Chapter 5: Potential Failure Modes Associated with Seepage Barriers

This chapter presents an assessment of potential failure modes in dams that are specific to dams with seepage barriers. The potential failure modes presented herein were developed based on insights garnered from the review of the performance of 30 dams that have had seepage barriers in place for a minimum of 5 years, and analyses performed to enhance the understanding of the mechanisms involved. Descriptions of the 30 cases are presented in Chapter 3 and the analyses are presented in Chapter 4.

Because the purpose of a seepage barrier is to reduce seepage through the pervious portions of the embankment, foundation or abutments, installation of a barrier can radically change the seepage conditions. The result is increased water pressures and hydraulic gradients behind and around the barrier. These increased pressures and gradients have potential to provide the catalyst for initiation of several modes of internal erosion that were either unlikely or less likely without the seepage barrier. This is not to say that the installation of seepage barriers increases the risk of failure for a dam. Indeed, in most cases seepage barriers have significantly increased the reliability of the dams in which they have been installed. It is to say, however, that there are several potential modes of seepage, erosion and piping that are unique to dams with seepage barriers. Understanding these failure modes is essential to predicting the behavior and assessing the associated risk of dams with seepage barriers. The information presented in this chapter will be useful in 1) assessing the possibility of internal erosion and piping in dams with seepage barriers, 2) designing to minimize that possibility, and 3) assessing the risks associated with these mechanisms of erosion and piping.

Development of Failure by Piping

Piping and internal erosion failures in dams have been described by Foster, Fell and Wan (Fell et al. 2004, Foster and Fell 1999) as a four-phase process consisting of 1) initiation, 2) continuation, 3) progression, and 4) breach. In order for piping or internal erosion to cause failure, the process must progress through all four phases. Because the Foster, Fell and Wan process outline provides a useful framework for assessing potential failure modes in the context of risk assessment analyses and reliability assessments, the four-phase process has been used in this chapter to present the potential failure modes specific to dams with seepage barriers. The necessary conditions for each of the four phases are discussed below and the first three phases are illustrated schematically in Figure 5-1.

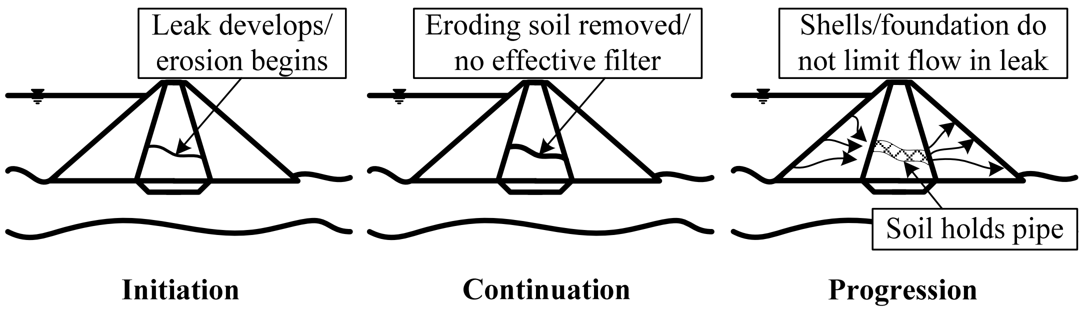


Figure 5-1 Phases of development for internal erosion and piping (modified from Fell et al. 2004 and Foster and Fell 1999, with permission from University of New South Wales)

Initiation. This phase consists of the initiation of erosion along a seepage path through the dam or foundation. Cracks or defects providing potential seepage paths may result from a number of causes: differential settlement, desiccation, backward erosion, earthquake shaking, high permeability zones due to poor compaction or segregation of fill during placement, internal instability (suffusion) of gap-graded soils, or hydraulic fracture. Erosion will begin when the hydraulic gradient in the seepage path becomes large enough to move soil particles. Thus the requirements for this phase are: 1) a path for concentrated flow (usually a crack of some kind) and 2) the initiation of erosion along the seepage path.

Continuation. The requirements for continuation of erosion are the lack of an effective filter and the ability for the eroding particles to be removed at the downstream end of the seepage path. While a designed filter is the most reliable means for stopping removal of particles along a seepage pathway, other fill zones and native soil deposits may also provide restraint, even if they do not meet modern filter design criteria. In such cases, some erosion of the base soil may take place before the filtering material becomes effective. Foster and Fell (1999) discuss the ability of soils that do not meet modern filter criteria to be effective as long-term filters after some initial erosion has occurred. Fractured bedrock masses may also be capable of stopping movement of soil particles along a seepage pathway. Bedrock joint structure is never uniform. Pinch-points and tortuosity within a system of joints may provide locations where soil particles are restrained.

The effectiveness of soil deposits and bedrock joints as filters may decrease as hydraulic pressures and gradients increase. Under extremely high hydraulic gradients, such as those below seepage barrier discussed in Chapter 4, gap-graded and very widely graded materials may not be internally stable, and may undergo redistribution of the fine portion of the soil (a process often referred to as suffusion). Redistribution or removal of the fine portion of the shell materials may result in the coarse matrix of the shell remaining once the fine particles have migrated downstream. In such a case, the remaining coarse gradation may no longer be effective as a filter for the adjacent soils.

Progression. In the progression phase the seepage pathway enlarges to form a pipe or open eroded conduit through the embankment. This requires sufficient flow through the leak to maintain the eroding velocities, and the ability of the surrounding soil to support a pipe without collapse, as illustrated in Figure 5-1.

The flow limiting ability of upstream and downstream zones can control the flow volume through a leak in the core or through the foundation and prevent progression. In addition, crack fillers can migrate from the upstream zones into cracks and defects within the core and foundation, and seal off concentrated leaks.

Soils with the ability form and hold an arch (soils with plastic fines and cemented granular soils) are capable of supporting a pipe. It is also possible for a pipe to be supported by bedrock or competent soil capable of forming a roof above the eroding soil. In plastic clays, it is possible for the soils to close a leak by swelling.

Breach. Breach mechanisms may include gross enlargement of the pipe, crest settlement, unraveling of the downstream slope, and slope instability. The breach phase is not discussed in the following sections.

Potential Failure Modes Associated with Seepage Barriers

Four potential failure modes associated with seepage barriers in dams are presented in Table 5-1 and discussed in detail below. These failure modes are not necessarily the only possible modes to be considered in assessing the effects that a seepage barrier has on a dam's performance. Rather, these failure modes are examples of potential failure modes for dams with seepage barriers. Other failure modes are also no doubt possible, depending on detailed characteristics of particular dams and foundations, and should be evaluated thoroughly.

Mode 1 - Leaks through Seepage Barrier

This mechanism involves concentrated leaks through the barrier due to defects in the barrier or cracks resulting from hydraulic fracture or deformation of the barrier.

Initiation. This mechanism requires a concentrated leak in the seepage barrier that is aligned with a seepage path through the dam embankment or foundation. Cracking due to deformation of rigid seepage barriers is possible due to differential water pressure on the barrier or deformation in the embankment and foundation during construction or initial filling.

Table 5-1 Conditions and mechanisms considered in the development of potential failure modes involving seepage barriers

Phase	**Initiation**	**Continuation**	**Progression**
		Mode 1 – Leaks through seepage barrier	
Conditions/ mechanisms considered for Mode 1	Leak in barrier • deformation crack • hydraulic fracture • construction defect Concentrated flow in embankment • existing crack • high permeability zone • embankment/foundation interface • hydraulic fracture Erodibility of soils surrounding the leak	Absence or ineffectiveness of filter Internal instability of embankment soils potentially allowing internal redistribution of fines (suffusion) Concentrated flow reaches uncontrolled exit point	Seepage velocity in leak not limited by upstream and downstream zones Erodibility of seepage barrier backfill Ability to support a pipe • soil properties • foundation over-hangs or other geometries
		Mode 2 – Erosion of soil through bedrock joints	
Conditions/ mechanisms considered for Mode 2	Increased hydraulic gradient in joints Orientation and interconnection of joints facilitate flow Erodibility of joint infill material	No intercepting or effective filter Concentrated flow reaches uncontrolled exit point	Erodibility of adjacent alluvium or fill Ability to support a pipe
		Mode 3 - Erosion of solution void infill	
Conditions/ mechanisms considered for Mode 3	Increased hydraulic gradient in solution voids Erodibility of solution cavity infill	No intercepting or effective filter Concentrated flow reaches uncontrolled exit point	Erodibility of adjacent alluvium or fill Collapse of soil into open solution void
		Mode 4 – Erosion in internally unstable foundation soils	
Conditions/ mechanisms considered for Mode 4	Increased hydraulic gradient Redistribution of fines creates concentrated flow Erodibility of soils	No effective filter blanket Concentrated flow reaches uncontrolled exit point	Development of pipe Ability to support a pipe

Construction-related defects are difficult to detect, but may not be uncommon. For example, sectional concrete slurry walls are constructed with vertical panel joints which, depending on the method of forming the joint, can create a defective surface or slurry film. Construction methods have been developed for removing these defective surfaces during construction. Continuous soil bentonite, soil cement bentonite or cement bentonite walls have no joints. However, sloping backfill placement can entrap slurry or sediment within the backfill, and incomplete mixing can leave defects within the mass. Other problems have been observed with poor alignment between adjacent panels, inadequate desanding or cleaning of the bottom of the trench, or raising the tremie pipe prematurely during placement. However, a good QA/QC program should pick up these problems and allow for repairs to be made. In spite of efforts to ensure barrier integrity and continuity, strong evidence of leakage through seepage barriers has been detected in five of the dams reviewed in this study: Wolf Creek Dam, Fontenelle Dam, Camanche Dike, Crane Valley Dam, and Lewiston Levee and has probably occurred, though undetected, in other dams.

A major design concern for soil bentonite cutoff walls is the significant differential settlement of the compressible wall backfill relative to the surrounding embankment fill or foundation material. The settling backfill tends to hang up on the adjacent soils, creating lower vertical stresses than would develop under conditions of uniform compressibility. This phenomenon of arching of the barrier backfill can lead to hydraulic fracturing under reservoir hydraulic loading. As discussed in Chapter 3, his phenomenon was a major design concern for Manasquan Dam (Khoury, Fayad et al. 1992).

Based on the preceding discussion, it seems likely that leaks in seepage barriers are not uncommon. However, for the initiation phase of this failure mode to develop fully, the leak in the barrier must be aligned with a low-resistance seepage path through the embankment or through the foundation, or must connect to zones of higher permeability upstream and downstream. There are several conditions where the leaks in the barrier and in the embankment are likely to coincide. Some of these are presented schematically in Figure 5-2 and are discussed below.

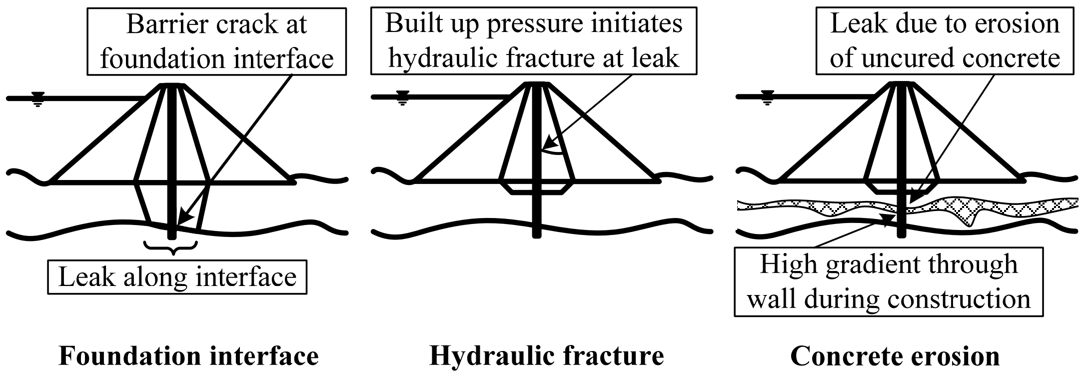


Figure 5-2 Conditions where coincidence of barrier defects and concentrated seepage pathways are likely.

The first condition occurs at the embankment/foundation interface. As shown by the deformation analyses presented in Chapter 4, the bending moment imposed on the barrier at the top of rock is likely to be higher than in other areas due to the sharp contrast in stiffness between the soil and bedrock, and thus cracking of the barrier is more likely to occur at this location. This is also a location where there is likely to be a concentrated seepage pathway due to either (1) the concentration of gravelly soils at the base of the alluvium deposits, or (2) differential movement between the embankment soils and the bedrock. Thus, the likely locations of the seepage pathway in the dam foundation and a defect in the barrier coincide. Similarly, the coincidence of a crack in a seepage barrier and a seepage pathway may come about where barrier cracking occurs at the interface between bedrock types having different stiffnesses, a location where bedrock jointing also often occurs.

A second condition where there is coincidence of a barrier defect and embankment seepage pathway is where hydraulic fracturing occurs on the downstream side of the barrier as a result of the elevated water pressures due to flow through the defect in the barrier. The combination of high water pressures on the upstream side of the barrier and leakage though a defect, and stress redistribution in the dam core that may occur during barrier construction or post-construction deformation may result in initiation of hydraulic fracturing at the location of the barrier defect.

A third condition occurs where the barrier is constructed through a zone of high conductivity, and a large hydraulic gradient will be imposed on the uncured concrete backfill. Such a condition may result in a barrier leak in this location due to the high gradient eroding the finer portions of the concrete mix before it cures. As discussed in Chapter 3, his mechanism may be the cause of segregated concrete backfill encountered in some of the seepage barrier elements at Wolf Creek Dam, which were constructed through solution voids in limestone.

Another aspect of piping initiation is the erodibility of the surrounding embankment soils. If the soils are erosion-resistant under the applied gradients, then a concentrated leak may never develop, even if there is a defect in the seepage barrier. On the other hand, highly erodible soils may quickly allow a concentrated leak to develop. Backward erosion from an unprotected exit must also be considered under normal seepage conditions, even when an identified concentrated leak pathway is not present.

<u>Continuation.</u> Continuation of this mechanism is dependant on removal of the eroded soil particles from the zone of erosion. If a filter is present then this may limit the extent of internal erosion. However, many dams in which seepage barriers were installed years after initial construction do not have filters that meet modern filter criteria.

<u>Progression.</u> Progression of this mechanism can be slowed or halted if the flow through the concentrated leak is limited by the size of the leak in the seepage barrier and its resistance to enlargement by further erosion.

Where the defect in the barrier is located within a low permeability zone the seepage velocity through the defect is likely to be low, and the potential for enlargement of the defect will be small. A good example of this is the Crane Valley Dam in California (see Chapter 3) where a significant crack formed in the seepage barrier as a result of embankment deformation. Erosion of the concrete in the barrier was not observed and the crack was found to be filled with material from the surrounding puddle core of the dam embankment (Perkins 1932). Another example is Fontenelle Dam (see Chapter 3), where a leak apparently formed along a construction joint (URS 2002). While leakage has been detected along the joint for many years, it does not appear to have worsened, apparently because the seepage velocity is too low to cause erosion of the resistant concrete.

Where a defect in the barrier is surrounded by materials with very high permeability (such as open-work gravels), the flow velocity through the barrier can reach extreme levels. This phenomenon was a major design concern for the seepage barrier in the Island Copper Mine in British Columbia (Davidson et. al 1992) where the barrier was subjected to high gradients and was installed through open-graded gravels and boulders. The solution at Island Copper was to install a non-erodible plastic concrete backfill. Jet erosion tests revealed that under the anticipated gradients and tidal flux, cement bentonite or soil bentonite would not have sufficient erosion resistance. Soil bentonite backfill has the lowest erosion resistance and is most susceptible to concentrated leak erosion.

However, it was shown in the analyses in Chapter 4 that, without erosion of the soil adjacent to the entrances of a crack, the water velocity in the crack will decrease as the crack widens. This is due to the volume of the flow through the crack being controlled by the adjacent soils rather than the crack width. Therefore, for barriers able to withstand moderate seepage velocities without extensive erosion, cracks and defects in barriers are not expected to enlarge significantly by erosion unless there is a pathway for removal of eroding particles. It should be noted that where the surrounding soil has extremely high permeability, such as open-graded gravels, the velocities may be expected to remain erosive due to the high transmissivity of the layer.

Mode 2 - Erosion of Soil through Bedrock Joints

This mechanism can develop where concentrated flow occurs through bedrock joints beneath or at the ends of the barrier. The increased water pressure developed due to the seepage barrier will reduce the effective stress on the joint, and has the potential to dilate the joint and initiate seepage pathways through bedrock that were previously not significant. The increased gradient along the joint also increases the potential for erosion of joint infilling. This mechanism is shown schematically in Figure 5-3.

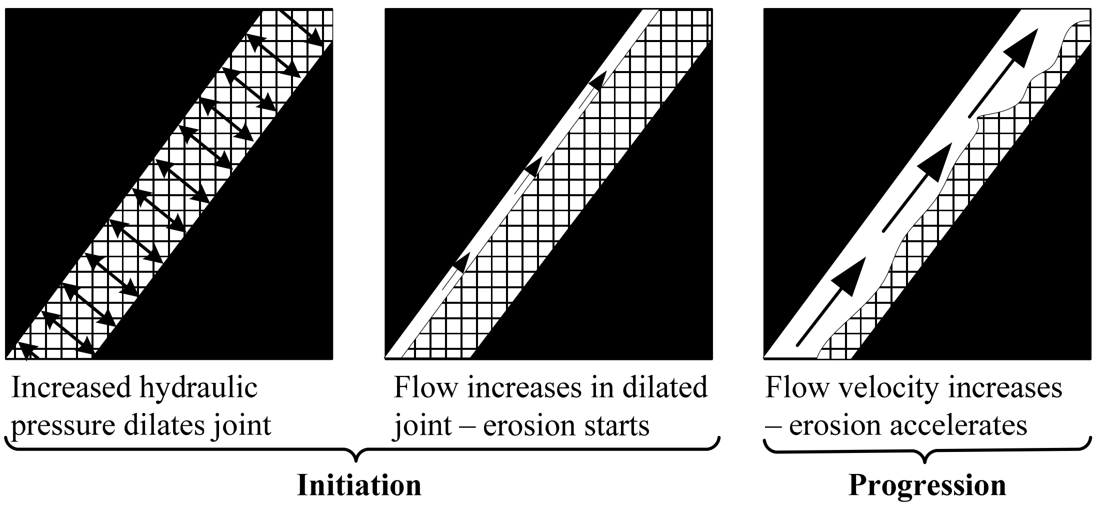


Figure 5-3 Erosion of soil through bedrock joints

Initiation. The results of analyses presented in Chapter 4 indicate that high gradients are likely to occur beneath and across seepage barriers. The factors that control the likelihood that a concentrated leak will develop are the deformation properties of the bedrock mass, the orientation and connectivity of the joints, and properties of the joint infill. The stiffness properties of the rock determine the amount of dilation that occurs when the hydraulic pressures increase, which in turn determines the increase in conductivity through the joints. The orientation and connectivity of the joints will determine the length of the seepage path, which will determine the amount of head loss that occurs along the joint and, as a result, determine the hydraulic gradients and seepage velocities that occur in the seepage path. Joint infill having a high expansion potential may be capable of swelling sufficiently as the joint dilates to prevent significant increase in conductivity through the joint. If a concentrated leak does form in the joint, the erodibility of the joint infill and the bedrock will determine whether erosion will initiate.

Continuation. The continuation phase for this mechanism is dependent on the erodibility of the joint infill and the presence of a filtering mechanism. In the absence of an effective filter, erodible soil or bedrock particles will be removed and the mechanism will continue.

Progression. Because the ability to support a pipe is almost a certainty in bedrock joints, the progression of this failure mode within the bedrock will largely be controlled by the extent of erodible material along the joints, and the ability of the flow in the joint to erode adjacent layers. Erosion of the joint infill material may continue until all of the erodible infill has been removed. At this point the seepage flows through the bedrock may stabilize and fluctuate mainly with changes in reservoir level, never resulting in failure and breach.

However, if the seepage in the joints is exposed to an adjacent layer, such as an overlying alluvium or embankment fill zone, there is potential for erosion and removal of the adjacent soils, which will allow further progression of the piping as shown in Figure 5-4. This phenomena of erosion of soil particles adjacent to open joints was well documented in the failure of Quail Creek Dike in Utah (Von Thun 1990, Gehring 1990) and is also a mechanism that has potential to impact the behavior of Navajo and Mud Mountain Dams, as discussed in Chapter 3. It should be noted that while the portion of Quail Creek Dike involved in the failure did not contain a seepage barrier, many of the conditions described in this failure mode were occurring due to concentration of the seepage by the grouting of bedrock joints.

Mode 3 - Erosion of Solution Void Infill

Solution voids in limestone deposits are often partially filled with loose soil infill deposited from low velocity flow through the voids. The potential for erosion of the infill increases when the velocity of flow increases. As discussed in Chapter 3, this mechanism was observed at Wolf Creek Dam following installation of a seepage barrier in 1975 and 1979 (Zoccola et al. 2005). Seepage redeveloped at Wolf Creek in the 25 years after the installation of the barrier, apparently by erosion of solution void infill beneath and around the end of the seepage barrier. A similar situation developed at Walter F. George dam (see Chapter 3), where construction of seepage barriers in the dam abutments exacerbated seepage problems under the central portion of the dam (USACE 2004). A seepage barrier has since been constructed under the central portion of the dam.

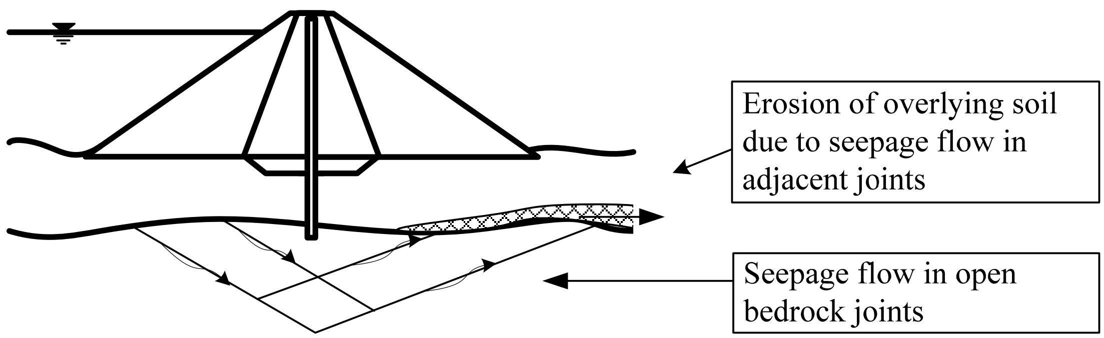
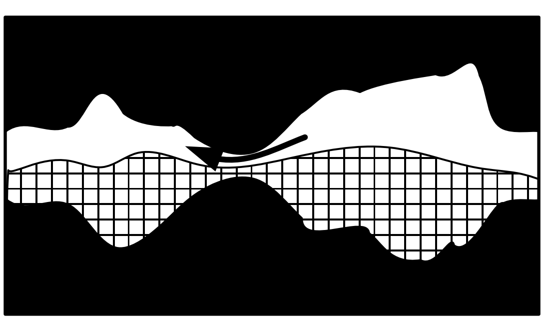
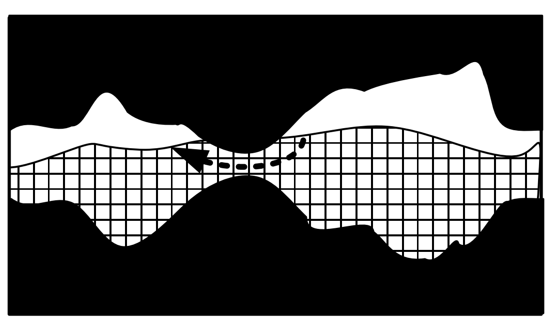


Figure 5-4 Erosion of adjacent soil due to seepage flow in bedrock joints

Initiation. Voids in jointed or solutioned rock characteristically are interconnected and have irregular cross-sections. When the solution voids are partially filled with soil, these characteristics lead to the development of the highest seepage velocities where the flow path is constricted, as shown in Figure 5-5a. Where the constricted portion is completely filled with soil, high gradients will develop, as shown in Figure 5-5b. Both conditions result in increased potential for erosion.



a) High seepage velocity at constriction points.



b) High hydraulic gradient where the solution void is blocked.

Figure 5-5 Schematic illustration of increased erosion potential in solution voids

If the base and sides of the seepage barrier are embedded deep enough into rock without interconnected solution voids that has consistently high resistance to seepage flow, the drop in hydraulic head will be distributed over a longer seepage path and the hydraulic gradients will be lower. This strategy was successfully employed at Beaver Dam Dike 1, as discussed in Chapter 3.

Continuation. It is often the case with solution voids that there are open cavities within the system of voids that can accept large amounts of eroded material. Furthermore, the network of solution voids often extends far beyond the dam, allowing for exit points of eroded material that are not easy to intercept and control. As a result, control by filtering is usually not possible.

Progression. There are two means by which this mechanism can progress: 1) by erosion and transport of the adjacent soils by the flow through the cavities, and 2) by collapse of the overlying soils into an open solution cavity to form a sink hole, as shown in Figure 5-6. Such sink holes were observed at Wolf Creek Dam prior to construction of the seepage barrier (Zoccola et al. 2006). The critical factors that affect progression of this mechanism are the size of the voids, the connectivity of the voids to the overlying alluvium or embankment fill, and hydraulic gradients through the overlying layers into the voids.

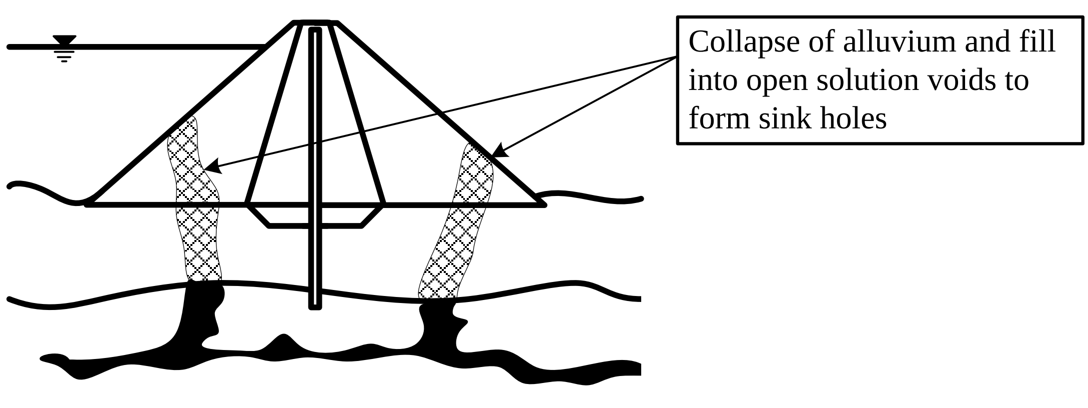
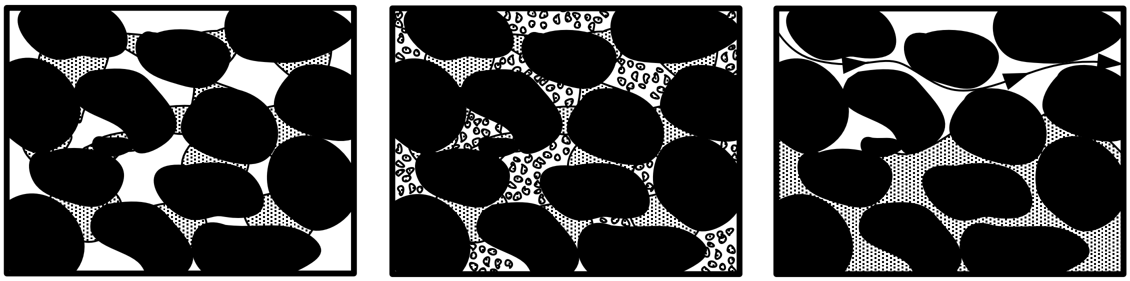


Figure 5-6 Collapse of overlying soils into open solution voids

Mode 4 – Erosion in Internally Instable Foundation Soils

Redistribution of fines (suffusion) occurs when the finer particles within a gap-graded or very widely-graded soil are able to move into open voids within the soil structure, as shown in Figure 5-7. This reduces the amount of fines locally, resulting in increased permeability and a concentrated flow in the zone from which the fines are eroded.



Gap graded soil deposit – original configuration

Increased hydraulic gradient dislodges fine partilces

Fine portion redistributed by suffusion – flow path established

Figure 5-7 Development of concentrated flow pathway by suffusion

Initiation. The development of concentrated flow due to internal instability is likely to be progressive, and erosion occurs when seepage velocities in zones of concentrated flow reach sufficient levels to erode the fine-grained portion of the soil.

Continuation. If the internally unstable (gap-graded or very widely-graded) soil is surrounded by deposits of internally stable soils, the stable soils may act as a filter and prevent the continuation of the mechanism. Thus, the probability of this failure mode continuing is a function of the depositional structure of the native deposits in the foundation in addition to the gradation of the individual layers.

Progression. Progression of this mechanism is contingent on maintaining flow through the concentrated leak and the ability to support a pipe. In addition to maintaining flow velocities in an enlarging leak, larger flow velocities may be required to erode the courser particles in the soil.

Conclusions

Due primarily to the buildup of hydraulic pressure and increased hydraulic gradients that are caused by seepage barriers, dams with seepage barriers are subject to a unique set of mechanisms that may combine to form a potential failure mode that would be infeasible or less feasible in a dam without the seepage barrier. While in a vast majority of cases the addition of the seepage barrier increases the reliability of a dam, it is important to recognize these additional failure modes, so that they can be taken into consideration when designing new barriers, assessing existing barriers, or monitoring the performance of dams with barriers.

The mechanisms considered in this Chapter include concentrated leaks through the barrier, erosion through bedrock joints, erosion of solution-void infill, and erosion in internally instable foundation soils.