# CHAPTER 8
# SEEPAGE CONTROL IN EMBANKMENTS

8-1. 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.

8-2. 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.

8-3. 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 assured 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. A horizontal drain may still be required for control of underseepage (see Chapter 9). Examples of dams constructed with flat slopes without vertical or horizontal drains are Aquilla Dam, Aubrey Dam, and Lakeview Dam (U. S. Army Engineer District, Fort Worth 1976a, 1976b, 1980). Figure 8-1 shows the analysis of through embankment seepage for Aubrey Dam, Texas (now called Ray Roberts Dam). As shown in figure 8-1a, this is a zoned embankment with relatively flat slopes due to a weak stratum in the foundation. The slopes could be steepened from IV:10.6H to lV:8H if the weak foundation gains shear strength due to consolidation during construction (the dam is scheduled for completion in 1988). A 3-ft-thick horizontal drainage blanket and collector system will be provided under the downstream embankment from sta 136+00 to sta 142+60 to control any seepage through the foundation. For the analysis of through embankment seepage, shown in figure 8-1b, the steady state phreatic surface was developed graphically for the conservation pool by considering a homogeneous nonisotropic embankment and an impervious foundation. Since the escape seepage gradients were computed to be less than 0.3 to 0.4 (see paragraph 4.9b), it was concluded that no vertical or horizontal drains were required.

8-4. Zoning Embankments.

a. General. Embankments are zoned to use as much material as possible from required excavation and from borrow areas with the shortest haul distances and the least wastage and at the same time maintain stability and control seepage. The different zones of an embankment are shown in figure 8-2. For most effective control of through seepage and seepage during reservoir drawdown, the permeability should progressively increase from the core out toward each slope as shown in figure 8-2 (EM 1110-2-2300).

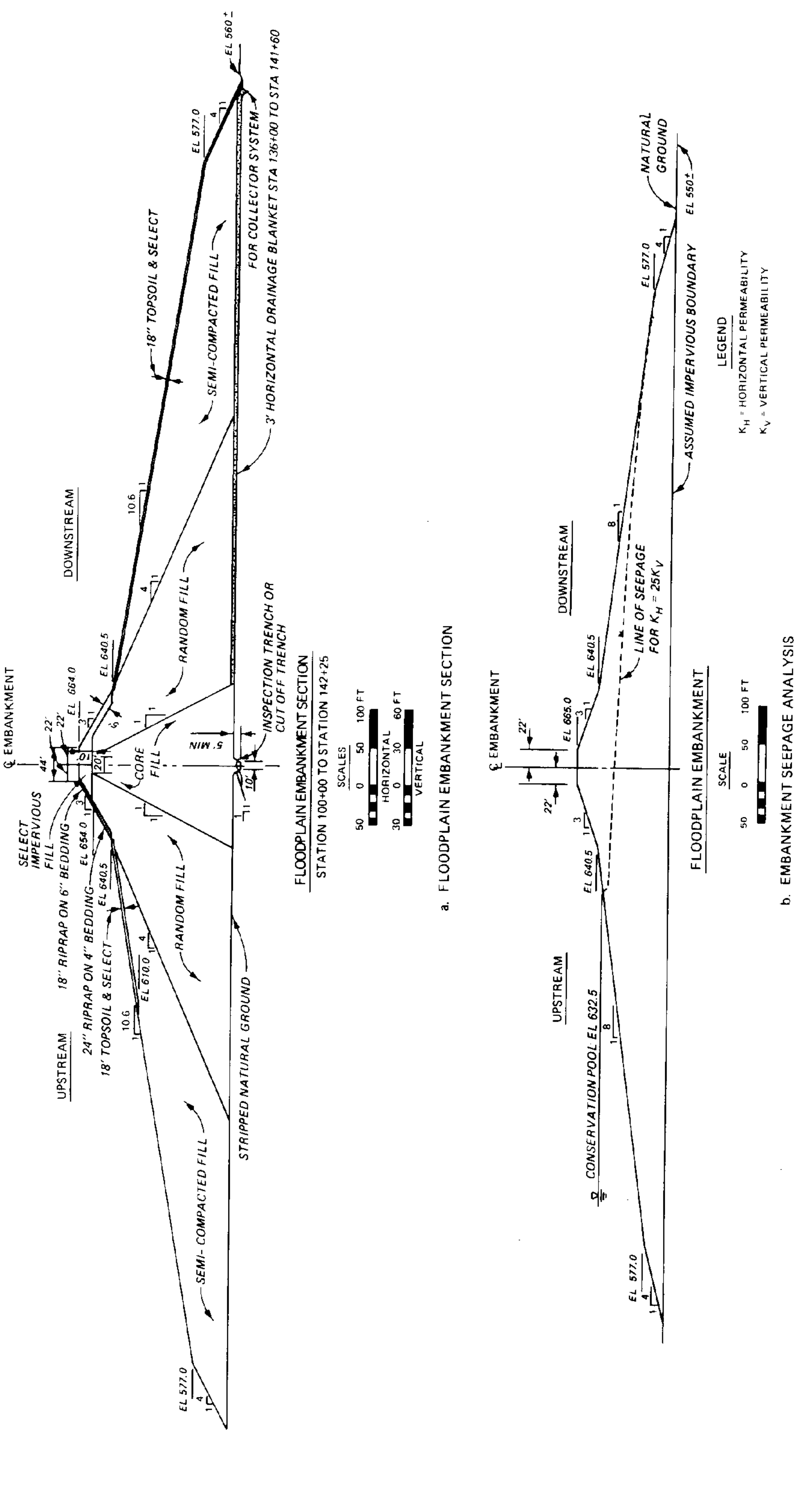
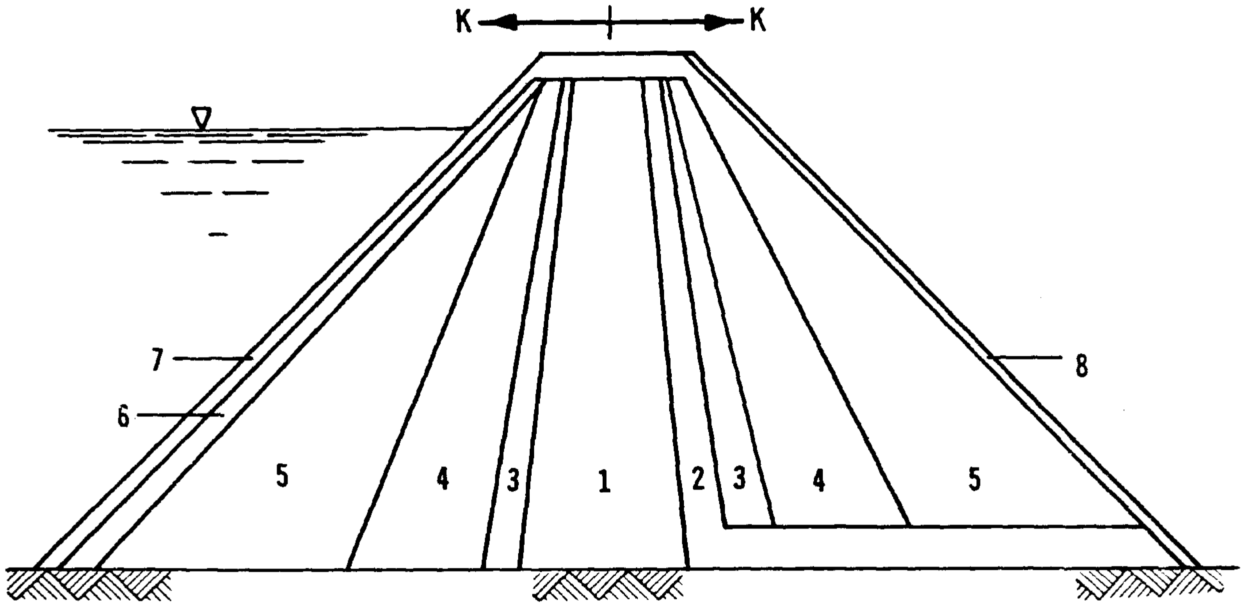



**Figure 8-1. Analysis of through embankment seepage for Aubrey Dam, Texas (from U. S. Army Engineer District, Fort. Worth[81])**




| ZONE | DESCRIPTION |
|---|---|
| 1 | CORE |
| 2 | FILTER OR DRAIN |
| 3 | TRANSITION |
| 4 | RANDOM |
| 5 | SHELL |
| 6 | US DRAWDOWN BLANKET |
| 7 | US SLOPE PROTECTION |
| 8 | DS SLOPE PROTECTION |

Figure 8-2. Different zones of an embankment (prepared by WES)

b. Impervious Zone or Core. The purpose of the core is to minimize seepage losses through the embankment. As a general rule, sufficient impervious material is available to result in small seepage losses through the embankment. Therefore, the quantity of seepage passing through the foundation and abutments may be more significant than the quantity passing through the core. Important material properties of the core are permeability, erosion resistance, and cracking resistance. A core material of very low permeability may be required when the reservoir is used for long-term storage. A core material of medium permeability may be utilized when the reservoir is used for flood control. The erosion resistance of core material is important in evaluating piping potential (Arulanandan and Perry 1983). The tensile strength of the core material is important in evaluating the cracking resistance (Al-Hussaini and Townsend 1974). In general, the base of the core or the cutoff trench should be equal to or greater than a quarter of the maximum difference between reservoir and tailwater elevations (U. S. Army Engineer District, Mobile 1976, EM 1110-2-2300). A core top width of 10 ft is considered to be the minimum width on which earth-moving and compaction equipment can operate. The maximum core width is controlled by stability and by availability of material. The top of the core should be above the maximum reservoir elevation but below the bottom of the frost zone, A vertical core located near the center of the dam is performed over an inclined upstream core because the former provides higher contact pressure between the core and foundation to prevent leakage, greater stability under earthquake loading (Sherad 1966, 1967), and better access for remedial seepage control. An inclined upstream core allows the downstream portion of the embankment to be placed first and the core later and reduces the possibility of hydraulic fracturing (Nobari, Lee, and Duncan 1973).

c. Filter Zones. Filters may be required in various locations in earth dams such as vertical (or inclined) and horizontal drains within the downstream section of the embankment as shown in figure 8-2, around outlet conduits passing under the downstream portion of the embankment, under concrete structures such as stilling basins, around relief wells, beneath riprap where drawdown may occur, and between the embankment and abutment. Important properties of the filter material are gradation, compacted density, and permeability. Filters are designed to permit free passage of water and prevent migration of fines through the filter as discussed in Appendix D. The average in-place relative density of the filter should be at least 85 percent and no portion of the filter should have a relative density less than 80 percent (EM 1110-2-2300). This requirement applies to vertical (or inclined) and horizontal drains and filters under concrete structures but not to bedding layers under riprap. Special care must be taken to assure that compaction does not degrade the filter material (by grain breakage and/or segregation) and reduce its permeability. When the filter material is sand or contains significant portions of sand sizes, the material should be maintained in as saturated a condition as possible during compaction to prevent bulking. The discharge capacity of the filter zones should be determined in dimensioning the filters (Cedergren 1977). The filter material should pass the 3-in. screen for minimizing particle segregation and bridging during placement. As discussed previously in Chapter 2 (see figure 2-12), the permeability of sands and gravels varies significantly with the amount and type of fines (material smaller than the No. 200 sieve) present. Also, the amount and type of fines present influence the capacity of a filter to self-heal by collapsing any cracks within the filter (see figure 8-3). Therefore, the maximum percent fines and type (silt, clay, etc.) to be allowed in the filter of an earth dam must be shown to be sufficiently pervious by laboratory filter tests[(1)] and self healing by collapse tests (Vaughn 1978). If vibration is present, such as in the vicinity of a stilling basin or powerhouse, the. laboratory filter tests should be conducted with vibration effects. If the base material to be protected is dispersive, large-scale box filter tests will be required (McDaniel and Decker 1979, Bordeaux and Imaizumi 1977, and Logani and Lhez 1979). The procedure to use in identifying dispersive clays is given in EM 1110-2-1906. Generally, two or more filter zones, each with a uniform or narrow gradation (sand, pea gravel, etc.) are preferable to a single well-graded filter zone which often becomes segregated during processing, stockpiling, and placement. Care must

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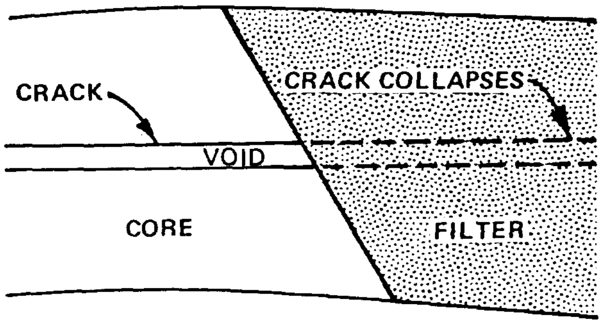
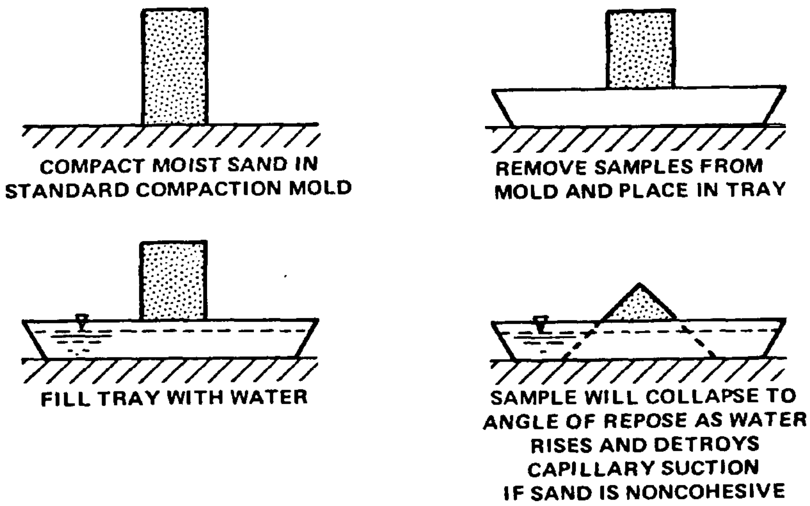
[(1)] Laboratory filter tests are not a routine laboratory test. Standard testing procedures have not been developed. The conduct of laboratory filter tests should be under the direction of a specialist and should be carried out in a research laboratory.




a. Self-healing (by collapse) of filter




b. Laboratory test for ability of filter material to self-heal (by collapse)

Figure 8-3. Self-healing (by collapse) of crack within a filter downstream of a core (courtesy of American Society of Civil Engineers[282])

be taken during construction to prevent reduction in permeability of the filter by intrusion of fines carried by surface runoff, spillage by compaction equipment, or degradation during compaction. Also, care must be taken to prevent coarse material from rolling down the surface of the filter and collecting between the core and filter (or between filter zones if two or more filters are used) forming a "tube" (in cross section) of more permeable material through which core (or filter) material could be lost by piping.

d. Transition Zones. The purpose of transition zones is to separate zones of different permeability and compressibility within the embankment, to prevent core material from being drawn into the upstream shell during rapid drawdown of the reservoir, to provide a source to feed material into a crack in the core and preventing piping (see figure 8-4). Important material properties of the transition material are angularity of particles (upstream of core, rounded particles and better for feeding material into cracks and preventing piping), gradation, permeability, and compressibility. Transition zones may be located both upstream and downstream of the core and generally have a width >10 ft. Wide transition zones between the filter and the downstream shell will control the rate of flow through a crack in the core and extending through the filter in the event that self-healing (by collapse) of the filter does not occur. Transition zones (and filter zones) should be widened near abutments where tension zones may induce cracking.

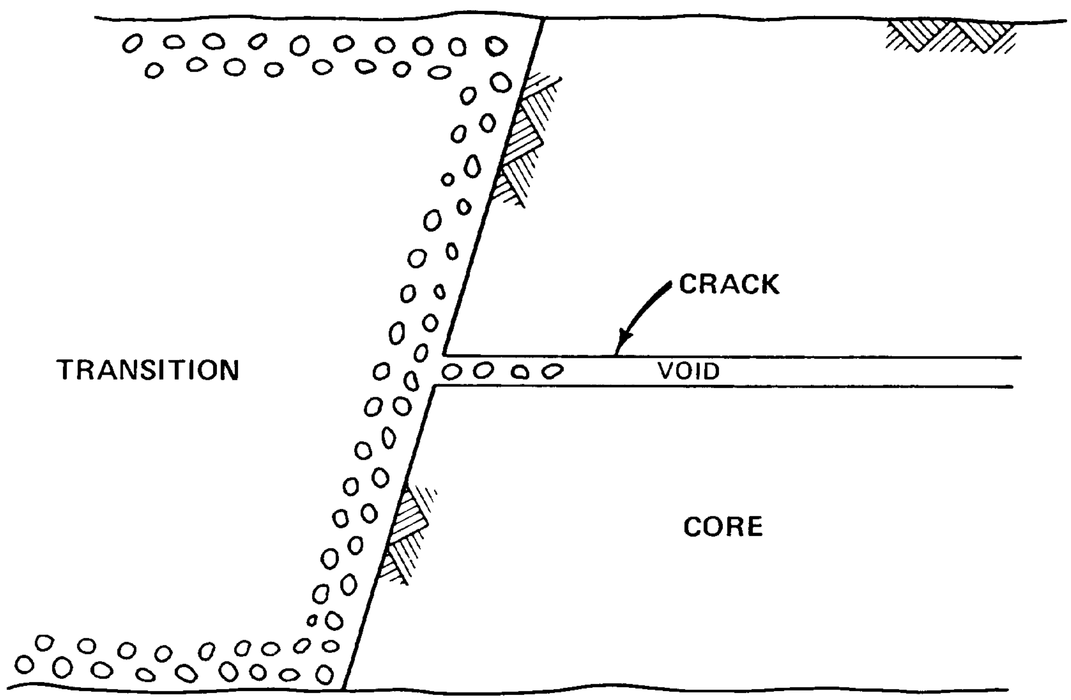



Figure 8-4. Crack stopping transition upstream of a core (prepared by WES)

e. Random Zones. The purpose of random zones is to utilize required excavation. Random zones are assumed to have the properties of the least desirable material in the excavation. Random zones may be located either upstream or downstream of the core. For most effective control of through seepage and seepage during reservoir drawdown, the more pervious material should be routed to the outer portions of the embankment.

f. Cuter Zones or Shells. The purpose of the outer zones or shells is to permit steeper embankment slopes. Important material properties of the shell material are durability (soundness) of rock, gradation (well-graded), and permeability (free-draining). The upstream shell affords stability against end of construction, rapid drawdown, and earthquake loading. The downstream shell acts as a drain and controls the line of seepage and provides stability under high reservoir heads. When suitable materials are not available for pervious downstream shells, control of seepage through the embankment is provided by vertical (or inclined) and horizontal drains.

g. Upstream Drawdown Blanket. The purpose of the upstream drawdown blanket is to provide stability of the upstream slope during rapid drawdown of the reservoir. Important material properties of the upstream drawdown blanket are durability (soundness) of rock and permeability (free-draining). Figure 8-5 shows the improvement in the factor of safety resulting from the

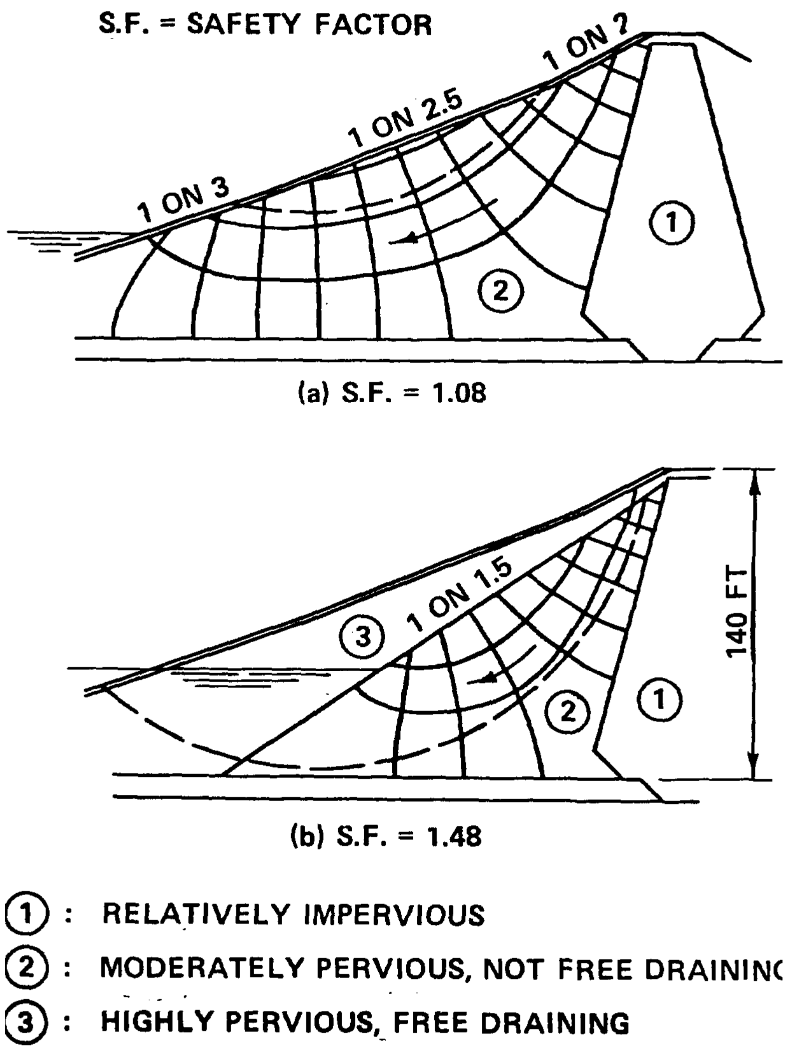



Figure 8-5. Improvement in factor of safety resulting from the upstream drawdown blanket (courtesy of John Wiley and Sons[155])

upstream drawdown blanket (Cedergren 1977). The required minimum permeability of the upstream drawdown blanket can be calculated from (Cedergren 1977):

$$k_{min} = \frac{\nu_{dd} L n_e}{h \sin \alpha} \tag{8-1}$$

where

$k_{min}$ = minimum permeability of the upstream drawdown blanket

$v_{dd}$ = velocity of drawdown of the water surface in the reservoir

L = defined in figure 8-6

$n_e$ = effective porosity of the upstream drawdown blanket

h = defined in figure 8-6

$\alpha$ = angle between the median flow line in the upstream drawdown blanket and the horizontal

The ratio h/L should not exceed 10.

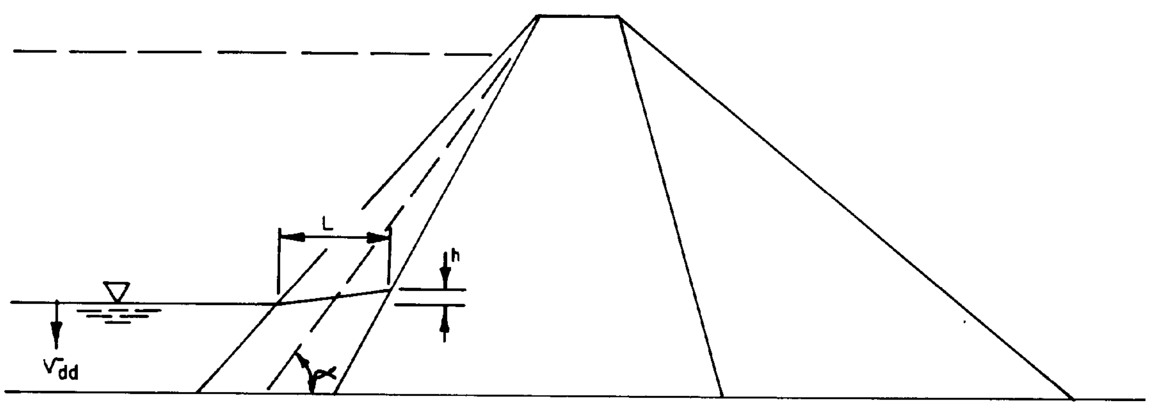
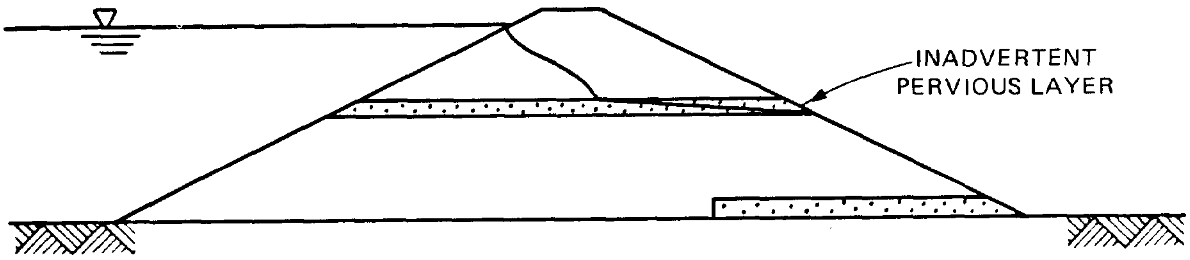


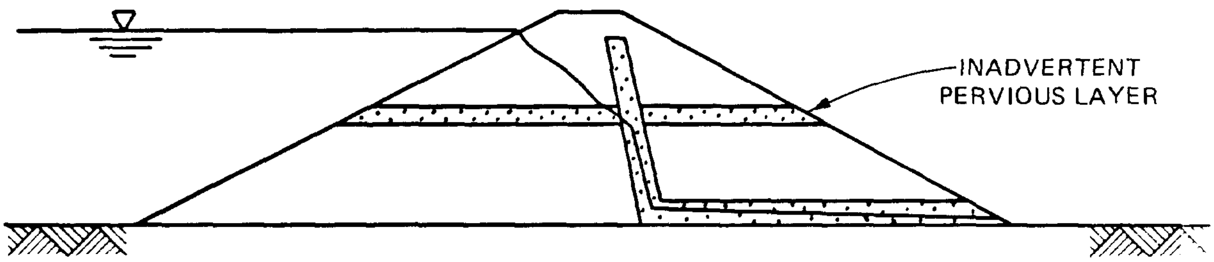

Figure 8-6. Computation of required minimum permeability of the upstream drawdown blanket (courtesy of John Wiley and Sons[155])

8-5. Vertical (or Inclined) and Horizontal Drains.

a. Need. As stated previously, vertical (or inclined) and horizontal drains may be required to control seepage through the embankment by preventing material eroded through a crack in the core from washing into the downstream shell by seepage water under reservoir head. Also, because of the often variable characteristics of borrow materials, it is frequently advisable to provide vertical (or inclined) and horizontal drains within the downstream section of the embankment, as shown in figure 8-7, to ensure satisfactory seepage control. For a stratified soil, the vertical permeability is




a. HORIZONTAL DRAIN ONLY




b. INCLINED AND HORIZONTAL DRAINS

Figure 8-7. Use of inclined and horizontal drains to ensure seepage control against variable characteristics of borrow materials (courtesy of John Wiley and Sons[155])

controlled by the least permeable layer. Therefore, the horizontal permeability is always greater than the vertical permeability. Compacted soils in earth dams are stratified due to variability in the characteristics of borrow materials and the tendency for soil particles to align horizontally during compaction. The ratio of vertical to horizontal permeability may range from 2 to 10 or greater. For stratified soils, as shown in figure 8-8, a horizontal drainage blanket is not sufficient to prevent the downstream slope from becoming saturated and susceptible to piping and/or slope failure. However, when a properly designed and constructed inclined drain and horizontal drain is used, as shown in figure 8-8, complete control is provided over seepage through the embankment.

b. <u>Filter Requirements</u>. Vertical (or inclined) and horizontal drains should be designed as filters (see Appendix D). If crushed rock is used for the drain material (see paragraph 2-2.g), material to be protected is dispersive, or material to be protected contains cracks, filter tests will be

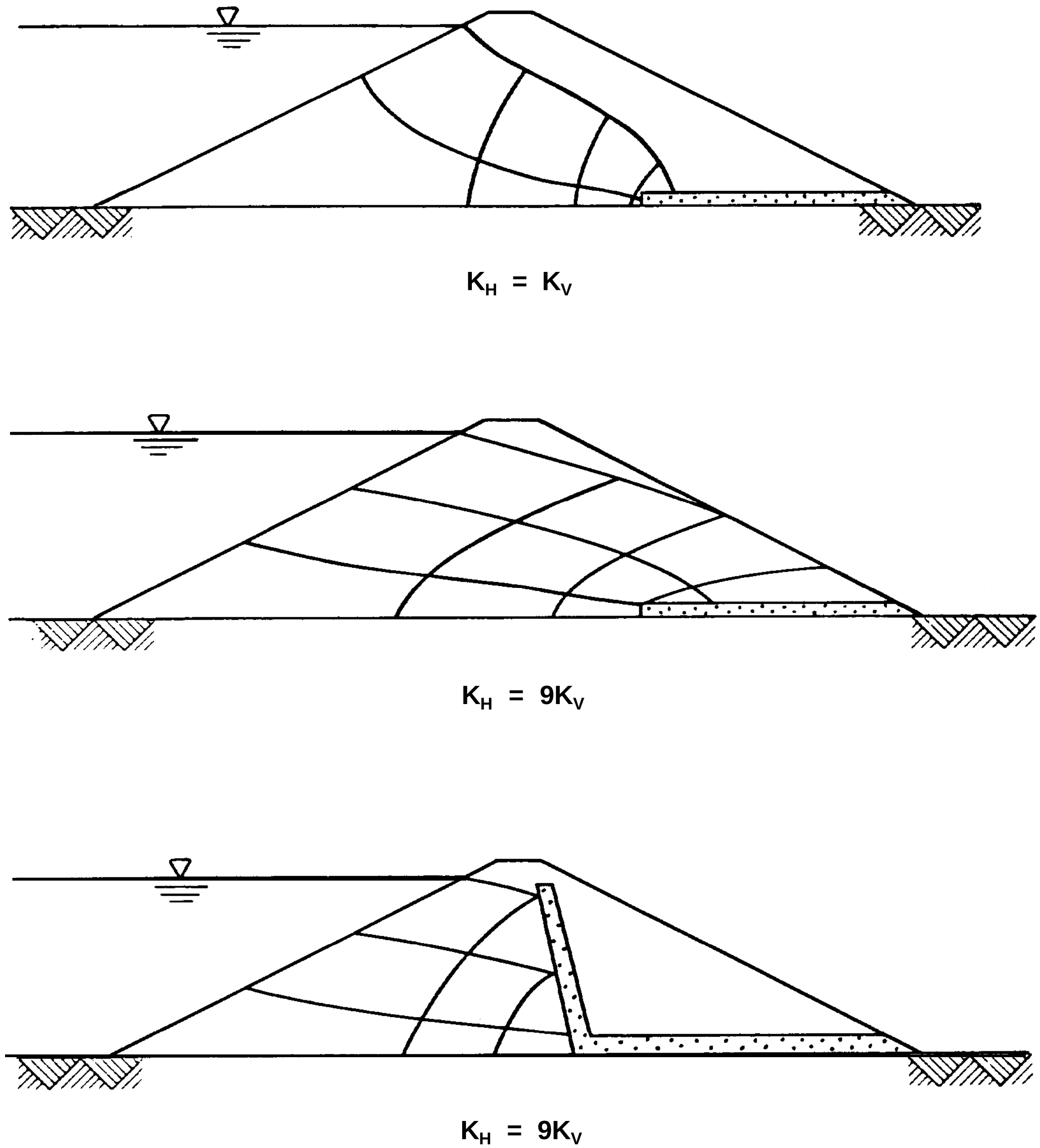



Figure 8-8. Effect of anisotropy of permeability on seepage through earth dam with and without an inclined drain (courtesy of John Wiley and Sons[155])

required. Well-graded materials are internally unstable and should not be used as filters when $C_u \geq 20$.[1]

c. Discharge Requirements. Vertical (or inclined) and horizontal drains must have sufficient discharge capacities to remove seepage quickly without inducing high seepage forces or hydrostatic pressures (Cedergren 1977). When drains are designed and constructed with ample discharge capacity, the line of seepage will not rise above the drain zone. Since drains are small compared to the overall dimensions of the earth dam, it is difficult to construct accurate flow nets within the drains themselves. The total quantity of seepage from all sources that must discharge through the drain should be evaluated from a flow net analysis in which it is assumed that the drains have an infinite permeability. Figure 8-9 shows an example of the design procedure for inclined and horizontal drains to assure adequate drain capacity (Cedergren 1977). The probable rate of discharge through the dam and foundation is estimated from composite flow nets (see figures 4-13 and 4-14). For the example shown in figure 8-9, the seepage through the dam $Q_1$ = 2 cu ft/day and the seepage through the foundation $Q_2$ = 10 cu ft/day. Therefore, the inclined drain must be capable of discharging $Q_1$ = 2 cu ft/day and the horizontal drain must be capable to discharging $Q_1 + Q_2$ = 12 cu ft/day. These are discharge rates per running foot of dam and drain. Assuming the inclined drain was designed with a width of 12 ft to permit its placement with normal earth-moving equipment, the cross-sectional area normal to the direction of flow within the inclined drain $A_c$ = 11 sq ft (see figure 8-9b) and its required minimum permeability may be found from Darcy's law:

$$k = \frac{Q}{iA} \tag{8-2}$$

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(1)

$$C_u = \frac{D_{60_F}}{D_{10_F}}$$

where $C_u$ = coefficient of uniformity

$D_{60_F}$ = size of filter material at 60 percent passing

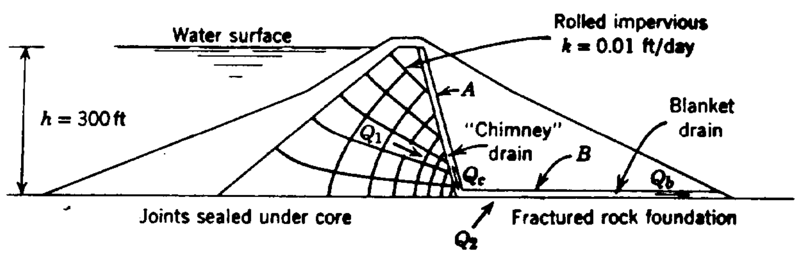
$D_{10_F}$ = size of filter material at 10 percent passing where

k = coefficient of permeability

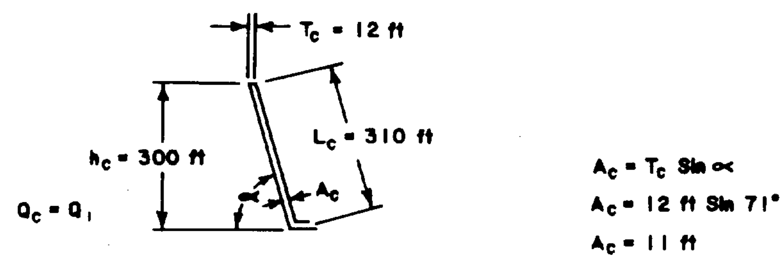
Q = quantity of discharge

i = hydraulic gradient

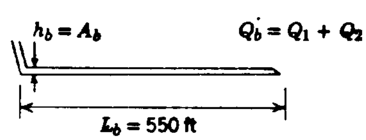
A = cross-sectional area of flow




a. Cross section and flow net




b. Dimensions of inclined drain




c. Dimensions of horizontal drain

Figure 8-9. Example of design procedure for inclined and horizontal drains to assure adequate drain capacity (courtesy of John Wiley and Sons[155])

Substituting for Q , 1 , and A

$$k_c = \frac{Q_1}{\frac{h_c}{L_c}\left(A_c\right)}$$

$$k_c = \frac{2 \text{ cu ft/day}}{\left(\frac{300 \text{ ft}}{310 \text{ ft}}\right) 11 \text{ sq ft}} \tag{8-3}$$

$$k_c = 0.2 \text{ ft/day}$$

Every filter must be permeable enough to have a reasonable reserve for higher than expected flows. The filter should have a minimum permeability after placement and compaction of at least 20 times that calculated theoretically. Therefore, the required permeability for the inclined drain is

$$k_{c_{design}} = 20k_c$$

$$k_{c_{design}} = 20(0.2 \text{ ft/day}) = 4 \text{ ft/day} \tag{8-4}$$

$$k_{c_{design}} = 1.4 \times 10^{-3} \text{ cm/sec}$$

Clean, washed concrete sand is usually about this permeable. As previously stated, the horizontal drain must be capable of discharging $Q_1 + Q_2 = 12$ cu ft/day. Since the drain is to be designed so that the line of seepage does not rise above the drain zone, the allowable maximum head in the horizontal drain can be no greater than its height. The required minimum permeability from Darcy's law is

$$k_b = \frac{Q_1 + Q_2}{\left(\frac{h_b}{L_b}\right) A_b} \tag{8-5}$$

Substituting $A_b = h_b$ (width is one running foot of dam and drain)

$$k_b = \frac{Q_1 + Q_2}{\left(\frac{h_b}{L_b}\right) h_b}$$

$$k_b = \frac{(Q_1 + Q_2) L_b}{h_b^2}$$

(8-6)

$$k_b = \frac{(12 \text{ cu ft/day})(550 \text{ ft})}{h_b^2}$$

$$k_b = \frac{6{,}600}{h_b^2}$$

To design the horizontal drain, select a drain height and calculate the required minimum permeability. Apply a factor of safety of 20 to the calculated permeability and select a drain material from available aggregates. Select a drain height of 4 ft.

$$k_b = \frac{6{,}600}{4^2}$$

$$k_b = 412.5 \text{ ft/day}$$

The required permeability for design is

$$k_{b_{design}} = 20\ k_b$$

$$k_{b_{design}} = 20\ (412.5 \text{ ft/day}) = 8{,}250 \text{ ft/day}$$

$$k_{b_{design}} = 2.9 \text{ cm/sec}$$

This permeability could be obtained by screened fine gravel (3/8-in. to 1/2-in. size) which has a permeability of about 30,000 ft/day or 10.6 cm/sec

(Cedergren 1977). Seepage in coarse aggregate is likely to be turbulent and a reduction factor should be applied to the permeability. The hydraulic gradient in the horizontal drain is

$$i = \frac{h_b}{L_b} = \frac{4\ \text{ft}}{550\ \text{ft}} = 0.007 \tag{8-7}$$

From figure 8-10, for screened fine gravel (3/8-in. to 1/2-in. size) with 1 = 0.007 the reduction factor for permeability is 0.9.

$$k = 0.9\ (30{,}000\ \text{ft/day})$$

$$k = 27{,}000\ \text{ft/day} \tag{8-8}$$

$$k = 9.5\ \text{cm/sec}$$

The permeability of the screened fine gravel (3/8-in. to 1/2-in. size) reduced for turbulence is greater than the required permeability for design:

$$27{,}000\ \text{ft/day} > 8{,}250\ \text{ft/day}$$

Therefore, it should be adequate when properly placed and compacted to conduct seepage water through the horizontal drain. The screened fine gravel (3/8-in. to 1/2-in. size) will be protected top and bottom with a 1-ft-thick clean washed concrete sand filter. Since the seepage from the foundation must flow across the fine filter to enter the coarse drainage layer, the fine filter must be permeable enough to allow the water to enter the coarse drainage layer freely under only a small hydraulic gradient (0.5 or less). Assume an average hydraulic gradient of 0.5 across the fine filter layer and $Q_2$ = 10 cu ft/day for the amount of water that will enter the first (left) 200 ft of the drain. From Darcy's law the required minimum permeability of the fine filter is (see equation 8-2)

$$k = \frac{Q}{iA}$$

$$k = \frac{10\ \text{cu ft/day}}{0.5(200\ \text{ft})(1\ \text{ft})}$$

$$k = 0.1\ \text{ft/day}$$

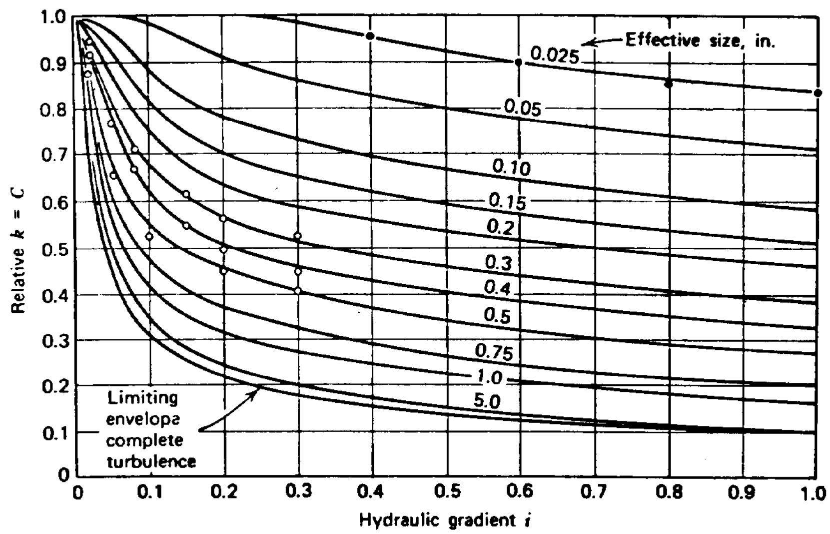
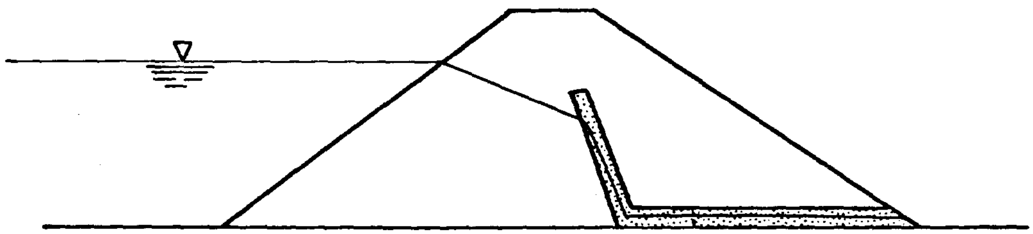



Figure 8-10. Approximation for estimating reduction in permeability of narrow size-range aggregate caused by turbulent flow (courtesy of John Wiley and Sons[155])

Clean washed concrete sand with a permeability of 10 ft/day should allow seepage from the foundation to enter the coarse drainage layer without restriction. As stated previously, the inclined and horizontal drains used in this example would have to meet the filter requirements (see Appendix D) in addition to the discharge requirements.

d. Location and Geometry. Vertical (or inclined) drains are located adjacent to and downstream of the core as shown in figure 8-2. The top of the vertical (or inclined) drain should be above the phreatic surface for maximum reservoir elevation to prevent seepage flow above the drain. In drawing the flow net for the dam to use in selecting the height and location for the vertical or inclined drain, a conservative (high) value of anisotropy of permeability of the soil should be used in order to prevent the seepage from flowing over the top of the drain (see figure 8-11). If the dam is located where earthquake effects are likely (see paragraph 8-6), the vertical (or inclined) drain should extend the full height of the dam. The width of the vertical (or inclined) drain is controlled by the availability of materials and the discharge requirements of the drain. A vertical (or inclined) drain width of 6 ft is the practical minimum for earth-moving and compaction equipment (U. S. Army Engineer District, Kansas City 1974 and U. S. Army Engineer District, Philadelphia 1974). When filter or drain material is not available locally and must be hauled to the site at a substantial cost, a narrow (3 ft or greater) vertical drain may be constructed by excavating into the core material, backfilling, and compacting with vibratory equipment (U. S. Army Engineer District, Mobile 1965, U. S. Army Engineer District, Tulsa 1974). The width of the vertical drain must be sufficient to satisfy the discharge requirements. Horizontal drains are located under the downstream section of the dam and convey seepage from the vertical (or inclined) drain and underseepage from the



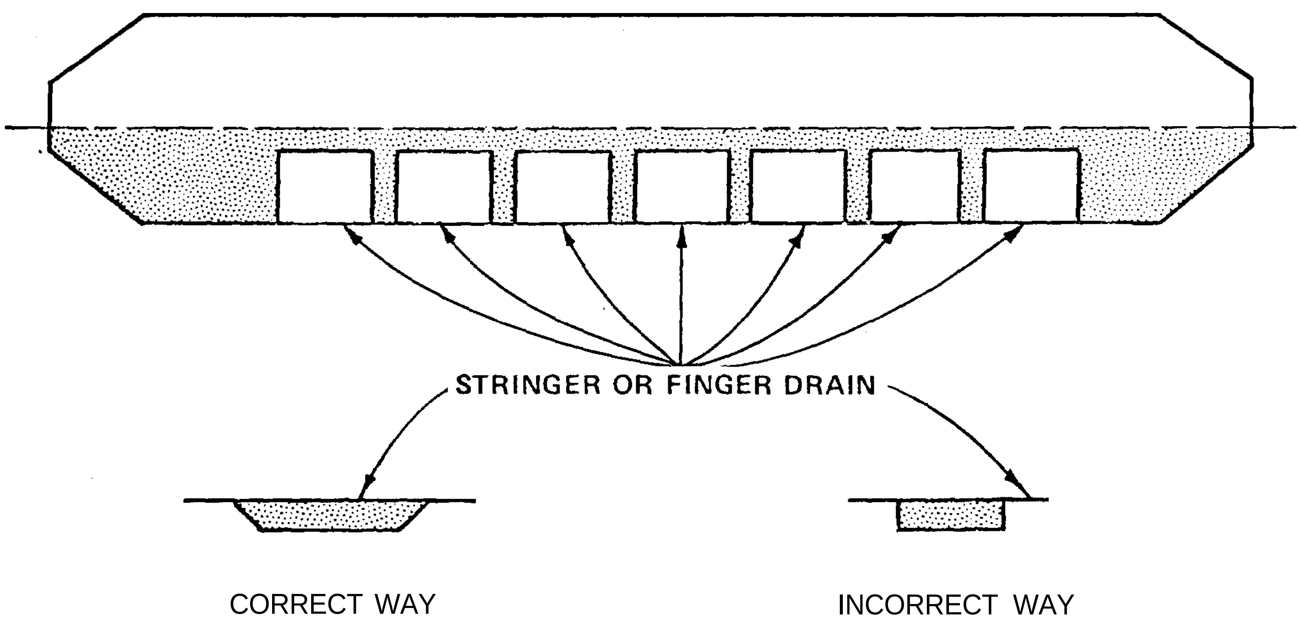
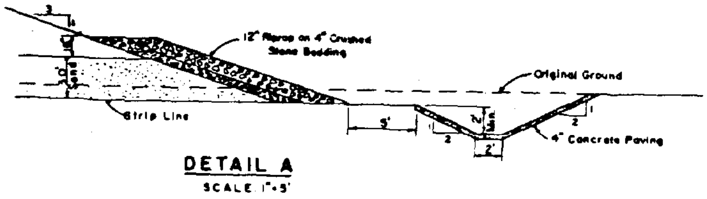


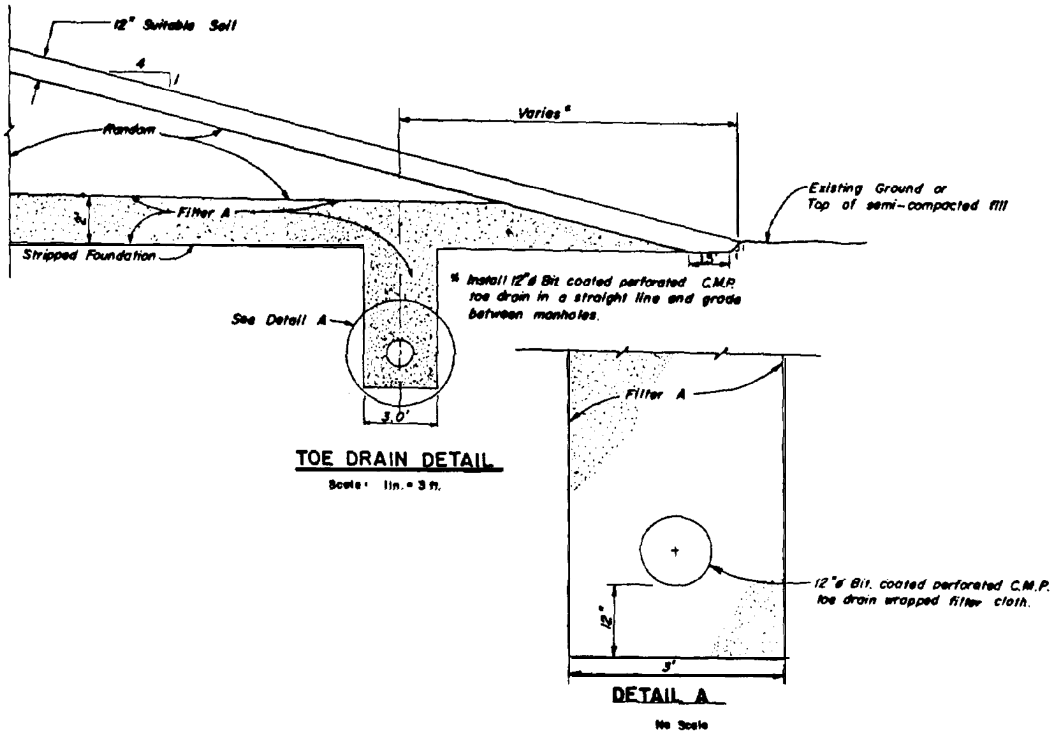

Figure 8-11. Use of stringers or finger drains as an alternative to a continuous horizontal drain (prepared by WES)

foundation to the toe of the dam. The thickness of the horizontal drain must be sufficient to satisfy the discharge requirements. When filter or drain material is not available locally and must be hauled to the site at substantial cost, a thin (2 ft or greater) horizontal drain has been used (U. S. Army Engineer District, Tulsa 1975 and U. S. Army Engineer District, Louisville 1974). Stringers or finger drains may be used as an alternative to a continuous horizontal drain, as shown in figure 8-11, when the drain material is costly. The cross-sectional area of the stringer drains must be sufficient to satisfy the discharge requirements. The stringer drain may be constructed either by trenching into the embankment or foundation for narrow (6 ft) widths or by placing the adjacent impervious fill and then the drain material for wider (50 ft) widths (U. S. Army Engineer District, Kansas City 1974, 1978). In either case, the side slopes of the stringer drains should be sloped instead of vertical (see figure 8-11) to avoid stress concentrations which could cause vertical transverse cracks. The stringer drain material must be thoroughly compacted (see paragraph 8-4c) to ensure that consolidation does not occur upon saturation leaving an open seepage conduit in the top of the trench, bridged by the overlying embankment, and susceptible to progressive erosion (Jansen 1980). The downstream end of horizontal drains and stringer drains must be able to discharge freely and must be protected against siltation and erosion. This may be accomplished by providing a weighted filter (riprap overlying bedding material) or a toe drain as shown in figure 8-12 (U. S. Army Engineer District, Mobile 1965 and U. S. Army Engineer District, Tulsa 1975). The toe drain has the advantage of lower maintenance requirements and preventing the development of localized wet areas at the surface along the downstream toe of the embankment.

8-6. Seepage Control Against Earthquake Effects. For dams located where earthquake effects are likely, there are several considerations which can lead to increased seepage control and safety.- 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 for 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. Geometric considerations include using a vertical instead of inclined core, wider dam crest, increased freeboard, and flatter embankment slopes, and flaring the embankment at the abutments (Sherard 1966, 1967).




a. Weighted filter (courtesy of U. S. Army Engineer District, Mobile[97])




b. Toe drain (courtesy of U. S. Army Engineer District, Tulsa[113])

Figure 8-12. Protection of downstream end of horizontal and stringer drains