Unit I

Overview

I. OVERVIEW: SIGNIFICANCE OF SEEPAGE PROBLEMS IN DAM SAFETY

INTRODUCTION

Dams must be designed and maintained to safely control seepage. Nevertheless, most dams experience at least some seepage and many suffer from excessive seepage. Excessive seepage may lead to a problem with the safety of a dam if not treated properly. The basic problem is trying to discern how seepage is affecting a particular dam and what measures, if any, must be taken to ensure that the seepage does not adversely affect the safety of the dam.

You may be called upon to make a visual inspection of a dam and its appurtenant structures and inspect a project's document files for clues to the likelihood of failure due to seepage problems. You may need to review background information on geologic characteristics, construction specifications and records, and safety and inspection records to discern critical information pertaining to seepage. If a seepage problem has already been identified you may be asked to determine the probable cause of the seepage and the remedial action needed.

If you are an owner or otherwise have responsibility for a dam you should understand seepage, and know whether your dam and its appurtenant structures are safe with regard to seepage. It is also important to monitor seepage and maintain seepage control measures that are already in place.

This module provides background information on the evaluation and monitoring of seepage, the evolution of seepage control measures, maintenance of seepage control measures, and the various modes of failure related to seepage. Unit I concerns the historical evolution of seepage control measures and causes of dam failure due to excessive seepage.

I. OVERVIEW: HISTORICAL PERSPECTIVE

INTRODUCTION

Stored water represents stored energy that is continually seeking release downstream. Seepage is simply reservoir water finding its way downstream through pervious material or through imperfections in the dam or its foundation. The force or pressure behind the seeping water can create new or enlarge existing seepage pathways until the dam is breached. Thus, the control of seepage is extremely important in the design, construction, and safe operation of dams. (For definition of terms, see Appendix A, Glossary.)

EARLY METHODS OF DAM DESIGN

Before the 20th century, dam building, particularly of earth and rockfill dams, was considered primarily an art. Dams were designed by rules of thumb, designer's intuition or judgment, or simply by copying something that had succeeded in the past (empirical methods). Unfortunately, the reasons for success or failure of the dam were rarely understood, and failures continued to occur—many due to uncontrolled seepage.

Even into the 20th century, the design of earth dams was based largely on past experience or observation. In 1936, a study of earth dam failures revealed that about 80 percent were caused by uncontrolled seepage. Many lives were lost and there was much property damage as a result of those failures. For example, in the May 31, 1899 failure of a dam in Johnstown, PA, over 2,200 lives were lost. One reason for the rather late development of analytical embankment dam design is that the mechanics of seepage were not understood. As a result, concrete and masonry dams had a much better chance of success than early embankment dams.

However, concrete dams are also subject to failure due to seepage. The Kolnbrein dam, a 656-foot high concrete arch buttress dam was built in Austria in 1979. Uplift pressures and excessive seepage occurred on the first filling, and a large crack appeared in the dam. Repairs were initiated that eventually cost over $190 million. The St. Frances Dam, a 205-foot high concrete structure in California, failed in 1928 and as many as 2,000 lives were lost. The failure was due to reactivation of a prehistoric landslide on the right abutment. Uncontrolled seepage pressures from the reservoir aggravated this reactivation (Dams and Public Safety, 1992). Much of the early interest in understanding seepage was generated by numerous failures of concrete or masonry diversion dams built on sand and gravel alluvial foundations in India, the Middle East, and Africa.

CURRENT PRACTICES IN DAM DESIGN

Science and mathematics have become more important in the design and construction of dams and seepage control measures in dams built after the 1920's. However, empirical methods continue to play an important role. In spite of these advances, failures still occur as a result of the following:

I. OVERVIEW: HISTORICAL PERSPECTIVE

CURRENT PRACTICES IN DAM DESIGN (Continued)

- Unrecognized foundation conditions
- Poor design
- Inadequate construction quality control/quality assurance
- Lack of necessary maintenance
- Lack of monitoring systems

EVOLUTION OF SEEPAGE CONTROL METHODS

The history of dam construction dates back to about 3000 B.C. in Egypt, and then into the Middle East cultures associated with the Euphrates and Tigris Rivers (Dams and Public Safety, 1992). Early dams were constructed to allow storage of water for uses such as irrigation and human and animal consumption during dry periods.

Lacking means to transport massive amounts of material, the early dam builders used readily available local earth and rock materials. Trial and error led to an early preference for masonry or quarried rock construction because the successful masonry dams required less material to remain stable and are not as susceptible to failure from uncontrolled seepage. Thus, the Romans built many significant masonry dams throughout their empire wherever their accumulated experience indicated that sites and local rock materials were suitable.

Earth dams were constructed at locations where experience showed that the site would not properly support the concentrated loads of a masonry dam or where durable rock was not readily available. There was no formal knowledge of seepage or seepage control; however, empirical evidence indicated that if some portion of the dam was constructed of a relatively watertight earth, the chance of success was better. Thus a seepage reduction zone of some sort was the earliest method of control. This took various forms. In India and Ceylon, dam builders learned that relatively low dams of clay or even less watertight material with flat downstream slopes were often successful.

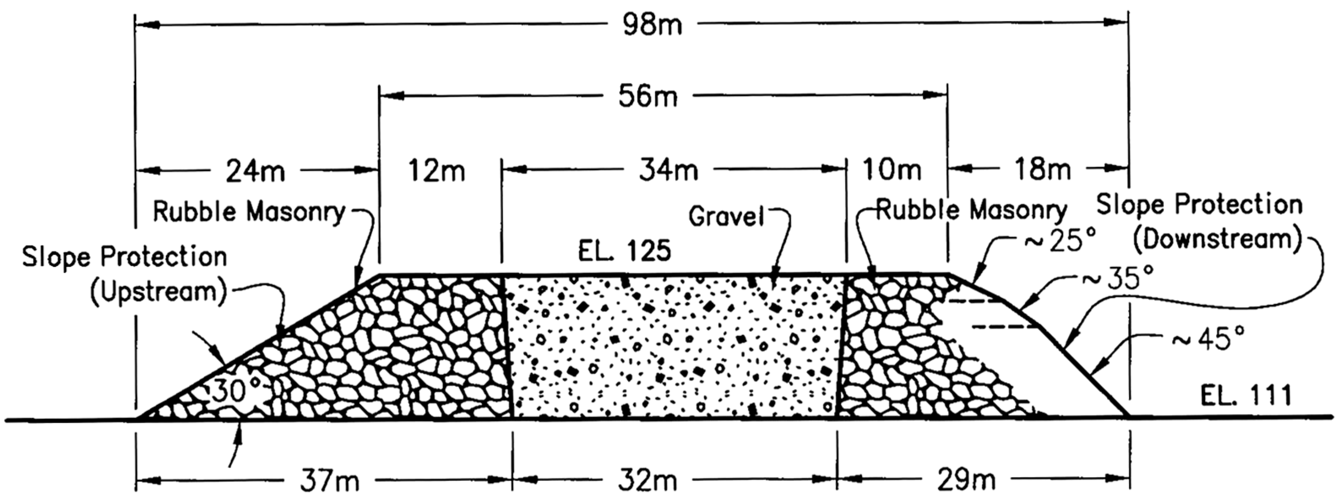
In other cases, dam builders learned that an earth core supported by upstream and downstream masonry walls or rockfill was often successful if the earth did not disappear into the voids of the coarse-grained shells. An example of such a dam, the Sadd-el Kafara Dam, is shown in Figure I-1. The Sadd-el Kafara Dam was built in Egypt in about 2700 B.C. for domestic water supply (Dams and Public Safety, 1992).

In some cases, a zone of intermediate-sized material was placed between the earth zone and the rock zone to hold the earth in place. Though the engineering principles involved were not well understood, the concepts of seepage control by zoning, filter action, and drainage were being introduced.

I. OVERVIEW: HISTORICAL PERSPECTIVE

EVOLUTION OF SEEPAGE CONTROL METHODS (Continued)

FIGURE I-1. CROSS-SECTION OF THE SADD-EL KAFARA DAM

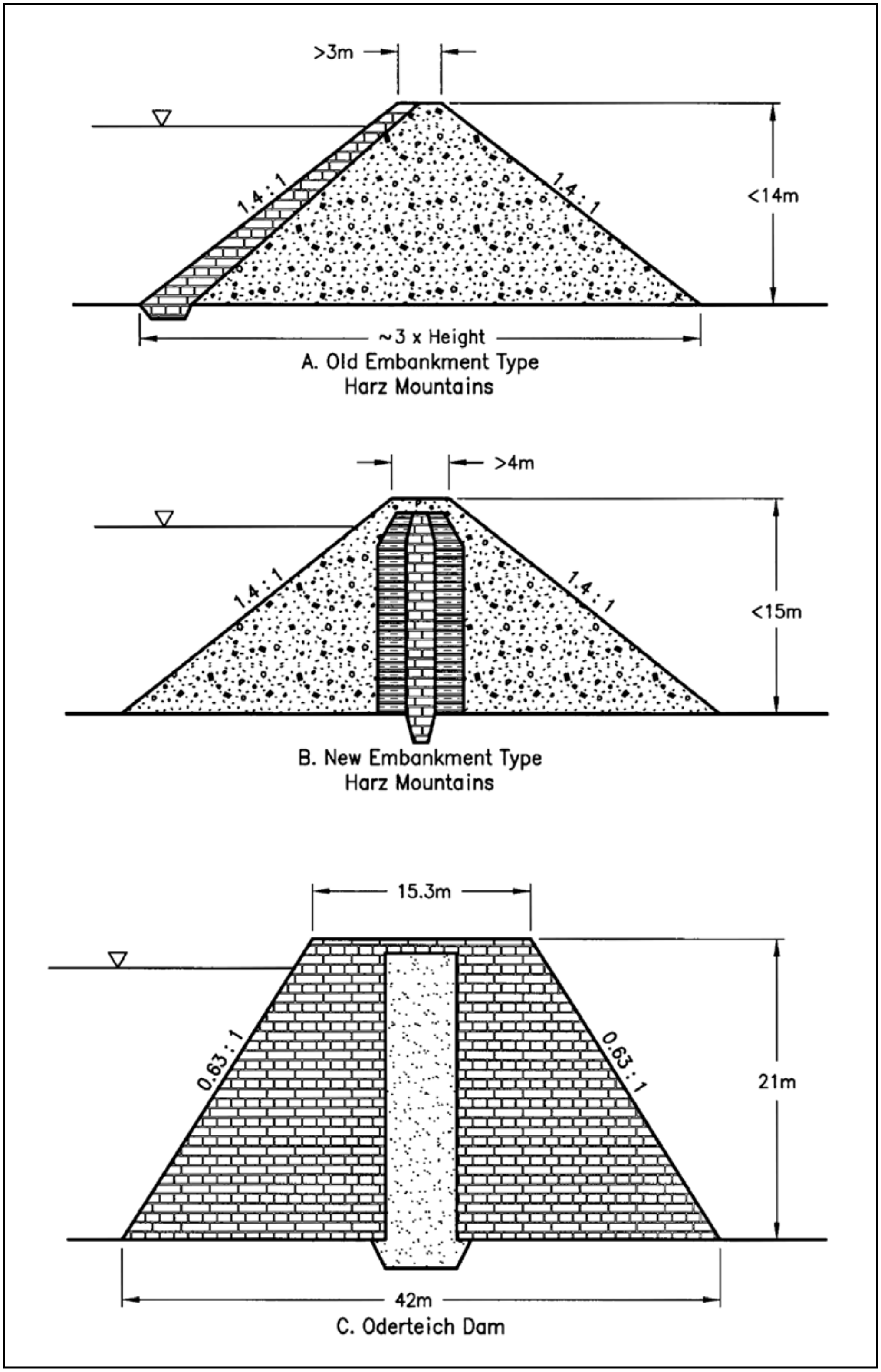


Toward the end of the Middle Ages, some large embankments were built in Europe. The cross-sections were fairly standard, with relatively steep outer slopes and an upstream water barrier that needed considerable maintenance (see Figure I-2 (A)). Thereafter, starting about 1715, the barrier was moved to the center of the dam, with transition zones of clay on both sides (see Figure I-2 (B)).

Between 1714 and 1721, sand was used for the core of the Oderteich Dam (Figure I-2 (C)) with shells of dry masonry. It could be considered a gravity dam with an earth core, as had been used by the Romans and earlier dam builders.

I. OVERVIEW: HISTORICAL PERSPECTIVE

FIGURE I-2. STANDARD PROFILES OF THE OLD AND NEW EMBANKMENT TYPES IN THE HARZ MOUNTAINS AND CROSS-SECTION OF THE ODER DAM

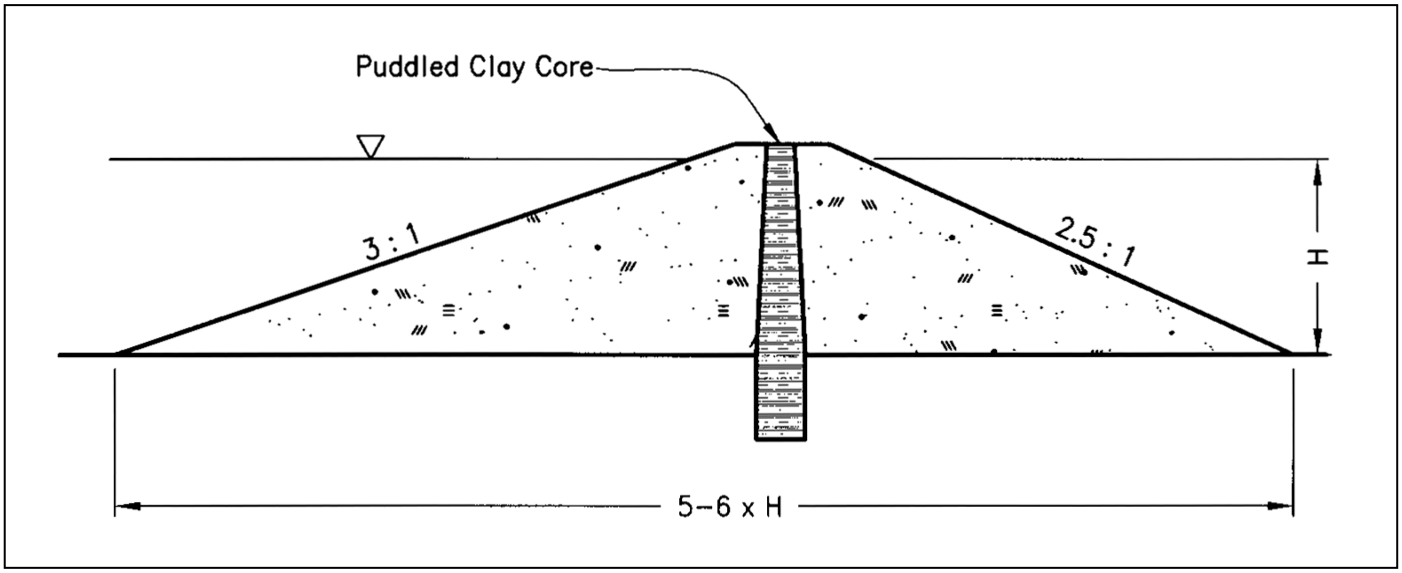


I. OVERVIEW: HISTORICAL PERSPECTIVE

EVOLUTION OF SEEPAGE CONTROL METHODS (Continued)

By the late 1700's, the emerging science of statics led French engineers to prefer masonry dams, while England was continuing the development of embankment dams. A thin central core, usually of puddled clay, became the trademark of British embankment dams (see Figure I-3). A small group of engineers designed many of these dams, which resulted in a concentration of empirical knowledge and standardization.

FIGURE I-3. TYPICAL CROSS-SECTION OF 19TH CENTURY BRITISH EARTH DAM WITH A CENTRAL PUDDLED CLAY CORE



The earliest dams in the United States followed the English practice of using a puddled clay core. Because of low inherent stability and difficulty in placing the puddled core, this design was replaced first by a masonry core wall and later by a concrete core wall. Concrete core walls were never totally watertight because they often cracked. Many concrete core wall dams were successful and are still in service.

During this era, the accumulation of experience led to a variety of general rules. One rule stated that the core should be comprised of the best available watertight material and should be placed by puddling. Also, if necessary, materials should be placed in thin layers, and supporting rockfill should be resistant to deterioration from air, frost, and water. Finally, it was believed that a transition zone should be used between earthfill and rockfill.

All of these requirements apply to a well-designed earth embankment dam today.

I. OVERVIEW: HISTORICAL PERSPECTIVE

EVOLUTION OF SEEPAGE CONTROL METHODS (Continued)

In the 1860's, the hydraulic fill method for dam construction was pioneered. Hydraulic fill dams were constructed of materials conveyed to their final position as a slurry suspension in water. At the dam, the suspended material and water were released from pipelines laid along the upstream and downstream shoulders of the dam. Coarser materials were deposited near the outer slopes of the dam to form shells, and finer materials were deposited at the center of the dam to form the core, or seepage barrier. The available materials had to have the proper proportions of coarse and fine particles, and careful control was required to achieve the proper deposition. The center of the dam, or core, was essentially a low-strength, dense liquid.

However, this method of construction has several disadvantages. Hydraulic fill dams are known to be highly susceptible to liquefaction of the low-density materials under seismic loading. Several construction accidents occurred where the semi-liquid core was too large relative to the shells and burst. After the Fort Peck Dam failure in 1938, the use of hydraulic fill construction methods ceased in the United States. This method is still used occasionally in other parts of the world.

The failure of many dams in the 1700's and 1800's indicated the need for a more scientific approach to the design and construction of dams. In 1856, Henri Darcy published studies that provided a quantitative representation of the flow of fluid through a porous media. Following Darcy, the work of several mathematicians and physicists was expanded and adapted to provide a logical basis for understanding the effects of seepage through porous media (soil and rock materials) and how the seepage might be controlled.

The single most important milestone in the design and construction of embankment dams was the publication in 1925 of Soil Mechanics on Soil-Physical Basis by Karl Terzaghi. Since the introduction of soil mechanics, rapid improvements have been made in both design and construction practices. Rather than simply applying the designs of successful dams to new projects without an adequate understanding of why those designs worked, dam engineers can now modify designs in a variety of ways to accommodate the unique conditions of a particular site.

Once the mechanics of seepage and soil mechanics were better understood, zoning and use of materials in dam construction could be designed in a rational way. Of equal importance, past experience, either good or bad, could be understood and organized into rational and logical empirical guides for new designs and different circumstances. Many technical advances in the design of embankments and seepage control measures were made in the period from 1930 to 1990 by universities, contractors, engineers and governmental agencies including the Bureau of Reclamation, the U.S. Army Corps of Engineers, and the Natural Resources Conservation Service.

I. OVERVIEW: HISTORICAL PERSPECTIVE

EVOLUTION OF SEEPAGE CONTROL METHODS (Continued)

Other important advances have included:

- Understanding and developing guidelines for filters to preclude the movement of soil particles by piping and internal erosion.
- Developing drain systems to control seepage pressure, to intercept seepage pathways, and to provide for safe discharge of seepage from dams, foundations, and abutments.
- Developing methods and equipment to construct seepage cutoffs.
- Developing instrumentation to monitor seepage.

CURRENT PRACTICES IN SEEPAGE CONTROL

There are currently three basic methods for controlling seepage. They are:

- Using filters to prevent soil particle movement caused by seepage.
- Employing methods to reduce the quantity of seepage.
- Using drainage methods to relieve seepage pressures and to collect seepage and convey it to a safe outlet.

Frequently, these methods are used in combination.

Each of these methods of seepage control will be discussed in Unit II of this module. Remember, however, that effective control of seepage requires that both the dam and its foundation be considered together.

Despite the advances that have been made in the design of dams and seepage control methods, significant failures still occur. Seepage was the cause of failure of several modern dams, such as the Teton Dam in 1976 and Quail Creek Dike in 1989. Each failure has brought new understanding and advances in the control of seepage. In other words, seepage control is still an evolving and empirical engineering science.

I. OVERVIEW: MODES OF FAILURE

INTRODUCTION

Water stored behind a dam always seeks to escape or flow along the path of least resistance. This route may be through the dam, beneath it, or around it. Four basic categories of seepage problems can lead to failure:

- Seepage causing excessive uplift, heave, or blowout.
- Seepage causing piping.
- Seepage causing internal erosion.
- Seepage causing solutioning of soluble rock.
- Seepage causing excessive internal pressures and/or saturation causing sloughing or failure of slopes.

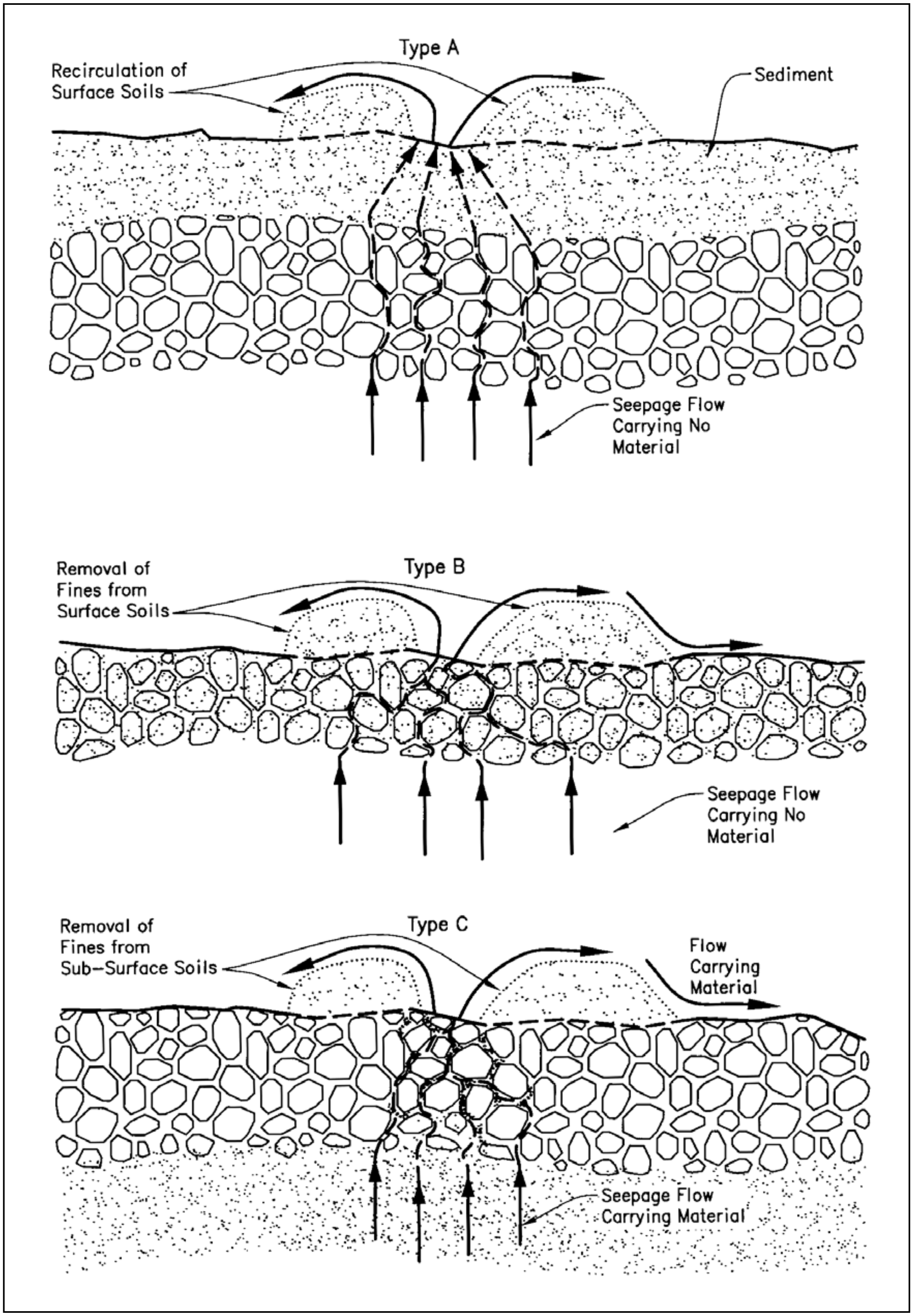
UPLIFT, HEAVE, OR BLOWOUT

Foundation seepage pressure in pervious layers can exert significant uplift force on a confining layer of lower permeability soil downstream from a dam. This pressure occurs when there is a more permeable layer underneath that transmits a large percentage of the reservoir head downstream. Failure begins when the pore pressure on the bottom of the confining layer exceeds the overburden pressure created by the weight of the overlying soils. The resulting uplift eventually breaches or breaks through the confining layer in what is known as a blowout.

When upward flow of seepage water is strong enough to carry sand particles, the sand commonly is deposited around the springs in a conical ring, referred to as a sand boil. If a sand boil continuously removes material due to an excessive hydraulic gradient, they may eventually lead to piping, collapse or failure of the structure. Figure I-4 (adapted from Von Thun, 1996) illustrates various types of sand boils. Type A is indicative of a static condition for the current hydraulic gradient and is not necessarily indicative of an immediate problem developing. However, if the hydraulic gradient could increase during an extreme event, a Type A boil may become a Type B or Type C boil depending on the magnitude of the hydraulic gradient and soil conditions within the foundation or embankment. Type B is a boil that is carrying material, but the material is originating from near surface soils rather than deeper zones. A Type B boil may be indicative of a more serious problem developing that could warrant corrective action. Type C is indicative of a critical condition, where the present hydraulic gradient is removing subsurface soils. A Type C boil would need immediate action to remedy. Piezometers can be used to monitor downstream foundation uplift pressure and detect unsafe conditions before failure occurs. A key indicator of a potential problem developing is fine soil carried in water draining from a boil. In this case, the water is cloudy rather than clear or it may contain scattered fine particles.

I. OVERVIEW: MODES OF FAILURE

FIGURE I-4. Types of Sand Boils

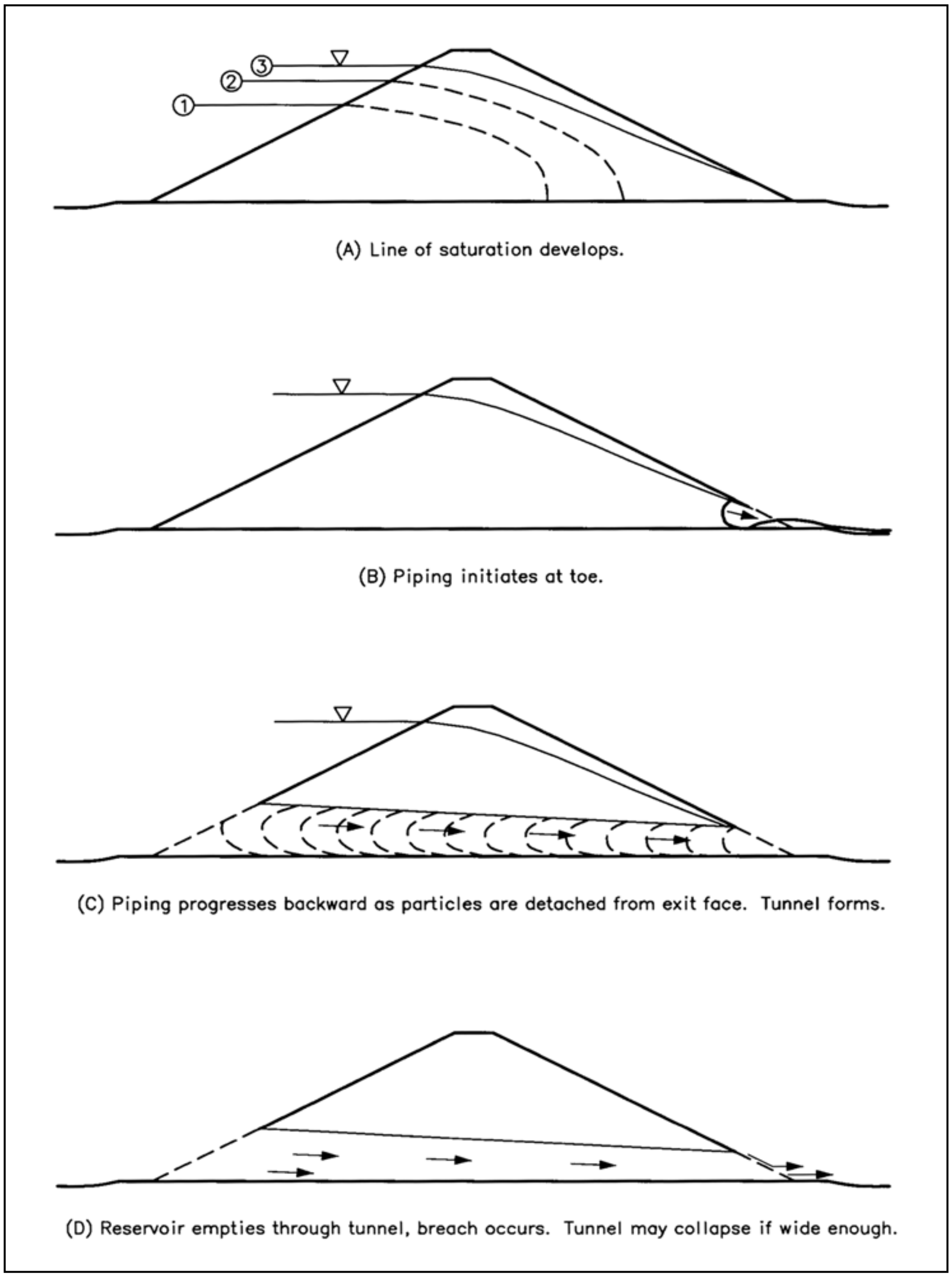


I. OVERVIEW: MODES OF FAILURE

PIPING

Piping occurs when reservoir water moving through the pores of the soil (i.e., seepage) exerts a tractive force on the soil particles through which it is flowing, sufficient to remove them at an unprotected exit point of the seepage. Figure I-5 illustrates piping failure due to an excessive hydraulic gradient at the toe of a dam. The initial physical expression of piping is often a cone shaped mound of soil called a boil or a stream of muddy water exiting the slope. The removal of soil may progress upstream forming a characteristic open tube or "pipe" through the dam, from which the phenomenon derives its name.

FIGURE I-5. PIPING



I. OVERVIEW: MODES OF FAILURE

PIPING (Continued)

Other forms of piping include movement of materials across internal material zone boundaries where proper filter protection was not provided. This movement often happens between fine-grained core materials and rockfill or coarse gravel. The movement of embankment soil into untreated foundation rock openings is another possible type of piping failure.

Five conditions must exist for piping to occur:

1. There must be a flow path/source of water.
2. The hydraulic gradient must exceed a certain threshold value that is dependent on the type of soil through which the flow path travels.
3. There must be an unprotected exit (open, unfiltered) from which material can escape.
4. Soils that are susceptible to piping must occur within the flow path near the discharge point of the seepage.
5. The material being piped or the soil directly above it must be able to form and support a "roof" to keep the pipe open.

In a piping failure, soil particles are initially removed at the discharge point of the seepage if the hydraulic gradient exceeds a threshold value. Erosion channels or pipes tend to enlarge and progress upstream often associated with increasing flow quantity. This occurs because the hydraulic gradient (h/L) increases as the length of the flow path (L) decreases. The hydraulic head (h) between the upstream and downstream pools remains about the same as long as the reservoir level is maintained, but the length of the seepage flow path decreases as soil is removed and the open pipe is created. Thus, the rate of advance of a pipe once it forms will tend to accelerate in a progressive fashion until the hydraulic head is relieved. This is also why it is important to stop piping very early in the process, if possible.

Once formed, the pipe progresses upstream following the most susceptible materials until it reaches the reservoir. The pipe continually enlarges as erosion removes soil adjacent to the pipe, creating large voids susceptible to collapse. The whole process, from pipe initiation to dam failure, can occur over a relatively short period of time measured in minutes or hours rather than days. Piping is often triggered during first filling of a new reservoir, or by abnormally high reservoir levels in an existing reservoir.

Physical features that may shorten the flow path such as open drill holes, post holes, root holes, rodent holes, ditches, and animal burrows can also incite a piping failure. Piping failures may occur at different rates. Failures can be gradual or rapid depending on the seepage gradient and the cohesiveness of the soil. The more cohesive the soil the more resistant it is to piping. Piping can go unnoticed for many years if seepage exits in swift tailwater, under thick brush or riprap, into conduits, or other areas not easily inspected. Hence, although piping is occurring within a structure it may not always be visible from the outside.

In some cases, seepage can initially be slow and clear but the flow may gradually increase over time and become visibly turbid until failure occurs. Any concentrated seepage that is expressed in the form of springs downstream from a dam is potentially dangerous and should be carefully evaluated and monitored.

I. OVERVIEW: MODES OF FAILURE

PIPING (Continued)

Piping happens most commonly when:

- Seepage occurs through soil layers that are susceptible to piping and seepage reduction methods are not used to reduce the hydraulic gradient that causes piping, or
- Filters and pressure relief measures are not used at seepage discharge points to prevent the particle movement of susceptible soils, or
- Seepage reduction measures are not properly maintained.

Soils most susceptible to piping are loose, poorly graded fine sands. Also highly susceptible are silts and sands with low-plasticity fines (Plasticity Index less than 6), as well as loose, well-graded sand and gravel mixtures that are very broadly graded and have low-plasticity fines. Clay soils with significant plasticity (Plasticity Index greater than 15) are less susceptible to piping. However, some soils that are not susceptible to piping may be susceptible to internal erosion failures (described in the following section).

INTERNAL EROSION

A failure resulting from internal erosion may appear similar to a piping failure. After the failure, a piping tunnel extending through or under the embankment is the usual physical expression of the breach of the structure. However, the mechanisms of piping and internal erosion failures are very different. In both cases the tractive forces of high gradient flow move particles. In the case of piping, the tractive forces result from the intergranular flow of water between soil particles. Internal erosion, on the other hand, occurs when water flows:

- Along cracks or other defects in the soil or bedrock in the cross-section.
- Along boundaries between soil and bedrock.
- Between soil and concrete or metal appurtenances.

The physical laws governing the flow of water through cracks and fractures are very different than those governing the flow of water through the pores of granular materials. Intergranular flow in granular materials is studied using Darcy's law and the Darcy permeability (covered in Unit IV). Flow through cracks is studied with permeability and flow equations developed from the hydraulic laws of open channel or pipe flow. In both cases, the quantity of flow is proportional to the hydraulic gradient as expressed in Darcy's law but there are differences.

Soils that are not susceptible to piping may be highly susceptible to internal erosion. A good example is a dispersive clay soil. This type of soil is highly impervious and not readily susceptible to intergranular seepage forces. A dispersive soil would normally not be expected to experience piping. But if a crack occurs within a dispersive soil, or between the dispersive soil and bedrock or concrete, the erosive force of water flowing through or along the crack can quickly lead to an enlargement of the flow path and a failure.

INTERNAL EROSION (Continued)

Internal erosion failures are most common in areas where hydraulic fracturing can occur. Prime areas for hydraulic fracturing are where soils are not properly compacted adjacent to outlet pipes or other structures, or where there are sharp changes in foundation grades or slopes. The embankment/abutment contact is another area where internal erosion is possible. Observe these areas closely during operation for signs of fracturing or unusual settlement.

Internal erosion can occur when cracking, separation of joints, or deterioration of pressurized outlet pipes through a dam allow pressurized water into the embankment. Conversely, erosion of embankment material into non-pressurized conduits can also lead to dam failure.

Water flowing between the embankment and the foundation at foundation or abutment contacts through open joints, fractures, or other rock defects that were not properly treated or protected may create another type of internal erosion failure. Recent failures such as Teton Dam have been in this category.

Many experts believe that internal erosion is the most dangerous seepage problem because there may be no visible sign of distress until failure is imminent.

SOLUTIONING

Problems can arise in foundations or abutments where water-soluble rock can be dissolved by ground water or reservoir seepage. Soluble rocks are dissolved at the earth's surface by rain, in the zone above the water table by percolating water, and below the water table by groundwater in motion. The concern with dams and dam foundations is that seepage contacting soluble rocks can dissolve additional material or remove fillings in existing passages, thus gradually increasing seepage flow and accelerating the dissolution and removal process over a period of time. An associated problem, internal erosion, may occur when seepage flows along passages in the rock caused by solutioning in areas adjacent to soil in the foundation or embankment. The flow can erode the adjacent soil enlarging flow paths and possibly creating sinkholes or other failure features.

Minerals such as gypsum, anhydrite, and halite (rock salt), and to a much lesser extent limestone rock, can be dissolved by seepage from a reservoir. Limestone may be dissolved by groundwater over very long periods of time. If a dam is constructed on rock such as limestone, there are often pre-existing large water passages or caverns that may go undetected and untreated during design and construction, only to cause very serious problems after reservoir impoundment. Foundations containing soluble rock or minerals should always be treated with extreme caution. In addition, gypsum, halite, and a few similar minerals are so soluble that severe solutioning and distress can occur during the life of a project. The failure of Quail Creek Dike is an example of this type of failure.

In some cases soils, particularly in arid areas, may contain considerable amounts of soluble salts that can be dissolved by seepage. This dissolving of salts may lead to loss of density, volume, and strength.

I. OVERVIEW: MODES OF FAILURE

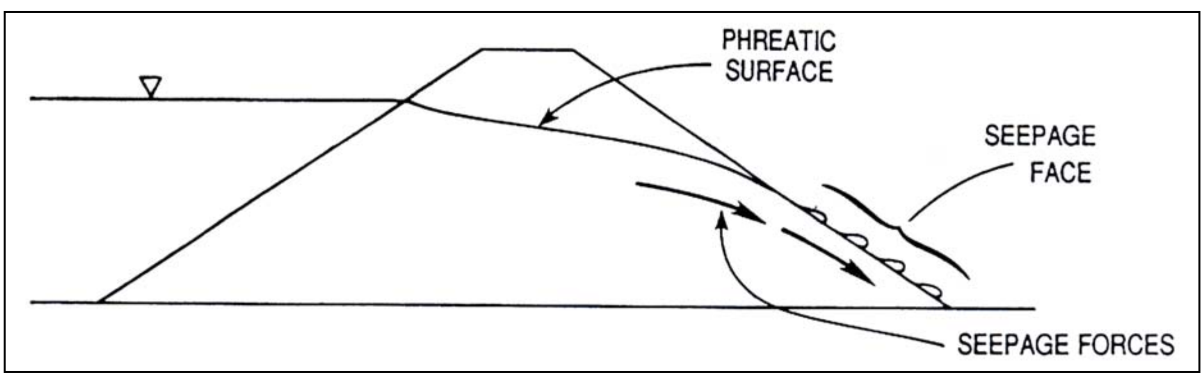
INTERNAL PRESSURES AND SATURATION

This type of failure is caused by seepage flow that leads to saturation, excessive seepage forces, and/or excessive uplift. Examples of failure caused by seepage pressure and saturation in dams are:

- Sliding of embankment and abutment slopes caused by excessive seepage forces or uplift pressures.
- Retaining wall failures caused by unrelieved hydrostatic pressures. These can include overturning and sliding failures.
- Canal linings, spillway chutes, and stilling basin floor slabs uplifted by unrelieved pressure (blowout).
- Failure of concrete dams caused by excessive pressure in abutments or foundations.

Figure I-6 is a drawing of a homogeneous embankment dam depicting seepage exiting on the downstream slope. In the example, as the elevation of the phreatic surface rises with rising reservoir elevations, the portion of embankment below the phreatic surface becomes saturated and the exposed downstream slope becomes wet and soft. Seepage forces acting in the direction of flow add to the instability of the slope. This instability may lead to a massive slope failure. These types of failures are most likely in soils with low clay content. The increased elevation of the phreatic surface and seepage forces acting along a potential failure plane lower the effective stress on the plane and reduce the resistance to movement. The degree of stability of a given slope varies, depending on the strength of the soil, the steepness of the slope, and seepage forces acting within the slope. Dry or well-drained slopes are the most stable.

FIGURE I-6. SEEPAGE THROUGH AN EMBANKMENT DAM



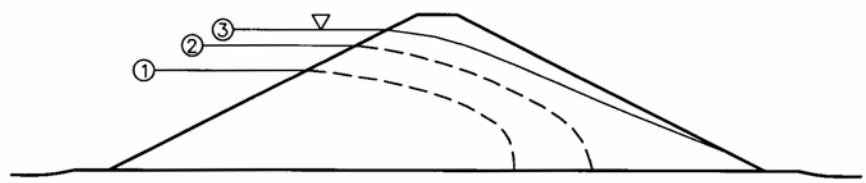
Progressive sloughing is a type of damage that results from both saturation and the seepage forces' effect on stability. As illustrated in Figure I-7, progressive sloughing begins when a small amount of material erodes at the downstream toe and produces a small slump. This leaves an over-steepened face, called a scarp, which slumps again forming a higher unstable scarp. This process can continue until the dam becomes too thin to withstand the water pressure and

I. OVERVIEW: MODES OF FAILURE

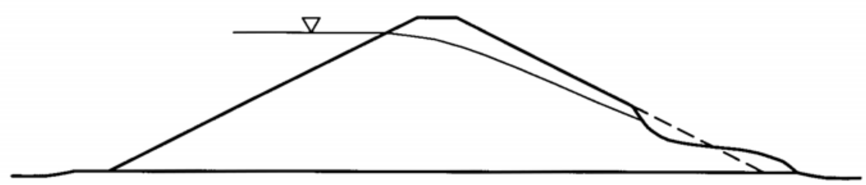
INTERNAL PRESSURES AND SATURATION (Continued)

complete failure occurs. This type of failure is most common in homogeneous fill dams constructed of fine, relatively clean sands or silts with low plasticity. Equations are available to calculate the safety factor against a sloughing failure. The equations use the tangents of the slope angle and the internal friction angle of the soil to predict the safety factor of the saturated slope. These are termed infinite slope equations (Lambe, etal., 1968).

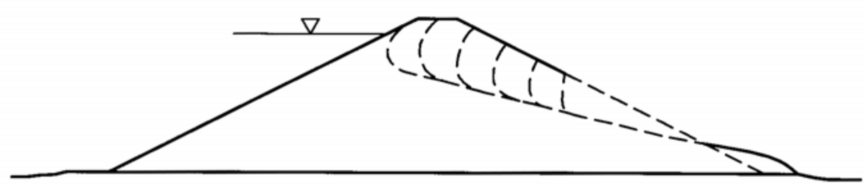
FIGURE I-7. PROGRESSIVE SLOUGHING FAILURE OF AN EMBANKMENT DAM



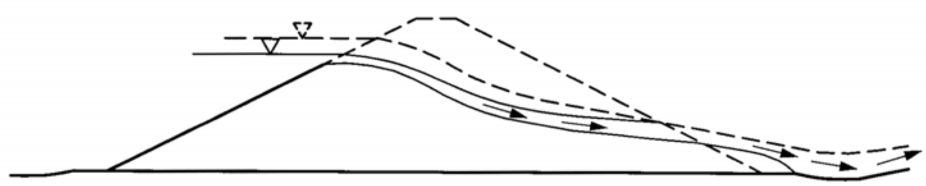
(A) Line of saturation develops.



(B) Sloughing of saturated slope begins.



(C) Sloughing progresses.



(D) If sloughing intersects upstream reservoir, overtopping and breaching can result.

I. OVERVIEW: MODES OF FAILURE

SUMMARY: SEEPAGE CONDITIONS

Unit I described the impact seepage has on dam safety, and the various modes of failure associated with seepage. These failure modes are summarized in Table I-1.

TABLE I-1. MODES OF FAILURE

THIS FAILURE MODE . . .	OCCURS WHEN . . .
UPLIFT, HEAVE, OR BLOWOUT	Foundation seepage pressure in pervious layers exerts an excessive force on an overlying confining layer. Failure begins when the pore pressure on the bottom of the confining layer exceeds the overburden pressure created by the weight of overlying soils. The resulting uplift eventually breaches or breaks through the confining layer in what is known as a blowout, commonly forming a sand boil.
PIPING	Reservoir water moves through the pores of the soil (seepage) and exerts a tractive force on the soil particles through which it is flowing, sufficient to remove them at an unprotected exit point of the seepage. The removal of soil may progress upstream, forming a "pipe." Piping may also occur when foundation seepage pressure exerts uplift force on a confining layer of lower permeability soil downstream from a dam, causing a blowout or heave condition.
INTERNAL EROSION	The tractive forces of hydraulic flow erode particles. Soil particles are removed along cracks or other defects in the soil or bedrock in the cross-section. Erosion may also occur along boundaries between soil and bedrock or between soil and concrete or metal appurtenances.
SOLUTIONING	Ground water or seepage dissolves soluble bedrock in the foundation or abutments.
SEEPAGE PRESSURE AND SATURATION	Uncontrolled seepage saturates a portion of the dam, causing sloughing. Other problems include uplift of concrete structures and failures of retaining walls.

Unit II

Review and Evaluation of Project Data

II. REVIEW AND EVALUATION OF PROJECT DATA: OVERVIEW

INTRODUCTION

The evaluation of seepage conditions involves three phases: review and evaluation of project data, investigation, and analysis. This unit describes the review and evaluation of project data (i.e., all pertinent available records, including the documentation of inspections and past operation). Investigating seepage conditions is discussed in Unit III. Analysis of seepage conditions is covered in Unit IV. Remedial actions are described in Unit V.

In many cases, it may be very obvious that seepage is damaging a dam, its foundation, or both. Remedial action is clearly needed and a decision must be made on the type and urgency of remedial measures. However, in most cases seepage may be present but there are no visible signs of distress because the seepage is benign. The difficulty in evaluating seepage conditions is that most projects fall into the latter category. Design, construction, inspection, and operating data and records are invaluable when evaluating the seepage safety of a dam. It is important to understand the range of seepage conditions the structure may experience during its lifetime. However, even when extensive records are available, evaluating the safety of the structure with respect to seepage is ultimately dependent on the quality of the data and quality of construction.

II. REVIEW AND EVALUATION OF PROJECT DATA: DOCUMENTATION REVIEW

INTRODUCTION

To properly evaluate seepage, you should review project data to gain a better understanding of:

- The geology of the dam site.
- How the dam was designed and constructed.
- The materials used to construct the dam.
- The seepage control measures incorporated into the dam and reservoir.
- How seepage could affect the project.
- The physical features of the dam.
- The instrumentation to monitor seepage pressures and quantity.

It is necessary to review project data to gain an understanding of the physical features and performance history of the dam, and to identify any known or potential design, construction, or operating deficiencies.

DOCUMENTATION

Documentation for a dam will cover many areas that can be helpful when evaluating seepage conditions. For this reason, it is important to always record and maintain good documentation for your project. Useful types of documentation include:

- Results of field and laboratory investigations.
- Design analyses and reports, and construction plans and specifications.
- Construction reports, logs, records (including construction inspector's daily report), photographs, and as-built drawings.
- Operation and maintenance records.
- Monitoring instrumentation records.
- Past inspection reports.
- Any special reports prepared for the project.

These records should be permanently retained and accessible at a central location, possibly in a dam safety file. A thorough review of these records will aid in identifying potential seepage-related dam safety deficiencies. Unfortunately, for many older dams, design and construction records as well as other vital information may be meager or nonexistent. If this is the case, then the only sources of review data may be local newspaper files, old photographs,

II. REVIEW AND EVALUATION OF PROJECT DATA: DOCUMENTATION REVIEW

DOCUMENTATION (Continued)

professional journals, or interviews with local people or the dam owner or operator. The sections that follow describe these types of documentation in greater detail.

Field and Laboratory Investigations

Records of field and laboratory investigations will include much of the geologic data of the dam site. Review this information to become familiar with the:

- Regional and site geology, including engineering characteristics of foundation rock and soil.
- Geologic features of the dam foundation, abutments, and reservoir rim.
- Relationship of the geologic features to the components of the dam.
- Adequacy of the data as it pertains to evaluation of the specific problem being addressed.

Evaluation of geologic data should be performed by a qualified individual, such as an engineering geologist, who understands how various earth and rock materials behave under the loading conditions imposed upon them by the construction of a dam and reservoir. For each geologic setting, there are known types of defects. You should assume these typical defects exist unless proven otherwise.

Design Analyses and Construction Plans and Specifications

Design analyses and construction plans and specifications will include information on the original design of the dam and all appurtenant structures, and how the contractor was to have built them. This applies to original designs as well as any post-construction modifications. It is very important to maintain original documents related to the design and construction and subsequent modifications made to a dam. In terms of seepage, these documents can be used to determine:

- What assumptions regarding seepage were made and what problems were anticipated in the original design or subsequent modifications.
- What methods of seepage control were incorporated into the dam and foundation design, and how they were to be constructed.
- How these seepage control methods were originally designed to work and if more recent information is available, does it require a reevaluation of the seepage control design.
- Whether any of these seepage control and construction methods are outdated. For example, sheet piling is no longer considered adequate to provide a seepage cutoff; therefore, you should check to see if any second lines of defense were incorporated.

II. REVIEW AND EVALUATION OF PROJECT DATA: DOCUMENTATION REVIEW

Design Analyses and Construction Plans and Specifications (Continued)

Understanding how various seepage control devices are designed and how they function will help you evaluate the quality and validity of the original design and construction. A brief description of the most common types of seepage control devices that may be incorporated into the design of a dam is presented at the end of this unit. Other seepage control methods that may be recommended to alleviate seepage problems for an existing dam are discussed in Unit V.

Construction Reports, Logs, Records, Photographs, and As-Built Drawings

Design analyses and construction plans and specifications provide information on the original design of a dam and any modifications and how they were to be constructed. Construction reports, logs, records, photographs, and as-built drawings show how the dam was actually constructed.

Review construction reports, logs, records, photographs, and as-built drawings to determine:

- How the foundation was prepared and treated.
- If grouting was done and if there were any zones of large grout takes.
- If the original design intent is still consistent with latest information about existing field conditions.
- If design changes were made to accommodate field conditions.
- If the proper materials and gradations were utilized in all embankment zones.
- What construction methods were used to prevent contamination of the filter or drainage zones.
- If any major problems were encountered during construction and, if so, how they were resolved.
- How seepage control methods were installed and if problems were encountered during installation.
- If as-built drawings are accurate.

The extent and completeness of these types of records will vary from site to site. In any case, they will provide clues as to the potential for serious seepage problems. These clues should follow a logical trail. For example, if your initial review of documents indicates a pervious foundation, check construction records to determine if:

- Adequate techniques were used to control seepage through the foundation.
- Redundant systems were used.

II. REVIEW AND EVALUATION OF PROJECT DATA: DOCUMENTATION REVIEW

Construction Reports, Logs, Records, Photographs, and As-Built Drawings
(Continued)

If outdated methods were used to control seepage through a pervious foundation, and seepage has been discovered at the toe of the dam, it is possible that the seepage control method was not adequate or has failed.

Operation and Maintenance Records

Operation and maintenance (O&M) records document the ongoing operation and maintenance of a dam. Reviewing O&M records will provide information on any reported seepage problems and what actions have been taken to monitor or correct the problems. Appendix C contains a partial O&M checklist showing typical routine measures. You should determine if these have been followed during the history of operation of the dam. Drain cleanouts, relief-well rehabilitation efforts and similar records are especially important and should be maintained.

Instrumentation Records

Design, construction, and operation records will show whether instrumentation to monitor seepage, such as piezometers and weirs, was installed. Review reports and records of instrument readings to determine:

- If seepage quantities and pressures have increased or decreased over time.
- How these parameters fluctuate with changing reservoir levels and seasons.
- If seepage water is clear or turbid.

Instrumentation readings should be regularly recorded and the data reduced to an easily interpreted format. The historical record of these readings is invaluable in determining the nature and extent of a potential seepage problem.

Past Inspection Reports

Review past inspection reports to identify the areas of seepage discovered during visual inspections of the dam and to determine what past recommendations were made regarding the seepage. Past inspection reports may contain photographs of the seepage area, drawings, or the location of the seepage pinpointed on a map or photograph of the dam. Such information as quantity of seepage, turbidity, approximate extent of seepage and reservoir level may be recorded, which will yield important clues as to the nature of the seepage.

RELATING DATA TO VISUAL INSPECTION

Because potential seepage conditions vary widely between projects, and predicting seepage during design is difficult, inspection of completed projects should be performed periodically.

Armed with the information gained from reviewing all of the records regarding seepage, and

II. REVIEW AND EVALUATION OF PROJECT DATA: DOCUMENTATION REVIEW

RELATING DATA TO VISUAL INSPECTION (Continued)

with a general knowledge of the limitations of design and construction techniques to control seepage, you can make a more thorough and meaningful visual inspection. For example, if you understand that compaction of earth embankments adjacent to concrete structures, along embankment penetrations (e.g., outlet works), and at the abutments is very difficult, you will know that these areas deserve special attention during inspection.

If an embankment is zoned with vertical and horizontal filters, use histories of flow measurements to determine if deterioration is occurring or if drains are becoming clogged. On the other hand, if the embankment is homogeneous you may observe wet spots, sloughing, or erosion on the downstream slope.

Other potential seepage problems may not be readily obvious in a visual inspection. For example, reservoir seepage through a soluble foundation rock may not be obvious on the ground surface. Or, serious seepage along abutments that contain fractured rock, which was not properly removed or treated, could result in undetected internal erosion. In the past, large rock toe zones were used as seepage control methods or for tailwater slope protection. Piping and internal erosion could occur beneath or through such a zone without being readily visible.

Reviewing available records may provide the only clues to a potential seepage problem without direct investigation, such as drilling or trenching.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

INTRODUCTION

Review the project design to understand what seepage control measures were incorporated into the dam and appurtenant structures. These seepage control measures may include:

- Filters and filter transition zones
- Seepage reduction methods
- Various types of drains
- Treatment of foundation and abutment contacts

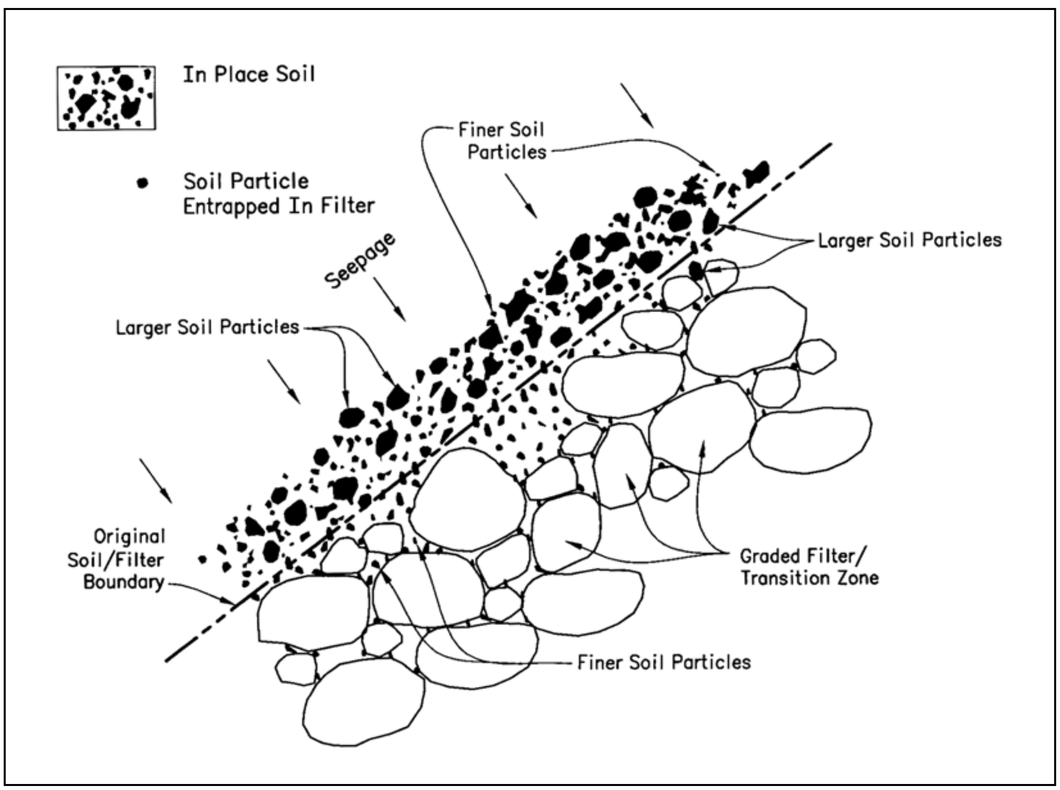
These measures and how they are designed to control seepage are described below.

FILTERS

Filters are used to prevent the intergranular water that percolates through embankment dams and their foundations from moving soil particles, while at the same time allowing the water to escape without building up excessive pore water pressures. Filters may be designed to function with an independent drain, or a drain may be designed to function as both the filter and drain. The gradation of the embankment soil and quantity of anticipate seepage will dictate whether a separate filter is required to augment a drain.

The basic concept of filters as a means of preventing migration of material or piping is illustrated in Figure II-1.

FIGURE II-1. ILLUSTRATION OF PREVENTION OF PIPING BY FILTERS



II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

FILTERS (Continued)

Filters may also be used where piping is not a concern, but internal erosion is a concern. For those designs, removal of water may be secondary to blocking movement of soil particles being carried by water flowing through cracks or along boundaries between soils and appurtenances and into the foundation.

Basic concepts of filter design are:

- **Piping and Internal Erosion Requirement—**The pore spaces of a filter or drain, located adjacent to material prone to erosion, must be small enough to prevent soil particles from the protected material from being washed through them.

- **Permeability Requirement—**The pore spaces of the filter or drain must be large enough to permit the seepage water to escape freely without buildup of excessive pressure. For filters protecting against internal erosion, a minimal amount of seepage usually is collected, because the filter forms a filter cake at the crack interface.

More than one filter/transition layer may be required if there is a large difference in soil gradations between the materials being protected and the adjacent materials.

Construction of filters and drains requires careful attention to prevent contamination or segregation during construction. Construction records and photographs should be examined to ensure that filters and drains were built uniformly and to the required dimensions. Because particles may break down during placement and compaction, the gradation of filters and drains should be tested for compliance to specifications after they are in place.

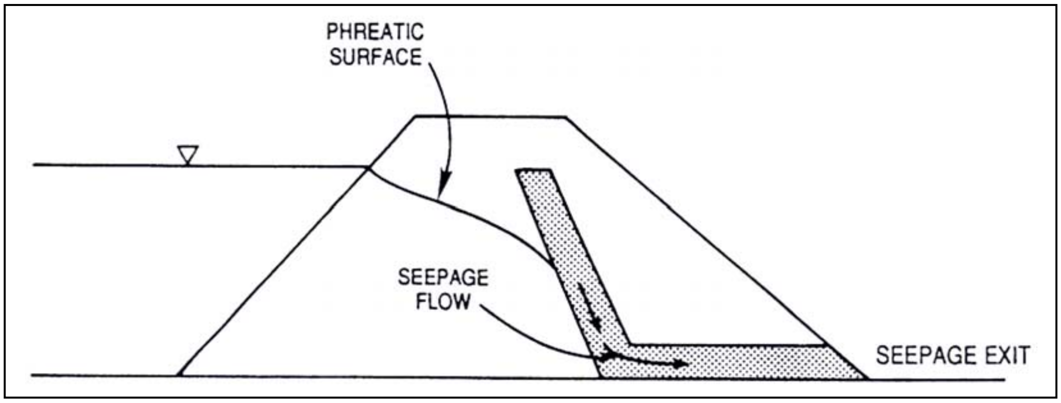
A detailed discussion on the design and construction of filters can be found in <u>Seepage, Drainage, and Flownets</u> by H.R. Cedergren (see Appendix B) and in design guidelines followed by government agencies such as the Corps of Engineers, Bureau of Reclamation, and Natural Resources Conservation Service.

A properly designed and constructed filter, as illustrated in Figure II-2, will intercept seepage in an embankment. The intercepted seepage will flow freely to a safe exit at the downstream toe without allowing migration or loss of soil particles. If cracks are intercepted, the cracks should terminate at the filter face and only the intergranular seepage flow need be considered in design. When basic criteria are met for a graded filter, piping should not occur under even large hydraulic gradients. This assumes that the filter zone is wide enough that cracks cannot extend through it, that the filter is self-healing, and the filter zone has adequate capacity to pass flows without excessive pressures.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

FILTERS (Continued)

FIGURE II-2. SEEPAGE FILTER



A filter can also serve the added purpose of preventing the phreatic surface from exiting on the downstream slope, thus preventing slope saturation and reducing the potential for sloughing or sliding of the slope.

A properly designed and constructed filter should meet specific criteria. When reviewing design and construction records, check to see if:

- Documented and accepted design procedures were followed.
- A properly graded material was used for the filter zone.
- Construction methods were used in constructing filter zones that do not produce segregation of the filter during placement (such as limiting the placement drop height, lift thickness and/or maximum particle size).
- Filter materials were not placed at water contents that would allow bulking to occur. Saturation during placement or using very dry filters may minimize this problem.
- Care was taken to prevent the contamination of filters from construction traffic, slope wash, etc. Documentation should show that the placed filter met the design compaction specification.
- Continuity of filter/drain zones (width and thickness) was achieved. The filter/transition zones must be continuous and in full contact with all protected zones.
- Special considerations, such as increased filter/transition zone thickness or compaction methods, were incorporated regarding appurtenant structures (at abutments, along spillway walls, and around outlet works conduits).

Also look for evidence that the construction of the filter was thoroughly and carefully inspected.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

SEEPAGE REDUCTION METHODS

Seepage reduction methods include:

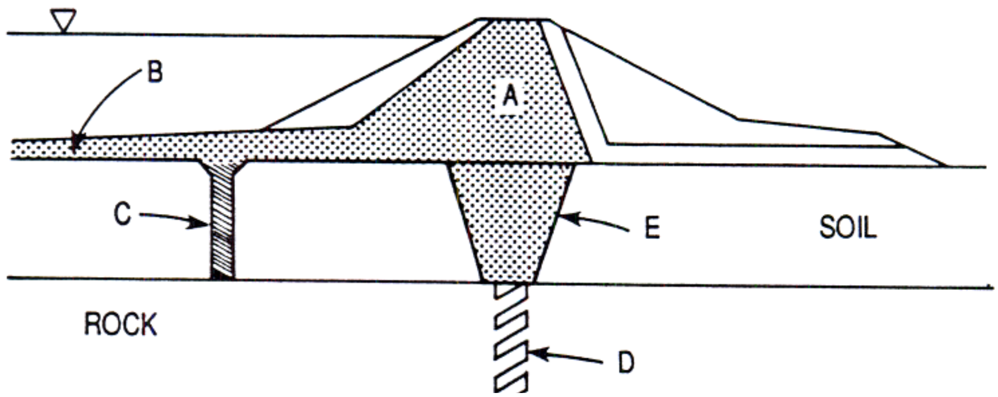
- Relatively impervious or watertight materials that intercept seepage flow paths and dissipate the head that causes excess seepage flow. Examples include a thin upstream sloping impervious zone, an impervious core, compacted-fill cutoff trenches, and upstream blanketing.
- Constructing a homogeneous dam with relatively flat slopes. This increases the length of the flow path and reduces the seepage exit gradients.
- Other seepage reduction measures may be used on the foundation and abutment, such as cutoff walls and grouting.

The remainder of this unit is devoted to discussion of these techniques and measures.

Seepage reduction methods will not eliminate the need for filters and drainage features, because seepage reduction alone may be only partially effective in preventing piping and internal erosion.

Seepage reduction methods are very important in both embankment and concrete dam design. Figure II-3 illustrates some of the different seepage reduction features used for embankment dams. (No one dam would incorporate all of these measures.)

FIGURE II-3. FEATURES FOR REDUCING SEEPAGE THROUGH EARTH DAMS AND THEIR FOUNDATIONS



Seepage Reduction Methods

A - Impervious Core
B - Upstream Impervious Blanket
C - Slurry Trench Cutoff
D - Grout Curtain
E - Compacted Impervious Cutoff Trench

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

EMBANKMENT SEEPAGE REDUCTION METHODS

Embankment seepage reduction methods are used to dissipate the head of reservoir water seeping through the embankment. There are several methods for reducing embankment seepage:

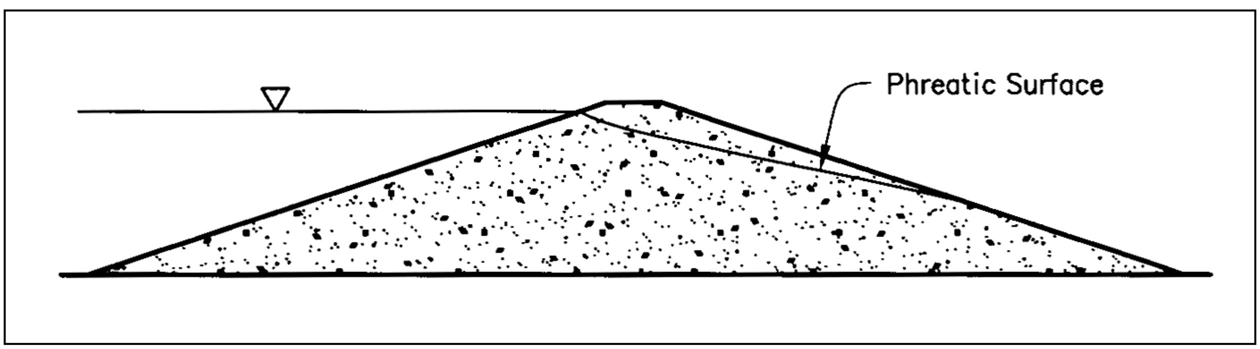
- Constructing a homogeneous dam with relatively flat slopes.
- Constructing a thin, upstream sloping impervious core zone.
- Constructing a dam with a central impervious core.
- Constructing a concrete or soil-bentonite core wall.
- Installing filter drain collars around conduits. (Note: multiple anti-seep collars are no longer recommended due to common poor compaction of backfill around the collar).

The sections that follow will describe each of these methods in more detail.

Flat Slopes

By constructing a homogeneous dam with relatively flat slopes, the hydraulic gradient and seepage discharge rates are reduced. The wide embankment cross-section better dissipates the reservoir head as the seepage flows across it, because the water must travel a greater length before exiting the downstream slope. The flatter slopes are also less susceptible to sloughing failures. A typical example of such a dam is shown in Figure II-4. While relatively expensive because of the larger volume of material, such a dam might be built if a weak foundation provided additional justification for using flat slopes for stability, or if the cost of other seepage reduction measure is prohibitive.

FIGURE II-4. EMBANKMENT DAM WITH FLAT EMBANKMENT SLOPES



Thin Upstream Sloping Impervious Zone

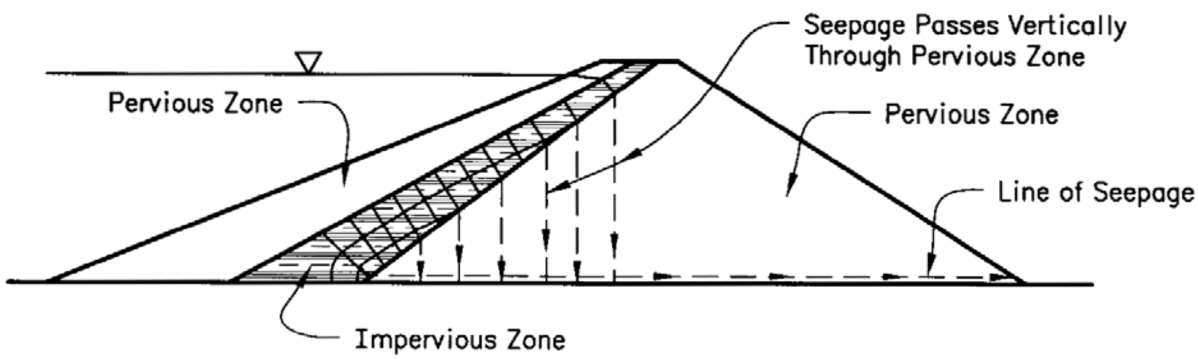
Some embankment dams have a thin upstream sloping impervious zone (Figure II-5). The reservoir head is dissipated by friction as water seeps through the impervious zone. Water then flows downward and then more or less horizontally along the foundation to a safe exit at the

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Thin Upstream Sloping Impervious Zone (Continued)

toe. If the permeability of the thin upstream impervious zone is very low (several orders of magnitude less) in comparison to the permeability of the downstream zone, then the downstream part of the dam is relatively unaffected by the seepage.

FIGURE II-5. EMBANKMENT DAM WITH THIN UPSTREAM SLOPING IMPERVIOUS ZONE



Zoned Embankment with Impervious Core

Modern embankment dams are zoned in order to use as much material as possible from required excavation and from the closest borrow sources, while at the same time maintaining stability and controlling seepage. The different types of zones that may be incorporated into an embankment dam are shown in Figure II-6. For the most effective control of seepage and optimum stability, the material permeability should generally increase from the core outward. Note that zone boundaries must meet filter criteria so that materials don't migrate from one zone to another and from the foundation into the downstream zones. This requirement is more important for downstream zones than for upstream ones.

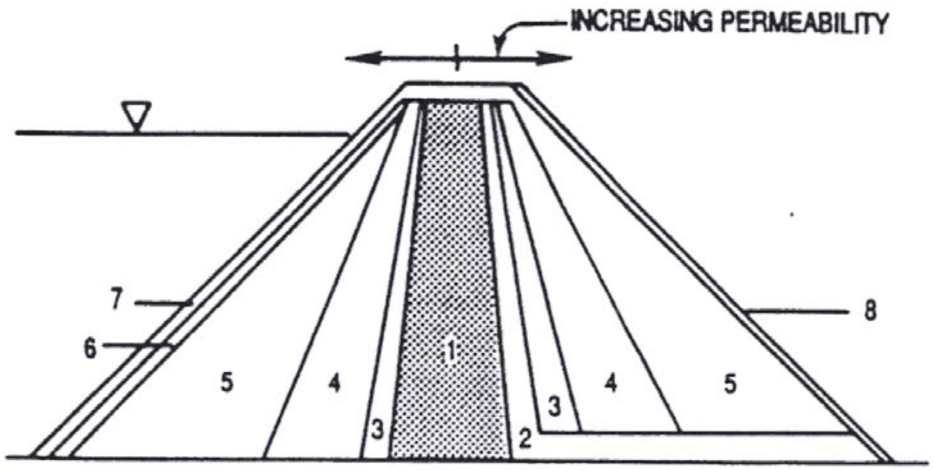
The purpose of the core is to minimize seepage through the embankment and to dissipate hydraulic head by frictional losses. Some engineering properties used for evaluating the suitability of core material include permeability, strength, erosion resistance, and cracking resistance. A core material of very low permeability is desirable for sustained reservoir storage. It is important to consider the erosion resistance of the core when evaluating the potential for internal erosion.

Cracking resistance is also important in preventing internal erosion failures. The core should be wide enough to reduce hydraulic gradients to acceptable levels. A common rule of thumb is that the base width of the core should be at least equal to one-quarter the maximum difference between reservoir and tail water elevations. The top of the core should extend above maximum reservoir level and have a minimum 10-foot top width to accommodate construction equipment.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Zoned Embankment with Impervious Core (Continued)

FIGURE II-6. DIFFERENT TYPES OF ZONES INCORPORATED INTO AN EMBANKMENT DAM



ZONE	DESCRIPTION
1	Core
2	Filter or Drain
3	Transition
4	Fill
5	Shell
6	Upstream Transition (gravel or riprap)
7	Upstream Slope Protection (typically riprap)
8	Downstream Slope Protection

Zoned Embankment with Concrete Core Wall

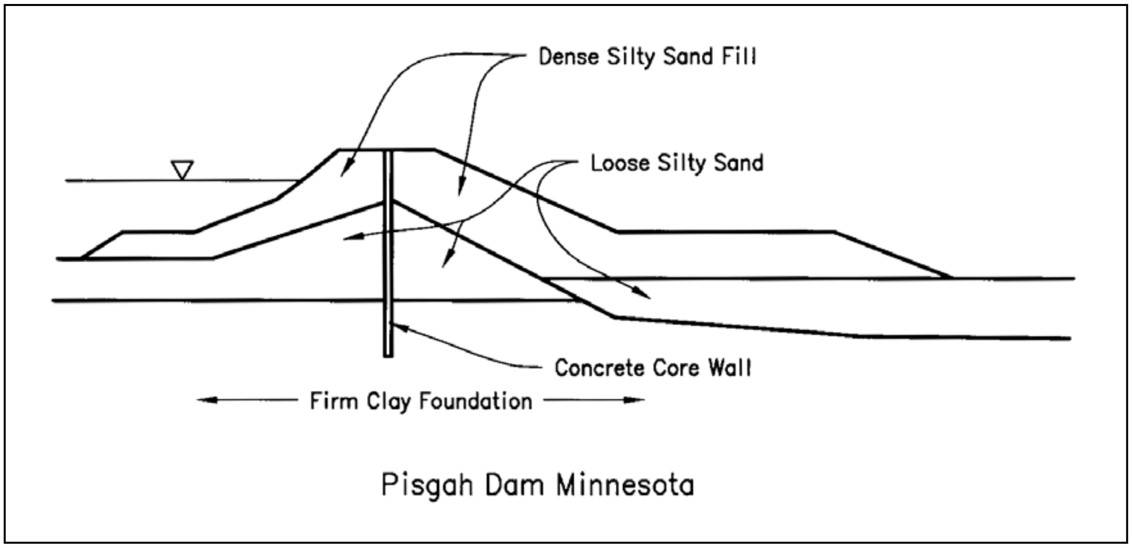
Many existing embankment dams were constructed with cast-in-place concrete core walls. Figure II-7 illustrates a concrete core wall within an embankment dam. While the core walls may be prone to cracking, they do reduce the total seepage through the dam. The embankments are generally well graded granular materials derived from local borrow sources. As with other dams, the foundation seepage control methods may be varied, as discussed later in this unit.

Modern practice is to use slurry trench techniques to construct concrete core walls for remediation of existing embankments. This technique can also be used to construct soil-bentonite and cement-bentonite stabilized walls within existing embankments as a seepage reduction method. Figures II-8 and II-9 illustrate slurry trench construction methods for dam foundations, which may also be employed for adding a core wall to an existing embankment dam.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Zoned Embankment with Concrete Core Wall (Continued)

FIGURE II-7. CONCRETE CORE WALL



Anti-Seep Collars Around Conduits

Current embankment design practice no longer employs a series of seepage collars along conduits extending through an embankment. However, many older dams used these design features to increase the theoretical length of the seepage path along the conduit and thereby try to reduce the gradient at the toe of the structure. The use of anti-seep collars around conduits was abandoned in the early 1980's by most governmental agencies. The reasons included the difficulty in compacting soils around the collars and their contribution to differential settlement. Also, anti-seep collars are not useful in preventing internal erosion failures as evidenced by the failure of numerous dams built with them. Some engineers still recommend at least one collar along the conduit to provide a barrier to burrowing activity or root penetration.

The current recommended seepage control design method to prevent internal erosion and piping failures associated with conduits is a filter diaphragm surrounding the conduit. This method is discussed further in a later section of this unit.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

FOUNDATION AND ABUTMENT SEEPAGE REDUCTION METHODS

Foundation and abutment seepage reduction methods are designed to control seepage through the foundation and abutments of a dam. They may be used in conjunction with embankment seepage reduction methods. Foundation and abutment seepage reduction methods include:

- Cutoffs
- Partial cutoffs
- Upstream impervious blankets
- Downstream seepage berms
- Grouting

Cutoffs

Cutoffs are designed to lengthen the seepage path, dissipate reservoir head to reduce exit gradients to safe levels, and reduce seepage quantities. A cutoff is an extension of the impervious zone of a dam. A full (or positive) cutoff is constructed either to impervious soil layers or to bedrock. If the depth to an impervious stratum is great, a partial cutoff may be constructed to a depth sufficient to lengthen the seepage path and reduce seepage exit gradients to safe levels. The location of the cutoff will depend on how the dam is zoned. The cutoff will usually be located under the impervious zone of the dam. There are several different types of cutoffs:

- Compacted impervious trench cutoffs
- Slurry trenches (soil-bentonite or cement-bentonite cutoff walls)
- Concrete cutoff walls
- Sheet piles

<u>Compacted Impervious Trench Cutoffs</u>

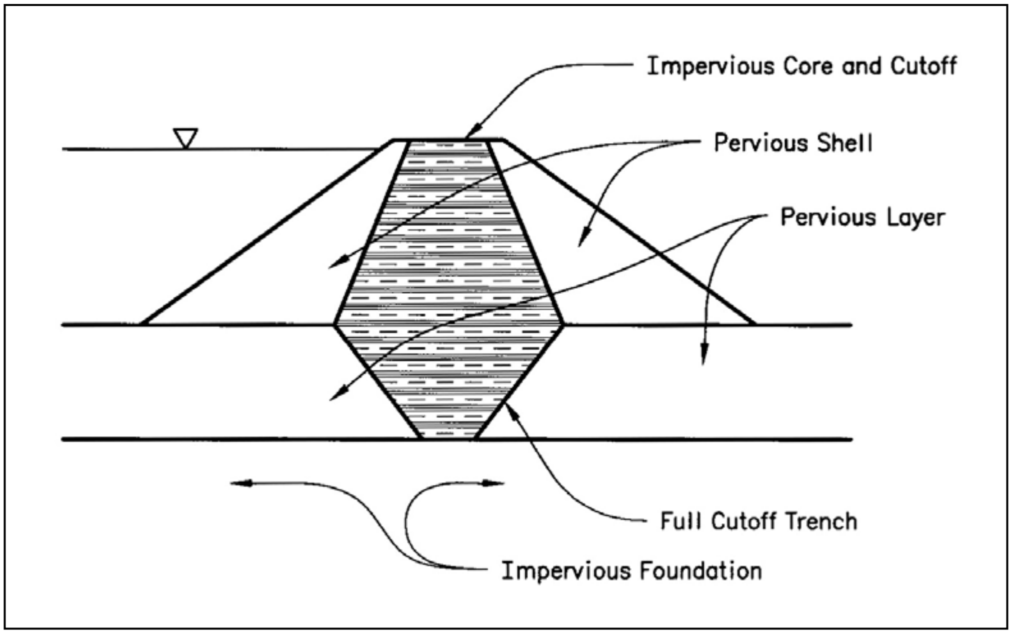
An effective method to control seepage under a dam is to excavate a trench into the pervious foundation beneath the core of the dam and backfill it with compacted impervious material. The excavation for the cutoff trench also allows the designer to see the actual foundation conditions and to adjust the design as necessary. It is the only method of seepage reduction that has this additional benefit.

The base of the trench must be wide enough for construction equipment, dewatering equipment, grouting activity, etc. Figure II-8 illustrates a compacted impervious cutoff trench constructed as a positive cutoff to the rock foundation.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Compacted Impervious Trench Cutoffs (Continued)

FIGURE II-8. FULL (OR POSITIVE) CUTOFF



Cutoff trenches can be constructed to significant depths. The main difficulty in constructing deep cutoff trenches is in dewatering the excavation and the cost. The water table must be kept lowered until the trench is backfilled.

Slurry Trenches (Soil-Bentonite or Cement-Bentonite Cutoff Walls)

Because dewatering and excavating deep cutoffs can be expensive, slurry trenches are often used instead. The slurry trench method is to excavate a trench through the pervious foundation using sodium bentonite-clay and water slurry to support the vertical trench walls. The slurry-filled trench is then backfilled by displacing the slurry with a soil that contains enough fines to make the cutoff relatively impervious, but provides sufficient coarse particles to minimize settlement. Alternatively, cement may be mixed with the slurry forming a cement-bentonite cutoff wall.

The soil-bentonite wall is generally the most economical if satisfactory backfill is locally available. For deep cutoffs where the foundation is prone to failure during excavation, or where erosion of the backfill material is of concern, the soil-cement-bentonite trench cutoff may be more applicable.

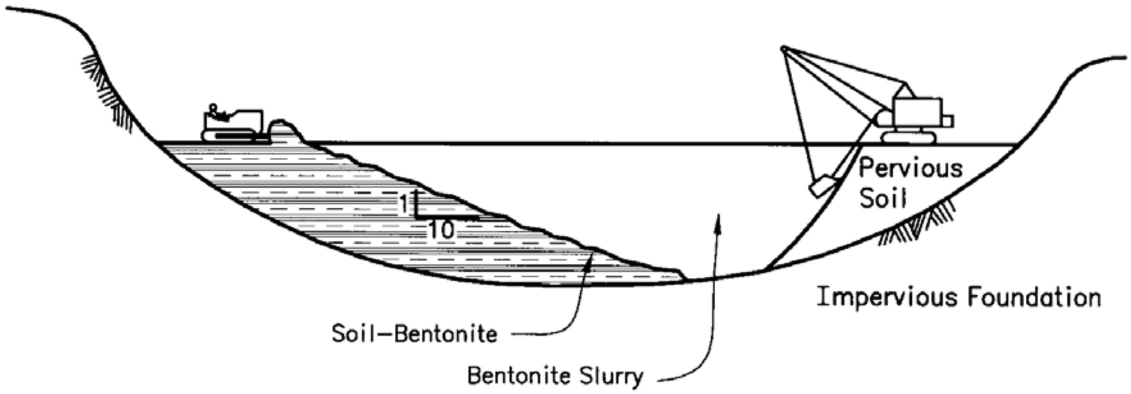
Figure II-9 shows construction procedures for both a soil-bentonite cutoff and a cement-bentonite cutoff. The soil-bentonite cutoff is a continuous trench-and-backfill operation, whereas the cement-bentonite cutoff is often a series of discrete panels. Primary panels are constructed first and then connected with secondary panels.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

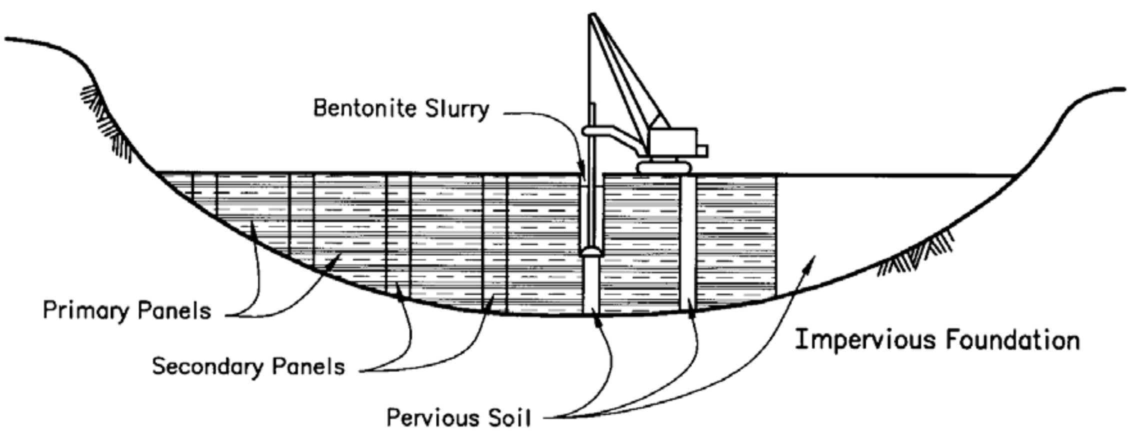
<u>Slurry Trenches (Soil-Bentonite or Cement-Bentonite Cutoff Walls)</u> <u>(Continued)</u>

FIGURE II-9. TYPICAL CONSTRUCTION PROCEDURES FOR SOIL-BENTONITE AND CEMENT-BENTONITE DAM-FOUNDATION CUTOFFS

SOIL-BENTONITE FOUNDATION CUTOFF-WALL



CEMENT-BENTONITE FOUNDATION CUT-OFF

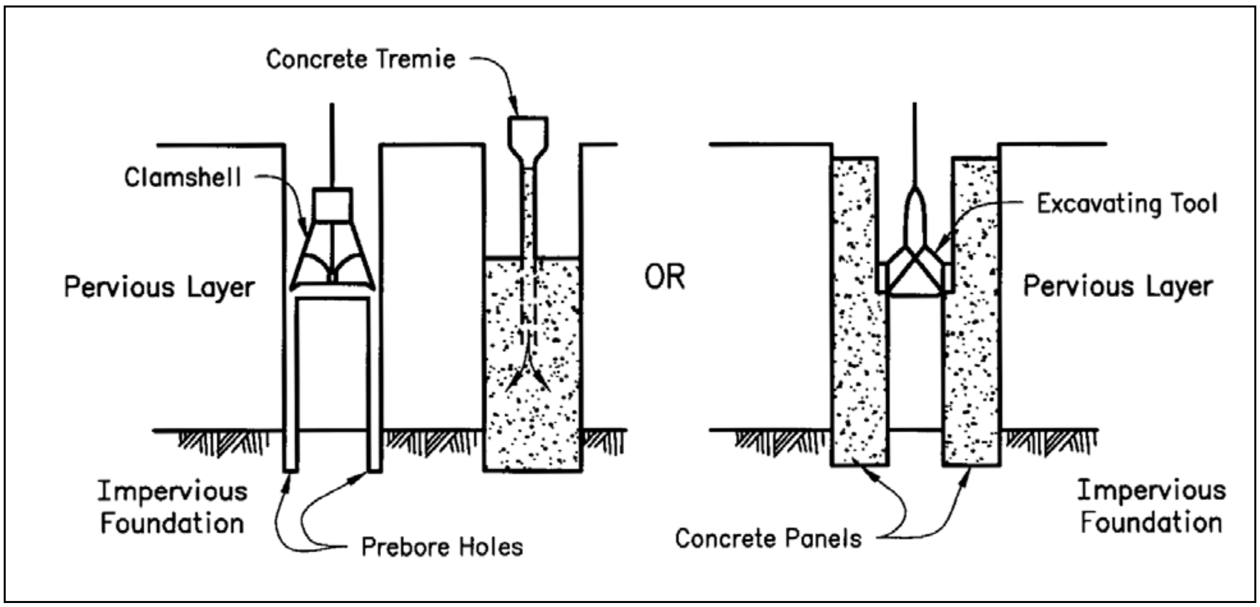


II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Concrete Cutoff Walls

A concrete cutoff wall may be an effective method of controlling underseepage when the depth of the pervious foundation exceeds the depth limitation of the equipment used to excavate a slurry trench (80 to 100 feet). It is also used when the foundation contains cobbles, boulders, or fractured or solutioned pervious rock. Using this method, a cast-in-place continuous concrete wall is constructed by tremmie placement of concrete in bentonite slurry-supported panels. Figure II-10 shows the general steps in constructing a concrete cutoff wall. Different methods are used for excavating the trench including rock milling machines, but the overall sequence of construction is very much the same. Construction of a concrete cutoff wall requires special knowledge, equipment, and skilled workers to achieve satisfactory results. It is critically important to form a tight seal at the joint between panels to ensure a continuous cutoff and that all panels are in continuous contact for their full depths.

FIGURE II-10. STEPS IN THE CONSTRUCTION OF A CONCRETE CUTOFF WALL



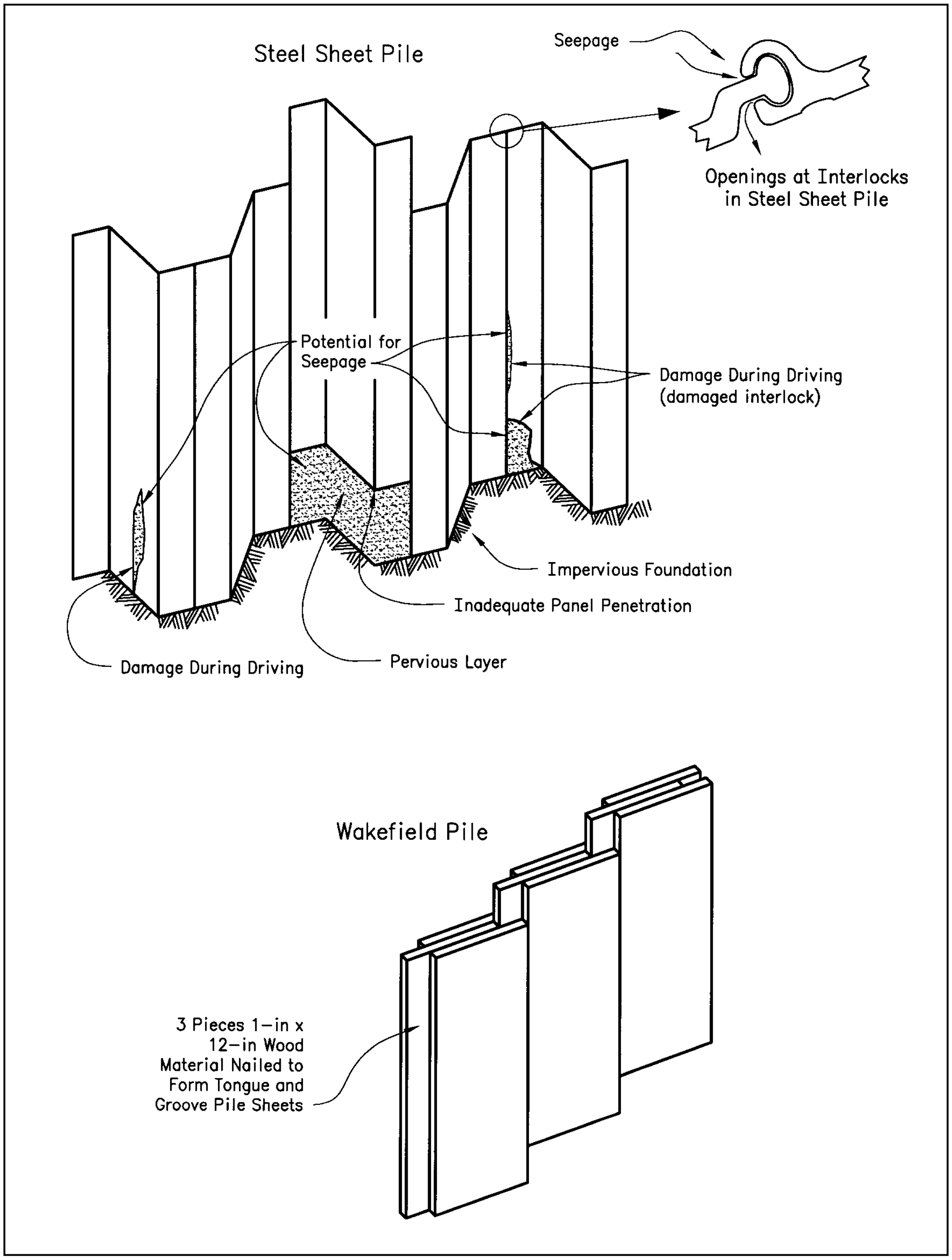
Sheet Piles

Sheet piles were among several types of seepage barriers that were used in the past. However, they have often proven to be rather ineffective as a permanent means of reducing seepage and it is difficult to justify their use when more effective methods are available today. Sheet piles can be damaged during driving resulting in damaged interlocks or tips, tearing, splitting, etc. (see Figure II-11). Sheet piles are considered to be only partially effective as a seepage control measure.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Sheet Piles (Continued)

FIGURE II-11. SOURCES OF LEAKAGE ASSOCIATED WITH SHEET PILES



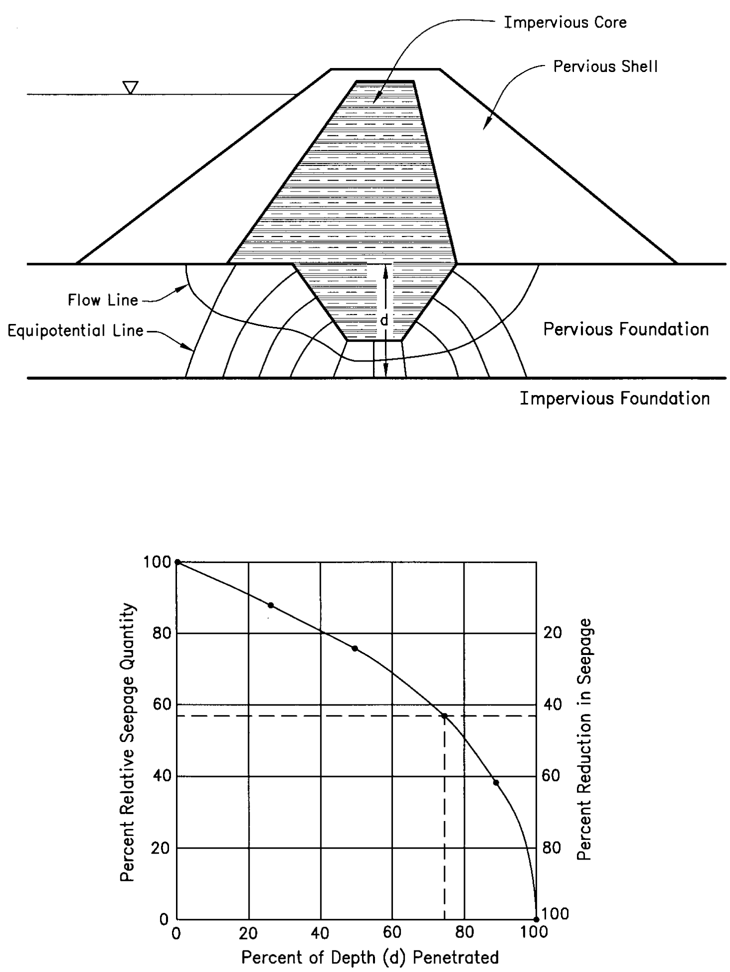
Sheet piles are often used in conjunction with concrete diversion and navigation structures to confine the foundation soil and thereby prevent it from piping out from under the structure. Sheet piles are usually steel; however, they can also be precast concrete and vinyl. Historically, sheet piles were often made from wood (Wakefield sheeting).

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Partial Cutoffs

A partial cutoff is any cutoff that does not fully extend to an impervious layer. A partial cutoff lengthens the seepage path and thus decreases exit gradients at the downstream toe. They are not as effective in reducing seepage quantities. At sites where the average permeability of the foundation soil is practically the same in both vertical and horizontal directions, partial seepage cutoffs have little influence on volume of seepage unless they penetrate at least 90 percent of the foundation depth. Figure II-12 illustrates this point. Most soils are stratified horizontally, and horizontal permeability is greater than vertical permeability, so partial cutoffs become more effective on this type of foundation. Partial cutoffs are reasonably effective when they extend down through an intermediate stratum of lower vertical permeability.

FIGURE II-12. PARTIAL CUTOFF



Reference: Bureau of Reclamation, Design Standard 13-Chapter 8, Seepage Analysis and Control, 1987

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Partial Cutoffs (Continued)

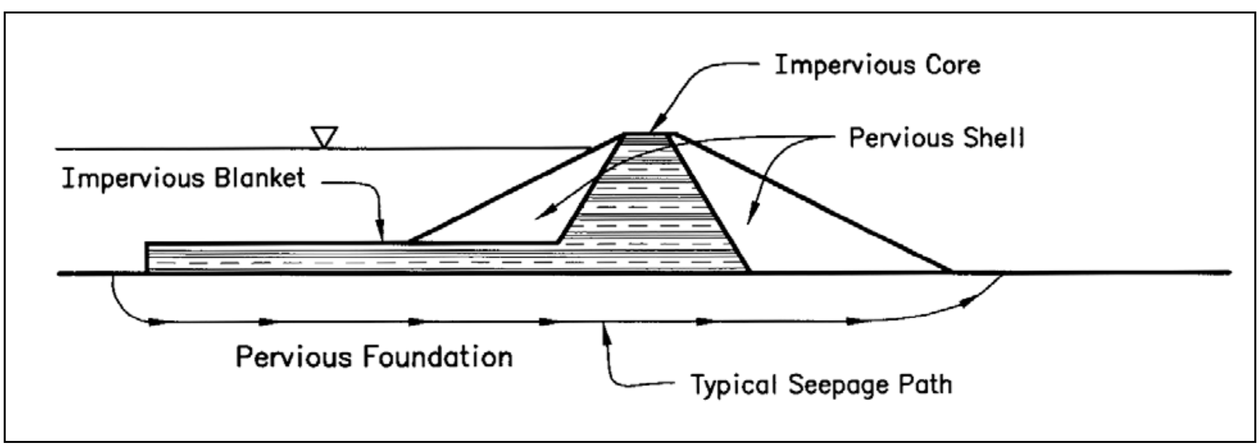
Figure II-12 shows that partial cutoffs may be ineffective in reducing the quantity of underseepage, especially when foundations are homogeneous, having the same permeability in both a horizontal and vertical direction. The figure shows that for a homogeneous foundation, a cutoff that extends 75 percent of the foundation depth only reduces seepage flow by about 30 percent, and reduces the discharge gradient at the toe by about 40 percent.

Any dam on a soil foundation should have at least a shallow partial cutoff or inspection trench about 5 to 10 feet deep, backfilled with rolled impervious core materials. These trenches are used to intercept layers of top soil, buried open-work gravel, fractured rock, pipes, desiccation cracks, animal burrows, root holes and other shallow deleterious materials. They also allow for close inspection of the foundation prior to construction of the dam.

Upstream Impervious Blankets

Upstream impervious blankets tied to the impervious core or zone of the embankment may be used to reduce seepage by lengthening the path of seepage (see Figure II-13). Upstream impervious blankets may be used when a complete cutoff is not required or would be too costly. Downstream control methods, such as drains, may also be used with upstream blankets, and will help to prevent excessive uplift pressures and piping caused by the seepage that does occur. Blanket effectiveness depends on length, thickness, and vertical permeability as well as on stratification and permeability of underlying natural material. Upstream impervious blankets can be damaged if the blanket cracks from settlement of the foundation, or from drying during periods of low reservoir. Another problem is the potential for the blanket to pipe into the foundation if placed over coarse gravels or open rock fractures without a filter. If the reservoir level fluctuates above and below the blanketed areas, the blanket must be protected from wave action and runoff erosion, drying, and the growth of deep-rooted vegetation. Upstream blankets should seldom be relied upon as the primary means of seepage control.

FIGURE II-13. UPSTREAM IMPERVIOUS BLANKET

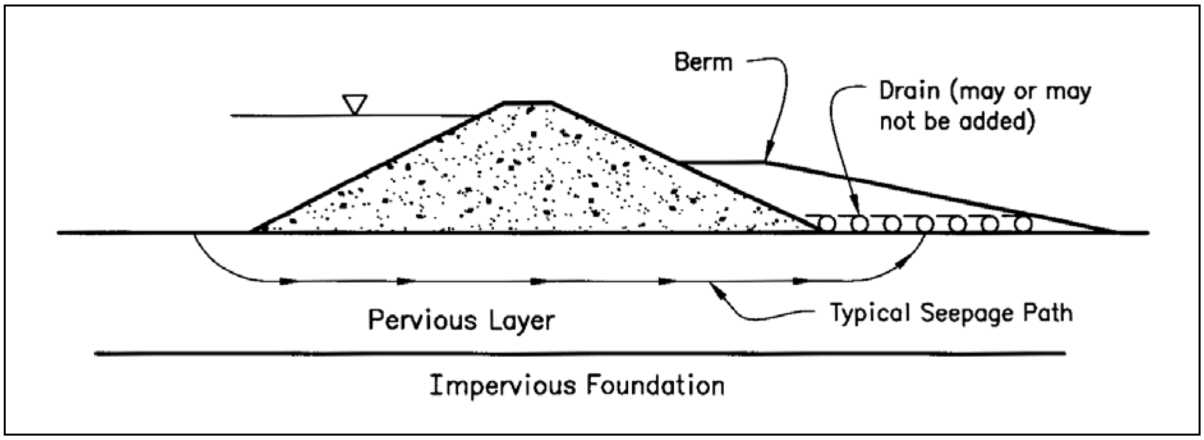


II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Downstream Berms

A seepage berm (see Figure II-14) may be used to counterbalance uplift pressures in the pervious foundation at the downstream toe of the dam. If the berm is impervious, it will increase the length of the seepage path. This will decrease exit gradients and seepage quantities. In other cases the berm may be built of pervious materials and incorporate a filter drain. If so, it becomes more of a drainage measure than an uplift control measure. The design intent of the berm, the type and availability of borrow materials, and relative cost will determine how the berm will be designed and constructed.

FIGURE II-14. DOWNSTREAM SEEPAGE BERM



Grouting

There are several types of grouting that are commonly used in and adjacent to the core foundation area. Examples include blanket (or dental) grouting, curtain pressure grouting, consolidation grouting, and others (Weaver, 1991). The more common types of grouting are briefly discussed in the following paragraphs.

Foundation grouting is performed to reduce:

- Seepage beneath or around the dam.
- Hydrostatic pressures (uplift) under the dam downstream of the grouting.
- The possibility of migration or internal erosion of embankment materials into the foundation.
- The possibility of internal erosion of embankment materials due to seepage entering the embankment from the foundation.
- The piping of soil from rock joints and seams.
- The dissolution of soluble materials.
- Internal erosion at the soil-bedrock interface.

Curtain grouting is most commonly performed in rock but can be performed in sands and gravels. Essentially, holes are drilled into the ground in a series of lines or in a grid pattern. The holes are cleaned with water and then, depending on the size of voids in the material being

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Grouting (Continued)

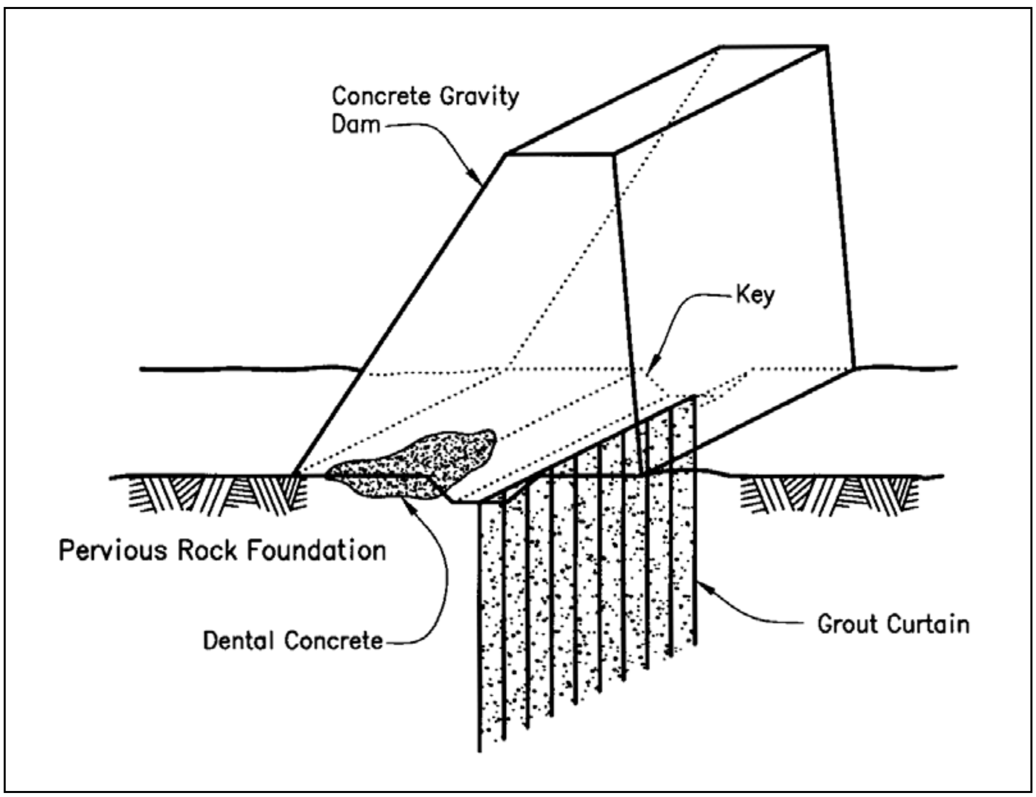
grouted, either a cement or chemical grout is pumped, under pressure, into the hole. If grouting is being performed in rock, the grout should fill the cracks, fissures, and other openings until the material around the hole being grouted is fairly impervious. If grouting is being performed in coarse sands or gravels, a thinner cement grout or chemical grout is used to fill the voids between the particles. In finer sands, the grout displaces the sand and compacts it tightly to create a barrier to seepage.

The permeability of a grouted zone must be relatively low if grouting is to be effective. Because the desired reduction in permeability may not be achieved, some method of drainage is normally provided in conjunction with the grouting to ensure seepage control.

Blanket grouting is performed over a broad area of an excavated foundation when the foundation rock is closely jointed or fractured at the surface. This method is used to seal the upper 10 to 30 feet of rock so as to minimize the possibility of piping of fines from the core into the rock crevices, to seal the near-surface rock against loss of grout during the deeper high-pressure curtain grouting that generally follows, and to reduce the compressibility of the fractured rock. Dental grouting can be used to treat isolated defects in the foundation.

Curtain grouting is performed to reduce deep underseepage through the foundation and abutments. Figure II-15 illustrates how grouting fills voids in a dam foundation to provide a seepage barrier.

FIGURE II-15. PROFILE OF GROUT CURTAIN



II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

DRAINAGE METHODS

Introduction

Drainage methods for embankment dams include the following:

- Pervious shells
- Horizontal drains
- Chimney drains
- Filter diaphragms around conduits
- Toe (or trench) drains
- Relief wells

Each of these methods will be examined on the following pages.

Adding a properly designed filter zone with an internal drain to an embankment dam can help to control seepage and lessen the potential for piping and internal erosion of the core material. Drains may also form permeable discharge elements or zones in the dam or foundation. Drains should be able to remove the anticipated seepage quantity without building up excessive pressure. Filter zones should be capable of intercepting and trapping particles eroding from open cracks or protected soil zones, and prevent migration of the embankment materials into the drain. Throughout this section of the module, discussions of drains assume a properly designed filter is used in conjunction with them.

Because the quantity of seepage may be difficult to predict and because drains may become plugged over time, drain capacity must be at least two orders of magnitude greater than the anticipated quantity. Refer to Appendix C for more discussion on maintenance of drain systems.

Drainage methods for concrete dams include the following:

- Galleries
- Lateral drains into rock abutments
- Relief wells

The addition of properly designed drains to the foundation and abutments of concrete dams can lessen the potential for undermining, increase dam stability, reduce uplift, and prevent abutment slope failure. Drain systems for concrete dams vary depending on foundation properties.

Drainage methods for structures such as retaining walls, aprons, and powerhouse walls may include the following:

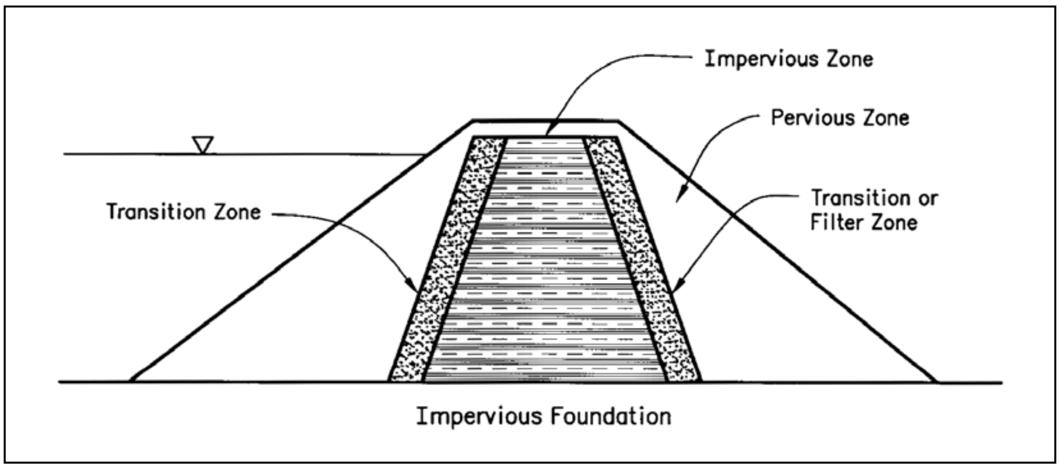
- Vertical drains, weep holes, and toe drains
- Geosynthetic drains
- Sub-drain systems

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Pervious Shells

At many sites, adequate quantities of at least two different materials with significantly different permeabilities are available for the construction of embankment dams. In such cases, the pervious material is placed upstream and downstream of the less pervious material. A narrow transition or filter zone is usually placed between the core and shell to prevent piping and internal erosion (see Figure II-16). Some sites with limited drawdown potential may not require the upstream zone. The downstream shell may consist of sands, gravels, cobbles, or rockfill—material with considerably greater permeability than the core. If the shell materials are very different in gradation from the core zone, multiple filter/transition zones may be required. In such cases, the phreatic surface will be very low in downstream zones and will have negligible effect on the stability of the downstream slope.

FIGURE II-16. PERVIOUS SHELLS AND DOWNSTREAM TRANSITION ZONE



Horizontal Drains

Horizontal or blanket drains (Figure II-17) can be used to control seepage through a homogeneous embankment or to prevent excessive uplift pressures from foundation seepage. Likewise, a horizontal drain can be used to prevent seepage from emerging on the downstream slope of a homogeneous dam. However, horizontal drains may not be completely effective in drawing down phreatic levels in horizontally stratified embankments. Hence, horizontal drains should be evaluated with caution if the purpose is to lower phreatic levels. The use of horizontal drains significantly reduces the uplift pressure in the foundation under the downstream portion of the dam; however, it also increases the quantity of seepage under the dam.

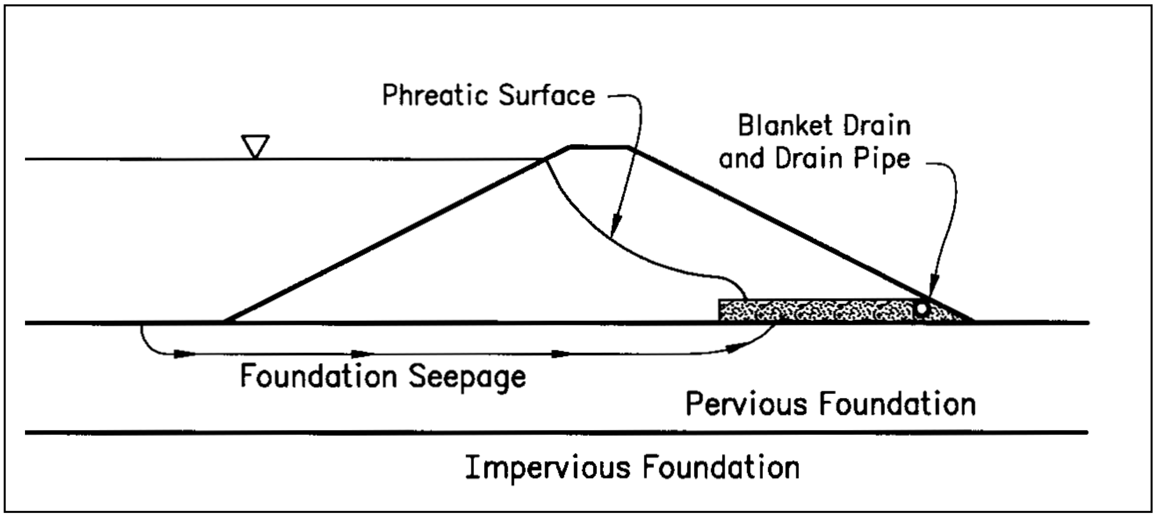
Horizontal drains are effective where seepage occurs through jointed or fractured bedrock or homogeneous pervious soil foundations. The wide contact area of the blanket drain provides confidence in contacting more of the crack features in bedrock than a narrow drain. Horizontal drains are also effective in providing a large area for a seepage outlet for pervious, relatively homogeneous soil foundations. However, horizontal drains are not as effective in controlling seepage in stratified foundations, because seepage in pervious deeper layers may bypass the horizontal drain at the foundation surface.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Horizontal Drains (Continued)

Horizontal drains should seldom be the sole method for controlling embankment seepage because in a stratified embankment, the horizontal drain at the base may not affect seepage in the upper portion of the embankment. A chimney drain as described in the following section would be more effective.

FIGURE II-17. HORIZONTAL (BLANKET) DRAIN



Chimney Drains

Chimney drains (also known as inclined drains) are either inclined or vertically oriented drains of granular materials, commonly constructed with a filter zone at the upstream and downstream sides of the drain. In some cases, the drains themselves may act as a filter. They are commonly used in embankment dams. A combination of both chimney and horizontal drains is a very effective method for seepage control through an embankment. Chimney drains are typically installed anywhere from 45 degrees from horizontal to a vertical orientation depending on the geometry of the structure, construction practice, and the anticipated seepage paths. Compacted embankment soils are often stratified and the horizontal permeability is greater than the vertical permeability. This occurs because borrow materials are varied and lifts of soils have slightly different characteristics. For stratified soils, a horizontal drain will not necessarily prevent the downstream slope from becoming saturated. Horizontal drains will also not protect against hydraulic fracturing of the embankment and internal erosion. Hence, a chimney drain is best suited to intercept seepage along horizontal planes through a stratified embankment, whereas horizontal drains are best suited for reducing uplift pressures along the base of a structure.

Current recommended practice is to provide a chimney drain to control seepage and internal erosion of embankment soils and some type of foundation drain, either a horizontal drain, trench type drain, or relief wells for controlling foundation seepage. In addition to adequate hydraulic capacity, drains must provide proper filter action between themselves and adjacent zones of the embankment if a separate filter zone is not installed. The chimney filter and drain

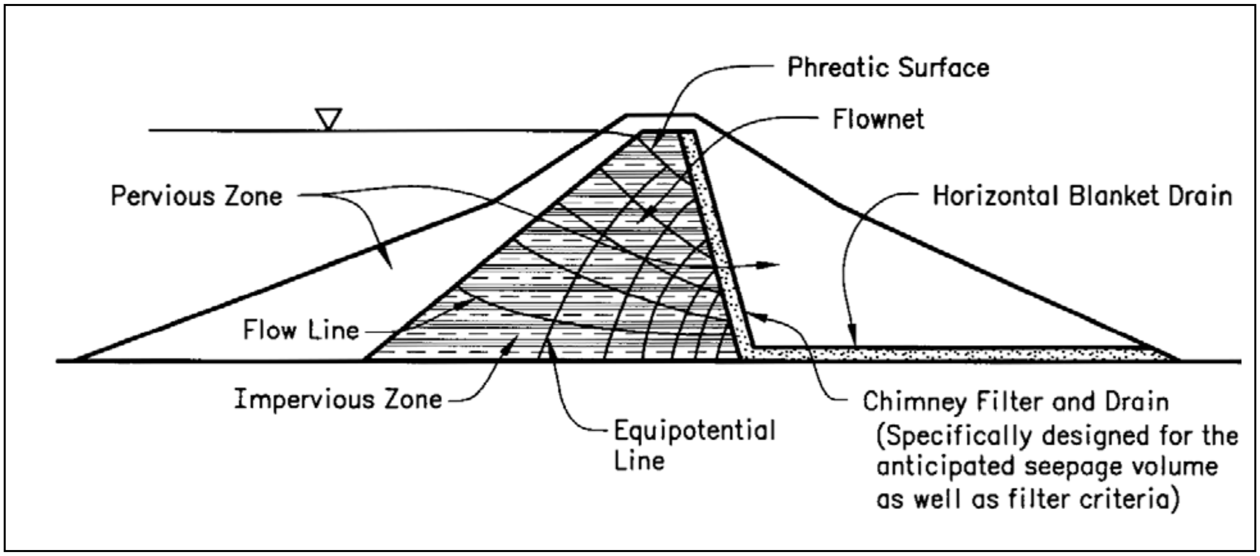
II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Chimney Drains (Continued)

are the best defense against transverse cracking through the core, which may result from differential settlement or seismic shaking. In addition, if dispersive or other highly erosive soils are used in the core, the chimney filter and drain is the best defense against internal erosion.

Figure II-18 shows an example of an embankment dam constructed with a chimney and horizontal drain combination.

FIGURE II-18. CHIMNEY AND HORIZONTAL DRAIN COMBINATION



Filter Diaphragms Around Conduits

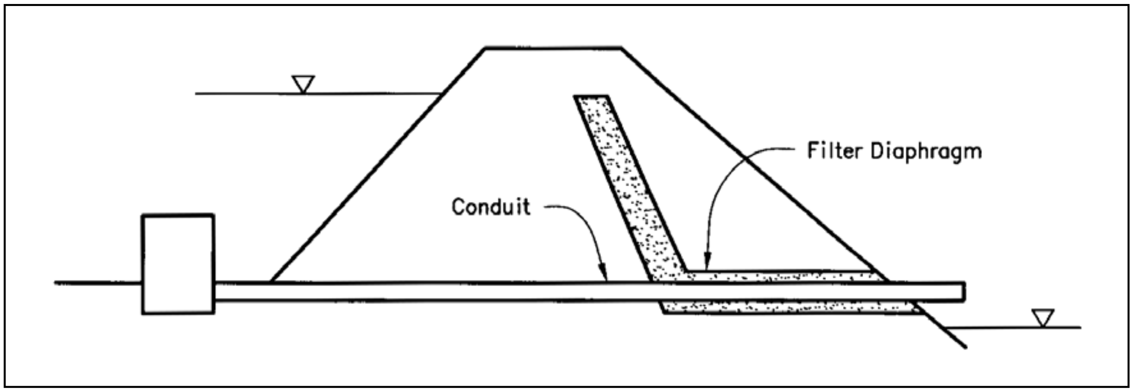
Flow along conduits is a traditional concern to embankment designers. Many observed failures of embankments have occurred along or in close proximity to conduits. Both piping and internal erosion failures are of concern, depending on the type of soils in which the conduit is located. To prevent flow along a pipe or to increase the length of the flow path, seepage collars constructed of concrete or other materials were formerly the primary line of defense.

Current practice is the use of a diaphragm of properly designed filter material around the conduit, extending outwards far enough to intercept any anticipated cracks in the adjacent earthfill (Figure II-19). The intent of this filter diaphragm is to intercept flow through any cracks in the earthfill or flow at the earthfill/conduit interface, and to filter particles that may erode along these features.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Filter Diaphragms Around Conduits (Continued)

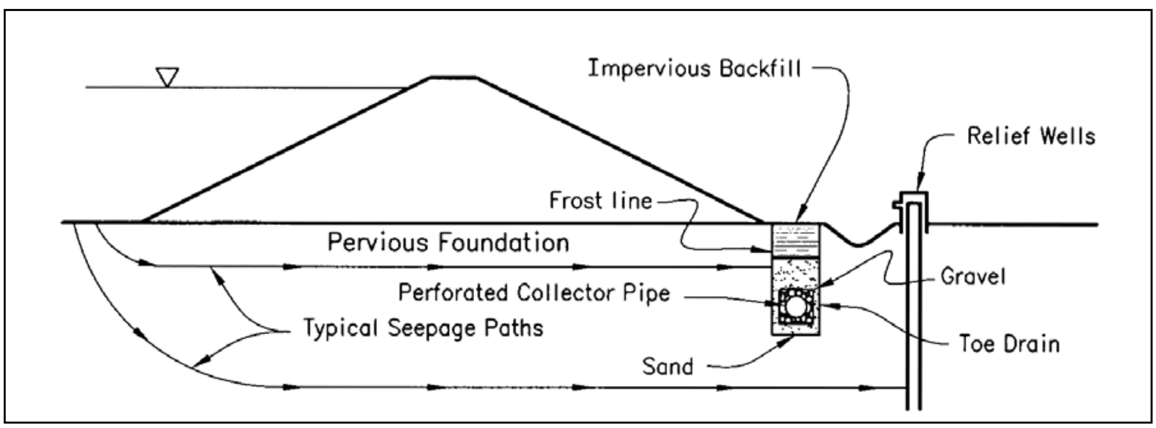
FIGURE II-19. FILTER DIAPHRAGM



Toe (or Trench) Drains

A toe (or trench) drain (Figure II-20) may be used in conjunction with other seepage control measures. The toe drain generally consists of a perforated collector pipe in a trench; the trench is then backfilled with filter material surrounding the toe drainpipe. Where the pervious foundation is deep or stratified, a toe drain may only attract a small portion of underseepage, with other detrimental underseepage bypassing the drain. In such cases, relief wells are used to relieve uplift pressure and collect water at greater depths.

FIGURE II-20. TOE DRAIN USED IN CONJUNCTION WITH RELIEF WELLS



Relief Wells

Relief wells (Figure II-20) reduce excess pressures that may develop deep in a pervious foundation near the downstream toe of a dam. They intercept seepage water, relieve pressure, and direct the flow into conduits where it cannot affect the dam. They also are used in rock foundations under concrete gravity dams. Relief wells should extend into the underlying, more pervious foundation layers if the foundation is stratified. Relief wells may be designed as either fully or partially penetrating.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

Relief Wells (Continued)

Although relief wells reduce excess pressures, they can also increase the quantity of underseepage depending on the foundation conditions. Relief wells should be located so they are accessible for sounding, cleaning, and pumping to monitor and/or rejuvenate discharge capacity. Pumps may be installed to increase the drawdown effect of the wells. See Appendix C for operation and maintenance suggestions for relief wells.

STRUCTURAL DRAIN METHODS–CONCRETE DAMS

Introduction

Concrete dams and dams founded on rock may have unique drainage features. Galleries, adits, relief wells, and lateral drains are often used to relieve excess uplift pressures and to collect and monitor seepage.

Galleries and Relief Wells

Large concrete dams are often constructed with internal galleries. The galleries serve a dual purpose of providing access for inspection and providing for internal drainage. Galleries collect seepage from construction joints through a network of smaller vertical and horizontal drains directed into the structure, and may collect seepage from the foundation through a network of vertical relief wells drilled into the foundation. A conduit may be present in the gallery that directs the combined seepage from all the drains to a low-level downstream outlet. A change in the total quantity of flow within the conduit or from individual drains or wells is indicative of potential problems developing with the concrete, waterstops, or other seepage control systems of the dam. Unusual seepage may indicate increasing pressures along concrete lift lines or joints within the dam or along the base of the dam that may lead to eventual instability of the dam. A change in seepage quantity is a cause for concern, because it may indicate seepage pressures are approaching levels that exceed the design loads for the structure or that the drainage system is not working properly. It is essential that the internal drains and relief wells be regularly maintained to avoid plugging with precipitation, which is a common problem within concrete dams. Plugged drains or wells will mask increasing seepage pressures, which contribute to reduced stability. More information pertaining to maintenance may be found in Appendix C.

Drainage Adits and Lateral Drains Into Rock Abutments

When the abutments are composed of fractured or weak rock, it is often necessary to provide for drainage. An adit (a gallery excavated into rock) is commonly utilized to provide for drainage and inspection of the abutments. The adit is analogous to the gallery used in a concrete dam. It provides access for installing and monitoring lateral drains, for conducting remedial grouting, and it contains a conduit to convey seepage to a low-level outlet. Lateral drains are oriented to intercept fractures or joints within the rock and relieve seepage pressures. This increases the overall stability of the abutment. A change in the total quantity of flow within the conduit or from individual lateral drains is indicative of potential problems developing with the abutment. Periodic maintenance of the drains is also important for the lateral drains in rock abutments.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

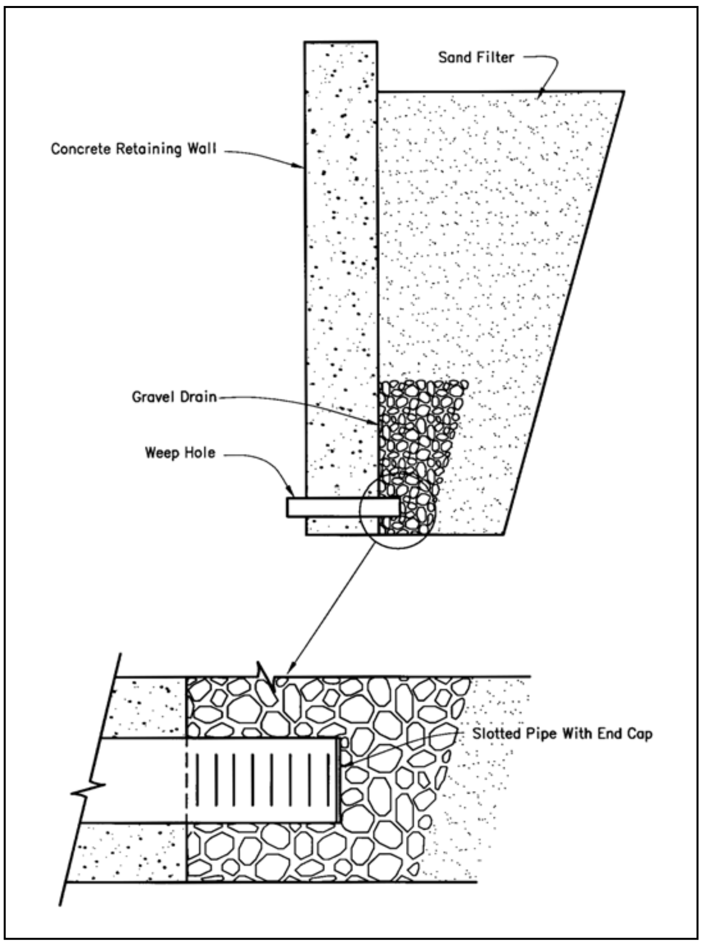
STRUCTURAL DRAIN METHODS–APPURTENANT STRUCTURES

Drainage methods for retaining walls, aprons, and a powerhouse are also important to the overall integrity of the dam. Failure of these appurtenant structures due to excessive seepage pressures could lead to catastrophic failure of critical water retaining structures, potentially leading to failure of the dam. Common techniques employed for these structures are vertical drains, weep holes, geosynthetic drains, toe drains, and sub-drain systems. The dam owner or operator should be familiar with these drainage systems and ensure they are properly maintained, as with any other drainage systems.

Vertical Drains, Weep Holes, and Toe Drains

A vertical drain is commonly used behind retaining walls. It is composed of a granular backfill designed to relieve hydrostatic pressure from behind the wall. Toe drains allow an exit for seepage near the base of a vertical drain. Properly maintained drains reduce the possibility of failure of the wall, and will prolong the life of the structure by keeping it relatively dry. Weep holes, commonly placed into the face of a wall, are another method used to relieve hydrostatic pressure from behind a wall. Figure II-21 is an example of these types of drainage features.

FIGURE II-21. VERTICAL DRAIN, WEEP HOLE, AND TOE DRAINS



STRUCTURAL DRAIN METHODS–APPURTENANT STRUCTURES (Continued)

Geosynthetic Drains and Filters

Geosynthetic drains and filters are being used with greater frequency in modern construction. Such drains and filters may be composed of woven or non-woven fabrics. Geosynthetic drains sometimes consist of geogrids or wafer-type boards designed to convey seepage. These products are typically made of low- or high-density plastics, depending on whether they need to be flexible or rigid. The material is installed on the surface or interface from which the seepage is to be collected. The type and size of material is specifically designed to convey or filter the anticipated amount of flow to a drainpipe. The drawback with geosynthetics is that they are difficult to maintain and monitor. However, if properly designed, they may provide another method of collecting and diverting seepage in non-critical areas where replacement is practical if they should fail.

Geotextile filters in drain systems should be used with caution for any critical water retaining structures. Geotextile filters are commonly used in applications where potential failure of a drainage system would not lead to potentially catastrophic circumstances. However, current practice for the design of dams or other hazardous water retaining structures is to use sand filters rather than geotextile filters, due to concerns related to potential plugging or possible deterioration of the geotextile filters.

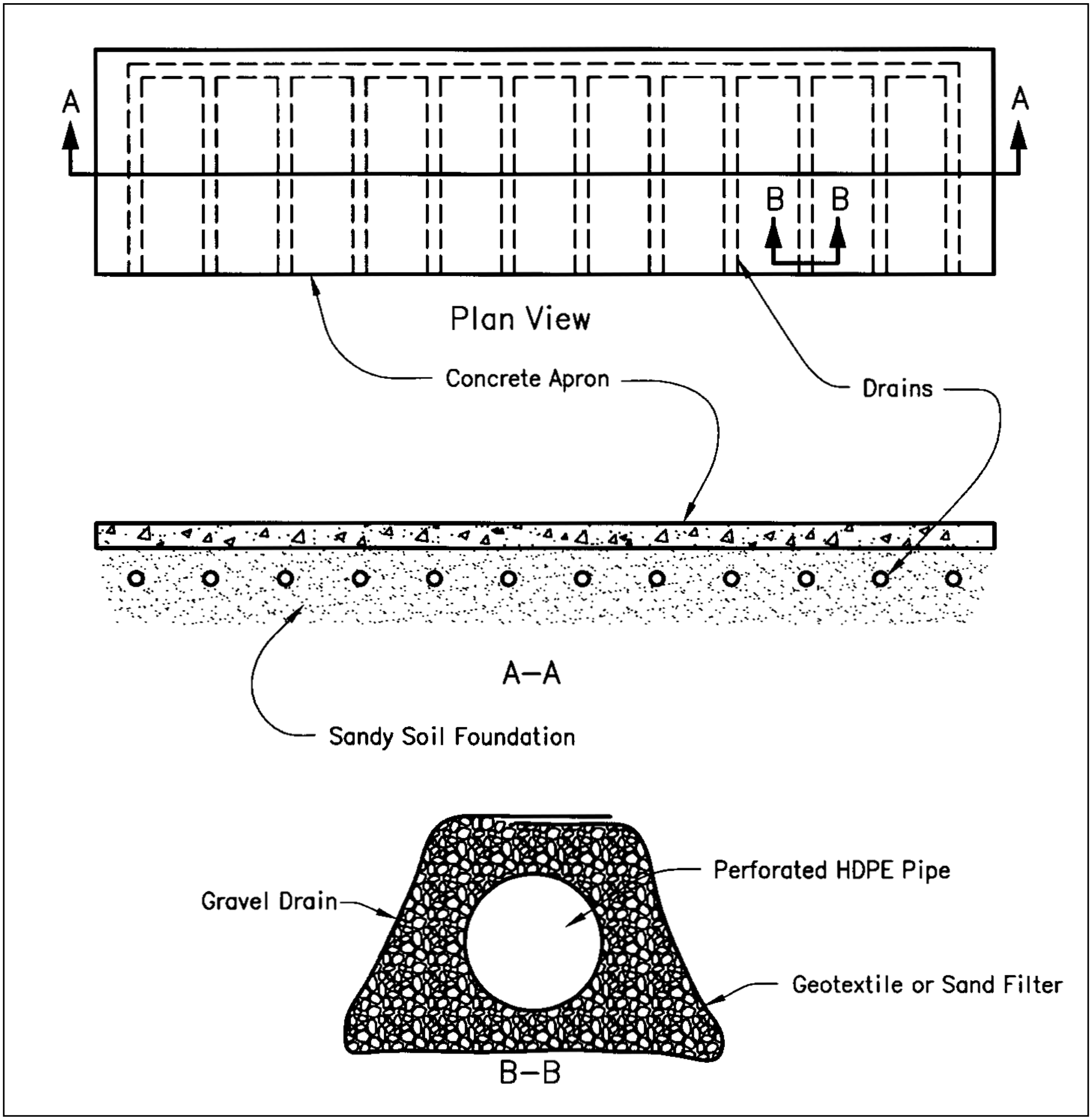
Sub-Drain Systems

Sub-drain systems are designed to reduce the uplift forces under slabs or walls. They are commonly used under spillway aprons or retaining wall footings. The sub-drain may be simply a layer of aggregate with embedded slotted pipes to convey water away from the structure. Sub-drain systems must be properly designed to meet filter criteria to prevent foundation materials from piping or eroding into the drain. The number and size of pipes must also be designed to provide the necessary capacity to remove the amount of anticipated seepage. There have been cases of powerhouse failure due to piping through a sub-drain system (St. Anthony Falls Lower Powerhouse, Minnesota). As with all drainage systems, periodic inspections and cleaning are necessary maintenance.

Figure II-22, shown on the next page, is a conceptual example of a sub-drain system employing sand or geotextile filters.

II. REVIEW AND EVALUATION OF PROJECT DATA: SEEPAGE CONTROL MEASURES

FIGURE II-22. SUB-DRAIN SYSTEM WITH GEOSYNTHETIC FILTER



SUMMARY: REVIEW AND EVALUATION OF PROJECT DATA

Unit II described the different types of data you can review to gain a better understanding of:

- The geology of the dam site.
- How the dam was designed and constructed.
- The materials used to construct the dam.
- The seepage control methods incorporated into the dam.
- How seepage could affect the project.
- The physical features of the dam.

The types of data include:

- Results of field and laboratory investigations.
- Design analyses and reports and construction plans and specifications.
- Construction reports, logs, records (including construction inspector's daily report), photographs, and as-built drawings.
- Operation and maintenance records.
- Instrumentation records.
- Past inspection reports.
- Any special reports prepared for the project.

This unit also described some of the seepage control measures that might be incorporated into a dam and documented in the data. Knowing what seepage control methods have been used in a dam and what typical problems can occur with each method will aid you in determining how a given seepage control method is working, and what remedial action you should take regarding a particular seepage condition.

Unit III

Field Investigation

III. FIELD INVESTIGATION: OVERVIEW

INTRODUCTION

Evaluating the risk posed by seepage is difficult. In many instances, an evaluation of risk and safety must be made based on site-specific characteristics and individual judgment and experience. It may also be influenced by non-technical considerations such as public perception.

Some important indicators of seepage-related dam safety problems are:

- A progressive increase in volume of flow.
- Evidence of piping (sand boils), internal erosion, solutioning of solids, or increased turbidity of seepage.
- Increase/decrease in hydrostatic pressures.
- A changing pattern of seepage.
- Seepage appearing at a critical location, such as adjacent to a conduit.
- Evidence of slope instability as a result of seepage (sloughing).
- Appearance of sinkholes.
- Soft, unstable areas downstream.
- Unusual vegetative growth (green grass in an arid environment).

Decisions on whether the risk of failure from seepage is acceptable are straightforward for some projects and extremely difficult for others. Nevertheless, all seepage is potentially unsafe and there is merit in adding additional instrumentation to better define the risks and to evaluate measures for control.

AREAS OF INVESTIGATION

When investigating the seriousness of seepage and determining remedial actions to alleviate the effects of seepage, consider these factors:

- Where and through what type of material is the seepage occurring?
  - What is its path and lateral extent?
  - Is it through the embankment, through the foundation, adjacent to a conduit, at an abutment/dam contact, or elsewhere?
  - Is the material through which it flows susceptible to piping, erosion, or solutioning?
  - Does the design include engineered seepage control elements?

III. FIELD INVESTIGATION: OVERVIEW

AREAS OF INVESTIGATION (Continued)

- How does the volume of seepage vary with seasons, rainfall, and fluctuating reservoir levels?
  - Does the seepage increase with increasing reservoir levels?
  - Does this increase occur suddenly or over a long period of time?
  - As the reservoir level recedes, does the seepage volume decrease to the previous amount or to some higher volume?
  - Does seepage exit the ground at different points?
  - Do seepage measurements have an annual cycle?
  - Do seepage measurements rapidly track rainfall, or track a seasonal rainfall pattern?
- How do seepage pressures or seepage forces respond to various reservoir levels?
  - Is the response instantaneous?
  - Do the seepage pressures or forces respond at an increasing rate with increasing reservoir levels?
- Are the seepage control measures maintained properly?

You should always conduct a visual inspection and you may need to conduct field and laboratory investigations, including installing monitoring instruments, to answer the above questions. Relate this information with the information obtained from the project review to the geometry, configuration, and types of materials comprising the dam and foundation. Then analyze the problem, evaluate the risk and determine appropriate remedial actions. Document all field observations including photographs for discussion with experienced engineers.

III. FIELD INVESTIGATION: SOURCES OF DATA

INTRODUCTION

Once you identify a potential seepage problem and determine the need for additional information, you must collect the information in order to analyze and assess the potential problem. Various ways to obtain this information are discussed below. Usually the investigation and data collection will have been put under the control of a qualified individual or firm who will have identified the information needed and developed a plan to obtain it.

VISUAL EVIDENCE FROM ONSITE OBSERVATION

The first step is to make a personal inspection of the dam, the seepage area, and the related conditions. Photographs should be taken. This personal inspection can accomplish several things:

- Put in perspective, clarify, and focus the information obtained from the project records.
- Provide a mental picture for reference in conducting future work.
- Help in interpreting and calibrating what others have reported.
- In most cases, provide a "feel" for what the problem is and how serious it is.

For less complex situations, a qualified engineer can often determine if a problem exists, judge its severity, and recommend appropriate action with a minimum of additional effort.

INTERVIEWS

Interviewing persons who are most familiar with the project may provide information and insights that can be of great assistance. For example, the owner, operating and maintenance people, the original designer, or the construction contractor may provide valuable information needed to assess a seepage problem. These individuals may be able to tell you:

- How the seepage area differs or reacts with changing conditions as compared with the rest of the project.
- If seepage occurs at certain reservoir levels and how quickly it appears.
- What happens in the area following rain, both with and without a reservoir level increase.
- Whether the seepage water is ever turbid.
- Whether the seepage water carries particles.
- Whether accumulations of particles occur in the area of seepage.
- Whether seepage changes with climatic conditions.
- Whether seepage always exits at the same location.
- If the area was wet before the dam was built.
- If the seepage changes on a cyclic annual, seasonal or daily pattern.
- If seepage is related to operation of the gates or other control structures.

III. FIELD INVESTIGATION: SOURCES OF DATA

INSTRUMENTATION

In most cases of complex seepage problems, instrumentation will be required to fully assess the problem. Instrumentation to monitor dam performance and the evaluation of the data obtained from the instruments are discussed in the module Instrumentation for Embankment and Concrete Dams. For new or developing seepage problems, additional instrumentation may be needed to supplement existing instruments or provide coverage in areas where there are no instruments. A variety of instruments can be installed in or near a dam to monitor seepage conditions, including the following:

- Vibrating wire, pneumatic, or hydraulic piezometers
- Downhole flow meters
- Thermal probes
- Downhole cameras
- Observation wells
- Weirs

Some general guidelines for instrumentation selection and location are as follows:

- All the rules for planning, selecting, locating, and installing original instrumentation apply to supplemental instruments. All instruments must be sited to provide useful information, not simply to provide a specified number of instruments.

- The plan should be very flexible; installation and initial data from one piezometer often shows the need for and best location of another.

- All seepage discharge points should be measured separately and as close to the source as possible.

- A reasonable array of piezometers is usually needed to trace the path and the real extent of seepage from the source to the exit point as well as the pressures generated by the seepage. This arrangement is particularly necessary in rock where seepage flows through the joints, fractures, faults, and shear zones rather than through the intact rock.

- The location of instruments should be coordinated with the need for field investigation. To save time and money, a hole drilled for a piezometer can also provide geologic information, sampling, and a location for in situ testing.

The existing and supplemental instrumentation must be carefully monitored to provide information on the performance of the dam and to establish trends in the seepage conditions. During evaluation of an emergency seepage condition, more frequent readings may be required and use of continuous data loggers with alarms may be necessary. All readings must be correlated with reservoir levels and weather conditions.

III. FIELD INVESTIGATION: SOURCES OF DATA

INSTRUMENTATION (Continued)

Many instruments, such as relief wells and observation wells, can serve the dual purpose of data collection and pressure relief. However, a relief well or drain should not be used as a piezometer by installing packers with pressure gauges. Installation of a packer with a pressure gauge in a relief well or drain will fundamentally alter the internal seepage patterns and cause higher uplift water pressures. These may aggravate the piping or slope stability problem, causing more rapid failure development.

A well-designed and executed instrumentation-monitoring program will provide the dam owner with early warning of potential problems and permit early intervention and remediation.

FIELD INVESTIGATION

Additional field explorations may be required and can vary considerably, depending upon particular site conditions and available data. Drilling, sampling, and testing of embankment and foundation materials may be required to better define conditions and to develop construction plans and specifications for remedial action. Geophysical-type investigations and field-testing may also be of use in better defining the location and extent of seepage.

Field investigations require the services of qualified engineers, geologists, drillers, and geophysical specialists. Field investigations are expensive; however, while economics are always a factor, minimum cost should not dictate the quality and quantity of work done. For example, a small diameter exploration boring may not yield satisfactory sample recovery as compared to a larger diameter boring that is more expensive. However, without sample recovery, a boring may be virtually worthless.

The following brief discussions cover various field investigations that may be employed in seepage investigations. Several of the references listed in Appendix B will provide more detailed information and additional references.

- **Field Mapping.** Obtain adequate geologic mapping of a dam site and reservoir. Knowing the geologic stratigraphy and structure of an area is essential, in most cases, to anticipating the sources and paths of seepage and locating instrumentation and subsurface explorations. Air photo interpretation is often a valuable tool, particularly thermal infrared imaging.

- **Drilling and Sampling.** Subsurface exploration and recovery of samples for examination and testing are generally necessary to establish stratigraphy and structure and type of soil or rock at a specific location and to locate seepage paths. The drilled holes also provide locations for piezometers and a wide variety of field (in situ) testing. Drilling should be supervised by qualified personnel and carefully performed to avoid causing serious problems such as hydraulic fracturing an embankment, breaching thin filter transition zones, contaminating filter drains with drilling fluids, or creating an uncontrolled exit for high-pressure seepage. If possible, it is best not to use drilling fluids when drilling into a dam.

III. FIELD INVESTIGATION: SOURCES OF DATA

FIELD INVESTIGATION (Continued)

- **Field Testing.** A wide range of field tests is available to aid in investigating seepage problems. Most common are various methods of testing to evaluate the permeability of the in situ soil or rock. With current technology, considerable use is made of the borehole and video camera technique to evaluate fractures, joints, and solution channels. A variety of well logging devices are used to obtain water temperature and chemistry profiles. Water chemistry is a useful tool for identifying the source of seepage water. Direction and velocity of flow, caliper logs, and other types of logs aid in evaluating materials in a specific hole and between holes. Frequently, dyes or trace elements are injected to locate seepage paths and to measure travel time from source to exit. In many cases, test grouting is done to evaluate the effectiveness and economics of grouting as a remedy. Pump tests may be conducted to determine foundation hydraulic properties. Underwater ROV units with side-scan sonar or other capabilities can further aid in assessing seepage issues related to upstream conditions or submerged conduits.

- **Geophysical Investigation.** Geophysical techniques used in seepage investigation include both surface and downhole methods. Techniques include electrical resistivity surveys, self-potential surveys, seismic and microseismic surveys, gravity and magnetic surveys, ground penetrating radar, acoustic emissions, gamma and neutron logging, and cross-hole thermography. Geophysical methods may provide valuable supplemental data at a reasonable cost. All these methods require a certain amount of specific verification (drill holes, samples, geologic mapping, water elevations, etc.) and qualified people to provide valid interpretations.

LABORATORY INVESTIGATION

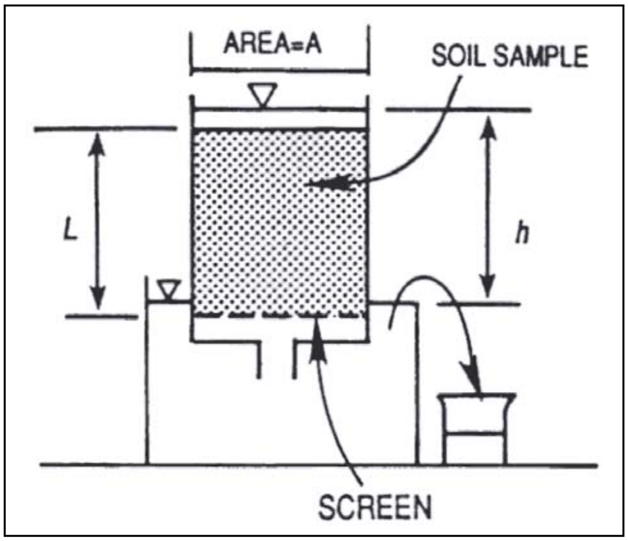
A variety of laboratory tests are often required. Laboratory permeability tests are performed on soil and rock samples to supplement field tests. The strength and other properties of soil and rock are often needed to determine remedial action. As an example, using a "rock mill" to excavate for a deep cutoff requires information on the strength and hardness of the rock to be excavated. Laboratory chemical testing of rock, soil, and water (reservoir and seepage) are conducted when dealing with soluble rock and solutioning, soluble salts (particularly gypsum) in soils, or dispersive soil.

III. FIELD INVESTIGATION: SOURCES OF DATA

Laboratory Methods

Laboratory methods may be quite accurate for the small sample tested, but are hardly representative of a large volume of in situ material. Laboratory methods are primarily either constant head or falling head tests. Falling head tests are generally used for less permeable soils and the methodology is described in ASTM D5084. For brevity, only the constant head test will be described in detail here. Figure III-1 illustrates a constant head permeameter.

FIGURE III-1. CONSTANT HEAD PERMEAMETER



In the constant head test, a sample of the material is placed in a cylindrical container and a constant supply of water is fed through the sample. The volume of water (**V**) that flows through in time (**t**) is measured. Using Darcy's law the hydraulic conductivity (**k**) is determined by:

$$k = \frac{V}{iAt} \; ; \quad \text{where } i = \frac{h}{L}$$

The constant head test is generally run on relatively pervious materials. Care must be taken to use de-aired water and saturated samples.

Field Methods

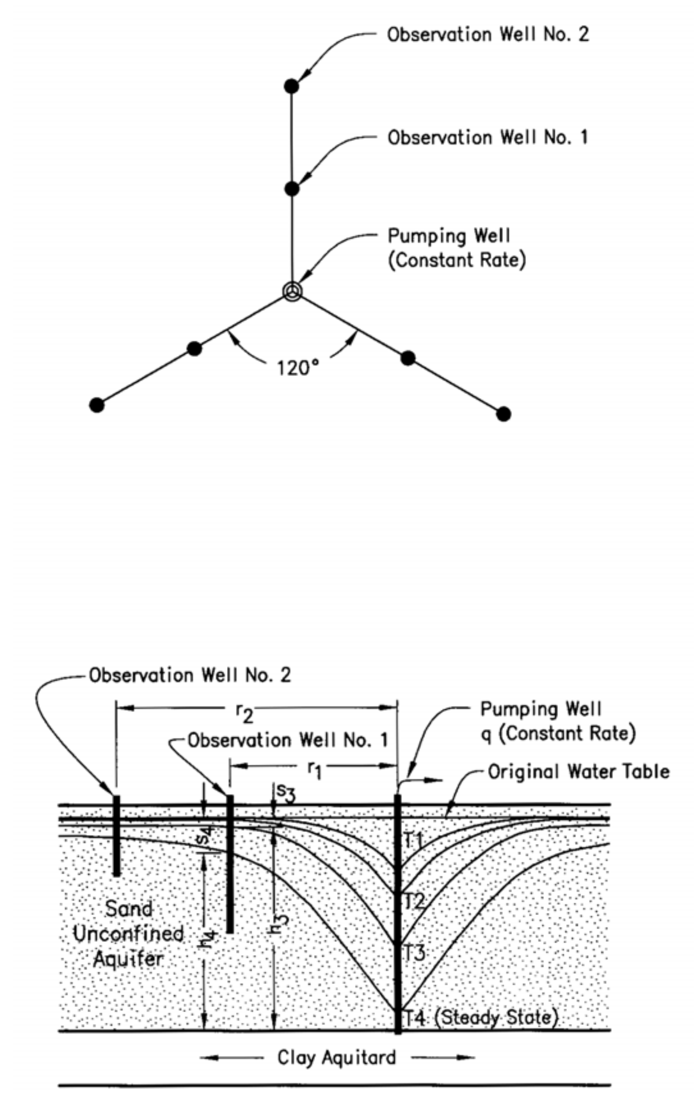
Field methods generally provide the best information, since field tests usually average the properties of a relatively large volume of material. While the following sections briefly describe various field tests, you should refer to the Bureau of Reclamation publication, Ground Water Manual, 1995 for detailed information on performing field tests.

Most field methods of determining hydraulic conductivity are based on changing the head in a well, borehole, or test pit. A widely used simple well pumping test is shown in Figure III-2.

III. FIELD INVESTIGATION: SOURCES OF DATA

Field Methods (Continued)

FIGURE III-2. WELL PUMPING TESTS



The coefficient of hydraulic conductivity (**k**) is computed from the following formulas:

Case 1- Steady State Test; Unconfined Aquifer

Case 1

$$k = \frac{q\ln(r_2/r_1)}{\pi(h_2^2-h_1^2)}$$

III. FIELD INVESTIGATION: SOURCES OF DATA

Field Methods (Continued)

Case 2- Steady State Test; Confined Aquifer

Case 2

$$k = \frac{q \ln(r_2/r_1)}{2\pi H(h_2 - h_1)}$$

where; H=thickness of aquifer

These formulas assume the following:

Case 1

- The pumping well penetrates the full thickness of the water-bearing formation.
- A steady-state flow condition exists.
- The water-bearing formation is homogeneous, isotropic, and extends an infinite distance in all directions.
- The Dupuit assumption is valid.

Case 2

- Pumping is at a steady rate
- s is small in relation to H
- Drawdown rate of change is small
- The water-bearing formation is homogeneous, isotropic, and extends an infinite distance in all directions.

It should be noted that there are field methods and equations for dealing with unsteady state tests and unsaturated materials as well as methods that determine permeability based on observing seepage velocity, etc. More detailed discussions of permeability testing can be found in the references in Appendix B by Harr, Todd, Cedergren, Bouwer, Powers, U.S. Bureau of Reclamation, U.S. Geologic Survey, and the U.S. Army Corps of Engineers.

III. FIELD INVESTIGATION: SPECIAL SEEPAGE CONDITIONS

INTRODUCTION

Much of the effort in evaluating and solving seepage problems involves:

- Observing the problem in the field.
- Organizing and evaluating the observations and other available information, and
  - Using the evaluations directly to explain the problem and assess the hazard, if any,

    or
  - Using the evaluations and observed data as input to a more formal analysis.

Whatever the case, you must base the interpretation and evaluation of observations on a thorough understanding of the principles and theory of seepage flow.

FIELD OBSERVATIONS

Field observations have been generally covered in the TADS modules included in the dam safety inspection component, and in one sense comprise site-specific verification connected with a particular problem.

Visual observations of the location, extent, and change in seepage can provide information on exit boundaries and, in some instances, on entrance conditions. In some cases, you can locate the seepage path by inference and experience. Observing seepage exiting around a conduit through an embankment dam would obviously indicate that the path is along the conduit. An observation of turbid or discolored seepage signals piping or internal erosion.

To determine if the seepage source is the reservoir, take seepage measurements using weirs and other devices, and correlate your findings to reservoir elevation, rainfall, and runoff. If the seepage source is the reservoir, determine whether the relation of seepage volume to reservoir head is stable or changing with time. This finding can indicate whether solutioning or internal erosion is occurring, or perhaps that seepage control measures are becoming less efficient. Because seepage flows are often masked by rainfall runoff, you need to look for extended dry spells to determine the seepage component.

Evaluating data from a comprehensive array of properly installed piezometers can provide information on water level and pressure that provide uplift pressures at specific points in the dam. Piezometer data can also provide information on the location of seepage paths, pressures, head loss, and gradients through the porous media, and how these change with reservoir elevation and time. In most cases, the initial piezometer system installed during construction will be expanded or supplemented to provide adequate coverage as seepage problems develop.

Use other observations (or tests) in the field such as dye and tracer injection, water temperature and water chemistry, and a variety of geophysical techniques to locate entrance boundaries and flow paths.

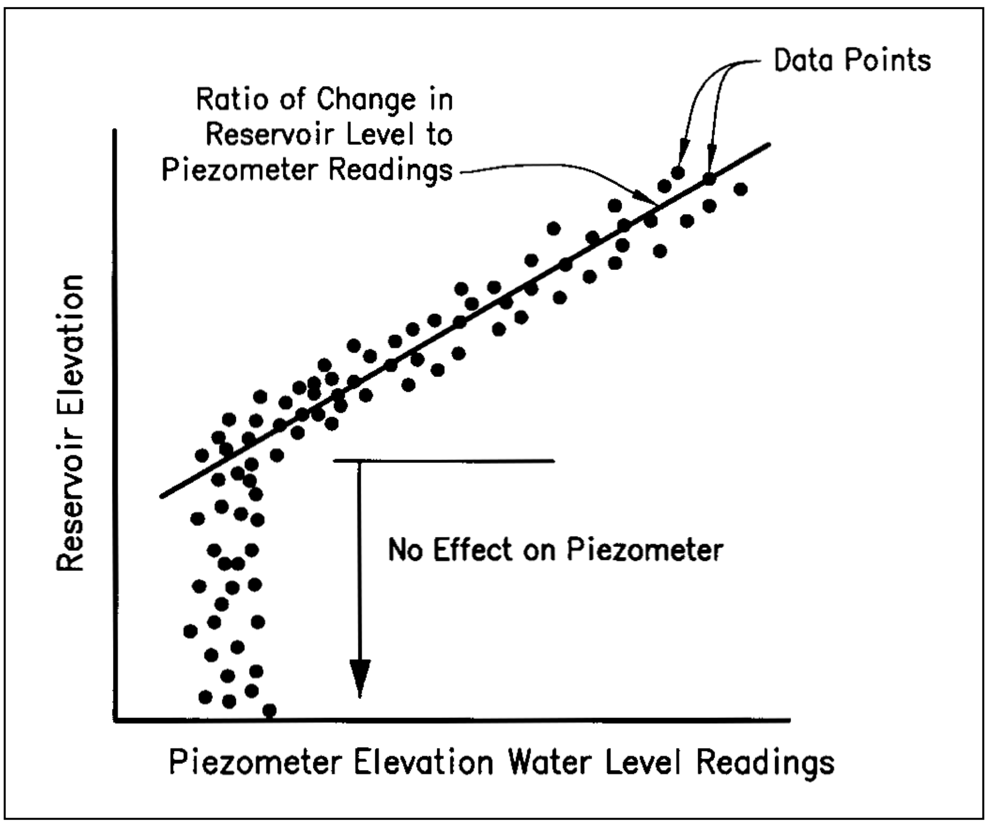
III. FIELD INVESTIGATION: SPECIAL SEEPAGE CONDITIONS

EVALUATING OBSERVATIONS

Observations can be utilized in a variety of ways depending on the specific problem and its extent. Data can be used in the form of a plot of piezometer elevation versus reservoir elevation (Figure III-3 below), or plots of piezometer elevation versus time for a single piezometer, or for several piezometers extending from upstream to downstream at a particular section of a concrete or embankment dam. Decreases in gradient over time at the same reservoir level may indicate that flow paths are enlarging.

In other cases, piezometer data can be plotted in sections for several reservoir elevations to illustrate the variation in uplift pressure under a dam. Piezometer data can be plotted in profile along the downstream toe of an earth dam to show areas of excessive uplift at different reservoir elevations. Many examples are shown in the TADS module entitled Instrumentation for Embankment and Concrete Dams. For more complex cases, transpose all information on topographic maps to show entrances and exits along with contours of piezometric elevation, and interpret flow paths for a particular reservoir elevation. If overlays of the same information for different reservoir elevations are developed, then evaluate the effects of change in head. In some cases, you may need to construct complex three-dimensional models showing the dam, geologic boundaries, and the observed seepage information.

FIGURE III-3. PIEZOMETER READINGS VS RESERVOIR ELEVATION



III. FIELD INVESTIGATION: SPECIAL SEEPAGE CONDITIONS

INTRODUCTION

Investigation and data collection may reveal conditions that contribute to different types of seepage problems. In addition to the various modes of failure described in Unit I, certain special seepage problems may exist. These special seepage problems are briefly described below.

SEEPAGE THROUGH SOLUBLE ROCK

One way to identify soluble rocks is by looking at landforms. Sinkholes are the most common and most easily recognized landforms and are associated with karst topography. At the surface, they may be simple, closed depressions. Sinkholes may be dry or contain water. Solution sinkholes are depressions formed by solution of bedrock, commonly in a fracture zone. Collapse sinkholes form by collapse of surface and near-surface materials into a subterranean opening, such as a cave. Sinkholes that develop after construction in the upstream reservoir or dam slope are strong evidence of untreated solution features in bedrock.

In certain geologic settings, you should assume soluble rock is present unless proven otherwise because it is known to be present in similar settings. Soluble bedrocks need special studies to evaluate the type, distribution, and filling of the solution channels. The location and distribution of soluble rocks and solution features should be determined during the original design and construction of a dam. If adequate data are not available, extensive field investigation and instrumentation are usually required.

SEEPAGE THROUGH DISPERSIVE SOILS

Some natural clay soils disperse or deflocculate in relatively pure water. These dispersive soils are very susceptible to internal erosion as well as surface erosion. Failures associated with dispersive clays often are sudden and disastrous with little warning. They often occur on first filling. However, failures have occurred when embankments stored water to a higher elevation than previously. One should always determine if dispersive soils were used in constructing the embankment at a site and whether dispersive soils occur in the foundation. Chimney drains with properly graded filters are the best protection against failures in dams constructed of dispersive clay.

In areas where dispersive soils are present, a particular pattern of erosion is often evident. Water percolates vertically downward several feet in cracks before flowing out to the surface of slopes, resulting in "jugs" or tunnels in the slopes. Tunnels up to several feet in diameter have been observed. Severe, deep, narrow erosion gullies forming “badland” topography are often an indicator of dispersive clay.

Dispersive soils cannot be differentiated from ordinary erosion-resistant clays by routine material properties tests. The field crumb test is a simple test that can be used to identify soils with dispersive properties. But dispersive soils can only be reliably identified with specialized laboratory tests. The best two tests are the so-called "pinhole" test and a test measuring the relative quantities of dissolved salts in the pore water.

III. FIELD INVESTIGATIONS: SUMMARY

SUMMARY: FIELD INVESTIGATION OF SEEPAGE CONDITIONS

Unit III described factors to consider when conducting field investigations of seepage conditions, and sources of data you can use in your investigation.

In addition to reviewing the types of data described in Unit II, you can also:

- Visit the site and make a personal inspection of the dam and seepage area.
- Interview persons who are most familiar with the project.
- Have additional instrumentation installed to monitor and provide feedback on the seepage.
- Conduct various field or laboratory investigations to better define conditions and help develop construction plans and specifications for remedial action.
- Understand site geology.
- Understand preconstruction conditions.
- Obtain correlating weather, operational, and reservoir level data.

This unit also described identification of special seepage conditions, such as seepage through soluble rock and dispersive soils.

Unit IV

Analysis

IV. ANALYSIS: OVERVIEW

INTRODUCTION

When seepage is identified at a dam, a determination must be made whether the seepage is a problem and, if so, the seriousness of the problem. This determination should always be a methodical, logical process and consider the effect on the dam both for present conditions and for possible future conditions. For example, consider the effects of reservoir levels significantly higher than historic levels.

To determine the effect seepage may have on a dam, consider the seepage path and the potential for piping, internal erosion, solutioning, and development of excessive pressures. Several methods and techniques are used in making these determinations. In some cases, a review of available information and experienced judgment are adequate, while in other cases, extensive field investigations and detailed analyses are required.

This unit describes:

- The theoretical basis for numerical seepage analysis.
- The variety of information required and how it is obtained.
- The various methods and techniques used in analyses.
- Where, when, and by whom the various methods will likely be used.
- How the results of analyses are used.

The method used to analyze seepage conditions may range from simple to complex. The best method to use will depend on site-specific conditions. There are many pitfalls in seepage analysis because properties, such as permeability, may vary tremendously over short distances and in different directions. Analyzing internal erosion and flow through bedrock with fractures is different than the study of intergranular seepage flow. Many of the pitfalls of seepage analysis are discussed in this unit.

To analyze seepage problems, you must possess a good knowledge of fundamentals of fluid mechanics, which can be obtained from the references listed in Appendix B and graduate courses in hydrogeology or geotechnical engineering covering the mechanisms of ground water flow. However, obtaining reliable results requires experience and judgment. The input of qualified engineering geologists and geotechnical engineers is essential. In all cases of numerical analysis, a parametric analysis must be conducted to judge the sensitivity of the results to various input parameters, and to establish the uncertainty in those parameters.

IV. ANALYSIS: BASIS FOR ANALYSIS

INTRODUCTION

Many of history's dam failures resulted from the lack of a consistent and logical framework for analyzing and anticipating seepage problems. Empirical rules based on observed good and bad performance, while of some help, were often not applicable to slightly different materials, foundations, and other circumstances. The logical analysis of seepage started with the development of Darcy's law in 1856, and the realization that the Laplace equation (discussed later in this section) governing heat and current flow was also applicable to the steady-state flow of an incompressible fluid through a porous media.

DARCY'S LAW

Henri Darcy, published in 1856 a formula governing flow through porous media. The formula, now known as Darcy's law, was based on the study of water flow through vertical filters in laboratory experiments. The experiments indicated that the quantity of flow is expressed by the equation:

$$Q = kiA$$

and

$$v_d = Q/A$$

where;

Q = rate of seepage (cm^3/sec)
v_d = discharge velocity, also equal to ki (cm/sec)
k = Darcy's coefficient of permeability (cm/sec)
i = hydraulic gradient equals the head loss (cm) divided by the length over which head loss occurs (cm)
A = cross-sectional area normal to the direction of flow (cm^2)

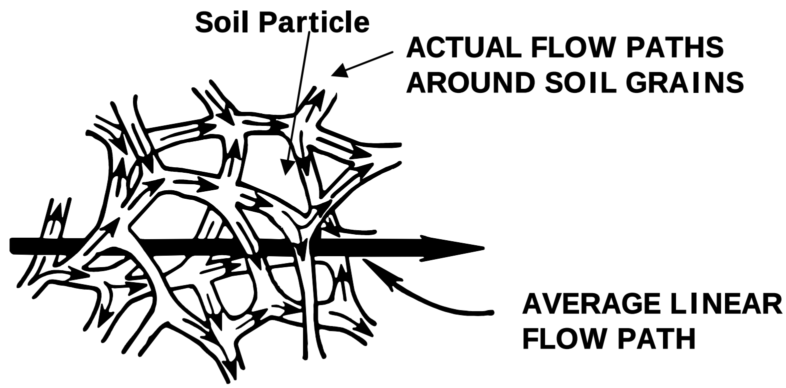
There are several aspects to note about Darcy's law:

- The discharge velocity **v_d** is an average fluid velocity and is defined as the gross quantity of fluid that flows through a unit cross-sectional area of soil in a unit of time. Since flow only occurs through the interconnected soil voids, the real velocity of flow or seepage velocity (v_s) for a single molecule of water traveling a unique path in the soil voids is greater than the discharge velocity. The seepage velocity is roughly equal to the discharge velocity divided by the porosity of the soil. Figure IV-1 illustrates this point.

IV. ANALYSIS: BASIS FOR ANALYSIS

DARCY'S LAW (Continued)

FIGURE IV-1. CONCEPTS OF FLOW PATHS THROUGH SOIL (MAGNIFIED VIEW)



- Darcy's law is applicable only to laminar flow (adjacent flow lines are parallel and straight and $\mathbf{v_d}$ is directly proportional to **i**). This law is reasonable for most soils, but flow through coarse gravels and rock openings may become turbulent and $\mathbf{v_d}$ is proportional to approximately the square root of **i**.

- Darcy's law is limited to flow through saturated materials. Flow through unsaturated materials is in a transient state and is time dependent.

- Darcy's law is not useful in studying flow through cracks or fractures and similar features in rocks or soil.

Darcy's law has many applications in seepage analysis, including:

- Determining permeability, both in the field and laboratory.

- Predicting quantity of laminar flow.

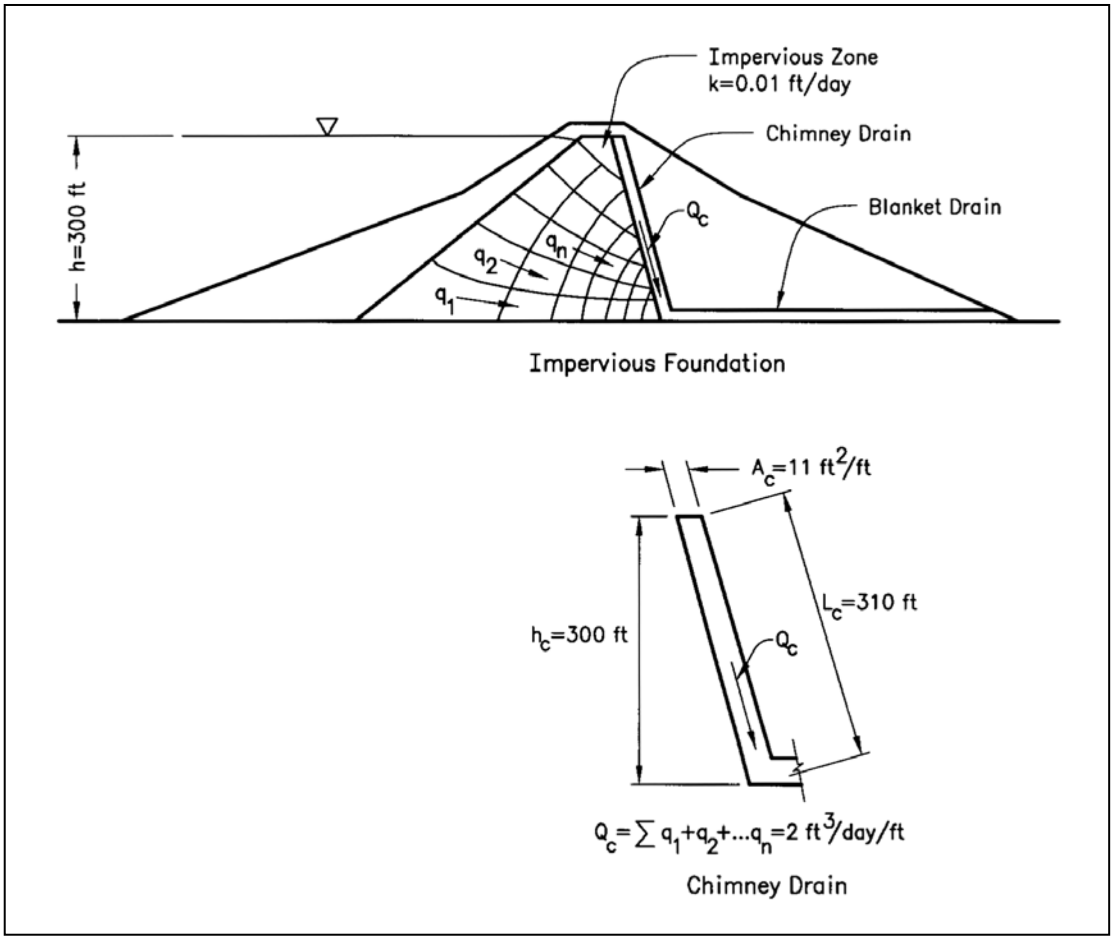
With approximate modifications, Darcy's law can be applied to problems of turbulent, transient (time-dependent), and partially saturated flow.

Darcy's law is also used in solving many seepage and drainage problems associated with dams. A common example is determining the necessary permeability or dimensions of inclined or horizontal drains in a dam. This application is illustrated in Figure IV-2.

IV. ANALYSIS: BASIS FOR ANALYSIS

DARCY'S LAW (Continued)

FIGURE IV-2. CHIMNEY DRAIN DESIGN USING DARCY'S LAW



LAPLACE EQUATION

The flow of water through a porous medium (soil) is only one of several forms of streamline flow that obey similar fundamental relationships, which can be represented by the Laplace equation. In two dimensions, the Laplace equation can be solved by drawing two families of curves that intersect at right angles to form a pattern of "square" figures, commonly known as a flownet. The Laplace equation for three-dimensional flow is shown below:

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} + \frac{\delta^2 h}{\delta z^2} = 0$$

Iterative methods are required to solve this partial differential equation for three-dimensional flow. Numerical solutions using two- and three-dimensional finite difference or finite element methods are typically used. These methods require sophisticated computer programs and

IV. ANALYSIS: BASIS FOR ANALYSIS

LAPLACE EQUATION (Continued)

require experienced engineers to use them. Most seepage problems related to dams can be approximated with two-dimensional solutions, often with hand-drawn flownets. However, there may be rare circumstances where a three-dimensional solution may be required.

Developing the Laplace equation for flow of water through porous media requires the following assumptions:

- The porous media (soil) is homogeneous.
- The voids are completely filled with water (i.e., saturated).
- The soil and water are incompressible.
- Flow is laminar and Darcy's law is valid.

The Laplace equations for two- and three-dimensional flow and their derivations can be found in the following publications, which are listed in Appendix B:

- Groundwater and Seepage by M.E. Harr
- Seepage, Drainage, and Flownets by H.R. Cedergren
- Seepage Analysis and Control for Dams (Manual EM 1110-2-1901) by the U.S. Army Corps of Engineers
- Introduction to Groundwater Modeling by Herbert F. Wang and Mary P. Anderson

FRACTURE FLOW

Darcy permeability is not directly applicable for studying water flow through discrete open fractures, joints, and other types of cracks in rock and soil. Evaluating fracture flow is complex because the flow is dependent on fracture geometry, fracture roughness, fracture fill material, and the size of fracture openings. Hence, the problem may require extensive field data to solve. Simplifications are often used, including simplifying the problem so that Darcy's law may be indirectly used to solve the problem by using a bulk hydraulic conductivity for a highly fractured rock mass.

Flow through fractures in soil may lead to internal erosion. Evaluating the potential for internal erosion is often empirical because suitable mathematical or other models are not available and due to the problem of characterizing the fracture characteristics. Evaluation often considers only whether the appropriate measures were designed and constructed properly on the assumption that internal erosion is likely to be a problem.

IV. ANALYSIS: BASIS FOR ANALYSIS

FRACTURE FLOW (Continued)

Fracture flow can be the dominant mode of seepage through rock foundations and abutments. It is also a primary mode of fluid transport common to internal erosion. Darcy's law does not strictly apply to flow through an open fracture, as it was derived from experiments on flow through a column of homogeneous sand. However, both Darcy and the Laplace equations may be applied for approximating flow through a uniformly fractured rock mass if the volume of rock under consideration is uniformly fractured and can be assumed isotropic. The methods used to solve the Laplace equation (numerical and graphical) and the Darcy permeability used in the Darcy equation are prone to scale effects when considering fracture flow. Fracture flow varies from highly anisotropic to a relatively isotropic phenomenon, depending on the size or scale of the rock volume under consideration and the spacing of interconnected fractures. For this reason, fracture flow problems should be left to a qualified engineer.

In simplest terms, fracture flow can be approximated as flow through two parallel plates. Experiments with flow through parallel plates led to the development of an equation for determining the hydraulic conductivity of a fracture. The hydraulic conductivity of a fracture (k_f) is expressed as:

$$k_f = \frac{\rho \, g \, a^2}{12 f \mu}$$

where **a** is the size of the fracture aperture and μ is the fluid viscosity, ***f*** is a fracture roughness factor that accounts for friction, ρ is the density of the fluid and **g** is the acceleration of gravity. The quantity of flow through a fracture (Q) is dependent on the hydraulic gradient, the hydraulic conductivity of the fracture, and the cross sectional area perpendicular to flow and may be expressed as:

$Q = vA$ where: $v = k_f \, i$ (v is the velocity of flow, i the hydraulic gradient)

$A = La$ (A is cross sectional area of the open fracture, L the length of fracture, a the aperture width)

Putting these equations together results in the "cubic law", which governs fracture flow:

$$Q = \frac{\rho \, g \, i \, L \, a^3}{12 f \mu}$$

The roughness of joint surfaces and sinuosity of the joint path will attenuate flow. Opening of the joint aperture when subjected to increasing hydrostatic pressure may increase flow through joints. The geometry of joint intersections and turbulent effects due to converging flow will

IV. ANALYSIS: BASIS FOR ANALYSIS

FRACTURE FLOW (Continued)

attenuate flow through a joint network. Variation in joint-filling materials may also attenuate flow. Joints are not infinite in extent and commonly have variable aperture widths.

Two methods have been used to simplify the problem of flow through fractures: discrete analysis and the method of equivalent homogeneous medium. Discrete analysis is used when site conditions lend themselves to simple characterization of the joint system. Equations governing flow through fractures are applied, using the cubic law with accommodations made for the effects at intersecting joints, joint roughness, and network geometry. A number of commercial and proprietary fracture flow models are available to solve discrete flow problems.

Where fracture networks are too complex and extensive to accurately portray in a discrete model, the problem may be simplified as equivalent flow through a homogeneous porous medium. Thus, large-scale pump tests may be used to determine an average hydraulic conductivity for the fractured rock mass and standard equations governing flow through homogeneous porous media may be used to solve the seepage problem. This may be a reasonable assumption for uniformly fractured rock, given the other uncertainties of the design.

UNSATURATED FLOW

The flow of water through a porous medium (soil) that is not saturated is studied with different equations, including the Green-Ampt Equation and others. Unsaturated flow does not often cause dam safety problems. Discussing these methods is outside the scope of this module. For more information, please refer to the references in Appendix B ("Dynamics of Fluids in Porous Media" by Jacob Bear, "Groundwater" by Freeze and Cherry, and "Groundwater Hydrology" by Bouwer).

IV. ANALYSIS: INFORMATION NEEDED FOR ANALYSIS

INTRODUCTION

The validity and quality of any seepage analysis depend upon the information available for input into the analysis. Necessary information includes:

- The location of various boundaries and flow paths.
- The type of flow.
- The permeability of the various materials through which the seepage flows.

Seepage problems are common because information available during the design and construction phase of a dam is often insufficient for accurately predicting seepage. Therefore, post-construction field observations are required and can supply much additional information needed to analyze and rectify any seepage problems once they develop.

BOUNDARY CONDITIONS

Boundaries define the limits and conditions of flow in the cross-section being analyzed. Boundaries include an impervious layer in the foundation below which no seepage is expected to occur, the entrance face for seepage, and the exit face. One must also define whether boundaries are fixed or transient.

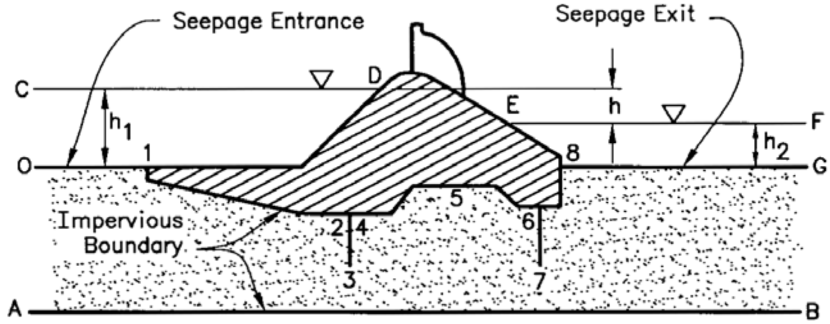
The nature and location of various boundaries are determined by:

- Field exploration and knowledge of site geology.
- Assumptions based on engineering judgment.
- Conditions imposed by design and type of structure.
- Geometry of the dam and its zoning.

In most cases, simplifying assumptions are required to establish boundaries that will permit an analysis. Figure IV- 3 shows several types of boundaries.

IV. ANALYSIS: INFORMATION NEEDED FOR ANALYSIS

FIGURE IV-3. EXAMPLES OF BOUNDARY CONDITIONS



(A)

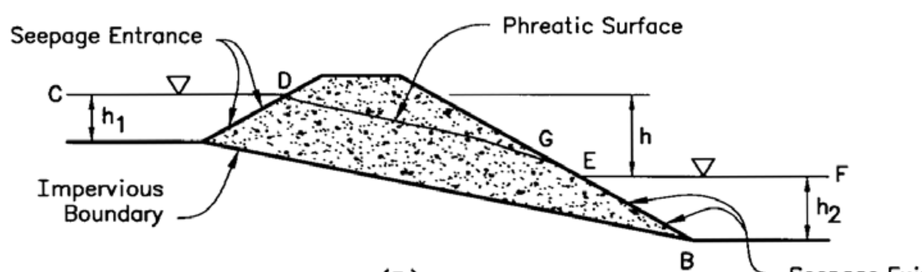
Confined Flow (Bounded on Top and Bottom by No Flow Boundaries)–

<u>Boundaries</u>

AB – No Flow Boundary
CD – Constant Head Boundary
EF – Constant Head Boundary
1–8 – No Flow Boundary
1–D – No Flow Boundary
E–8 – No Flow Boundary

<u>Other Seepage Parameters</u>

Line 1,2,3,4,5,6,7,8 – Seepage Flow Path
h_1 – Headwater Potential
h_2 – Tailwater Potential
h – (h_1-h_2) Drop in Head
0–1 – Line of Equal Potential
8–G – Line of Equal Potential



(B)

Unconfined Flow (Top Surface Not Bound by No Flow Boundary)–

<u>Boundaries</u>

AB – No Flow Boundary
CD – Constant Head Boundary
EF – Constant Head Boundary

<u>Other Seepage Parameters</u>

AD – Line of Equal Potential
GE – Seepage Face
DG – Phreatic Surface
h_1 – Depth of Headwater
h_2 – Depth of Tailwater
h – Drop in Potential
BE – Line of Equal Potential

IV. ANALYSIS: INFORMATION NEEDED FOR ANALYSIS

The interface between the saturated pervious media and adjacent materials such as low permeability soil or concrete is approximated by an impervious boundary. It is assumed that no flow crosses the boundary, and thus flow in the pervious material adjacent to the impervious boundary is parallel to the boundary. In Figure IV-3(A), lines AB and 1-8 are impervious boundaries.

The lines defining where water enters or leaves the pervious mass are known as entrances or exits, respectively. Along these lines (0-1 and 8-G in Figure IV-3(A) and AD and BE in Figure IV-3(B)) are lines of equal potential (i.e., the piezometric level is the same all along the line regardless of its orientation or shape). Flow is perpendicular to an entrance or exit.

The saturated pervious mass may also have a boundary exposed to the atmosphere and allow water to escape along this boundary, such as line GE in Figure IV-3(B). Pressure along this surface is atmospheric. The boundary is called a surface of seepage or seepage face.

The line DG in Figure IV-3(B) is a line located within the pervious mass where water is at atmospheric pressure. This line is known as a phreatic surface or free surface. Material below the phreatic surface is saturated. It is assumed that there is no flow across the phreatic surface; thus, flow in the adjacent saturated pervious mass is parallel to the phreatic surface. Unlike impervious boundaries and entrances and exits, the location of the phreatic surface is not known until the flow distribution in the pervious mass is known.

Figure IV-3 also illustrates the two general cases of seepage. Confined flow (Figure IV-3(A)) occurs in a saturated pervious mass below a concrete dam that does not have a phreatic surface. Unconfined flow (Figure IV-3(B)) exists when the pervious soil mass has a phreatic surface. Confined flow has all boundaries defined. The surface of seepage and phreatic surface must be defined for unconfined flow by analysis (or established by field observations).

TYPE OF FLOW

As noted previously, Darcy's law and the Darcy coefficient of permeability (k) are only strictly valid for laminar flow through porous soils. For coarse gravels and large flow passages through rock the flow is turbulent (i.e., the velocity is not directly proportional to gradient, and Darcy's law is not strictly applicable). Cedergren's Seepage, Drainage, and Flownets and the U.S. Army Corps of Engineers manual Seepage Analysis and Control for Dams discuss the problems of turbulent flow in seepage analysis and the adjustments and approximations that can be made.

PERMEABILITY

Determining the permeability of materials in the soil to be analyzed is a formidable problem. As illustrated in Table IV-1, no other engineering property of soil is as variable as is permeability.

IV. ANALYSIS: INFORMATION NEEDED FOR ANALYSIS

PERMEABILITY (Continued)

TABLE IV-1. VARIABILITY OF PERMEABILITY COMPARED WITH OTHER TYPICAL ENGINEERING PROPERTIES OF SOIL OR ROCK

Property	Typical Range of Values
Soil Permeability	0.000001 – 100,000 ft/day
Soil Grain Sizes	0.0001 – 300 mm
Rock and Soil Strength	.01 – 35,000 lb/in^2
Unit Weights of Rock and Soil	80 – 185 lb/ft^3

Soil zones to be analyzed in seepage problems are seldom, if ever, homogeneous with respect to permeability. Therefore, stratification or minor changes in geologic features can have a profound influence on seepage conditions. Several examples are listed below.

- Alluvial soil deposits are always stratified to some extent and even a sand foundation that appears to be homogeneous will have a horizontal permeability several times greater than the vertical permeability.

- The permeability of most intact (solid) rock is very low, but the permeability of a mass of the same rock may be quite high because permeability of the rock mass is controlled by the discontinuities in the mass, such as bedding planes, joints, faults, and shear zones.

- The permeability of a soluble rock mass can change rapidly with time either because of active solutioning caused by ongoing seepage or because seepage is eroding the soft fillings that are usually present in existing solution channels.

- Embankment fill that may appear to be homogeneous from a materials viewpoint always has a horizontal permeability that is four to nine times greater than the vertical permeability because the fill is placed and compacted in horizontal lifts.

- An assumed permeability may not account for potential problems associated with an embankment mass susceptible to cracking and/or internal erosion.

The factors affecting permeability used in seepage analyses for dams can be summarized as follows:

- Degree of saturation of the porous media.

- Particle size and shape, including angularity (well rounded grains versus highly angular grains).

- Soil unit weight.

IV. ANALYSIS: INFORMATION NEEDED FOR ANALYSIS

PERMEABILITY (Continued)

- Particle arrangement or structure. This includes stratification, flocculated structure in clays, high porosity silts and fine sands, and collapsible soils such as loess.

- Gradation of particle sizes. A poorly graded (uniform) sand or gravel is much more pervious than well-graded sand or gravel with the same average (D_{50}) size. The amount and type of fines (material smaller than the No. 200 sieve) strongly affects the permeability of a granular soil. A relatively small percentage of fines can render sands and well-graded gravels effectively impervious.

There are a wide variety of methods to determine permeability that can be broadly classified as empirical methods, laboratory methods, and field methods. The following sections briefly discuss how to determine the permeability for your particular problem.

Empirical Methods

Indirect methods are often used for preliminary analysis and, if tied to site or local data, may result in quite accurate estimates. Indirect methods usually are based on a correlation between permeability and grain size. A typical example is the Hazen equation, which was originally derived for clean, uniform size filter sands:

$$k = 100(D_{10})^2$$

where **k** is in centimeters per second, and $\mathbf{D_{10}}$ is the sieve size opening in centimeters which 10 percent of the sand sample will pass. Another example is an equation developed by the NRCS for estimating the permeability of relatively clean sands and gravels. It is as follows:

$$k = 992(D_{15})^2$$

where **k** is in feet per day and $\mathbf{D_{15}}$ is the sieve size in millimeters, which 15 percent of the sample will pass.

USING OBSERVATIONS

Use the observations and data obtained as suggested in Unit III to evaluate a seepage problem and, if necessary, to select an appropriate remedial action. Or, use the observed data as input for analyses using the various methods previously discussed. Always evaluate problems and solutions for the full range of potential parameters.

In many cases, a seepage problem is relatively simple and evaluating observed data is sufficient to resolve and remedy the problem. An example would be the uplift pressure under a gravity dam. If the uplift pressure, as measured by piezometers, is increasing with time at the same reservoir elevation while measured drain flow is decreasing, it is evident that the efficiency of the foundation drains is deteriorating and they should be cleaned or redrilled. Another example might be seepage problems observed during the initial filling of a reservoir formed by an embankment dam with relief wells spaced at 100-foot centers along the downstream toe in a

IV. ANALYSIS: INFORMATION NEEDED FOR ANALYSIS

USING OBSERVATIONS (Continued)

pervious foundation. Observations indicate that split-well piezometer pressures are higher than anticipated by design calculations, and small pin boils are observed in the relief well collector ditch. The problem here is that the relief wells are too widely spaced, and the remedy is to install intermediate wells.

In other cases, use observations to furnish input data for the various methods of analyzing seepage. All the methods require reasonable assumptions for boundary conditions, and material properties and observations are usually the best source of information for establishing or changing boundaries, or determining the flow paths through a complexly stratified foundation.

One example is locating the phreatic surface and surface of seepage for an embankment dam. In design, the ratio of vertical to horizontal permeability may be misjudged. After several years of operation, visual and piezometer observations can locate the surfaces with considerable accuracy. Or, a finite element computer model can be calibrated and adjusted by using actual pressures obtained from piezometers at the appropriate locations in the element grid.

After the seepage problem is clarified and a remedial action proposed, information is sometimes needed for design and construction. Consideration of potential future needs during your original investigation will minimize cost and time delay in implementing remedial action.

IV. ANALYSIS: ANALYTICAL METHODS

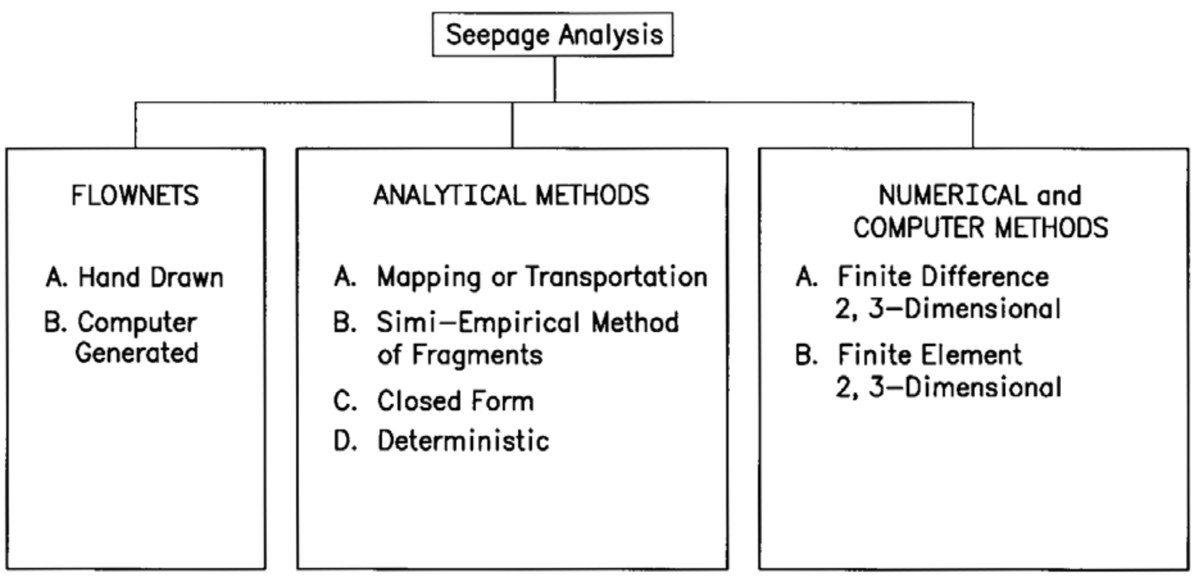
INTRODUCTION

While you may evaluate and solve some seepage problems using observational methods, others may require more detailed analyses to evaluate the problem and determine a solution. The various types of analyses you may use are briefly described below.

SOLVING LAPLACE and DARCY EQUATIONS

Solutions to steady-state, laminar-flow seepage problems can be obtained with the Laplace and Darcy equations. Several methods have been developed to solve these equations exactly or approximately for various seepage cases. A summary of methods is shown in Figure IV-4.

FIGURE IV-4. COMMONLY USED SEEPAGE ANALYSIS METHODS



MATHEMATICAL SOLUTIONS

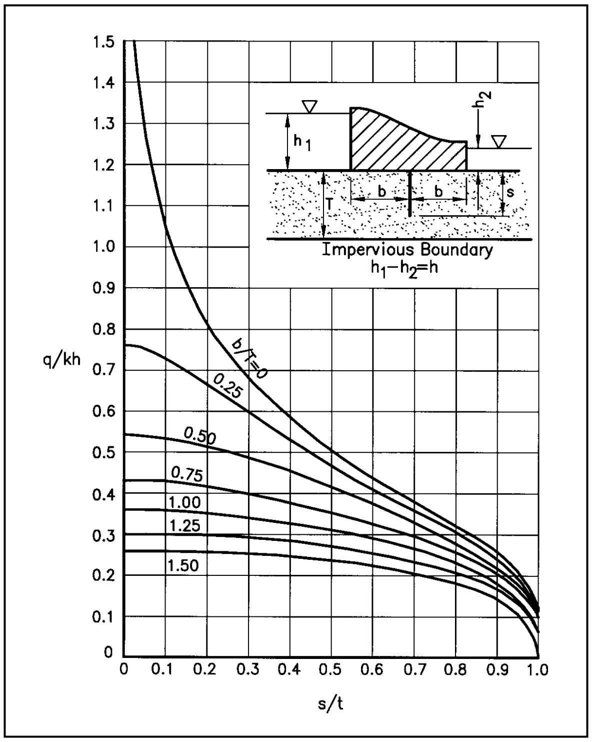
Mathematical solutions to the Laplace equation have long been of interest to mathematicians. There are relatively few closed form (exact) solutions, and these apply to simple problems such as flow to a fully penetrating well from a radial source. There are many approximate solutions using complex variables, various transformation and mapping techniques, methods of fragmentation, etc., that permit solution of a wide variety of problems. Most of these methods are too complex for design engineers. However, many problems and solutions have been reduced to graphical plots that, if available, can provide quick approximate answers. More information on mathematical solutions can be found in Groundwater and Seepage by M.E. Harr.

IV. ANALYSIS: ANALYTICAL METHODS

MATHEMATICAL SOLUTIONS (Continued)

Figure IV-5 shows the plotted solutions that can be used to determine the flow under a concrete weir on a pervious foundation of finite depth using a partially penetrating cutoff.

FIGURE IV-5. IMPERVIOUS STRUCTURE WITH PARTIAL CUTOFF ON LAYER OF FINITE DEPTH



NUMERICAL COMPUTER SOLUTIONS

Computer models are used increasingly to make acceptable approximations for the Laplace equation in complex flow conditions. The two primary methods of numerical solution are finite difference and finite element. Both can be used for two-dimensional and three-dimensional problems and software is available from several sources. Very simple problems can be solved by hand, but more difficult problems require a computer. Both methods use a grid system to divide the flow region into discrete elements. Element intersections are called nodes.

In either system, a series of linear algebraic equations are used to approximate the Laplace equation. In the finite element method, if the grid consists of N elements, there will be N equations in N unknowns to solve. Among the advantages of numerical methods are:

- Either two-dimensional or three-dimensional problems of very complex geometry, including layers and stratification as well as pockets of material, can be modeled.
- Zones where seepage gradients or velocities are high can be more accurately modeled by varying the size of elements.

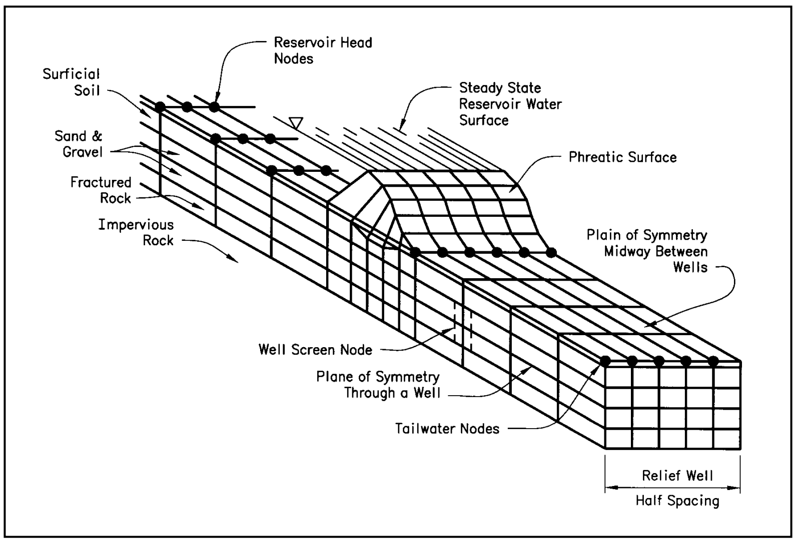
IV. ANALYSIS: ANALYTICAL METHODS

NUMERICAL COMPUTER SOLUTIONS (Continued)

- No transformation of dimensions or properties is necessary.
- Results are printed in digital form for easy plotting of flownets.
- Various programs have options and capability for computing seepage forces and handling transient or time-dependent flow and variable saturations.

Figure IV-6 illustrates the finite element modeling of an embankment on a pervious foundation with a toe drain and relief wells.

FIGURE IV-6. FINITE ELEMENT RELIEF WELL MODEL



The use of numerical computer methods is increasing and will accelerate as the methods are more widely understood. The speed of current computers is such that detailed solutions are obtained rapidly and thus parametric studies to determine the effects and consequences of varying assumptions can be made quickly. As in all analysis, the validity of computer output is dependent on the accuracy and quality of the input data and knowledge of the program user. Numerical models should be calibrated to existing field conditions to ensure that they accurately represent actual conditions. During a calibration process, hydraulic parameters such as permeability will need to be adjusted to obtain output that models observed conditions. Adjustments must be reasonable or the model is erroneous. Other checks on the accuracy of the model include mass balance (mass of flow in the model boundaries versus flow out).

GRAPHICAL FLOWNET CONSTRUCTION

Skill in drawing flownets is developed by practice and looking at completed correct flownets in the literature. Even crudely drawn flownets will provide reasonable estimates of seepage quantities. Much more effort is needed to determine information such as exit gradients with acceptable accuracy. It is important to have a working knowledge of flownet construction and the principles involved to accurately analyze seepage conditions.

IV. ANALYSIS: ANALYTICAL METHODS

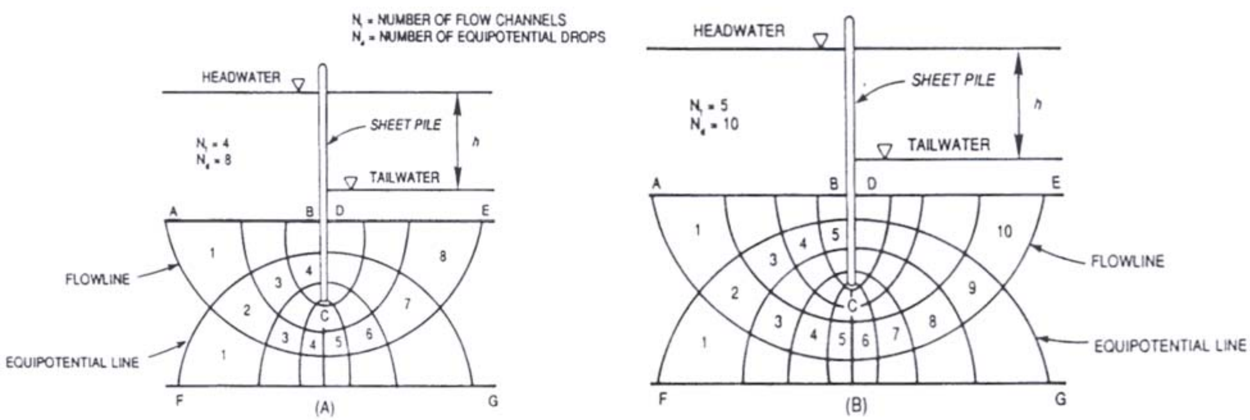
GRAPHICAL FLOWNET CONSTRUCTION (Continued)

Flownets are one of the most useful and accepted methods for solving the Laplace equation. If boundary conditions and geometry of a flow region are known and can be displayed two-dimensionally, a flownet can provide a strong visual sense of what is happening (pressures and flow quantities) in the flow region. A flownet is two sets of orthogonal (intersecting at right angles) curves. One set of curves represents flow paths (flowlines) through the porous media, while curves at right angles to the flow paths show the location of points within the porous media that have the same piezometric head (equipotential lines).

The flownet is a singular solution to a specific seepage condition; in other words, there is only one family of curves that will solve the given geometry and boundary conditions.

Figure IV-7 shows a flownet solution for a simple seepage problem assuming homogeneous isotropic permeability.

FIGURE IV-7. FLOWNET FOR A SHEET PILE WALL IN A PERMEABLE FOUNDATION



A given problem, however, may have more than one flownet that can accurately represent seepage. As in Figure IV-7, different sets of curves may be chosen from the family of curves to define the problem. In Figure IV-7(A), 3 flow lines are used to construct the flownet versus 4 flow lines in Figure IV-7(B). However, the ratio between the number of equipotential drops, N_d, and flow channels, N_f, does not change, with both solutions having a ratio of 2. Hence, estimates of seepage quantity and exit gradients derived from the two flownets are the same for both figures.

To draw a flownet, several basic properties of the seepage problem must be known or assumed:

- The geometry (zoning) of the porous media must be known.
- The boundary conditions must be determined.
- The assumptions required to develop Laplace's equation must hold.
- Anisotropic permeability must be considered.

IV. ANALYSIS: ANALYTICAL METHODS

GRAPHICAL FLOWNET CONSTRUCTION (Continued)

M.E. Harr, Seepage, Drainage, and Flownets by H.R. Cedergren, and Seepage Analysis and Control for Dams by the U.S. Army Corps of Engineers, which are cited in Appendix B, give detailed instructions and many examples of drawing flownets in Groundwater And Seepage. Note that flownets can be drawn for both confined and unconfined flow problems, for conditions of anisotropic permeability, for transient flow, and for composite sections such as stratified foundations and zoned embankments.

Because a flownet is a graphical representation of seepage conditions under given geometry and boundary conditions, it explains how pressures are distributed and where flow is directed. Coupled with knowledge of the hydraulic head imposed, and the permeability of the porous media, the flownet can supply important information about stability and flow quantity. Specific seepage quantities, exit gradients, seepage forces, and uplift pressures can be determined. As an example and referring to Figure IV-7(A), the quantity of flow is:

$$q = \frac{Kh\ N_f}{N_d} = \frac{Kh\ 4}{8} = \frac{Kh}{2}$$

Note that Figure IV-7(B) gives the same solution.

GRAPHICAL CONSTRUCTION OF PHREATIC SURFACE

A procedure is available for graphically constructing a phreatic surface through an embankment cross-section, termed the Casagrande procedure. Seepage Through Dams, by A. Casagrande (see Appendix B) shows the procedure and illustrates its use. Predicting the location of the phreatic surface through an embankment may help assess probable seepage locations.

IV. ANALYSIS: IMPLEMENTING SEEPAGE ANALYSES

INTRODUCTION

Where and when to use each method of analysis is an important consideration. Sometimes a visual inspection is adequate to assess a seepage condition. Other times, more detailed analyses are required.

WHERE AND WHEN TO USE METHODS OF ANALYSIS

Some general considerations when selecting a method of analysis include:

- What point in a dam's history is being considered?
- How complex is the problem?
- What information is available?
- What information can be obtained or is required, and at what cost?
- Is the problem urgent, or is there time for detailed analyses?

Table IV-2 presents example guidelines for using various methods of seepage analysis.

TABLE IV-2. GENERAL GUIDELINES FOR SEEPAGE ANALYSIS

SITUATIONS	TYPICAL INVESTIGATIONS	SUGGESTED ANALYSIS METHODS
Homogeneous embankment, impervious foundation, 2D steady state	Phreatic surface, pore pressure, seepage force (stability)	Graphical (Casagrande) or flownets
Zoned embankment, impervious foundation, 2D steady state	Phreatic surface, pore pressure, seepage force (stability)	Flownet or numerical model
Homogeneous embankment, uniform pervious foundation, 2D steady state	Phreatic surface, pore pressure, seepage force (stability)	Flownet
	Exit gradient, seepage quantity	Method of fragments (see Harr's Mechanics of Particulate Media (Appendix B))
	Seepage control alternatives, material properties variations	Numerical model
Zoned embankment, pervious foundation, 2D steady state	Same as above	Numerical model

IV. ANALYSIS: IMPLEMENTING SEEPAGE ANALYSES

WHERE AND WHEN TO USE METHODS OF ANALYSIS (Continued)

TABLE IV-2. GENERAL GUIDELINES FOR SEEPAGE ANALYSIS (Continued)

SITUATIONS	TYPICAL INVESTIGATIONS	SUGGESTED METHODS
Situations involving relief wells, heterogeneous foundation, quasi-3D steady state	Phreatic surface, pore pressure reduction, exit gradient, seepage quantity, seepage control alternative, material properties variation, relief well spacing, and flow	Numerical model
Situations involving relief wells, uniform foundation, quasi-3D steady state	Relief well spacing, pressure reduction, and flow	Equations (see Design, Construction and Maintenance of Relief Wells, U.S. Army Corps of Engineers, EM 1110-2-1914 (Appendix B))
Uniform pervious abutment, 3D steady state	Phreatic surface, seepage quantity	Plan flownet
Heterogeneous pervious foundation and abutments, 3D steady state	Phreatic surface, seepage quantity, exit gradient, materials, and control alternatives	Numerical model
2D transient flow, steady boundary conditions	Tracking saturation, time to steady state	Transient flownets
Situations involving nonsteady 2D flow, saturated/unsaturated, zone or homogeneous embankment, heterogeneous foundation, transient boundary conditions, 2D transient state	First fill, flood cycle, cyclic operation, moisture content and pore pressure changes, precipitation and evaporation effects	Numerical model (See Introduction to Groundwater Modeling, Wang, Herbert F., Anderson, Mary P.)

Not all potential situations that may arise are covered in Table IV-2. You may need to use your own judgment and seek the advice of qualified specialists. In general, analytical methods are used for design. Once a dam is constructed observations become more important as problems develop and information is gathered. The observations reveal true conditions compared to assumptions made during design, which may be in considerable error. Consequently, in solving known seepage problems either the observational method is used or analytical methods are refined based on input from observations.

IV. ANALYSIS: IMPLEMENTING SEEPAGE ANALYSES

WHERE AND WHEN TO USE METHODS OF ANALYSIS (Continued)

In most cases it is logical to start with the simplest and least expensive method and then proceed to more complex and costly methods as the complexity of the problem becomes apparent or the need for accuracy is evident. In seepage analysis, pinpoint accuracy is seldom obtained and, consequently, most remedial measures are conservatively designed. For example, if minor shallow seepage is emerging along the toe of a dam where relief wells are providing relief for deep-seated pressure, then the design of a shallow toe drain based on observed flows and a generous pipe size is likely adequate, and a finite element computer model is not needed.

If time is of the essence (in other words, the problem appears to be headed for a catastrophic conclusion), then a quick review of available information and an experienced judgment "analysis" is in order.

As a final consideration, no analysis is better than the adequacy and quality of the necessary input on boundaries and material properties. If information is limited, then a few simplified flownet sketches will serve just as well as a numerical computer model based on vague assumptions. In addition, the cost of a conservative remedial design is often less than the cost of detailed explorations and analyses.

CONDUCTING ANALYSES

The analysis and resolution of seepage problems generally rely heavily on the judgment of qualified geotechnical engineers and engineering geologists. Experience and knowledge of geologic and material factors, design principles, and the principles of fluid flow through porous media are more critical in most cases than the method of analysis. Consequently, it is desirable that qualified people at least guide and review the work.

APPLICATION OF RESULTS

The objectives of seepage analysis are to determine whether or not an observed or perceived problem is serious and represents an unacceptable risk and, if so, to develop effective remedial action at a reasonable cost. The current philosophy of dam safety generally embraces the idea that seepage should be controlled by redundant defenses to ensure safety.

The next unit provides information on remedial treatments, which must be designed in a rational manner. The rational manner may vary from a very simple application of Darcy's law to a complex numerical computer model. Selecting the best approach is judgmental, and both site specific and problem specific. Generally, as the hazard imposed by the problem or the cost of remedial action increases, more sophisticated investigation and design analyses may be warranted. However, in most cases obtaining adequate, accurate data from existing sources or additional field investigation is more important than the sophistication of the analysis.

IV. ANALYSIS: SUMMARY

SUMMARY: ANALYSIS OF SEEPAGE CONDITIONS

Unit IV described:

- The basis for seepage analysis.
- Information needed for seepage analysis.
- The observational methods of analysis.
- The analytical methods of analysis.
- How to implement methods of seepage analysis.

Basis for Seepage Analysis

The logical analysis of seepage started with the development of Darcy's law in 1856 and the realization that the Laplace equation governing heat and current flow conduction was also applicable to the steady-state flow of an incompressible fluid through porous media. Darcy's law and the Laplace equation are both used in the analysis of seepage conditions today with the aid of computers.

Information Needed for Seepage Analysis

The information needed to analyze seepage conditions includes:

- The location of various boundaries and flow paths to define the particular porous media mass considered in the analysis.

- Type of flow (whether the flow is laminar or turbulent).

- Permeability of the various materials through which the seepage flows.

Observational Methods of Seepage Analysis

The observational method of seepage analysis involves visually inspecting the area of seepage, the surrounding conditions and all potentially related factors. Observations can include taking readings from instrumentation, such as piezometers. Observations can be used to directly evaluate a seepage problem and, if necessary, select a remedial action, or to furnish input data for other methods of seepage analysis.

Analytical Methods of Seepage Analysis

Solutions to steady-state, laminar-flow seepage problems based on the Laplace equation rely on mathematical solutions, or numerical computer solutions to the finite difference equation for three or two-dimensional flow. Darcy’s law can be solved directly if the hydraulic gradient and Darcy permeability are known. Flownets may also be used to solve two-dimensional flow based on the known geometry of the structure and underlying strata.

Generally, analytical methods are used for design because observational data are not available

IV. ANALYSIS: SUMMARY

Analytical Methods of Seepage Analysis (Continued)

until the dam is constructed. Observations become more important as problems develop and information is gathered on an existing dam's performance.

Unit V

Remedial Action

V. REMEDIAL ACTION: OVERVIEW

INTRODUCTION

Once you have evaluated and assessed the seriousness of a seepage condition, you must determine how to treat the seepage condition. In situations where the seepage is not serious, you may only need to monitor the seepage for changes in flow quantity or sediment load. However, in situations where the seepage is serious or even an emergency, you must take immediate action.

GENERAL CONSIDERATIONS

Based on the experiences of historic dam failures resulting from uncontrolled seepage, the current trend of both initial design and remedial action is to provide multiple defenses against seepage. This trend is based on increasing awareness that circumstances and conditions may change and hidden defects in the dam and its foundation may not become evident for many years. Some of the factors to consider are:

- Undetected geologic anomalies at the site.
- Hidden mistakes from design and construction.
- Large unprecedented seismic or climatic events.
- Deterioration of one or more seepage control features.
- Changes in project purposes and operation.
- Changes in downstream hazard.
- Experiences at other similar type dams.

Seepage control measures can be broadly categorized as either seepage barriers or exit and drainage controls. The intent of seepage barriers is to reduce seepage and reduce the hydraulic gradient causing seepage, while the intent of exit and drainage controls is to provide safe discharge of seepage. Barriers are seldom perfect, and exit or drain controls may increase the flow of seepage. In most cases, water barriers and filters/drains are used together. As an example, a grout curtain under a concrete gravity dam is nearly always followed by a curtain of drain holes and drain gallery located immediately downstream of the grout curtain.

Seepage control measures are usually conservatively designed because seepage analysis is seldom accurate. The estimates of flow volume may be off by an order of magnitude or more. Designs often incorporate a safety factor of 2 orders of magnitude for flow quantities.

V. REMEDIAL ACTION: OVERVIEW

GENERAL CONSIDERATIONS (Continued)

Remember that in the design of remedial measures there is continuing change, as new case histories are published and the state-of-the-art advances. Examples include:

- The use of geotextiles (geofilters and geomembranes) in remedial work.
- Improved techniques to install concrete cutoff walls through embankments and foundations.
- Improved grouting techniques and materials, such as the use of increased pressure, computer controls, and micro-fine cement plus a wide variety of grout additives.
- Automated monitoring systems.

This unit describes emergency and temporary as well as permanent seepage control measures.

V. REMEDIAL ACTION: EMERGENCY AND TEMPORARY SEEPAGE MEASURES

INTRODUCTION

Catastrophic failure of a dam occurs when the reservoir water suddenly breaks through or breaches the dam and surges downstream as a rampaging flood wave. A very sudden, unexpected failure of a dam generally will not occur if:

- The project has been properly designed, constructed, and maintained;
- Inspections by qualified personnel are routinely performed;
- An adequate amount of instrumentation is installed, monitored, and evaluated on a timely basis; and
- Dam safety-oriented repairs are made as conditions dictate.

However, in many instances, all these conditions may not have been met and it may become necessary to perform emergency actions in an attempt to prevent catastrophic failure.

In an emergency situation, various individuals may be involved in the decision-making process. Decisions must be made rapidly using the mature judgment of the most experienced and qualified people available. It is preferable to plan for such decision-making in advance. This section describes various emergency seepage conditions that may be detected and some of the remedial actions to take to help alleviate the adverse conditions. In general, the remedial method selected will depend on the time required for implementation, available materials, serviceability, and cost. Hence, each method discussed may not always be suited for a particular problem.

SIGNS OF DISTRESS AND REMEDIAL MEASURES

As previously discussed, there are four primary modes of failure resulting from uncontrolled seepage: piping, internal erosion, solutioning of soluble rock, and instability (sliding, uplift) due to seepage pressures. Piping is normally associated with observable conditions such as muddy seepage water, sinkholes, and sand boils. The most serious concerns are for internal (seepage) erosion or piping within or between a dam and its foundation when the signs of distress are often hidden until severe internal damage has occurred. Whirlpools in the reservoir or sinkholes on the dam surface are signs that piping or internal erosion is progressing very rapidly.

Solutioning of soluble rock can go unnoticed for a long time, and when sinkholes or other expressions occur, quick remedial action may be needed to prevent a catastrophic failure.

Pressure-related seepage problems are normally associated with loss of strength and signs of instability such as wet, spongy, green vegetated areas, or soft areas on embankment slopes or near the toe of the dam, evidence of bulging or heaving, evidence of cracks, slides, or scarps indicating slope instability, etc. Frequent field inspections and analysis and review of instrumentation data can be valuable in the early detection of seepage conditions that could lead to failure.

V. REMEDIAL ACTION: EMERGENCY AND TEMPORARY SEEPAGE MEASURES

SIGNS OF DISTRESS AND REMEDIAL MEASURES (Continued)

Not all distress will lead to rapid failure of a structure. However, many seemingly insignificant events, if not corrected, may quickly deteriorate to a critical condition that requires emergency action.

Generally, there are two major procedures for quickly alleviating a seepage problem:

- Reduce the hydraulic head and pressure causing the problem (reservoir drawdown).
- Control the exits of the seepage.

Reduce the Hydraulic Head and Pressure

One of the first considerations in an emergency situation is to lower the reservoir or restrict reservoir levels in order to stop or reduce seepage and its effects. Lowering the reservoir reduces the hydraulic head producing the seepage and will have an immediate impact on serious seepage problems. For this reason, outlet works and other control structures should always operate properly. Current practice is to consider the need for emergency drawdown in sizing the capacity of outlet work facilities. For existing dams, the drawdown capability and downstream consequences of large releases should be considered. In some cases, pumps or siphons have been used to lower a reservoir.

If the reservoir cannot be lowered fast enough through outlet works or other control structures, a "controlled" breach of an earth dam can be accomplished to speed the reservoir-lowering process. The controlled breach should be in a location that would produce the least damage downstream from the released reservoir water. It is important to remember that a controlled breach is a dangerous operation that can quickly get out of control and lead to catastrophic failure. Potential risks associated with a controlled breach include unexpected floods and uncontrollable erosion.

When deciding whether to lower the reservoir, consider these factors:

- The effects on the purpose(s) of the project (municipal water supply, power generation, etc.).
- The potential for instability of the upstream slope from rapid drawdown.
- The potential damage or loss of life downstream because of higher than normal discharges through the control works.

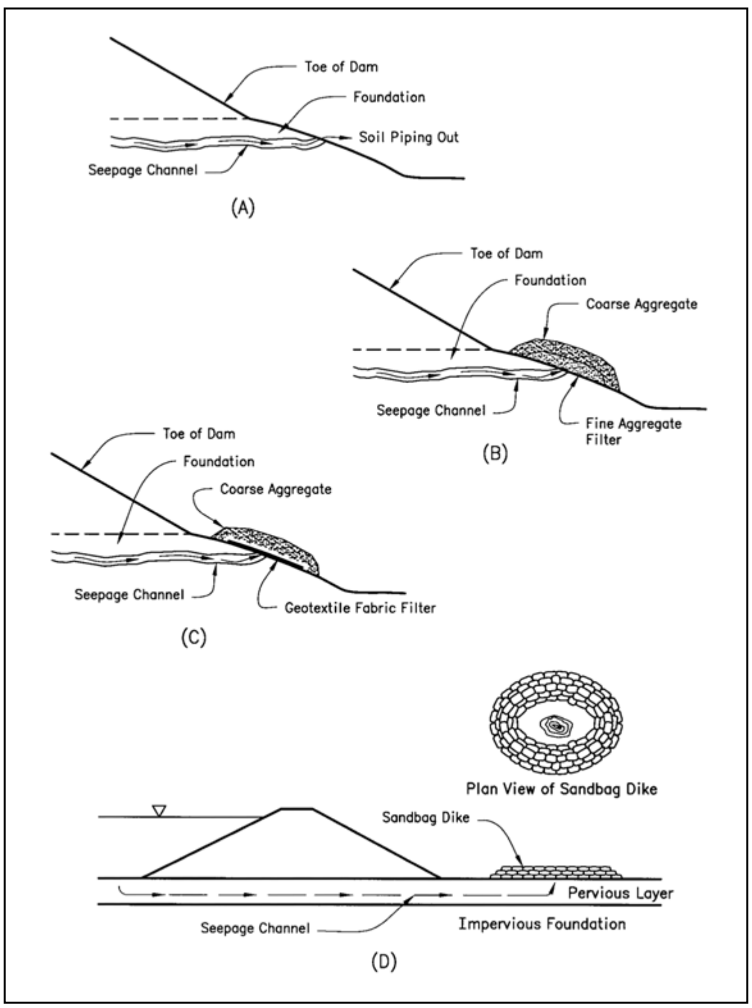
However, these factors may be of secondary importance if dam failure is imminent and it is already known that failure would result in loss of life and extensive property damage!

V. REMEDIAL ACTION: EMERGENCY AND TEMPORARY SEEPAGE MEASURES

Control the Seepage Exits

Constructing sandbag or other types of ring dikes around sand boils can be used to control the seepage exit. The dike allows the development of a pool or head of water to backpressure the boil, thus decreasing the net head and upward flow of water, and reducing the loss of material. Seepage exits can often be controlled with a weighted filter constructed by placing a layer of filter material over the seepage exit and overlaying that with pervious drainage material. A geotextile can be substituted as the filter material. These procedures are depicted in Figure V-1. If relief wells or standpipe piezometers are nearby, they can be pumped to reduce the uplift pressure. These emergency measures should be carefully monitored until permanent solutions are constructed. Standby personnel, equipment, and filter/drain material should be readily available, because the exit may shift to an unprotected location. Readily available concrete sand is a very good filter/drain material for emergency use.

FIGURE V-1. EMERGENCY MEASURES TO TEMPORARILY CONTROL PIPING BELOW DAMS



V. REMEDIAL ACTION: EMERGENCY AND TEMPORARY SEEPAGE MEASURES

EMERGENCY SITUATIONS AND REMEDIAL ACTIONS

Listed below are signs of distress relating to uncontrolled seepage and potential remedial actions that may be taken. The list is not all-inclusive. Remember that recommendations or actual remedial actions must be site specific.

- **Whirlpool in the reservoir in the vicinity of the dam.**

  A whirlpool is the most serious condition that can be observed because it is caused by flow through a large channel in or under the dam that will likely enlarge until the dam is breached. Initiation of the Emergency Action Plan (EAP) to begin evacuation should be undertaken immediately. The reservoir should be lowered as rapidly as possible. Attempt to plug the entrance of the whirlpool with riprap or large stone. If the plug attempt decreases the flow, add progressively smaller material such as gravel, sand, etc. Locate the exit point downstream and attempt to construct a ring dike or filter berm to retard the removal of material.

- **Boils.**

  The seriousness of sand boil activity will vary (see Appendix D). If small pin boils are flowing clear water with no apparent increase in flow over time, the area should be closely monitored and remedial measures probably need not be initiated unless subsequent investigation and analyses indicate the need.

  If the flow rate from the boils increases over time or over yearly annual cycles for similar reservoir levels, if the flow becomes turbid, or if additional boils develop, sandbag the area to form a ring dike or provide a filtered drainage berm and consider lowering the reservoir. If the boils rapidly increase in size, in flow rate, and in aerial extent with muddy discharge water, the dam could be in imminent danger of failure. Immediately implement the EAP and begin lowering the reservoir. Utilize all available equipment and supplies in constructing a large ring dike around the boil areas, or construct a filtered drainage berm over the boil area.

- **Sinkholes.**

  If sinkholes are observed on the embankment or downstream from the dam with no indication of seepage flow, the area should be closely monitored until detailed investigation and analyses can be performed and the cause is determined (see Appendix D). Sinkholes are evidence of active piping and the reservoir should be immediately lowered.

  If the sinkholes exhibit underlying seepage flow or increase in size or number, consider filling the holes with graded material. Sinkholes that appear in the reservoir floor or rim upstream from the dam represent seepage entrance locations. Unless the reservoir is drawn down periodically, these may not be detected. They should be filled with an impervious material to seal the entry, and the area carefully monitored thereafter. Investigation and analysis should be undertaken to determine the need for a more permanent solution.

V. REMEDIAL ACTION: EMERGENCY AND TEMPORARY SEEPAGE MEASURES

EMERGENCY SITUATIONS AND REMEDIAL ACTIONS (Continued)

- **Seepage.**

  Seepage occurs at practically every dam. The location and description will vary at each site and remedial measures will also vary. Seepage does not necessarily imply the dam is in danger of failure. However, all observed seepage conditions should be thoroughly investigated and analyzed by qualified individuals. Remember, seemingly insignificant events, if not corrected, may rapidly deteriorate to a very critical situation.

V. REMEDIAL ACTION: PERMANENT SEEPAGE MEASURES

INTRODUCTION

In this section, assume that a seepage problem with an existing dam has been identified, investigated, analyzed, and that some type of remedial action is deemed necessary. Also assume that the seepage problem is not an imminent threat to the safety of the dam and sufficient time is available to design and construct a permanent remedial measure.

Because seepage is often difficult to evaluate, the precise location and extent of remedial control may be difficult to define. Therefore, it is necessary to monitor the "fix" to see if it achieves its objective. In fact, the design of the remedial measure should be flexible to permit change as construction reveals actual conditions, or monitoring indicates the need to supplement the remedy.

Remedial action can range from continued or additional monitoring to the extremes of substantially rebuilding or decommissioning and removing the dam. Factors affecting the type of treatment needed include:

- Geological/Geotechnical environment
- Risk
- Amount of correction required
- Feasibility of correction
- Failure of prior remedies

When determining the appropriate remedial action, consider how the action might affect other aspects of the project. For example, could excavation for drains, cutoff trenches, or slurry trenches result in instability?

The various methods of seepage control currently in use for the design and construction of new dams were described in Unit II. The remainder of this module will discuss the primary considerations in the choice of remedial measures for existing dams. Some of the seepage control devices discussed in Unit II would not apply as remedial action for existing dams. For example, it may not be practical or economical to remove a major portion of an existing embankment to construct an inclined or horizontal drain blanket. However, other measures can be incorporated into an existing dam. Selection of the correct alternative should be left up to an engineering firm with extensive experience in dam remediation, and extensive knowledge of the site-specific conditions. The remedial actions described in this section include:

- Monitoring
- Lowering the reservoir and restricting reservoir level
- Grouting
- Cutoff walls (concrete, soil-bentonite)
- Upstream impervious blankets
- Downstream berm
- Drainage
- Combined treatments

V. REMEDIAL ACTION: PERMANENT SEEPAGE MEASURES

INTRODUCTION (Continued)

Permanent remedial measures to control seepage must consider the type of dam, foundation, and abutments as a unit. As pointed out for emergency and temporary seepage control measures, examples given here for permanent remedial measures are for general guidance only. Actual measures to employ are necessarily dependent on site-specific conditions and depend on dam and foundation characteristics, reservoir use, and operating history. Most of the remedies can be adapted to either embankment or concrete dams if found to be suitable to your specific situation.

MONITORING

In all cases, monitoring seepage is essential, and in some instances may be the only action necessary.

Monitoring seepage and seepage control measures can lead to a rational conclusion with a minimum of expenditure. The most common and easiest monitoring is simply to rely on visual observations and inspections at various intervals and reservoir elevations. Periodic photographing and videotaping of potential distressed areas can provide valuable documentation. If the latter monitoring methods are used, it is vital that the camera always be in the same position to permit easy interpretation.

If not already accomplished during construction, a common recommendation may be to install instrumentation such as piezometers, observation wells, and seepage collection systems to determine more definite patterns of seepage behavior.

Review the data on a regular basis to detect any major seepage changes and long-range trends. If monitoring indicates that a potentially dangerous seepage problem may exist, consider permanent structural or regulatory measures (i.e. permanent reservoir level restriction).

If monitoring is selected as a remedial measure, it may also be desirable to consider automated instruments with predetermined criteria or values to flag undesirable behavior.

LOWERING THE RESERVOIR

The most direct method to reduce or stop seepage is to lower the reservoir and restrict the reservoir level. Lowering and restriction of the reservoir level may not, however, be an acceptable permanent solution. Flood inflows may cause the reservoir to rise above restricted levels, and the benefits of the project will probably be greatly diminished or lost altogether.

If this alternative is selected, care should be taken to lower the reservoir at such a rate so as to prevent possible flooding downstream and also to reduce the risk of an upstream slope failure from rapid drawdown.

V. REMEDIAL ACTION: PERMANENT SEEPAGE MEASURES

GROUTING

Grouting is often attempted as a means of controlling seepage through soluble rocks. However, this method frequently is not successful or is only temporarily successful because the solution passages usually are partially filled with residual clay or other material that erodes when subjected to changed seepage forces. If one passage is plugged with grout, the seepage often finds another passage around the plug. Therefore, more aggressive methods may be required to ensure permanent and reliable seepage control in soluble rock. These seepage control methods require careful analysis on a case-by-case basis. In current practice, more use is being made of positive remedies such as concrete cutoff walls at the dam centerline.

Pressure grouting using a mixture of cement and water or other materials is probably the most frequently used method to remedy serious foundation or abutment seepage problems in rock. However, it should not be used indiscriminately. Before any grouting effort, conduct an investigation to determine the seepage conditions and locations. The investigation may include:

- Installing weirs or flumes to measure seepage quantity and monitor any particle movement.
- Drilling and sampling to determine rock type and joint and crack size and orientation.
- Conducting pump tests or pressure tests in drill holes to provide data on permeability, flow quantities, and lateral extent.
- Installing and monitoring piezometers or observation wells to measure water levels and pressures.
- Putting tracer dyes in the reservoir or drill holes to pinpoint locations of seepage.
- Using geophysical-type tests to determine material properties and flow patterns.
- Conducting a pilot grouting program to determine eventual grout quantities, mixes, pressures, and set times.

If grouting is feasible, the investigation will help to determine the type of grout mix best suited for the site. The type of grout may consist of solids suspended in water such as cement, bentonite, or chemical grouts.

Because of limitations of cement grouts to penetrate small joints or cracks and medium-grained to fine-grained soils, micro-fine cement or chemical grouts may be considered, although they are quite expensive. When using cement grout, the chemical composition of seepage water and its effect on the type of cement used must be considered. For example, sulfate-laden water will attack ordinary cement and the grout curtain will deteriorate.

There are many different types of chemical grouts. Choose the type of grout based on characteristics of the material being grouted, such as permeability, void size, continuity of voids, and the overall effect on the environment.

V. REMEDIAL ACTION: PERMANENT SEEPAGE MEASURES

GROUTING (Continued)

Because of the many variables in grouting, it is beneficial to consult qualified engineers, contractors, geologists, and inspectors. Excessive pressures, for example, may damage the dam or foundation. Possible damage could include clogging of drains or cracking of impervious cores or other impermeable areas of the embankment, foundation, or abutments. When grouting against reservoir head, grout may flow downstream, blocking seepage exits and causing excessive uplift. Also, drilling in or through an embankment using drilling fluid can result in hydraulic fracturing of the dam raising the risk of internal erosion. Always plot a profile of grout take quantities to locate more pervious zones for supplemental grouting.

In many instances, additional instrumentation should be placed to monitor changes and to evaluate the effectiveness of grouting. Post-grout drilling and testing may be required to determine if the grout has thoroughly penetrated the desired area, and if the water losses have been reduced from the pre-grout values. Grout curtains may not be permanent, particularly in soluble rock where continuing dissolution or erosion of fillings in solution channels can gradually bypass the curtain. Consider permanence and potential cost of repair when selecting grouting as a remedy. Continually monitor the effectiveness of the grout curtain as it is often necessary to grout again after a period of years.

CUTOFF WALLS

Cutoff walls are uniquely suited to remedy seepage through an existing embankment. The cutoff can be extended to remedy foundation and abutment seepage problems as well. However, cutoff walls are extremely costly and thus are usually considered only as a last resort.

Use caution when designing a cutoff wall for an embankment. The wall should be located as far upstream as possible because uplift pressures will increase upstream of the wall. If a slurry trench is chosen for a particular cutoff design, consider these major factors:

- The effect on the stability of the embankment due to excavation of a long slurry-filled trench, and the introduction of a plane of weakness through the dam (in the case of soil-bentonite backfill). A cement-bentonite or concrete backfill may be placed in panels in separately excavated elements rather than in an open trench. Relatively weak soil-bentonite backfill may be unacceptable.

- The possibility of cracking of the wall if the completed wall is not sufficiently plastic.

- The ability to tie the slurry trench to other existing or proposed seepage control measures. If a competent upstream blanket exists, the trench may be tied to the blanket or it may be placed through the dam and tied to the impervious core.

- The need for and impacts of lowering the reservoir during construction.

- The ability to tie the cutoff wall into existing facilities, such as outlet works, penstocks, or spillways.

- The need to treat panel joints to assure water-tightness between adjacent elements.

V. REMEDIAL ACTION: PERMANENT SEEPAGE MEASURES

CUTOFF WALLS (Continued)

- The need to remove the top portion of the dam to provide construction width.
- The need for adequate penetration into a relatively impervious boundary.
- The careful removal of suspended sand, gravel, etc., that falls to the bottom of the trench or panel.

The following techniques may be used for installing slurry walls, depending on site conditions:

- "Trench" method using a backhoe, dragline, clamshell, or similar equipment.
- "Ditch" method using a rapid-excavating ditching machine with multiple rotating buckets.
- Employing rock-milling machines to excavate panels into earth or rock materials.
- Jet grouting method using pressure jetting of slurry through ports in a drill rod.
- “Secant” wall using overlapping large diameter drills and concrete backfill.

Most slurry-type cutoffs are constructed by specialized contractors and require close inspection. Additional instrumentation may be required to evaluate the effectiveness of the cutoff. Because slurry-type cutoffs are not visible for inspection, very careful construction control is essential to ensure proper alignment and continuity of the cutoff wall.

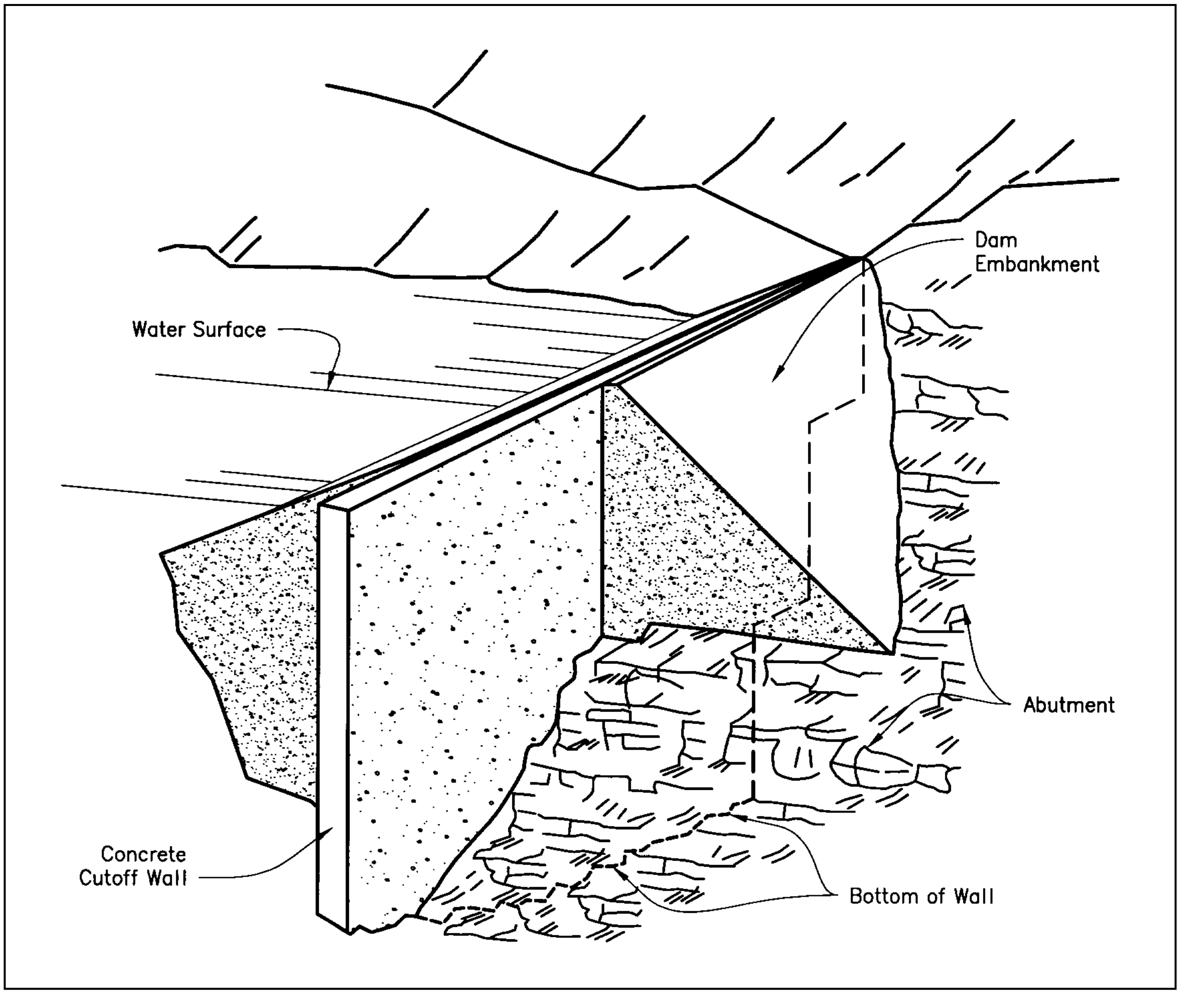
Other techniques for building cutoff walls include drilling a line of overlapping holes backfilled with concrete (secant piles), constructing mixed-in-place walls using overlapping auger holes, and installing steel, concrete, or vinyl sheet piles.

At an earth embankment dam in New Mexico, a combination of seepage, jointed rock foundation and abutments, and core materials prone to erosion were considered as major factors that could potentially result in failure of the dam. A concrete cutoff wall was installed to an unprecedented depth of 410 feet, utilizing a customized rock-mill excavator. Figure V-2 illustrates this type of cutoff wall.

V. REMEDIAL ACTION: PERMANENT SEEPAGE MEASURES

CUTOFF WALLS (Continued)

FIGURE V-2. CONCRETE CUTOFF WALL



For dams with dispersive clay cores on fractured rock foundations, a thin layer of lime-treated clay placed directly on the rock should aid in preventing the clay from washing into small cracks in the rock. The lime treatment makes the clay non-dispersive. For new dams, rigorous treatment of all fractures and cracks with slush grout and dental concrete is imperative and should be combined with downstream filters as a second means of defense. Recent research has shown that sand filters with an average D_{15} size of 0.5 mm will also safely control and seal concentrated leaks through the great majority of dispersive clays. (In a mechanical gradation analysis, the D_{15} size of a material is the sieve size, which 15 percent of the material would pass.)

Where the original design and construction did not include such defensive measures, seepage in dispersive clays can be very serious. While surface erosion problems can be fixed, if inadequate filters or foundation treatment were not incorporated in the structure, ensuring the safety of the dam against seepage problems can be difficult and expensive. Adding an inclined drain to an existing embankment is expensive but may be the only viable alternative for this problem.

V. REMEDIAL ACTION: PERMANENT SEEPAGE MEASURES

UPSTREAM IMPERVIOUS BLANKETS

An impervious blanket immediately upstream of a dam can be used to seal the reservoir bottom and sides and thereby reduce seepage quantities and pressures beneath a dam. If the dam contains a permeable shell, the impervious blanket must be extended up the embankment slope to effectively control the seepage problem.

Mechanical or manmade liners may be used, but have some disadvantages. Besides being expensive, they require a relatively smooth surface for placement, and must be protected from puncture and sometimes from UV rays from sunlight. Also, careful and proper seaming of the sections is necessary during placement; otherwise, appreciable seepage may still occur.

If blankets will be exposed by pool fluctuation, they must be protected against erosion from wave action and runoff, from desiccation or drying and cracking, from mechanical damage, and from piping into coarse granular or fractured rock subgrades.

DOWNSTREAM BERM

A downstream berm can be used as a remedial treatment against seepage forces and uplift pressures on the downstream face of the dam. A berm may prevent blowout by increasing the overlying weight sufficiently to resist the uplift pressures. If the berm is of low permeability, the seepage will be forced to exit further downstream.

The design of a pervious berm should ensure there is no upward migration of fine particles from the foundation. This implies filter compatibility between the berm and the foundation. An added advantage of a downstream berm is to increase slope stability because of the additional resistance to sliding provided by the berm.

In some cases, it may be necessary to add on to the downstream side of the dam using impervious elements, filter and drainage chimneys and blankets, and an outer stability shell. These cases include:

- Where the downstream slope is steep and unstable because of seepage through the dam.
- Where the dam has serious transverse cracking.
- Where dispersive soils were used in fill construction.
- Where the embankment was not properly zoned.

While these measures may be expensive, they are generally less expensive than building a new dam.

V. REMEDIAL ACTION: PERMANENT SEEPAGE MEASURES

DRAINAGE

Drainage can also be used as a treatment to control seepage. Generally, the work can be performed from the downstream side of the dam. For concrete dams with galleries, the work can be performed from inside the dam and often with a full reservoir. Drainage methods usually are in the form of:

- Trenches
- Pervious blankets or berms
- Relief wells
- Drain holes
- Drainage tunnels or adits

If seepage or uplift pressures become a problem in concrete dams, additional drainage may be added from existing tunnels or galleries. Drain holes are often used in foundations of concrete dams where they can be placed downstream of a grout curtain and drilled from a gallery, or slant-drilled into abutments.

Relief wells at the downstream toe of a dam are highly effective in relieving excessive uplift and potential piping forces. As compared to cutoffs, relief wells and most other drainage systems may marginally increase the loss of reservoir water. Relief well discharge requires proper handling.

When designing drainage systems, remember these important principles:

- The drain must provide an easy exit for seepage so that the pressure is relieved and not forced elsewhere.
- The drain must be properly filtered so that piping of adjacent material into the drain does not occur.
- The drain must have adequate capacity to handle the seepage volume anticipated from maximum reservoir elevations.
- The drain(s) must be properly spaced and of sufficient depth to relieve pressure over the necessary area and volume of material.
- Drains fine enough to filter particles being eroded through cracks can become plugged with fines or mineral deposits.
- Drains must be deep enough to penetrate confined aquifers.

V. REMEDIAL ACTION: PERMANENT SEEPAGE MEASURES

DRAINAGE (Continued)

In several recent cases, drainage tunnels or adits have been excavated into the downstream abutments of embankment dams to control seepage through the abutments. The seepage then exits from the tunnel or adit rather than into the downstream embankment drains. Another use has been to divert seepage away from poorly prepared contacts between fractured foundation rock and embankment materials prone to erosion. In each of these cases, a number of precisely drilled drain holes at various orientations have been installed from the tunnels to increase the effectiveness of control.

Some of the limitations of various drainage methods are listed below.

- While toe (or trench) drains are most effective in drying up wet surface areas or disposing of seepage collected by drainage blankets, it is seldom practical to trench sufficiently deep to control deep seepage or seepage in a stratified foundation.

- Relief wells are effective in controlling deep seepage in stratified foundations but are ineffective in mopping up shallow seepage.

- Inclined drains on slopes or abutments or inside dams or berms are susceptible to contamination from construction activity or slope wash, which causes siltation and reduces their capacity. They should always slope down from the high phreatic level to the low level or exit.

- Horizontal blankets, because of the low gradients available, must be relatively pervious to have acceptable flow capacity. As a consequence, they must often be multi-layered to provide both the filter action and discharge capacity. Perforated pipes are frequently added to provide capacity.

All drain systems are subject to deterioration. Monitor all drain systems and either repair or replace them, as necessary, to maintain adequate efficiency.

COMBINED MEASURES

In many instances, more than one method of seepage control may be used. Often, it is necessary to use multiple lines of defense to control seepage and to ensure a safe dam project with regard to seepage.

V. REMEDIAL ACTION: ANALYSIS FOR DESIGN

INTRODUCTION

For the most part, the methods of analysis of seepage problems as presented in Unit IV are the methods used in the design of remedial control measures. Certainly the principles are the same, and the use of Darcy's law and various methods for solving the Laplace equation must be thoroughly understood. In addition, the accuracy and adequacy of input data concerning boundaries, flow paths, and material properties is essential for effective, economical remedial design. In some cases, design will require additional investigation and observations beyond that required for analyzing the seepage problems.

GENERAL AND SPECIAL CONSIDERATIONS

As previously noted, seepage control should include multiple defensive measures. Consequently, it is desirable if the model used for analyzing the seepage problem can be modified to allow the assessment of various remedial measures either singly or in combination. Generally, the graphical flownet methods and the numerical computer models can be modified to evaluate a variety of alternatives. The numerical computer models are particularly adaptable to evaluating combined effects.

The observational method in combination with experienced judgment is often used to design remedial measures. The primary handicap, of course, is that the observations won't reflect the influence of a remedial measure until the measure is in place and operating. However, in very complex problems such as a highly stratified and lenticular foundation, remedial measures are often installed in increments or stages with observations providing the primary guidance on spacing of relief wells and the spacing and orientation of drain holes or the holes used to install a grout curtain.

Darcy's law, with suitable modification or manipulation, can be used effectively to design inclined, blanket, and other drains for both dimensions and permeability of materials required. Seepage, Drainage, and Flownets by H.R. Cedergren provides many design examples. Criteria for filter actions are covered in several of the references listed in Appendix B, but particularly in the U.S. Army Corps of Engineers publication Seepage Analysis and Control for Dams.

In addition to the general methods of analysis presented in Unit IV, there have been many studies and analyses of various seepage control measures that have been reduced to special formulas, tabulations, or graphs that will expedite design. These design aids are scattered throughout the technical literature. Many examples and references can be found in Cedergren's publication, as well as the U.S. Bureau of Reclamation's Design Standard No. 13, Embankment Dams, and the U.S. Army Corps of Engineers publication Seepage Analysis and Control for Dams. In particular, such special studies are available for the design of partial cutoffs, relief wells, toe drains, upstream blankets, and various downstream blankets and berms.

V. REMEDIAL ACTION: SUMMARY

SUMMARY: REMEDIAL ACTION

Unit V provided general considerations for selecting remedial actions to alleviate seepage conditions. This unit also described emergency and temporary seepage measures, as well as permanent seepage measures.

Emergency and Temporary Seepage Measures

Temporary seepage control measures are generally initiated when a seepage condition exists that, if not immediately corrected, may quickly deteriorate to a critical condition requiring emergency action. Generally, there are two major courses for quickly alleviating a seepage problem:

- Reduce the hydraulic head and pressure causing the problem by lowering the reservoir and restricting reservoir levels.

- Control the exits of the seepage by constructing a weighted filter, or constructing sandbag or other types of ring dikes around the exit point.

Emergency seepage control measures are initiated when signs of seepage indicate imminent danger. Signs of serious seepage conditions include a whirlpool in the vicinity of the dam, sand boils, and sinkholes.

Permanent Seepage Measures

Permanent seepage control measures are used when the seepage condition is not an imminent threat to the safety of the dam, and sufficient time is available to design and construct a long-term remedial measure.

Permanent seepage control measures include:

- Monitoring the seepage and seepage control measures.
- Lowering the reservoir and restricting the reservoir level.
- Pressure grouting to penetrate and seal cracks and voids in the area, thus blocking seepage paths.
- Constructing cutoff walls.
- Constructing an impervious blanket immediately upstream of the dam.
- Constructing a weighted filter/berm downstream of the dam.
- Installing drains, filters, and relief wells.
- Providing drainage.

V. REMEDIAL ACTION: SUMMARY

SUMMARY: REMEDIAL ACTION (Continued)

- Using a combination of methods.

If it is determined that remedial measures are not feasible due to cost or other obstacles, decommissioning and removal of the dam may need to be considered.

Appendix A

Glossary

GLOSSARY

ABUTMENTS - Those portions of the valley sides which underlie and support the dam structure, and are usually also considered to include the valley sides immediately upstream and downstream from the dam.

ADIT - A gallery that is used for entrance to a gallery system or that serves as a connecting passageway between galleries or other features in the dam. Also, a closed-end tunnel.

BERM - A step in the sloping profile of an embankment dam. A step in a rock or earth cut. Also, a placement of fill at the toe of a slide to buttress it against further movement.

BREACH - An eroded opening through a dam that drains the reservoir. A controlled breach is a constructed opening. An uncontrolled breach is an unintentional opening that allows uncontrolled discharge from the reservoir.

CUTOFF WALL - A wall of impervious material, usually concrete, soil-bentonite or cement-bentonite, asphaltic concrete, or steel sheet piling, constructed under or through a dam or structure to halt seepage through, beneath, or adjacent to the dam or structure.

DAM FAILURE - The catastrophic breakdown of a dam, characterized by the uncontrolled release of impounded water. There are varying degrees of failure.

DARCY'S LAW - A derived formula for the flow of fluids on the assumption that the flow is laminar and that inertia can be neglected.

EMBANKMENT DAM - Any dam constructed of excavated natural materials (includes both earthfill and rockfill dams).

EMERGENCY ACTION PLAN (EAP) - A formal plan of procedures designed to minimize consequences to life and property in the event of an emergency at a dam.

EROSION - The wearing away of a natural or manmade surface by flowing water, waves, or wind.

FAULT - A fracture or fracture zone in the earth crust along which there has been relative displacement of the two sides.

FLOOD - A temporary rise in water levels resulting in inundation of areas not normally covered by water.

FLOODPLAIN - The downstream area that would be inundated or otherwise affected by the failure of a dam or by large floods.

FOUNDATION - The portion of the valley floor that underlies and supports the dam structure.

GLOSSARY

FLOWNET - A pictorial method used to study the flow of water through a soil. A flownet is utilized to indicate the paths of travel followed by moving water and the subsurface pressures resulting from the presence of water. A flownet can also be used to estimate the quantity of seepage passing through an embankment or zone within a dam.

FRACTURES - A general term for any break in a rock whether or not it causes displacement, due to mechanical failure by stress. Fracture includes cracks, joints, and faults.

FREEBOARD - The vertical distance between a specified water level and the top of a dam or spillway crest.

GROIN - See SLOPE-ABUTMENT INTERFACE.

GROUT CURTAIN - A zone created by drilling a line of holes into the foundation of a dam into which grout is injected to reduce seepage under or around the dam.

HYDROSTATIC PRESSURE - The pressure at a point in water at rest due to the weight of the water above it.

IMPERVIOUS – Material with an extremely low permeability with a magnitude close to zero.

INSTRUMENTATION - An arrangement of devices installed into or near dams (e.g., piezometers, inclinometers, strain gauges, measurement points, etc.) that provide measurements used to evaluate the structural behavior and performance of the structure.

IN SITU - Refers to soil when it is at its natural location in the earth and in its natural condition.

INTAKE STRUCTURE - Placed at the beginning of an outlet works waterway, the intake structure establishes the ultimate drawdown level of the reservoir by the position and size of its opening(s) to the outlet works. Intake structures may be vertical or inclined towers, drop inlets, or submerged, box-shaped structures. Intake elevations are determined by the head needed for discharge capacity, storage reservation to allow for situation, the required amount and rate of withdrawal, and the desired extreme drawdown level.

ISOTROPIC - Describing a soil whose properties are the same in all directions.

KARST TOPOGRAPHY - A region characterized by distinctive features such as caverns, sinkholes, "lost" rivers, large springs, barren uplands, and thin soils. Such topography usually exists in areas of limestone bedrock that exhibits these features due to solutioning and weathering of the bedrock.

LAMINAR FLOW - Water flow in which the streamlines remain distinct and in which the flow direction at every point remains unchanged with time. It is characteristic of the movement of ground water.

GLOSSARY

LEAKAGE - The undesirable flow of water through joints, cracks, and openings in hydraulic structures.

LIQUEFACTION - a) The process whereby soil behaves as a viscous liquid. b) A condition whereby soil undergoes continued deformation at a constant low residual stress or with low residual resistance, due to the buildup and maintenance of high-pore water pressures, which reduces the effective shearing resistance to a very low value. Pore pressure buildup leading to liquefaction may be due either to static or cyclic stress applications. The possibility of its occurrence will depend on the void ratio or relative density of a cohesionless soil and the confining pressure.

OUTLET WORKS - A system of dam components that regulates or releases water impounded by a dam. Components of an outlet works include an entrance channel, intake structure, conduit, gate or valve housing, energy dissipaters, and return channel.

PHREATIC SURFACE - The free surface of water seeping at atmospheric pressure through soil or rock.

PUDDLED CLAY - A building component derived by mixing pure clay with one-fifth of its weight in water to form a plastic material which can be used in construction to prevent the passage of water (e.g., for lining ponds).

RELIEF WELL -Vertical wells or boreholes designed to collect seepage and control uplift pressures under a dam.

RESERVOIR RIM - The boundary of the reservoir including all areas along the valley sides above and below the water surface.

SAND BOIL - A condition resulting from the upward flow of seepage under pressure and characterized by a boiling action of the surface seepage. A sand boil is often accompanied by a cone of material around the boil, which develops from the deposition of foundation or embankment material carried by the seepage.

SCARP - An over-steepened surface on a slope resulting from instability or erosion (i.e., head of a slide).

SEEPAGE - The passage of water through embankment, foundation, or abutment material. Water may flow through the pores of soils used to construct the embankment or in the foundation. In other cases, water may flow through cracks in the soil or along the contact of soil with concrete or metal appurtenances. Water can also flow through features in the bedrock.

SETTLEMENT - The vertical downward movement of soil or a structure.

GLOSSARY

SHEAR ZONE - A zone of soil or rock that is characterized by many parallel fractures due to shear strain.

SINKHOLE - A depression resulting from loss of material underlying the surface.

SLIDE - The unplanned descent (movement) of a mass of earth or rock down a slope.

SLOPE-ABUTMENT INTERFACE - The contact between the abutment and the embankment slopes.

SPILLWAY - A structure that passes normal and/or flood flows in a manner that protects the structural integrity of the dam.

STRATIFICATION - Separation of concrete into horizontal layers, with increasingly smaller material concentrated toward the top.

TOE OF DAM - The junction of the downstream slope or face of a dam with the ground surface; also referred to as the downstream toe. For an embankment dam, the junction of the upstream slope with the ground surface is called the upstream toe.

TRACTIVE FORCE - In seepage, the drag developed on the soil particles through which the seepage flows.

TREMIE - A pipe through which concrete is placed under water without segregation or dilution, having its upper end at the top of the hole and its lower end at the location in the hole where the material is to be placed.

TURBIDITY - The discoloration or cloudiness of seepage water proportionate to the amount of soil particles suspended in the water.

UPLIFT PRESSURE - Upward water pressure in the pores of a material or on the base of a structure.

WATERSHED - The area drained by a river or river system.

WEIR - A structure of given shape and dimensions built across a stream or channel to control or measure flow quantities.

Appendix B

References

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Appendix C

O&M Checklist for Seepage Conditions

O&M CHECKLIST

I. Routine O&M

A. Frequent Activity

1. Measure, record and evaluate monitoring instruments. Data should be charted immediately after taking readings to facilitate a quick and accurate interpretation.
2. Maintain monitoring instruments in accordance with manufacturer's recommendations. Calibrate flow-measuring devices such as weirs to ensure continuity of accurate measurements.
3. Maintain slopes and grades and repair erosion on embankment to keep seepage paths from being shortened.
4. Cut woody growth and fill holes on embankment to prevent seepage paths from being shortened.
5. Mow slopes and keep them clear of vegetation that would impede inspection for seepage. Include an area downstream of the embankment where seepage could emerge, including abutment slopes.
6. Visually and physically inspect slopes and downstream areas for seepage and soft areas.

B. Periodic or Infrequent Activity

1. Perform hydrographic or side-scan sonar surveys. This type of survey is useful for detecting the formation of sinkholes, sloughing, or other movement beneath the reservoir surface that would otherwise go undetected. Similar surveys should be performed in downstream pools to detect formation of scour holes that could shorten seepage paths.
2. Physically inspect appurtenances and other features. If possible, dewater features such as basins and spillways. Use experienced divers or a remotely operated camera if the water surface cannot safely be lowered. Determine if any scour or erosion has occurred that could shorten seepage paths or otherwise indicate active seepage erosion.
3. Flush and inspect all drainage conduits, including manholes. Removing silt and other deposits is important to safe functioning of these features. This may require acid flushing and bacterial treatment to address iron ochre and mineral deposits. Include video camera inspection where appropriate.
4. Flush and treat relief wells, particularly if their flow diminishes with time.
5. Perform slug tests on piezometers and observation wells. Monitor the well response to ensure that the instruments are not becoming plugged.
6. Inspect conduits that extend through and beneath embankments or dams to determine if cracking has occurred, allowing soil to be washed into the conduit by piping or internal erosion. Physically inspect if possible, or use remotely operated video equipment.

O&M CHECKLIST

II. Emergency O&M – Note that this activity is in addition to normal emergency action plans.

A. Sinkholes

1. For active sinkholes, maintain a stockpile of suitable material for treating potential problems at the site. The stockpile should include a range of gradations of materials to construct inverted filters in any sinkholes that develop.
2. Maintain equipment suitable for placing inverted filters at the site.
3. Maintain a list of contractors that are experienced and keep materials for installing wells to treat severe conditions.

B. Sand Boils

1. Maintain a stockpile of sand bags or equipment for quickly filling bags to use for constructing dikes around sand boils that may develop downstream.
2. Maintain stockpiles of appropriate filter materials to construct inverted filters. Concrete sand may be a good source of material.
3. Maintain a list of contractors that are experienced and keep materials for installing wells to treat severe conditions.

C. Soft Areas on Downstream Slope and Floodplain of Embankment

1. Stake and monitor the size of the wet, soft areas. Increase the frequency of monitoring and determine if the area is growing in size.
2. Begin an investigation to determine the history of any similar seepage.
3. Photograph and survey any sloughing to determine if the problem is active or static.

D. Leakage Around Conduits

1. Determine if the source of the water is from the conduit or from exterior sources. Use remotely operated video equipment to inspect joints in the conduit. Also inspect for other damaged areas including spalling of the conduit.
2. Dewatering the conduit may help to determine if flow through the conduit is the source of the seepage or whether reservoir water is finding a path along the outside of the conduit.
3. If seepage flow is rapidly increasing and particles are observed in the seepage flow, consider constructing downstream cofferdams that can provide backpressure and reduce the hydraulic gradient causing flow. Lower the reservoir as quickly as possible using available outlet works and siphons.