GETTING WATER INTO PIPES - NOT AS EASY AS IT SEEMS

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Introduction

Slotted or perforated collector pipes are often included in toe drains and other seepage control features in embankment dams. Although it has generally been believed that water can flow freely into these pipes from any clean, free-draining surrounding soils, this has been found not to be true in all cases.

This paper will address the practical aspects of flow into drain pipes associated with embankment dams. As water flows to collector pipes it passes generally from small voids in the base material to increasingly larger voids in the sand filter and gravel drain. The perforations in the drain pipe and cross sectional area of the pipe itself can also be thought of as voids. The void ratio of typical foundation and drainage materials is evaluated and the most critical areas for evaluation are described.

It will be demonstrated that the configuration of filter and drainage materials outside a drain pipe is instrumental to effectively collecting flow. Seepage into single stage and two stage toe drains are analyzed using a 2D finite element method (FEM) computer program. The results of this analysis, as well as the overall advantages and disadvantages of the single stage and two stage designs are described and discussed.

The paper also describes standard materials listed in ASTM C 33 that can be used as effective filter and drain materials. A variety of commercially available pipe types and perforation sizes are discussed with respect to their seepage collection potential in combination with the ASTM C 33 materials. Recommendations are presented for typical drain design applications.

Waters Journey to the Pipe

Seepage flow in soil occurs through the void space created by the interstitial space between the soil grains. In a similar manner the perforations of a drain pipe can be thought of as voids surrounded by a solid (pipe). Fluid flow through voids is influenced by the size of the void through which it passes as well as by head and viscosity. This is illustrated conceptually in Figure A. In this example a tank is constructed with one perforated wall. Water will flow through the perforations and result in a total flow, Q. For the box on the left, more perforations of smaller diameter are used which results in a total area of 40 units. The box on the right includes the same total perforation area but with a smaller number of larger perforations. Due to the larger amount of fluid shear for each individual perforation for the tank on the left it will drain more slowly (lower flow rate) than the tank on the right.

In a similar manner, seepage through two soils with the same volume of voids will not necessarily have the same total flow. To illustrate this consider the voids in a soil as expressed in terms of void ratio, which is the ratio of the volume of voids to the volume of solids. Void ratios for typical foundation soils, materials used for filters and drains, and several pipes are presented in Table 1.

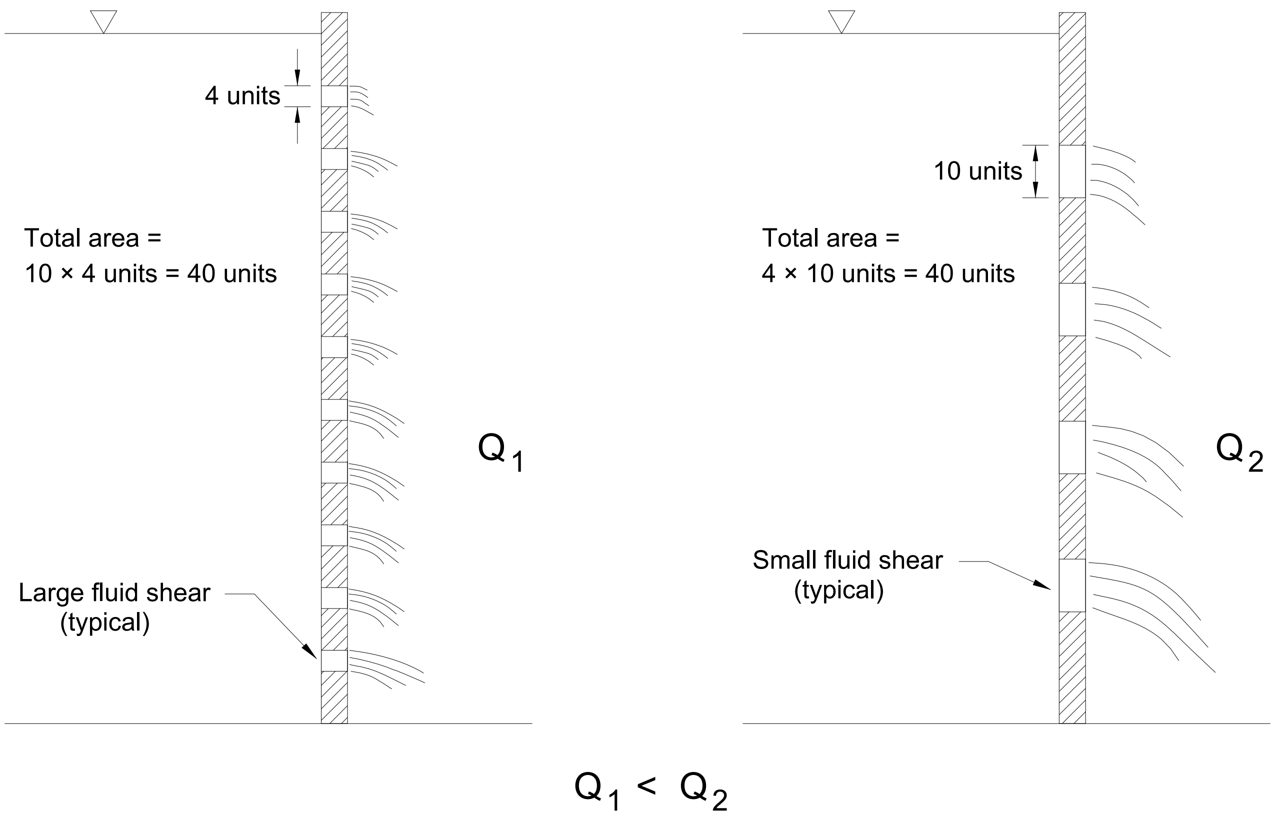


Figure A. Example of flow from two perforated tanks

For a particular soil type (e.g. sand or clay), as void ratio decreases, permeability increases [1]. However, soils permeability is also influenced by grain size shape, grain size distribution, mineralology, etc. because flow through the voids of finer grain soil is affected by capillary forces (fluid shear) and a turbulent flow regime similar to the tank example. This results in the somewhat unexpected result that a soil with a higher void ratio can have a lower permeability than another soil with a lower void ratio. That is, while the ratio of void space to grain volume is large for silt, the flow through the voids is relatively small due to the small size of the individual voids. Conversely, void space in gravel is smaller, as a percentage, to the particle volume but the individual voids are larger and the flow through those voids more closely approaches laminar conditions.

The soils presented in Table 1 have been listed in decreasing order of void ratio and likely increasing permeability. Void ratios for a number of perforated pipes have also been calculated and it is noticed that the 'permeability' of pipe is much greater than any surrounding backfill material. It should also be recognized that flow conditions through perforations in pipe has a similar behavior to that through soil, for similar reasons. Consider two perforation sizes, both of equal area but differing number of slots, similar to the tank example. The first consists of many smaller perforations and the second, fewer large perforations. Since flow through the pipe with larger perforations will be less turbulent it will be able to pass more flow than the pipe with the smaller perforations.

Table 1. Typical void ratios

Material	Typical Void Ratio
Glacial till, very mixed-grained[1] (foundation)	1.50
Windblown silt (loess) [1]	0.99
Uniform sand, loose[1], (foundation)	0.85
Mixed-grained sand, loose[1], (foundation)	0.67
Glacial clay, stiff[1] (foundation)	0.60
Uniform sand, dense[1], (filter)	0.51
Uniform gravel, dense[2] (drain)	0.45
Mixed-grained sand, dense[1] (single stage filter)	0.43
Pipe wall (PVC slots), 12 in. dia., 3/4 in. wall thickness, 0.125 slot width	0.894
Pipe wall (HDPE slots), 10 in dia, 0.118 in. slot width, 1.18 in. slot length, 3 hole pattern, 1/4 in. wall thickness	0.062
Pipe wall (clay butt joint), 12 in. dia, 1/2 in. joint width, 5 ft. joint spacing.	0.043
Pipe wall (HDPE holes) 12 in dia, 0.394 in. hole dia., 6 hole pattern, 1/4 in. wall thickness	0.019

[1] - From *Foundation Engineering*, Table 1.4 [2]
[2] - From *Foundations, Retaining, and Earth Structures*, Fig. 3-4 [3]

A third way to view flow through void space is to consider butt joint pipe drain design. That design, used on many older dams, consists of solid (nonperforated) clay, ceramic, or concrete pipe (sewer pipe), surrounded by an envelope of uniformly graded gravel. In this arrangement the gravel is laid in the trench invert, the pipe is placed leaving a gap between the individual pipe pieces and then covered by additional gravel to complete the envelope. The drain functions by collecting water in the gravel envelope and subsequently through the joints between the pipe segments. While this drain system does not meet modern filter criteria it is impressive in the quantity of water it can collect as indicated by the 'void ratio' shown in Table 1. Note that the joint open area is relatively small relative to the pipe cross sectional area but the opening width is large (≈1/2 inch). The same can be said for the voids in the gravel, relatively small volume but a large aperture. At Ochoco Dam in Oregon a drain of this type was able to collect about 6 cfs of flow over a 300 foot length [4].

As alluded to earlier, grain size distribution of any given soil will affect that soil's permeability. That is, a uniformly graded soil will have a greater permeability than a broadly graded soil when they have the same D_{10} size (size of particle for which 10 percent by weight is finer). This is because void space between sand particles in the uniformly graded sand is replaced by gravel particles in the broadly graded mixture as shown on Figure 1. The left side of the figure illustrates spheres of two sizes representing a uniformly graded soil (example: coarse sand). On the right side of the figure three larger spheres overlay the original figure and are shown in red. They represent the inclusion of gravel size particles making the soil broadly graded. The figure illustrates that the larger particles now replace previously available seepage space through voids and that lost space has been highlighted in blue. Note that the figure has not been corrected for the larger particles edge to edge contact with the surrounding particles. The elimination of void space in the broadly graded soil results in a lower permeability.

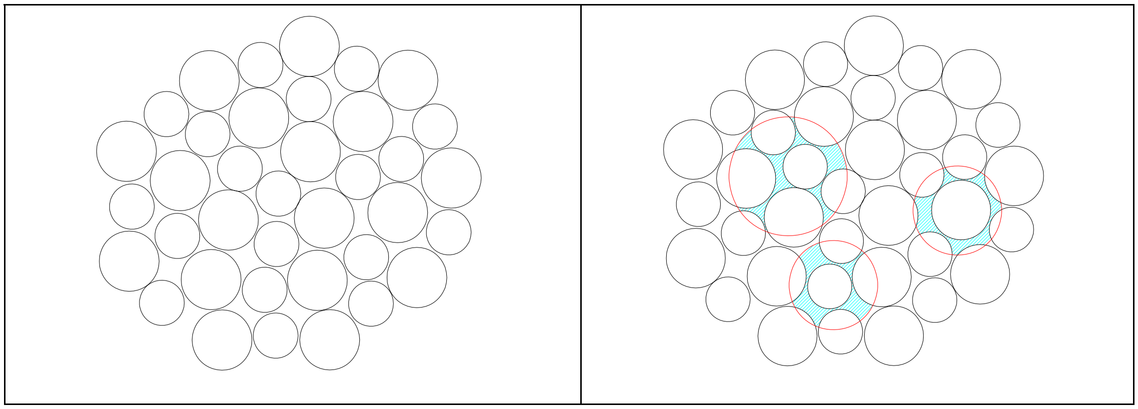


Figure 1. Comparison of void space for a uniformly graded soil and a broadly graded soil.

It is recognized that the seepage that passes through the foundation, filter, drain, and pipe is constant. That is, the system does not create or eliminate the total volume of water transported. The amount of seepage available is then dependent on the most constrained portion of the system. Since the foundation materials typically have the greatest void ratios (lowest permeabilities) they will be the controlling component. Consideration should be given though to assure that the filter does not act as a barrier (restriction to flow) to the foundation, which is discussed in more detail later. Seepage passing from material of higher to lower void ratio can also be thought of as focusing the seepage into the pipe.

In addition to the size of individual pipe perforations as described above consideration has been given to the amount of total perforation area in relation to the pipe cross sectional area. Knowing the perforation size, the equivalent length of pipe needed to match the pipe cross section area can be calculated. For commercially available HDPE pipe this length is typically in the range of 25 to 60 feet. That is, given an infinite water supply, a pipe could be made to flow full in 25 to 60 feet, a condition not required or desirable for toe drains. Therefore, the limiting factor of getting water into pipe is not through the perforations but rather getting the water out of the foundation.

Using standard filter design procedures it is possible to design a filter that is less permeable than portions of the foundation [5]. Such a barrier is illustrated in Figure 2. The figure represents a lenticular foundation of undifferentiated soil deposits. While no distinct layer of gravel is present, concentrated seepage can occur through the more pervious lenses. As shown in the figure a sand filter will then act as a barrier at the bottom of the trench. This can result in less than expected flow quantity entering the pipe.

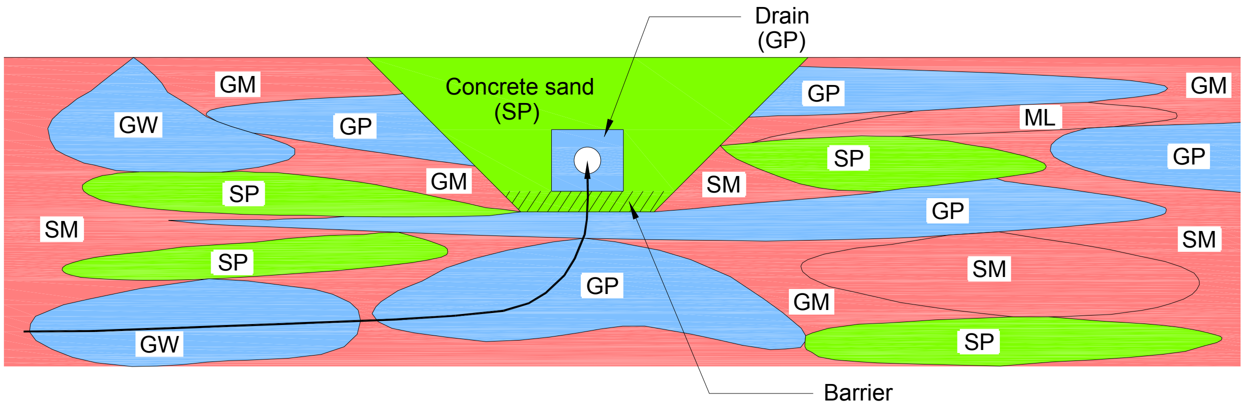


Figure 2. A filter for a toe drain which is acting as a barrier to a more pervious foundation layer.

Figure 3 is a second method of visualizing this issue. This figure summarizes the base soil gradations as well as a proposed filter. The base soil is shown by the limits of the regraded curves of the foundation soil samples. The regrading consists of scalping (mathematically) the material larger than the No. 4 sieve as described in filter design procedures [5]. Also shown on the plot is the average gradation for concrete sand, a common filter material. The hatched portion of the graph indicates the range of base soil gradations that would be coarser than the filter. Since this filter would be finer than these base soil gradations, it would act as a barrier to those materials (about 25% of the total base soil range taken at the D_{15} size).

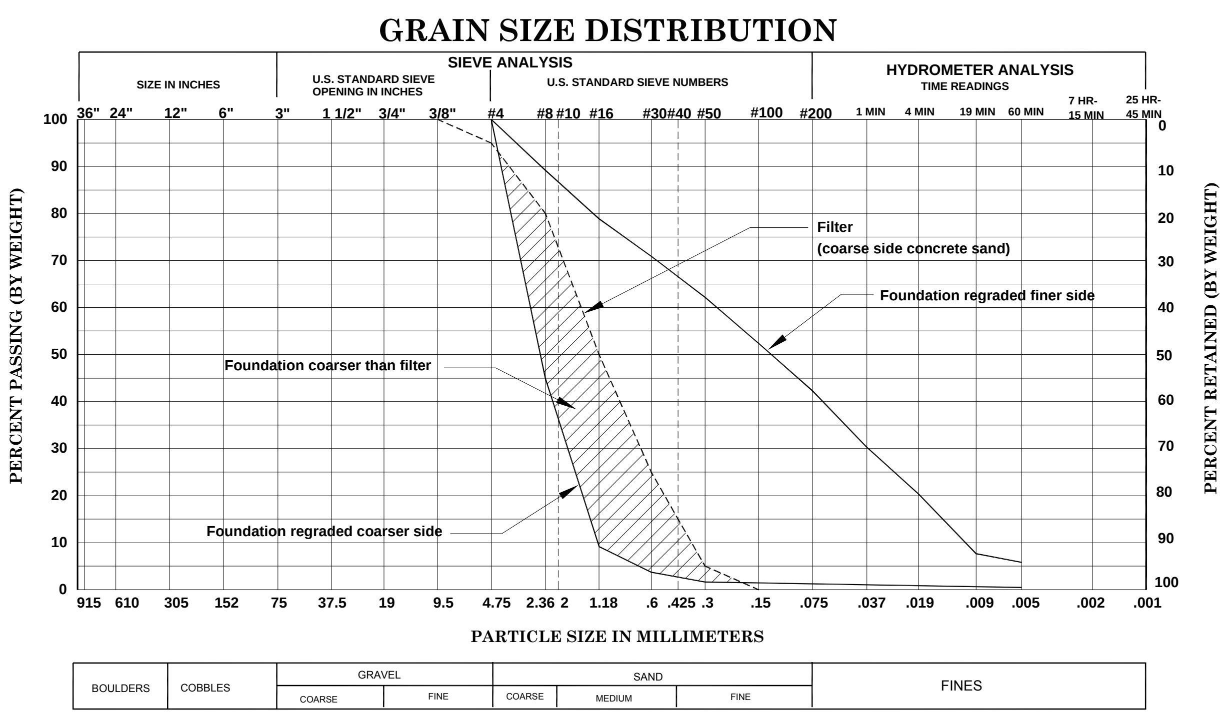
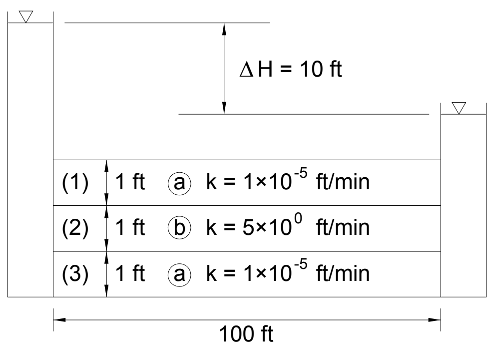


Figure 3. The filter barrier concept illustrated on a grain size distribution plot.

Figure 4 illustrates the effect of a filter barrier on theoretical soil deposits. The upper portion of the figure shows a box consisting of three layers of soil, each one foot thick. A head is applied to the left side of the box and drain on the right side. The configuration results in a head drop of 10 feet across the box. The box is 100 feet long as is the flow length. Utilizing Darcys equation, total flow through the box is calculated as indicated in the figure. The resultant total flow for this arrangement is 5 x 10^{-1} ft^3/min.

Taking the same arrangement and adding a filter barrier, shown on the right side of the box in the lower figure results in a total flow of 9.8 x 10^{-3} ft^3/min., 1/50th of the original flow.



$$Q_T = \Sigma\, k_i \cdot i_i \cdot A_i$$

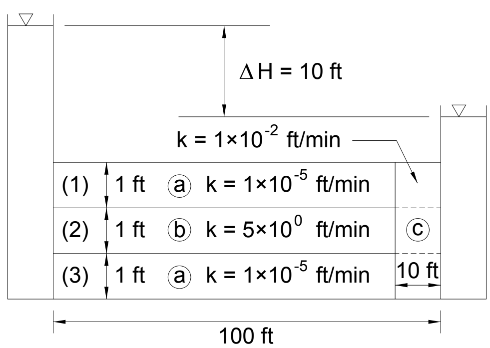
$$Q_1 = (1\times10^{-5})(10/100)(1) = 1\times10^{-6}\ ft^3/min$$

$$Q_2 = (5\times10^{0})(10/100)(1) = 5\times10^{-1}\ ft^3/min$$

$$Q_3 = Q_1 = 1\times10^{-6}\ ft^3/min$$

$$Q_T = Q_1 + Q_2 + Q_3 = 5\times10^{-1}\ ft^3/min$$

(a) $Q_{TOTAL} = 5\times10^{-1}\ ft^3/min$



$$k_{eq} = \frac{\Sigma L_i}{\Sigma \frac{L_i}{k_i}}$$

$$(k_{eq})_1 = \frac{100}{\frac{90}{1\times10^{-5}} + \frac{10}{1\times10^{-2}}} = 1.11\times10^{-5}$$

$$(k_{eq})_2 = \frac{100}{\frac{90}{5\times10^{0}} + \frac{10}{1\times10^{-2}}} = 9.82\times10^{-2}$$

$$(k_{eq})_3 = (k_{eq})_1 = 1.11\times10^{-5}$$

$$Q_T = \Sigma (k_{eq})_i \cdot i_i \cdot A_i$$

$$Q_1 = (1.11\times10^{-5})(10/100)(1) = 1.11\times10^{-6}\ ft^3/min$$

$$Q_2 = (9.82\times10^{-2})(10/100)(1) = 9.82\times10^{-3}\ ft^3/min$$

$$Q_3 = Q_1 = 1.11\times10^{-6}\ ft^3/min$$

$$Q_T = Q_1 + Q_2 + Q_3 = 9.82\times10^{-3}\ ft^3/min$$

(b) $Q_{TOTAL} = 9.82\times10^{-3}\ ft^3/min$

Figure 4. The filter barrier concept illustrated as flow through a laboratory box

Single Stage versus Two Stage Designs

A two stage filter consists of the drain pipe surrounded by a uniformly graded gravel which itself is surrounded by a uniformly graded sand as shown in Figure 5. The gravel material is often referred to as drain material and the sand envelope is known as the filter. Alternately the gravel has been referred to as the coarser filter and the sand as the finer filter. Others have also referred to them as the inner and outer envelopes, respectively. The filter grain size distribution is dependent on the foundation grain size distribution [6]. This dependency is prescribed by filter design requirements also known as filter compatibility. The grain size distribution of the gravel must be filter compatible with the filter as well as compatible with the pipe perforation opening size.

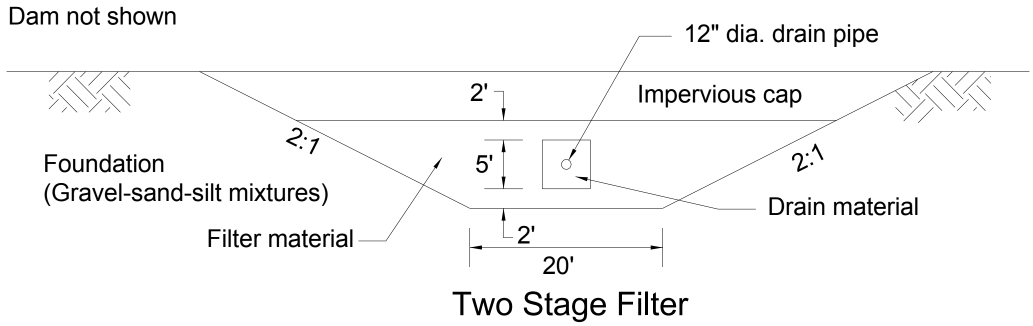


Figure 5. Typical two stage filter.

A single stage toe drain is similar to the two stage drain except one material is used to function as both the filter and the drain. This material must be compatible with both the foundation and the pipe perforations. Based on these requirements the material will consist of a broadly graded sand and gravel mixture. The advantage of a single stage filter is its simplicity of construction. However, there are a number of disadvantages such as; lower permeability as described above, segregation during placement, and possible perforation clogging. Additionally, the finer grained envelope will require a smaller opening size in the pipe which passes smaller amounts of flow than larger openings. A typical single stage filter is illustrated in Figure 6.

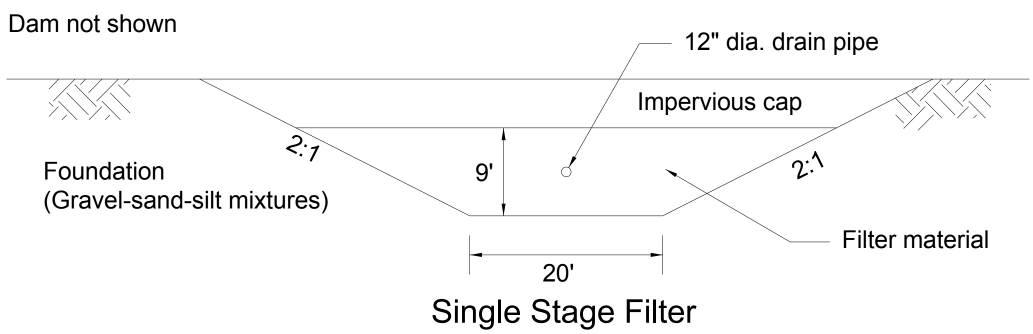


Figure 6. Typical single stage filter.

To illustrate the difference in seepage collection abilities of the two drain types, FEM (finite element method) seepage analysis was performed. The seepage model is not from a specific case history but does represent a typical toe drain system. The entire seepage model including loading and boundary conditions is illustrated in Figure 7.

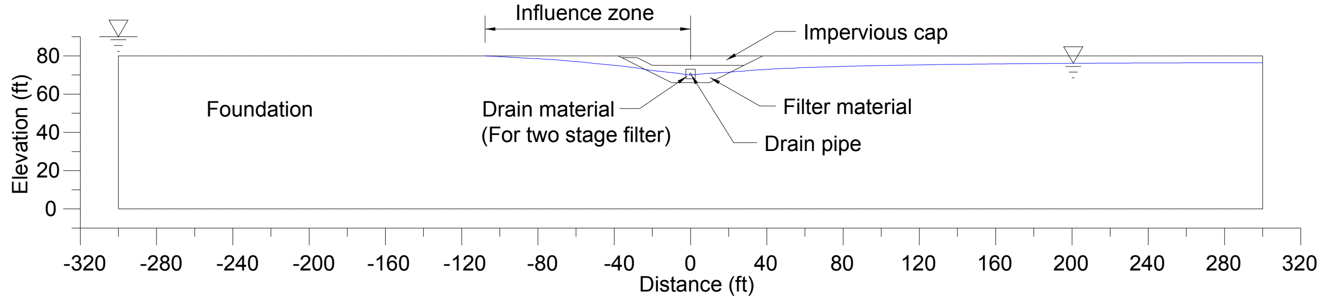


Figure 7. FEM seepage model.

Flow into the pipe was calculated for the two drain designs shown in Figures 5 and 6. The grain size distributions of materials used in the models are included in Figure 8 and the soil parameters are listed in Table 2.

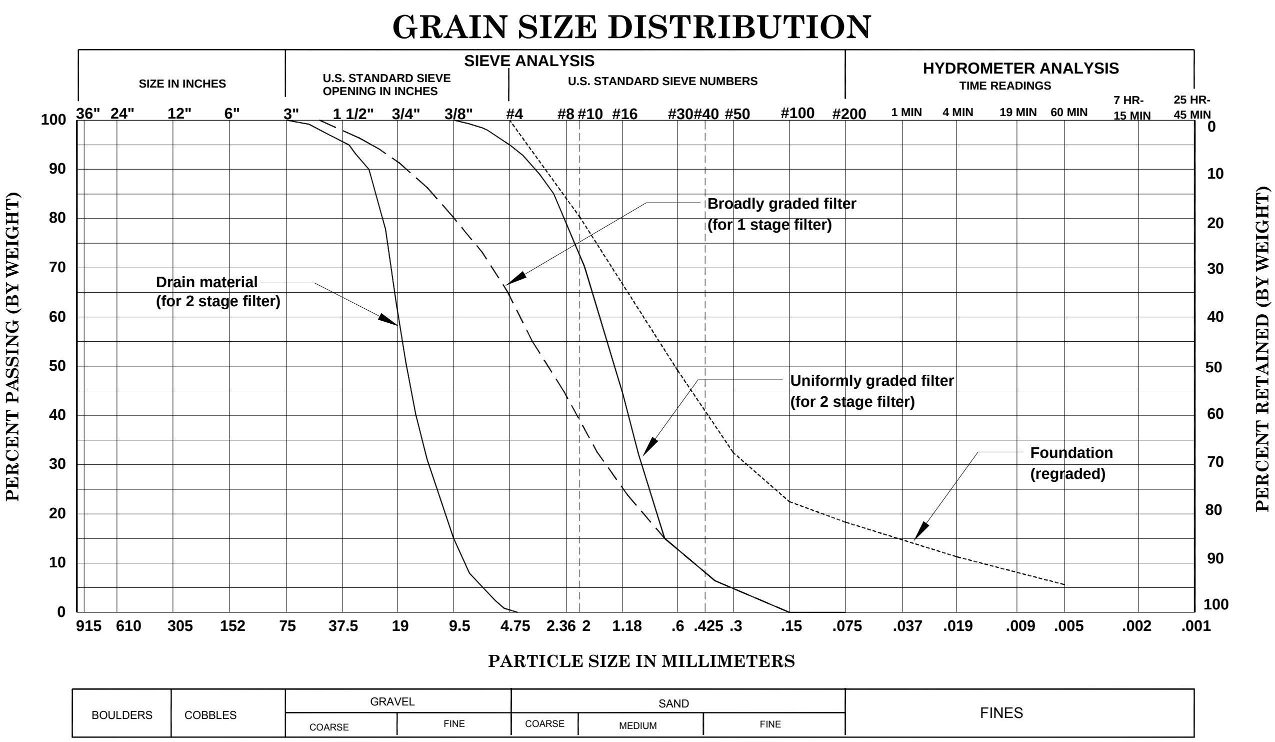


Figure 8. Soil gradations used in FEM analysis.

Table 2. Soil properties used in FEM model

Material	Permeability ft/yr (cm/sec)	Anisotropy k_h/k_v
Foundation (sandy gravel)	50,000 (4.9×10^{-2})	20
Uniformly graded filter (sand)	100,000 (1.0×10^{-1})	1
Broadly graded filter (sand and gravel)	75,000 (7.2×10^{-2})	1
Drain (gravel)	>10,000,000 (>9.7×10^{0})	1

Results of FEM analysis are presented in Figures 9 and 10. These results show total head of the single stage filter are about seven feet greater than the two stage case. This would result in artesian conditions at the location of the single stage drain. Additionally, for the example used here, the ability of the single stage filter to collect water is about half that of the two stage filter. It should be recognized that this example only addresses flow complications through differing filter elements. Problems also arise from the relationship between broadly graded single stage filters and pipe perforations. Case histories indicate that finer material of broadly graded filters can clog the pipe perforations further restricting flow.

Drain flow = 2.47 gal/min
Influence width = 107.6 ft

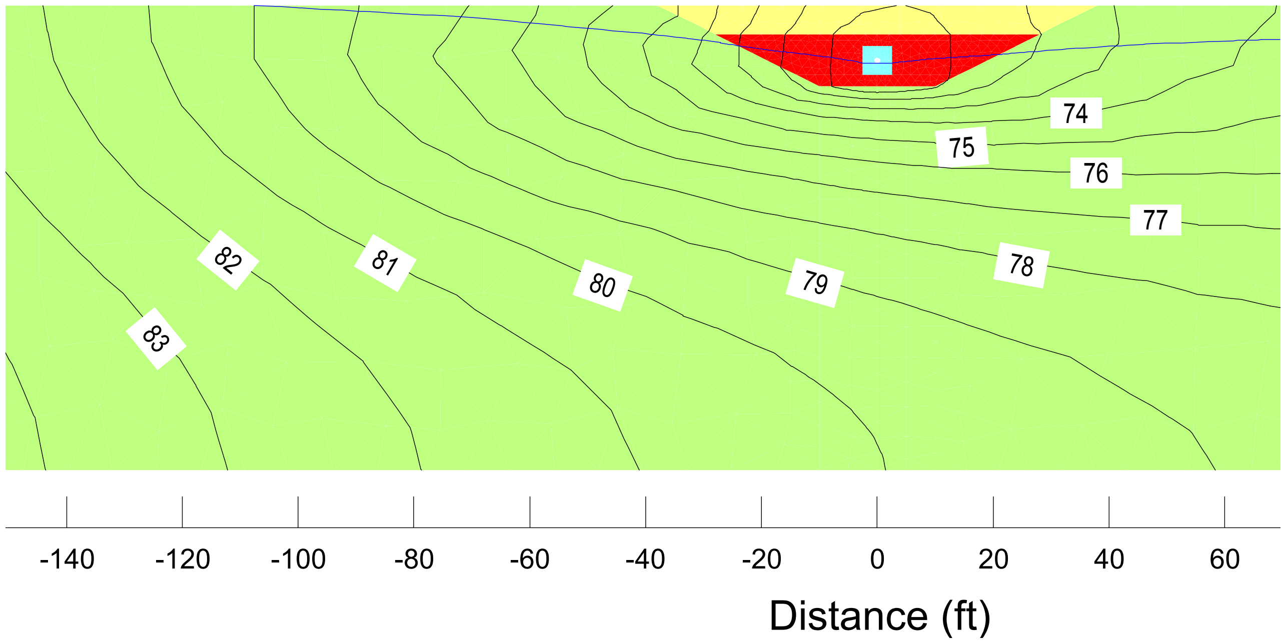


Figure 9. Graphical results of two stage drain FEM analysis.

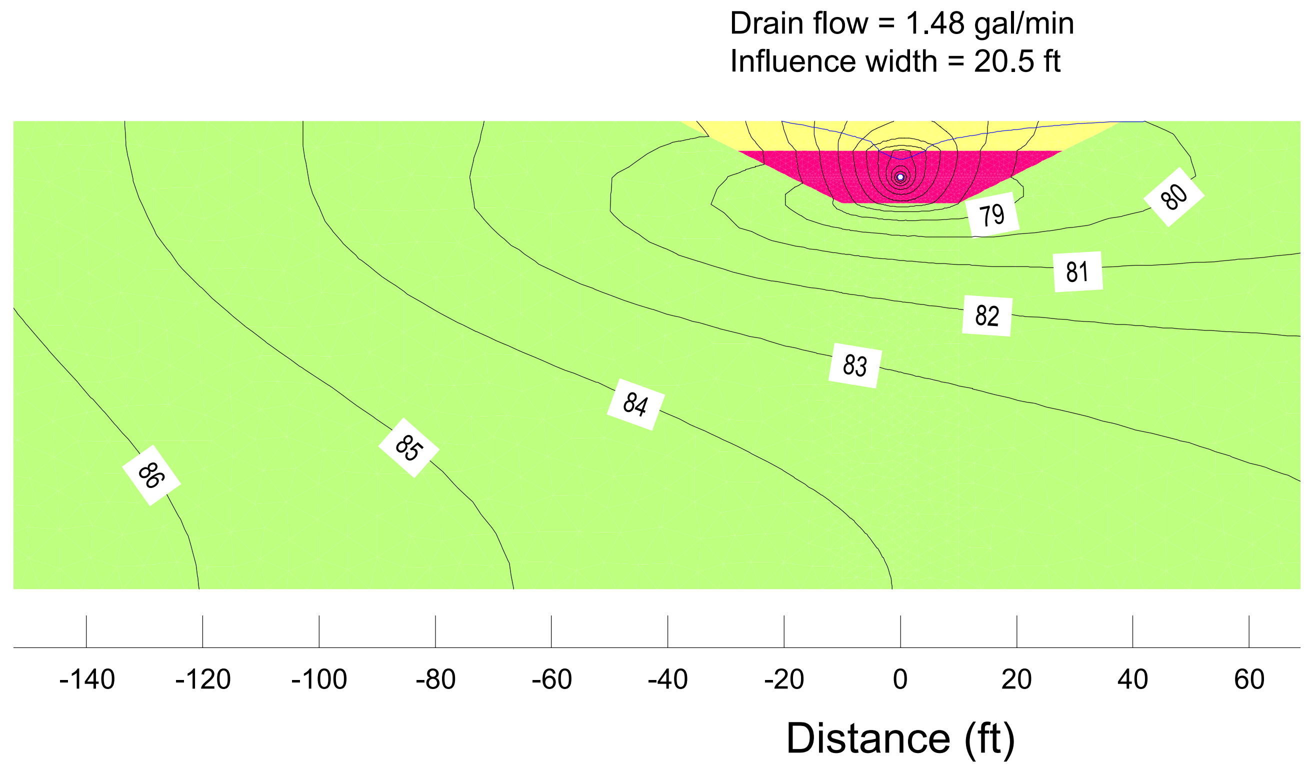


Figure 10. Graphical results of single stage drain FEM analysis.

The combined issue of the filter acting as a barrier [4] and single stage design [7, 8, 9] is presented in the following example. Figure 11 is a cross section through a typical embankment dam, including a toe drain, blanket filter, and chimney filter. In this situation the single stage chimney filter acts as a barrier to the undifferentiated high permeability layer under the dam. Although not shown on the figure, cracks or poor lift quality in the embankment can lead to similar conditions. These situations can lead to higher than expected hydrostatic pressures in the embankment. In fact, for the example illustrated, water would come out the face of the dam while water levels over the toe drain would be low, a condition which can lead to general confusion during incident examination. The solution for this situation would be to replace the single stage chimney and blanket filter with a two stage design. In the two stage design a coarse filter would be inserted into the chimney and blanket and connected to the coarse filter in the toe drain as shown in Figure 12.

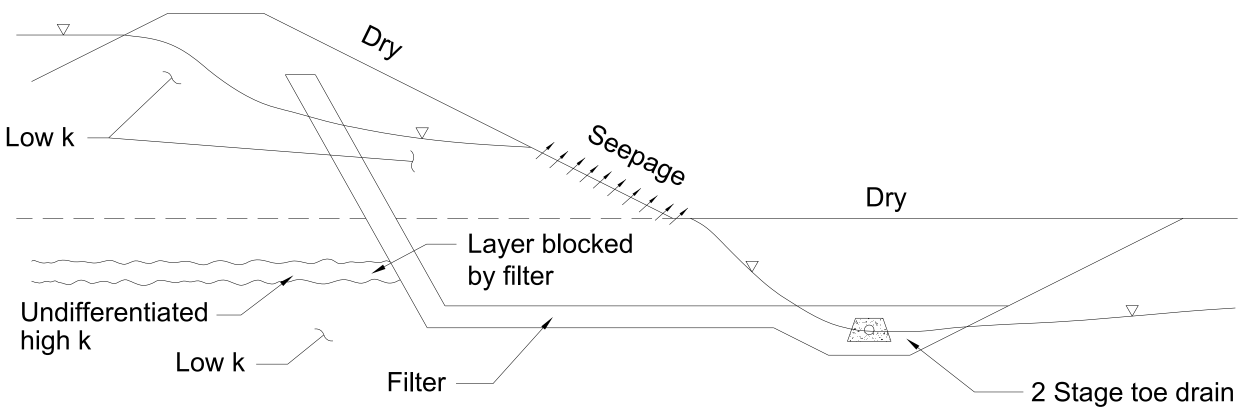


Figure 11. Example - Chimney filter as a filter barrier

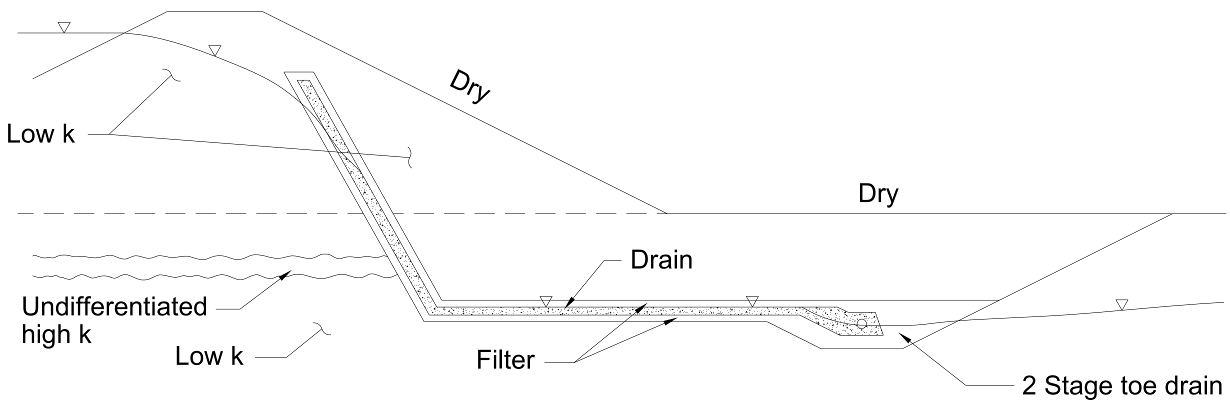


Figure 12. Example - Two stage chimney filter used to minimize the effect of filter barriers

Standard Materials for Use in Drains

Concrete sand (ASTM C 33 fine aggregate [10]) is often found to be an acceptable foundation filter for Category II and many Category I base soils, but its suitability should always be checked using a filter design procedure [5]. It is important to note that the ASTM specifications for C 33 fine aggregate include gradation requirements down only to the No. 100 sieve size. When specifying a filter of ASTM C 33 fine aggregate, it is necessary to add a gradation requirement for the No. 200 sieve size to assure that the fines are limited sufficiently so that the filter material has a high coefficient of permeability. The requirement for this modified material is presented in Table 3. Note that the fines requirement on the No. 200 sieve size is not to exceed 2% when measured in the stockpile and less than 5% when measured in place. The two requirements are provided to address material breakdown during fill placement operations.

When concrete sand is found acceptable there are a number of drain materials that are compatible with it. Design guidance varies on the procedure for sizing material in this situation. Many organizations use the rule that the D_{15} of the drain material should be no greater the four times the D_{85} of the filter. Reclamation (the U.S. Department of the Interior, Bureau of Reclamation) allows the drain material D_{15} size to be as large as nine times the D_{85} of the filter in the interest of maximizing the size of the drain pipe perforations. The larger multiplier is permitted because both materials are processed (engineered materials) and the material variability is much less than that seen in foundation materials. Also the gradients that can develop across the filter/drain interface are less than that found at the foundation/filter interface. Additionally, the larger particle sizes of the filter will require a larger gradient for particle movement than the gradient required to mobilize clay and silt size particles found in some foundations. The upper boundary of nine is based on laboratory research [6]. Since the four multiplier is recognized as the boundary between 'no erosion' and 'partial erosion', confirmation testing can be done when designing with values greater than four. Since the factor of safety against particle movement reduces as the multiplier approaches nine, confirmation should always be done for multipliers greater than seven. ASTM C 33 standard aggregates are given in Table 4 for both criteria.

Given the drain materials listed in Table 4 the recommended pipe perforation sizes have been found using the Reclamation design standard [5]. The sizes are given in Table 5. As described previously, larger drain material will allow larger perforation sizes, an attractive attribute. In order to maximize the pipe perforation size while maintaining the 4x criteria, a blended material has been identified. This blend is not an ASTM designated material but is produced from equal parts of three C 33 materials; No. 5, No. 7, and No. 9. These gradations are offered as guidelines and due to local availability other materials may also be satisfactory, such as state highway standard materials.

Table 3. Filter gradation

Modified Gradation of C 33 Fine Aggregate[1]

Sieve size	Percent passing, by weight
3/8-inch	100
No. 4	95 to 100
No. 8	80 to 100
No. 16	50 to 85
No. 30	25 to 60
No. 50	5 to 30
No. 100	0 to 10
No. 200[1]	0 to 2[2]

[1] Requirement beyond the ASTM C 33 designation.
[2] 2% stockpile, < 5% in-place.

Table 4. Drain gradations compatible with Modified C 33 Fine Aggregate

Gradation for ASTM C 33 Drain Materials (percent passing by weight)

Sieve size	No. 467	No. 57	No. 67	Blend 579	No. 8	No. 89
	$D_{15}F \doteq 9 \times D_{85}B$			$D_{15}F = 4 \times D_{85}B$		
2-inch	100	-	-	-	-	-
1½-inch	95-100	-	-	-	-	-
1-inch	-	95-100	100	90-100	-	-
¾-inch	35-70	-	90-100	75-85	-	-
½-inch	-	26-60	-	-	100	100
⅜-inch	10 - 30	-	20 - 55	45 - 60	85 - 100	100
No. 4	0-5	0-10	0-10	20-35	10-30	20-55
No. 8	-	0-5	0-5	5-15	0-10	5-30
No. 16	-	-	-	0-5	0-10	0-10
No. 50	-	-	-	-	-	0-5

The blend 579 gradation is a blend, in equal parts, of gradations No. 5, 7, and 9. It is not an ASTM standard aggregate.

Table 5. Maximum pipe perforation size for use with ASTM C 33 drain materials.

Maximum dimension inches (mm)*					
No.467	No. 57	No. 67	Blend 579	No. 8	No. 89
0.53 (13.4)	0.38 (9.6)	0.35 (9.0)	0.37 (9.5)	0.19 (4.8)	0.18 (4.5)

* - The minimum measurement should be used. For circular perforations, use the diameter; for slots, the width measurement is used.

Types of Pipe

A variety of materials have been used for drain pipes in the past including corrugated metal (CMP), clay, concrete, PVC and HDPE. The use of clay pipe is not recommended due to low strength and poor design life. Concrete pipe is acceptable although costly. The use of CMP is not recommended due to corrosion and short life span. HDPE single wall corrugated pipe, which comes on rolls, should not be used because of its low strength. Double wall corrugated HDPE pipe, which comes in tubes, is acceptable. HDPE noncorrugated (profile) pipe is acceptable although off the shelf perforated products are not available and it is costly. Similar to HDPE pipes not all forms of PVC pipe are acceptable. Due to low strength and brittleness well screen type pipe (described previously) and pipe smaller than schedule 80 are not recommended. Schedule 160 PVC pipe with an SDR (Standard Dimension Ratio) of 26 has been successfully used but pipe strength should be checked for each application. As with the heavier HDPE pipe, these heavier PVC pipes do not come preslotted.

As described previously, in order to maximize flow into the pipe, larger perforations are desirable. Two types of pipe are commonly available for toe drain applications. The first is marketed as 'drainage' pipe and typically has perforation sizes of 0.4 to 1.2 inches. The second is 'screen' pipe and has perforation sizes in the range of 0.01 to 0.125 inches. Since the larger number of perforations required for screen pipe results in weaker pipe as well as poor inflow characteristics, pipe with larger and less numerous perforations is recommended.

Recommendations

The critical design element in a toe drain system is the gradation of the filter. Filters should be uniformly graded with minimal fines content. The filter design should be checked to make sure that it does not act as a barrier against the foundation.

Broadly graded single stage filters have lower permeability and an assortment of other problems. This filter configuration should not be used in toe drain applications. Toe drain filters should include two stages consisting of a finer (sand) outer envelope and a coarser (gravel) inner envelope.

In order to optimize flow into the drain pipe materials the largest acceptable void size should be used. For the fine filter, uniformly graded fine to coarse sand should be used and for the coarse filter, uniformly graded fine to coarse gravel should be used. For the pipe perforations, fewer large perforations are preferable to numerous small perforations.

When concrete sand is acceptable for the fine filter, the coarse filter can be ASTM C 33 No. 57 coarse aggregate when adhering to Reclamation design criteria and a blend of C 33 No. 5, 7, and 9 can be used when using USACE (U.S. Army Corps of Engineers) or NRCS (Natural Resources Conservation Service) criteria.

When using ASTM C 33 No. 57 drain material, HDPE double wall pipe with 10 mm perforations should be used.

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