal loading is certain.

Node 2 – Inadequate filter of clay pipe drains creates unfiltered exit (0.90) – The base soil of the embankment is silty clay (CL) with average PI of 25 and a D85 of 0.22 mm. Review of project data confirms that the clay tile pipe was installed with open joints encapsulated with "rock fragments." The team agreed that the rock fragments were **likely** too course to provide filter protection for the embankment.

Node 3 – Erosion of embankment through clay tile drains begins (0.50) – The team agreed that the cohesive soils in the embankment would be resistant to erosion. The team also questioned whether the gradient at the pipe would be high enough to erode the embankment soil. There are two piezometers at or near Station 20+50 in the embankment but neither one is close to the longitudinal clay tile drains. The upstream piezometer indicates that there is a significant head drop in the upstream portion of the embankment. This may be due to silt in the reservoir. Another consideration is the embankment is rolled fill which is expected to result in anisotropic conditions where the horizontal hydraulic conductivity is greater than the vertical hydraulic conductivity. The team agreed that the phreatic surface was affected by the drains and developed an estimated phreatic surface shown in Figure 10-1. Because of the positive and negative factors, the team was **neutral** on whether erosion would begin.

Node 4 – Erosion continues (0.01) – The most pertinent data that the team had regarding this node was the seepage measurements taken from this section of the dam. The flow of seepage collected at the toe of this section averages about five gallons per minute. Because of the low flow rates, the team agreed that it was **very unlikely** that erosion would continue. The team concluded that it is likely that the rock fragments would clog and seepage flows would be redirected to another pipe joint opening. Another likely possibility is that the drain pipes could become clogged and the seepage could bypass the drain pipes altogether.

Node 5 – Evidence of piping not detected (0.90) – The team agreed that it is **likely** that piping would not be detected because eroded soils would be stopped by the downstream filters and the volume of the voids of the rockfill could hold a large quantity of soil.

Node 6 – Embankment soils support a roof (0.90) – The team agreed that the cohesive embankment soils would **likely** support a roof.

Node 7 – Large void forms (0.50) – The team discussed whether or not a large void could form through a series of small roof collapses or is it more likely that reverse erosion process slowly creates a piping channel to the reservoir. The team agreed that the piping channel should be developed as a separate failure mode because the piping process is different. One team member pointed out that the collapse of sinkholes is commonly associated with a lowering of the phreatic surface. This is because when the phreatic surface drops, the roof goes from buoyant to total unit weight resulting in collapse. The team looked at the historic reservoir levels and found that the owner periodically lowered the reservoir. While the lowering of the reservoir was infrequent (5-10 years) the postulated PFM is expected to develop slowly over many years. The team was **neutral** in whether the continued erosion would lead to a large void or erosion channel leading upstream.

Node 8 – Void not detected (0.50) – The team discussed case histories of sinkholes on dams and found that in many cases there was settlement at the surface that was observed during inspections or detected by deformation monuments prior to collapse. Additionally, sinkholes did not result in failure and were safely remediated in the cases that were examined. Deformations at the crest should be detected by cracks in the pavement; however, because of the rock fill on the downstream slope it would be extremely difficult to observe on the slope. This embankment does not have deformation monuments that could detect settlement. However, fluctuation of the upstream piezometer as a result of the sinkhole formation process or increase of seepage flow may aid in the detection of a sinkhole. The team remained **neutral** on whether the void would be detected.

Nodes 9 & 12 – Sinkhole collapse results in crest sinking below reservoir water surface elevation (0.01) – The crest elevation is 535 feet and the normal elevation of the reservoir is 520 feet. Based on the case studies that were examined of sinkholes in other dams, the team determined that it is **very unlikely** that the sinkhole would result in loss of the 15 feet of freeboard at the project.

Nodes 10 &13 – Intervention Unsuccessful (0.01) – The team determined that once the sinkhole collapsed below the reservoir, it is **very unlikely** that the owner is able to safely remediate. Immediate action would have to be taken to open all gates at the project to rapidly lower the reservoir.

Node 11 – Investigation not able to identify problem in time to safely remediate (0.50) – The team recognized that there may be signs that there is a problem with the dam, but studies and investigations into these concerns are often slow or inconclusive. Because of uncertainty, action could be delayed for additional studies and evaluations. The team was **neutral** on whether this would occur.

8. Consequences

- Discussion about how PAR and life loss are calculated

9. Results of Risk Analysis

- Include description of what programs/methods were used to reach the numbers calculated in the event trees for all PFMs

For PFM 3a, above, there are three paths to failure in the event tree. As described above, the events are as follows:

1. Reservoir at Normal Pool
2. Inadequate filter of clay pipe drains creates unfiltered exit
3. Erosion of embankment through clay tile drains begins
4. Erosion continues
5. Evidence of piping not detected
6. Embankment soils support a roof
7. Large void forms
8. Void not detected
9. Sinkhole collapse results in crest sinking below reservoir water surface elevation
10. Intervention unsuccessful

<u>Path 1 = Nodes 1-10 (void wasn't detected and sinkhole doesn't collapse below reservoir)</u>

Probability = 1.0 x 0.9 x 0.5 x 0.01 x 0.90 x 0.90 x 0.50 x 0.50 x 0.01 x 0.99
= 9.02×10^{-6}

11. Investigation not able to identify problem in time to safely remediate
12. Sinkhole collapse results in crest sinking below reservoir water surface elevation
13. Intervention unsuccessful

Path 2 = Nodes 1-8 and 11-13 (void was detected and sinkhole collapsed below reservoir)

Probability = 1.0 x 0.9 x 0.5 x 0.01 x 0.90 x 0.90 x 0.50 x 0.50 x 0.50 x 0.01 x 0.99 = 4.51×10^{-6}

10. Conclusions and Recommendations

- Generally discuss the decisions reached and reference the “Making the Case” document, which would be a separate document that will contain all the justification for the decision made based upon the results.

References

Appendices and Figures

- Show dam sections and event trees, etc.

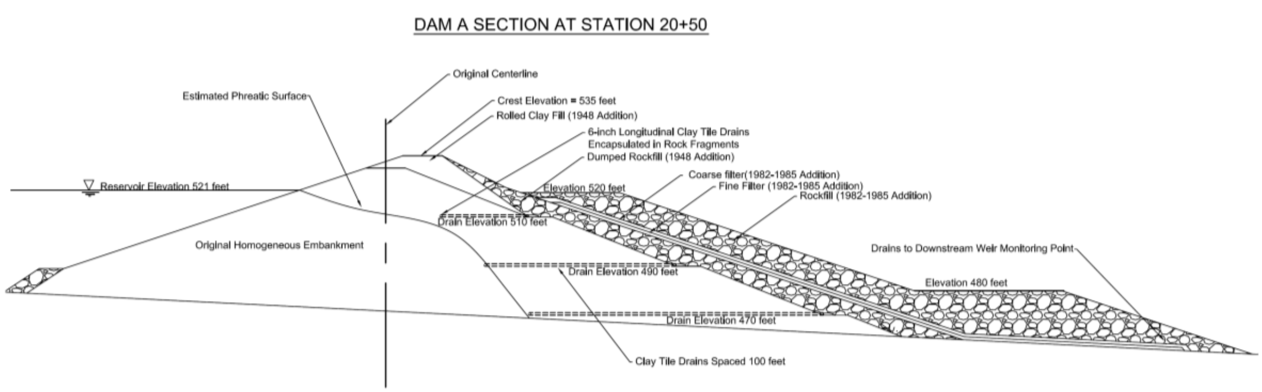

Figure 10C-1: Section View

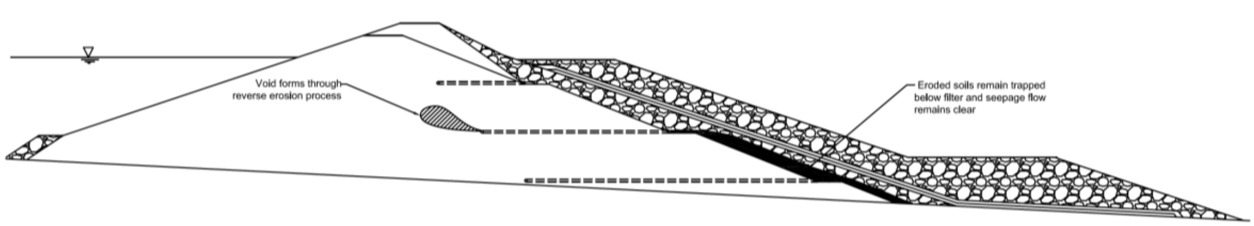

Figure 10C-2: Sketch of developing failure mode

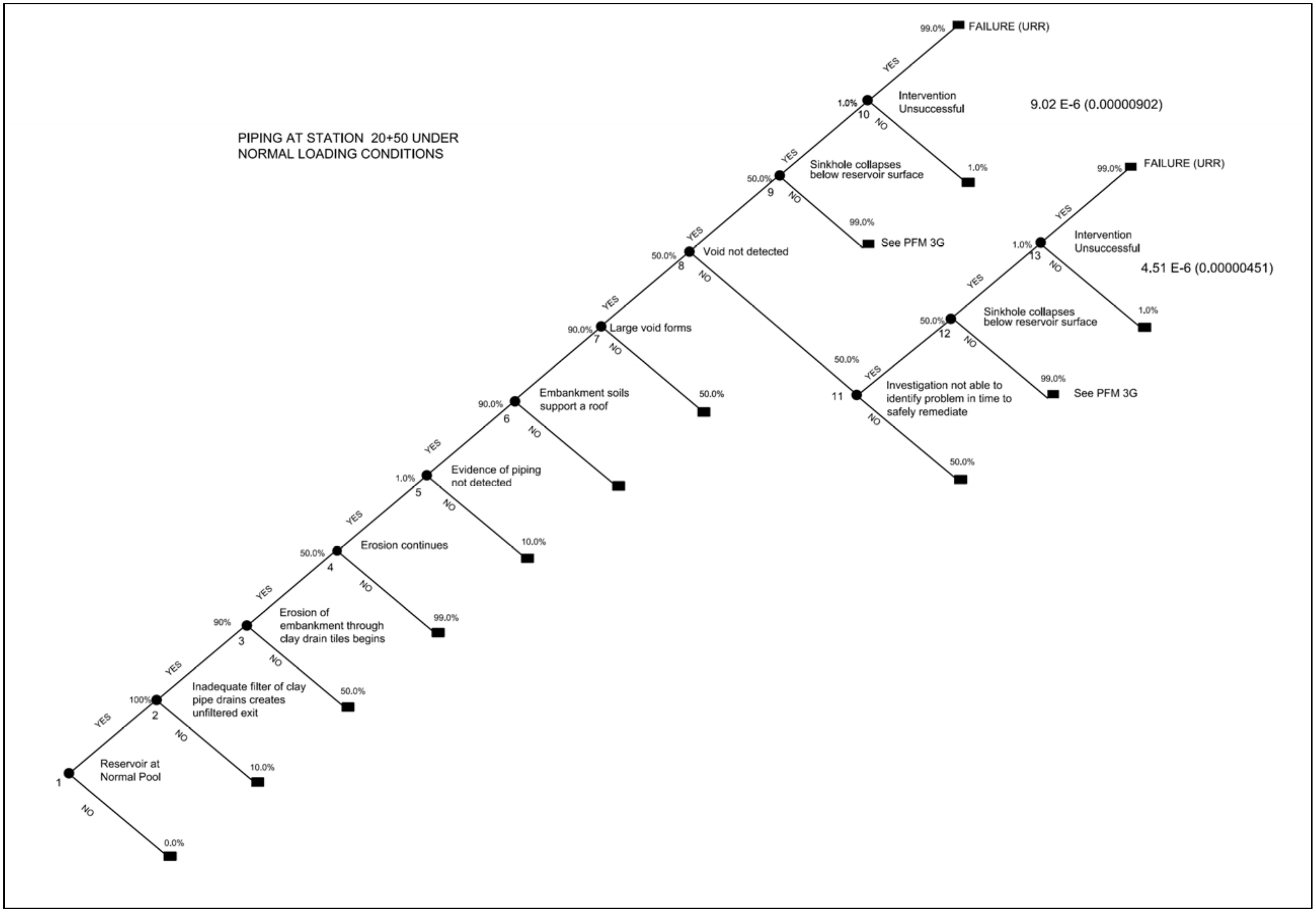

Figure 10C-3: Event tree for PFM 3A

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