Chapter 6
Seepage Control

6-1. General

All earth and rock-fill dams are subject to seepage through the embankment, foundation, and abutments. Seepage control is necessary to prevent excessive uplift pressures, instability of the downstream slope, piping through the embankment and/or foundation, and erosion of material by migration into open joints in the foundation and abutments. The purpose of the project, i.e., long-term storage, flood control, etc., may impose limitations on the allowable quantity of seepage. Detailed information concerning seepage analysis and control for dams is given in EM 1110-2-1901.

6-2. Embankment

a. Methods for seepage control. The three methods for seepage control in embankments are flat slopes without drains, embankment zonation, and vertical (or inclined) and horizontal drains.

(1) Flat slopes without drains. For some dams constructed with impervious soils having flat embankment slopes and infrequent, short duration, high reservoir levels, the phreatic surface may be contained well within the downstream slope and escape gradients may be sufficiently low to prevent piping failure. For these dams, when it can be ensured that variability in the characteristics of borrow materials will not result in adverse stratification in the embankment, no vertical or horizontal drains are required to control seepage through the embankment. Examples of dams constructed with flat slopes without vertical or horizontal drains are Aquilla Dam, Aubrey Dam (now called Ray Roberts Dam), and Lakeview Dam. A horizontal drainage blanket under the downstream embankment may still be required for control of underseepage.

(2) Embankment zonation. Embankments are zoned to use as much material as possible from required excavation and from borrow areas with the shortest haul distances, the least waste, the minimum essential processing and stockpiling, and at the same time maintain stability and control seepage. For most effective control of through seepage and seepage during reservoir drawdown, the permeability should progressively increase from the core out toward each slope.

(3) Vertical (or inclined) and horizontal drains. Because of the often variable characteristics of borrow materials, vertical (or inclined) and horizontal drains within the downstream portion of the embankment are provided to ensure satisfactory seepage control. Also, the vertical (or inclined) drain provides the primary line of defense to control concentrated leaks through the core of an earth dam (see EM 1110-2-1901).

b. Collector pipes. Collector pipes should not be placed within the embankment, except at the downstream toe, because of the danger of either breakage or separation of joints, resulting from fill placement and compacting operations or settlement, which might result in either clogging or piping. However, a collector pipe at the downstream toe can be placed within a small berm located at the toe, since this facilitates maintenance and repair.

6-3. Earth Foundations

a. Introduction. All dams on earth foundations are subject to underseepage. Seepage control is necessary to prevent excessive uplift pressures and piping through the foundation. Generally, siltation of the reservoir with time will tend to diminish underseepage. Conversely, the use of some underseepage control methods, such as relief wells and toe drains, may increase the quantity of underseepage. The methods of control of underseepage in dam foundations are horizontal drains, cutoffs (compacted backfill trenches, slurry walls, and concrete walls), upstream impervious blankets, downstream seepage berms, relief wells, and trench drains. To select an underseepage control method for a particular dam and foundation, the relative merits and efficiency of different methods should be evaluated by means of flow nets or approximate methods (as described Chapter 4 and Appendix B, respectively, of EM 1110-2-1901). The changes in the quantity of underseepage, factor of safety against uplift, and uplift pressures at various locations should be determined for each particular dam and foundation varying the anisotropy ratio of the permeability of the foundation to cover the possible range of expected field conditions (see Table 9-1 of EM 1110-2-1901).

b. Horizontal drains. As mentioned previously, horizontal drains are used to control seepage through the embankment and to prevent excessive uplift pressures in the foundation. The use of the horizontal drain significantly reduces the uplift pressure in the foundation under the downstream portion of the dam. The use of the horizontal drain increases the quantity of seepage under the dam (see Figure 9-1 of EM 1110-2-1901).

c. Cutoffs.

(1) Complete versus partial cutoff. When the dam foundation consists of a relatively thick deposit of pervious alluvium, the designer must decide whether to make a complete cutoff or allow a certain amount of underseepage to occur under controlled conditions. It is necessary for a cutoff to penetrate a homogeneous isotropic foundation at least 95 percent of the full depth before there is any appreciable reduction in seepage beneath a dam. The effectiveness of the partial cutoff in reducing the quantity of seepage decreases as the ratio of the width of the dam to the depth of penetration of the cutoff increases. Partial cutoffs are effective only when they extend down into an intermediate stratum of lower permeability. This stratum must be continuous across the valley foundation to ensure that three-dimensional seepage around a discontinuous stratum does not negate the effectiveness of the partial cutoff.

(2) Compacted backfill trench. The most positive method for control of underseepage consists of excavating a trench beneath the impervious zone of the embankment through pervious foundation strata and backfilling it with compacted impervious material. The compacted backfill trench is the only method for control of underseepage which provides a full-scale exploration trench that allows the designer to see the actual natural conditions and to adjust the design accordingly, permits treatment of exposed bedrock as necessary, provides access for installation of filters to control seepage and prevent piping of soil at interfaces, and allows high quality backfilling operations to be carried out. When constructing a complete cutoff, the trench must fully penetrate the pervious foundation and be carried a short distance into unweathered and relatively impermeable foundation soil or rock. To ensure an adequate seepage cutoff, the width of the base of the cutoff should be at least one-fourth the maximum difference between the reservoir and tailwater elevations but not less than 20 ft, and should be wider if the foundation material under the cutoff is considered marginal in respect to imperviousness. If the gradation of the impervious backfill is such that the pervious foundation material does not provide protection against piping, an intervening filter layer between the impervious backfill and the foundation material is required on the downstream side of the cutoff trench. The cutoff trench excavation must be kept dry to permit proper placement and compaction of the impervious backfill. Dewatering systems of wellpoints or deep wells are generally required during excavation and backfill operations when below groundwater levels (TM 5-818-5). Because construction of an open cutoff trench with dewatering is a costly procedure, the trend has been toward use of the slurry trench cutoff.

(3) Slurry trench. When the cost of dewatering and/or the depth of the pervious foundation render the compacted backfill trench too costly and/or impractical, the slurry trench cutoff may be a viable method for control of underseepage. Using this method, a trench is excavated through the pervious foundation using a sodium bentonite clay (or Attapulgite clay in saline water) and water slurry to support the sides. The slurry-filled trench is backfilled by displacing the slurry with a backfill material that contains enough fines (material passing the No. 200 sieve) to make the cutoff relatively impervious but sufficient coarse particles to minimize settlement of the trench forming the soil-bentonite cutoff. Alternatively, a cement may be introduced into the slurry-filled trench which is left to set or harden forming a cement-bentonite cutoff. The slurry trench cutoff is not recommended

when boulders, talus blocks on buried slopes, or open jointed rock exist in the foundation due to difficulties in excavating through the rock and slurry loss through the open joints. When a slurry trench is relied upon for seepage control, the initial filling of the reservoir must be controlled and piezometers located both upstream and downstream of the cutoff must be read to determine if the slurry trench is performing as planned. If the cutoff is ineffective, remedial seepage control measures must be installed prior to further raising of the reservoir pool. Normally, the slurry trench should be located under or near the upstream toe of the dam. An upstream location provides access for future treatment provided the reservoir could be drawn down and facilitates stage construction by permitting placement of a downstream shell followed by an upstream core tied into the slurry trench. For stability analysis, a soil-bentonite slurry trench cutoff should be considered to have zero shear strength and exert only a hydrostatic force to resist failure of the embankment. The design and construction of slurry trench cutoffs is covered in Chapter 9 of EM 1110-2-1901. Guide specification UFGS-02261A is available for soil-bentonite slurry trench cutoffs.

(4) Concrete wall. When the depth of the pervious foundation is excessive (>150 ft) and/or the foundation contains cobbles, boulders, or cavernous limestone, the concrete cutoff wall may be an effective method for control of underseepage. Using this method, a cast-in-place continuous concrete wall is constructed by tremie placement of concrete in a bentonite-slurry supported trench. Two general types of concrete cutoff walls, the panel wall and the element wall, have been used. Since the wall in its simpler structural form is a rigid diaphragm, earthquakes could cause its rupture; therefore, concrete cutoff walls should not be used at a site where strong earthquake shocks are likely. The design and construction of concrete cutoff walls is covered in Chapter 9 of EM 1110-2-1901. Guide specification UFGS-03373 is available for the concrete used in concrete cutoff walls.

d. Upstream impervious blanket.[1] When a complete cutoff is not required or is too costly, an upstream impervious blanket tied into the impervious core of the dam may be used to minimize underseepage. An example is shown in Figure 2-1f. Upstream impervious blankets should not be used when the reservoir head exceeds 200 ft because the hydraulic gradient acting across the blanket may result in piping and serious leakage. Downstream underseepage control measures (relief wells or toe trench drains) are generally required for use with upstream blankets to control underseepage and/or prevent excessive uplift pressures and piping through the foundation. Upstream impervious blankets are used in some cases to reinforce thin spots in natural blankets. Effectiveness of upstream impervious blankets depends upon their length, thickness, and vertical permeability, and on the stratification and permeability of soils on which they are placed. The design and construction of upstream blankets is given in EM 1110-2-1901.

e. Downstream seepage berm. When a complete cutoff is not required or is too costly, and it is not feasible to construct an upstream impervious blanket, a downstream seepage berm may be used to reduce uplift pressures in the pervious foundation underlying an impervious top stratum at the downstream toe of the dam. Other downstream underseepage control measures (relief wells or toe trench drains) are generally required for use with downstream seepage berms. Downstream seepage berms can be used to control underseepage efficiently where the downstream top stratum is relatively thin and uniform or where no top stratum is present, but they are not efficient where the top stratum is relatively thick and high uplift pressures develop. Downstream seepage berms may vary in type from impervious to completely free draining. The selection of the type of downstream seepage berm to use is based upon the availability of borrow materials and relative cost of each type. The design and construction of downstream seepage berms is given in EM 1110-2-1901.

f. Relief wells. When a complete cutoff is not required or is too costly, relief wells installed along the downstream toe of the dam may be used to prevent excessive uplift pressures and piping through the foundation. Relief wells increase the quantity of underseepage from 20 to 40 percent, depending upon the foundation conditions. Relief wells may be used in combination with other underseepage control measures (upstream impervious blanket or downstream seepage berm) to prevent excessive uplift pressures and piping through the foundation. Relief wells are applicable where the pervious foundation has a natural impervious cover. The well screen

[1] The blanket may be impervious or semipervious (leaks in the vertical direction).

section, surrounded by a filter if necessary, should penetrate into the principal pervious stratum to obtain pressure relief, especially where the foundation is stratified. The wells, including screen and riser pipe, should have a diameter which will permit the maximum design flow without excessive head losses but in no instance should the inside diameter be less than 6 in. Geotextiles should not be used in conjunction with relief wells. Relief wells should be located so that their tops are accessible for cleaning, sounding for sand, and pumping to determine discharge capacity. Relief wells should discharge into open ditches or into collector systems outside of the dam base which are independent of toe drains or surface drainage systems. Experience with relief wells indicates that with the passage of time the discharge of the wells will gradually decrease due to clogging of the well screen and/or reservoir siltation. Therefore, the amount of well screen area should be designed oversized and a piezometer system installed between the wells to measure the seepage pressure, and if necessary additional relief wells should be installed. The design, construction, and rehabilitation of relief wells is given in EM 1110-2-1914.

g. Trench drain. When a complete cutoff is not required or is too costly, a trench drain may be used in conjunction with other underseepage control measures (upstream impervious blanket and/or relief wells) to control underseepage. A trench drain is a trench generally containing a perforated collector pipe and backfilled with filter material. Trench drains are applicable where the top stratum is thin and the pervious foundation is shallow so that the trench can penetrate into the aquifer. The existence of moderately impervious strata or even stratified fine sands between the bottom of the trench drain and the underlying main sand aquifer will render the trench drain ineffective. Where the pervious foundation is deep, a trench drain of practical depth would only attract a small portion of underseepage, and detrimental underseepage would bypass the drain and emerge downstream of the drain, thereby defeating its purpose. Trench drains may be used in conjunction with relief well systems to collect seepage in the upper pervious foundation that the deeper relief wells do not drain. If the volume of seepage is sufficiently large, the trench drain is provided with a perforated pipe. A trench drain with a collector pipe also provides a means of measuring seepage quantities and of detecting the location of any excessive seepage. The design and construction of trench drains is given in EM 1110-2-1901.

h. Drainage galleries. Internal reinforced concrete galleries have been used in earth and rockfill dams built in Europe for grouting, drainage, and monitoring of behavior. Galleries have not been constructed in embankment dams built by the Corps of Engineers to date. Some possible benefits to be obtained from the use of galleries in earth and rockfill dams are (Sherard et al. 1963):

(1) Construction of the embankment can be carried out independently of the grouting schedule.

(2) Drain holes drilled in the rock foundation downstream from the grout curtain can be discharged into the gallery, and observations of the quantities of seepage in these drain holes will indicate where foundation leaks are occurring.

(3) Galleries provide access to the foundation during and after reservoir filling so that additional grouting or drainage can be installed, if required, and the results evaluated from direct observations.

(4) The additional weight of the overlying embankment allows higher grout pressures to be used.

(5) Galleries can be used to house embankment and foundation instrumentation outlets in a more convenient fashion than running them to the downstream toe of the dam.

(6) If the gallery is constructed in the form of a tunnel below the rock surface along the longitudinal axis of the dam, it serves as an exploratory tunnel for the rock foundation. The minimum size cross section recommended for galleries and access shafts is 8 ft by 8 ft to accommodate drilling and grouting equipment. A gutter located along the upstream wall of the gallery along the line of grout holes will carry away cuttings from the drilling operation and waste grout from the grouting operation. A gutter and system of weirs located along the downstream wall of the gallery will allow for determination of separate flow rates for foundation drains.

6-4. Rock Foundations

a. General considerations. Seepage should be cut off or controlled by drainage whenever economically feasible. Safety must be the governing factor for selection of a seepage control method (see EM 1110-2-1901).

b. Cutoff trenches. Cutoff trenches are normally employed when the character of the foundation is such that construction of a satisfactory grout curtain is not practical. Cutoff trenches are normally backfilled with compacted impervious material, bentonite slurry, or neat cement. Construction of trenches in rock foundations normally involves blasting using the presplit method with primary holes deck-loaded according to actual foundation conditions. After blasting, excavation is normally accomplished with a backhoe. Cutoff of seepage within the foundation is obtained by connecting an impervious portion of the foundation to the impervious portion of the structure by backfilling the trench with an impervious material. In rock foundations, as in earth foundations, the impervious layer of the foundation may be sandwiched between an upper and a lower pervious layer, and a cutoff to such an impervious layer would reduce seepage only through the upper pervious layer. However, when the thicknesses of the impervious and upper pervious layers are sufficient, the layers may be able to resist the upward seepage pressures existing in the lower pervious layer and thus remain stable.

c. Upstream impervious blankets. Impervious blankets may sometimes give adequate control of seepage water for low head structures, but for high head structures it is usually necessary to incorporate a downstream drainage system as a part of the overall seepage control design. The benefits derived from the impervious blanket are due to the dissipation of a part of the reservoir head through the blanket. The proportion of head dissipated is dependent upon the thickness, length, and effective permeability of the blanket in relation to the permeability of the foundation rock. A filter material is normally required between the blanket and foundation.

d. Grouting. Grouting of rock foundations is used to control seepage. Seepage in rock foundations occurs through cracks and joints, and effectiveness of grouting depends on the nature of the jointing (crack width, spacing, filling, etc.) as well as on the grout mixtures, equipment, and procedures.

(1) A grout curtain is constructed beneath the impervious zone of an earth or rock-fill dam by drilling grout holes and injecting a grout mix. A grout curtain consisting of a single line of holes cannot be depended upon to form a reliable seepage barrier; therefore, a minimum of three lines of grout holes should be used in a rock foundation. Through a study of foundation conditions revealed by geologic investigations, the engineer and geologist can establish the location of the grout curtain in plan, the depths of the grout holes, and grouting procedures. Once grouting has been initiated, the extent and details of the program should be adjusted, as drilling yields additional geological information and as observations of grout take and other data become available.

(2) Careful study of grouting requirements is necessary when the foundation is crossed by faults, particularly when the shear zone of a fault consists of badly crushed and fractured rock. It is desirable to seal off such zones by area (consolidation) grouting. When such a fault crosses the proposed dam axis, it may be advisable to excavate along the fault and pour a wedge-shaped concrete cap in which grout pipes are placed so that the fault zone can be grouted at depth between the upstream and downstream toes of the dam. The direction of grout holes should be oriented to optimize the intersection of joints and other defects.

(3) Many limestone deposits contain solution cavities. When these are suspected to exist in the foundation, one line (or more) of closely spaced exploration holes is appropriate, since piping may develop or the roofs of undetected cavities may collapse and become filled with embankment material, resulting in development of voids in the embankment. All solution cavities below the base of the embankment should be grouted with multiple lines of grout holes.

(4) The effectiveness of a grouting operation may be evaluated by pre- and post-grouting pressure injection tests for evaluating the water take and the foundation permeability.

(5) Development of grouting specifications is a difficult task, and it is even more difficult to find experienced and reliable organizations to execute a grouting program so as to achieve satisfactory results. Grouting operations must be supervised by engineers and geologists with specialized experience. A compendium of foundation grouting practices at Corps of Engineers dams is available (Albritton, Jackson, and Bangert 1984). A comprehensive coverage of drilling methods, as well as grouting methods, is presented in EM 1110-2-3506.

6-5. Abutments

a. Through earth abutments. Earth and rock-fill dams, particularly in glaciated regions, may have pervious material, resulting from filling of the preglacial valley with alluvial or morainal deposits followed by the downcutting of the stream, in one or both abutments. Seepage control through earth abutments is provided by extending the upstream impervious blanket in the lateral direction to wrap around the abutment up to the maximum water surface elevation, by placing a filter layer between the pervious abutment and the dam downstream of the impervious core section, and, if necessary, by installing relief wells at the downstream toe of the pervious abutment. Examples of seepage control through earth abutments are given in EM 1110-2-1901.

b. Through rock abutments. Seepage should be cut off or controlled by drainage whenever economically possible. When a cutoff trench is used, cutoff of seepage within the abutment is normally obtained by extending the cutoff from above the projected seepage line to an impervious layer within the abutment. Impervious blankets overlying the upstream face of pervious abutments are effective in reducing the quantity of seepage and to some extent will reduce uplift pressures and gradients downstream. A filter material is normally required at the interface between the impervious blanket and rock abutment. The design and construction of upstream impervious blankets is given in EM 1110-2-1901.

6-6. Adjacent to Outlet Conduits

When the dam foundation consists of compressible soils, the outlet works tower and conduit should be founded upon or in stronger abutment soils or rock. When conduits are laid in excavated trenches in soil foundations, concrete seepage collars should not be provided solely for the purpose of increasing seepage resistance since their presence often results in poorly compacted backfill around the conduit. Collars should only be included as necessary for coupling of pipe sections or to accommodate differential movement on yielding foundations. When needed for these purposes, collars with a minimum projection from the pipe surface should be used. Excavations for outlet conduits in soil foundations should be wide enough to allow for backfill compaction parallel to the conduit using heavy rolling compaction equipment. Equipment used to compact along the conduit should be free of framing that prevents its load transferring wheels or drum from working against the structure. Excavated slopes in soil for conduits should be no steeper than 1 vertical to 2 horizontal to facilitate adequate compaction and bonding of backfill with the sides of the excavation. Drainage layers should be provided around the conduit in the downstream zone of embankments without pervious shells. A concrete plug should be used as backfill in rock cuts for cut-and-cover conduits within the core zone to ensure a watertight bond between the conduit and vertical rock surfaces. The plug, which can be constructed of lean concrete, should be at least 50 ft long and extend up to the original rock surface. In embankments having a random or an impervious downstream shell, horizontal drainage layers should be placed along the sides and over the top of conduits downstream of the impervious core.

6-7. Beneath Spillways and Stilling Basins

Adequate drainage should be provided under floor slabs for spillways and stilling basins to reduce uplift pressures. For soil foundations, a drainage blanket under the slab with transverse perforated pipe drains discharging through the walls or floor is generally provided, supplemented in the case of stratified foundations by deep well systems. Drainage of a slab on rock is usually accomplished by drain holes drilled in the rock with formed holes or pipes through the slab. The drainage blanket is designed to convey the seepage quickly and effectively to the transverse collector drains. It is designed as a graded reverse filter with coarse stones adjacent to the perforated drain pipe and finer material adjacent to the concrete structure to prevent the migration of fines into the drains. Outlets for transverse drains in the spillway chute discharge through the walls or floor at as low an elevation as practical to obtain maximum pressure reduction. Wall outlets should be 1 ft minimum above the floor to prevent blocking by debris. Cutoffs are provided at each transverse collector pipe to minimize buildup of head in case of malfunction of the pipe drain. Drains should be at least 6 in. in diameter and have at least two outlets to minimize the chance of plugging. Outlets should be provided with flat-type check valves to prevent surging and the entrance of foreign matter in the drainage system. For the stilling basin floor slab, it may be advantageous to place a connecting header along each wall and discharge all slab drainage into the stilling basin just upstream from the hydraulic jump at the lowest practical elevation in order to secure the maximum reduction of uplift for the downstream portion of the slab. A closer spacing of drains is usually required than in the spillway chute because of greater head and considerable difference in water depth in a short distance through the hydraulic jump. Piezometers should be installed in the drainage blanket and deeper strata, if necessary, to monitor the performance of the drainage system. If the drains or wells become plugged or otherwise noneffective, uplift pressures will increase which could adversely affect the stability of the structure (EM 1110-2-1602, EM 1110-2-1603, and EM 1110-2-1901).

6-8. Seepage Control Against Earthquake Effects

For earth and rock-fill dams located where earthquake effects are likely, there are several considerations which can lead to increased seepage control and safety. Geometric considerations include using a vertical instead of inclined core, wider dam crest, increased freeboard, flatter embankment slopes, and flaring the embankment at the abutments (Sherard 1966, 1967). The core material should have a high resistance to erosion (Arulanandan and Perry 1983). Relatively wide transition and filter zones adjacent to the core and extending the full height of the dam can be used. Additional screening and compaction of outer zones or shells will increase permeability and shear strength, respectively. Because of the possibility of movement along existing or possibly new faults, it is desirable to locate the spillway and outlet works on rock rather than in the embankment or foundation overburden.