Chapter 6: Summary and Conclusions

The objective of this study was to assess the long-term performance of seepage barriers by studying how dams with seepage barriers have performed over time. The study involved review of the performance of 30 dams that have had seepage barriers in place for more than 10 years. The performance of the dams and seepage barriers was assessed by reviewing monitoring data, observations made during inspections, and maintenance records obtained from the dam owners or regulatory agencies. Analyses were performed to provide a better understanding of the behavior of dams with seepage barriers. Based on these observations, and the results of the analyses, conclusions were developed regarding the overall behavior of dams with seepage barriers and the mechanisms that are key to this behavior. Based on these conclusions, potential failure modes were identified that are specific to dams with seepage barriers.

A summary of the work performed for this study, the conclusions derived from the work, and recommendations for further research are presented in the following sections.

Summary of Work Performed

The following summarizes the tasks performed for this study:

1. A literature review was performed to assess the work and findings of previous research on topics related to the long-term performance of seepage barriers in dams. Specific literature topics include: (1) the long-term performance of seepage barriers, (2) theoretical seepage barrier performance, (3) construction techniques and material properties, and (4) development of piping in dams and dam foundations.

2. Data was collected on 30 dams having seepage barriers in place for at least 10 years. The data was collected from the files of dam owners and regulatory agencies and consisted of original dam design and construction documentation, reports of seepage incidents, the design basis or justification for the seepage

barrier, seepage barrier design and construction information, and most importantly, long term monitoring data.

3. The collected data was reviewed and analyzed to assess the performance of the seepage barriers. In addition to assessing the overall performance of the barriers, the assessments included identifying mechanisms that may be in effect as a result of the seepage barrier and have potential to affect the long-term performance of the barriers.

4. Numerical analyses were performed on selected dams from this study in order to provide a better understanding of the behavior of dams with seepage barriers. The analyses performed include analyses of seepage through the dam and foundation, and the deformation of the dam and foundation. Seepage analyses were also performed on a theoretical model to investigate the effects that cracks in seepage barriers have on the performance of the barrier and the potential for long term deterioration of the barrier.

5. Potential failure modes that are specific to dams with seepage barriers were developed based on insights garnered from the review of the dam performance and the results of the analyses performed.

Summary of 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 potential failure modes that would be infeasible or less feasible in dams without a 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 mechanisms, so that they can be taken into consideration when designing new barriers, assessing existing barriers, or monitoring the performance of dams with barriers. The following sections provide a summary of the conclusions to various topics related to the unique mechanisms affecting seepage barriers in dams.

Assessment of Overall Seepage Barrier Performance

In general, most of the 30 dams with seepage barriers included in this study have performed well. In only four of the dams studied (Wolf Creek Dam, Walter F. George Dam, Mill Creek Dam, and Lewiston Levee) remediation was deemed necessary to mitigate seepage issues that remained or developed after the completion of the seepage barriers. Repairs were made to two additional dams built in the early 1900s (Lake Wolford Dam and Lake Valley Dam) to mitigate seepage issues related to seepage barriers constructed by methods not commonly used in modern dams. However, while the remaining dams appear to be performing satisfactorily, evidence was identified in many of these dams of seepage barrier-related mechanisms that may affect the long-term performance of these dams and dams having similar characteristics. Understanding these mechanisms is essential for the design of seepage barriers for long-term performance.

Measures of Seepage Barrier Effectiveness

In assessing the performance of the 30 case study dams, several methods for quantifying barrier effectiveness were employed: (1) head efficiency, (2) flow efficiency, (3) exit gradient efficiency, and (4) effective hydraulic conductivity. Head efficiency was found to be easily calculated, but of little value for comparing the performance of barriers, since it was found to be more a function of the ratio of the hydraulic conductivities of the barrier and the pervious layer being cut off than the effectiveness of the barrier itself. Flow efficiency was found to be a good measure of barrier effectiveness. However, the inability to measure the flow volume in most dams prevents the application of this measure. Exit gradient efficiency was found to be a good measure of barrier effectiveness in dams where downstream exit gradients were high. However, in many cases the seepage concern was internal erosion rather than backward piping; thus high exit gradients were not a concern. Effective hydraulic conductivity was found to be a good measure of seepage barrier efficiency, especially where there is moderate seepage resistance in the downstream zones of the dam and foundation. The precision with which effective hydraulic conductivity can be calculated diminishes if a highly permeable, drained layer is located downstream of the barrier.

Based on the above assessments, it is concluded that quantitative assessment of seepage barrier performance is somewhat subjective, and quantitative comparisons between dams is difficult. Thus, performance assessments of seepage barriers for individual dams need to be based on the desired results and the specific site conditions.

Dams on Solutioned Limestone

Dams on foundations containing solutioned limestone had a higher per-dam occurrence of serious post-seepage barrier problems than any other subgroup of dams in the study. Both Wolf Creek and Walter F. George Dams developed post-seepage barrier problems that required extensive mitigation measures. The factors affecting seepage barrier performance that are unique to solutioned limestone foundations are the interconnectedness of the solution void system and the ability of the solution void system to remove eroding particles in the subsurface. One example of a dam with a seepage barrier on a solutioned limestone foundation that has performed well is Beaver Dam, where the barrier was extended in depth and length well beyond the highly solutioned formations.

Dams on Jointed Bedrock Foundations

A mechanism was identified in several dams with jointed bedrock foundations where increased hydraulic gradients and velocities below and around seepage barriers have increased the potential for erosion of joint infilling and bedrock along the joints. The erosion along the joints has resulted in increasing flow in these locations which, subsequently, may lead to increased hydraulic gradients and velocities. A related erosion mechanism is where high seepage velocities in joints comes in contact with and erode an adjacent soil layer or the dam embankment. While there were no cases where it appears that this mechanism has resulted in a threat to dam stability, there are several cases (Wister, Fontenelle, Navajo, Mud Mountain and Mill Creek Dams) where there is evidence that this mechanism is occurring.

Dams on Soil Foundations

While a number of the dams in this study are founded fully or partially on native soil deposits, no significant evidence was found of long-term changes in the seepage regimes of these dams due to mechanisms acting in the soil portions of the foundations. However, given the high hydraulic gradients that were calculate in the analyses presented in Chapter 4, it should be considered possible that, if these gradients were imposed on internally instable soils, internal erosion of these soils could occur.

Post-Construction Development of Leaks in Barriers

Several of the cases reviewed in this study showed direct evidence of the development of cracks or leaks in seepage barriers after construction (Wolf Creek, Fontenelle, Navajo, Twin Buttes, Crane Valley, and Camanche Dams, and Lewiston Levee). Furthermore, it appears likely that post-construction cracking has occurred in most of the barriers having rigid barrier backfill (concrete). The causes of leaks in the barriers vary between rigid barriers and ductile barriers. Analyses performed on five dams with rigid seepage barriers indicate that the deformation caused by post-seepage barrier changes in the seepage regime can cause large enough deformations of the barrier to induce cracking. The analyses showed that the most likely location of the cracking is at the interface between the foundation or embankment soil and the bedrock. Evidence was also observed in Navajo Dam of cracking at the interface between bedrock layers having different stiffness. Cracking observed in other locations could also be due to post-construction settlement of the dam, shrinkage, or thermal cracking. In ductile seepage barriers, the causes of cracking include settlement of the soil-bentonite backfill away from the low permeability cap layer, and hydraulic fracture induced by stress redistribution.

Consequences of Leaks in Barriers

The consequences of leaks in seepage barriers can be grouped in three categories: (1) decreased barrier efficiency, (2) erosion of the barrier, and (3) soil or rock erosion due to concentrated flow through the barrier. The seepage analyses indicate that cracks with relatively small apertures (as small as 0.1 mm) can have a large effect on the effective hydraulic conductivity of the seepage barrier, but as the crack aperture increases, the effect on the effective hydraulic conductivity becomes a function of the permeability of the surrounding soil. As a result, unless the soil near the ends of the crack can erode and be removed from the area, widening of the crack will not increase the flow volume through the crack, and the seepage velocity in the crack will decrease. Thus, even if the initial velocities in the crack are erosive to the barrier backfill, the widening of the crack due to erosion will decrease the velocity and the erosion potential of the seepage water. However, if the soils around the crack are able to erode, the velocities can be maintained or continue to increase and erosion of the barrier will continue.

Instrumentation and Monitoring

Various means of monitoring seepage barrier performance were utilized in the case studies discussed in Chapter 3, including: piezometers, flow measurement devices (weirs or flumes), settlement monuments, inclinometers, and stress cells. Because each dam and foundation has different characteristics, there is no "best way" to instrument a dam to monitor seepage barrier performance. However, the following insights were garnered from the review of the 30 cases:

1. Where it is possible to measure a portion of the seepage flow through a dam, the data collected provide the best indicators of changes that occur due to seepage barrier construction and long-term changes after barrier construction.

2. Sets of piezometers located on the upstream and downstream sides of the seepage barrier offer valuable piezometric data for assessing seepage barrier performance and the values of hydraulic gradients through and around the barrier.
3. Locations where upstream/downstream sets of piezometers have the greatest potential for providing valuable information regarding the performance of the seepage barrier are: (1) at the top of the low-permeability layer that the base of the barrier is tied into, (2) within a soil or rock layer having higher permeability than the surrounding layers, and (3) near the ends of the barrier.
4. The downside of piezometers is that they can only measure pressure at a single point, and as a result, a piezometer would have to be located very near a leak in the barrier in order to detect the resulting change of head before it dissipates into the surrounding soil.
5. Surface settlement monuments have been successful in detecting anomalous surface settlements that may be indicative of internal erosion in the embankment or foundation.
6. Inclinometers installed within or adjacent to seepage barriers are useful for measuring lateral deflection and assessing the likelihood and location of potential cracking.

Potential Failure Modes Associated with Seepage Barriers

Following a four-phased outline developed by Foster, Fell and Wan (Fell et al. 2004, Foster and Fell 1999) for assessing potential seepage-related failure mechanisms in dams, four failure modes were developed as examples of potential failure modes associated with dams having seepage barriers. Brief descriptions of the potential failure modes are as follows:

1. Leaks through the 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.

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.
3. Erosion of solution void infill. This mechanism involves the erosion of soil infill from solution voids, thus decreasing the seepage resistance in the dam foundation.
4. Erosion of internally instable foundation soils. This mechanism occurs when high hydraulic gradients and flow velocities are developed in internally instable soil deposits as a result of seepage barrier construction. The erosion occurs through a process of redistribution of fines (suffusion) where the finer particles within a gap-graded or very widely-graded soil are able to move into open voids within the soil structure.

Recommendations for Further Research

Through the course of this study several topic have become apparent where the profession would benefit from further research. Brief descriptions of these topics are as follows:

1. Further research is needed into the potential for erosion of joint infilling in bedrock joints. Relationships relating the properties of the joint infill with erosion potential and field and laboratory testing techniques would aid designers in assessing the potential for erosion based on the expected gradients imposed by the construction of seepage barriers.
2. Laboratory research into the behavior and erosion potential of cracks in seepage barriers is needed to confirm the analytical results presented in this dissertation. Of particular value would be the flow velocities developed through various defect shapes and sizes and the erosion potential of various types of seepage barriers.
3. Further research into methods for mitigating seepage problems related to seepage barriers is needed. Of particular concern is the mitigation of solution voids that have been cleaned of soil infill as a result of increased hydraulic gradients and velocities.

4. Development of a design procedures and guidance for use of seepage barriers are needed. This may be in the form of a manual that provides design guidance for addressing the design issues associated with potential failure modes identified in this study.