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Seepage Through Mine Tailings Dams

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SYNOPSIS A determination of the phreatic surface in dams constructed of coal refuse, under the criteria set forth in the National Dam Safety Act was made. All of these dams were over 20 years old. Most of the embankments studied were not constructed with any compaction specification and no effort was made to compact the coal refuse. A comparison of actual phreatic surface to the theoretically predicted surface is made using the classical seepage theory and the computer program SEEP. The embankments are old enough to present the steady slope phreatic surface, and thus, provide a good check of the ability of current methods to predict the actual phreatic surface. It was found that the fine refuse deposited in the reservoir acts as an upstream "impermeable" blanket and the phreatic surface remains relatively low. By back calculations, it was determined that the permeability anisotrophy ratio is between 1.1 and 4.2 in uncompacted coal refuse dams.

INTRODUCTION

Water permeates all earthen embankments which retain water. The effectiveness of these structures depends on how the structure is designed to route this seepage water. Thousands of water retaining embankments built from coarse coal refuse currently exist in the United States. All of these structures generate seepage which must be safely routed through the dam. Typically, internal drainage is designed for this purpose. Coal refuse embankments are constructed as part of the refuse disposal from coal preparation plants . Two types of solid waste products result from the preparation of coal. One is a coarse refuse consisting of rock, generally shale, mined along with the coal and removed by washing and, commonly, vibration tables. The second is fine refuse which is commonly produced by a flotation process. Often the volume of refuse which must be discarded is equal to the amount of coal mined, that is, for each ton of coal produced, a ton of refuse must be discarded. Many plants process upward of 1,000,000 tons of coal per year, so the amount of refuse that must be disposed of is large.

The refuse is generally separated between the coarse and the fine at the #28 sieve (0.6 mm). Sometimes the separation is at the #100 sieve (0.15mm), but most coarse refuse is plus #28 sieve (0.6 mm) material. It is necessary to dispose of these two materials. Typically, an embankment is constructed from the coarse refuse and the fine refuse is slurried into the reservoir created by the embankment. The construction of the dam must be sequenced with the production of the fine refuse; that is, the dam construction must stay ahead of the slurry deposits to provide enough volume for the disposal of the slurry, plus sufficient freeboard for storage and/or passage of the design storm which is usually the PMF. The embankment, while not a true dam holding back water, is, however, designed as if it were containing water and the slope stability, seepage and other requirements are calculated with the embankment being treated as if it were a water retention dam.

These embankments are normally designed for the life of mine which generally is 20 years or more. The embankment is, thus, constructed over a 20-year period and rises along with the level of the slurry being pumped behind it. The slurry is usually deposited near the face of the embankment forming a beach or delta near the embankment and there is seldom water impounded immediately against the coarse refuse embankment (Figure 1).

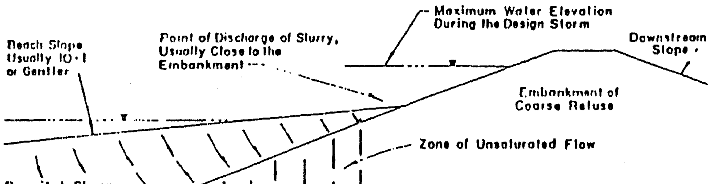


FIGURE 1. Typical Slurry Beach

Coarse refuse from the typical preparation plant generally is graded up from a #28 sieve to a top size of about 3 to 4 inches and therefore, classifies as a coarse sand and gravel. Typical coarse refuse grain size curves (as the refuse comes from the plant), along with typical curves for slurry, are shown in Figure 2.

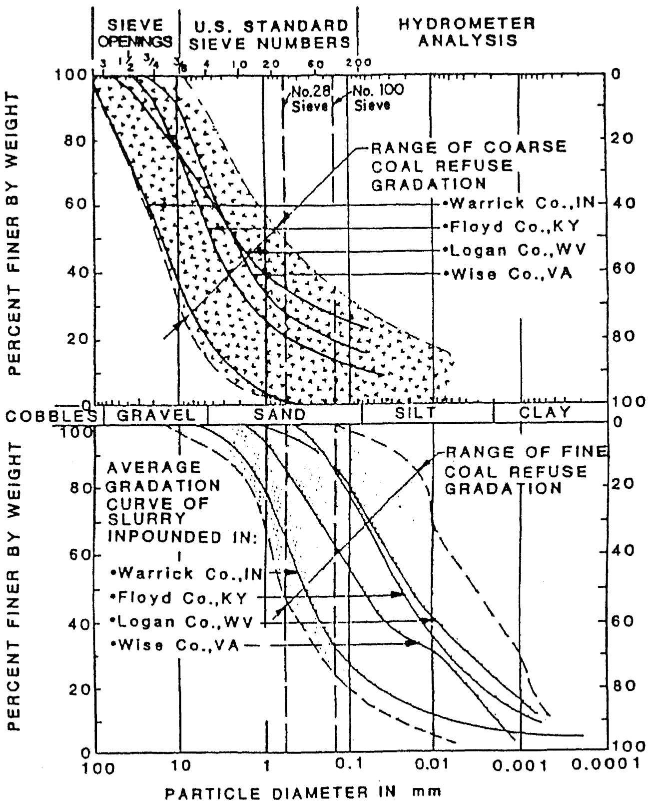


FIGURE 2. Typical Gradation of Coarse and Fine Refuse

Being a granular material, the drainage characteristics of the coarse refuse are typical of a porous media that can pass relatively large quantities of water in a short amount of time. Tests performed on "fresh" (newly processed) refuse typically reveals a high permeability and, being primarily a sand and gravel, a low ratio of horizontal to vertical permeability. The question arises, since coarse refuse may be a soft material, usually being a crushed black shale, how does this material perform with time as far as internal drainage is concerned? Of particular interest is what happens to the permeability (and thus the phreatic surface) once the material becomes saturated. Since the coarse refuse may be relatively soft, can it be relied on to maintain its' good drainage characteristics, or will it break down with time leading to a phreatic surface build-up in an embankment?

The position of the calculated theoretical phreatic surface has a great deal to do with the embankment stability and the design of drains to be constructed into a refuse embankment and, thus, the cost. It is, therefore, desirable to understand how the long-term phreatic surface performs in a refuse embankment. In order to answer these questions, six (6) existing refuse embankments ranging in age from 24 to 44 years were studied. In this study, actual long-term steady-state seepage phreatic surfaces were compared to computer generated phreatic surfaces using various assumptions relative to the permeability of the coarse refuse and the ratio of horizontal to vertical permeability.

SEEPAGE THEORY APPLIED TO COARSE REFUSE DAMS

The theoretical position of the steady-state phreatic surface in any homogeneous dam is independent of the actual value of permeability and is dependent only on the physical dimensions and the ratio of horizontal to vertical permeabilities. According to theory, the phreatic surface in any homogeneous dam would exit on the downstream surface of the dam at a position dictated by the ratio of horizontal to vertical permeability regardless of the actual value of permeability. The position of the phreatic surface for various ratios of horizontal to vertical permeability in a homogeneous dam with and without a drain are as shown in Figure 3.

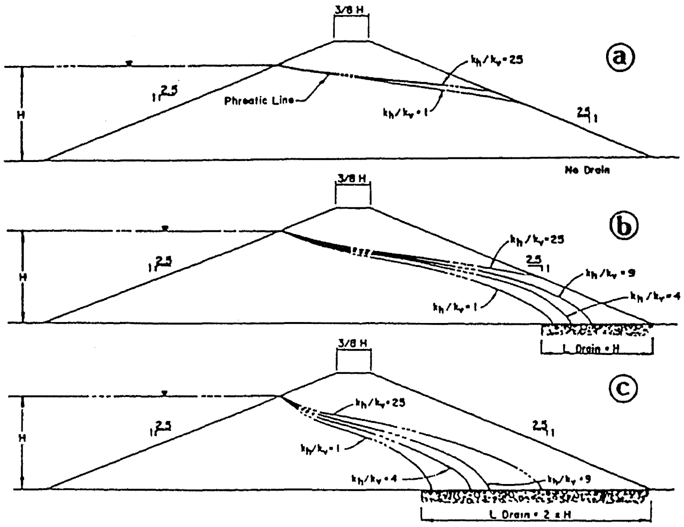


FIGURE 3. Variation of Phreatic Surface with Anistophy

As shown in Figure 3, seepage theory indicates that the phreatic surface would break out on the downstream slope of the embankment within a relatively narrow range regardless of the overall permeability. If however, the horizontal permeability is high enough to allow drainage faster than the vertical permeability will allow the seepage source to infiltrate into the dam, the phreatic surface will not build up as indicated by the theory. One method of predicting the phreatic surface is, therefore, to calculate the total seepage into the embankment and then calculate how much cross sectional area is needed to exit the water considering the coarse refuse as a "drain."

In actual fact, coarse refuse dams impounding fine refuse are not homogeneous structures. They, in essence, consist of a coarse shell (coarse refuse) and an upstream, relatively impermeable facing (fine refuse). The fine refuse usually has a permeability on the order of 100 to 1,000 times less than that of the coarse refuse, thus it acts as a less permeable upstream facing on the dam and the embankment functions as a drain. The presence of slurry on the upstream face of the dam must be taken into account to accurately predict both the location of the phreatic surface or the amount of seepage. The fine refuse is generally deposited at the embankment face forming a delta of fine material adjacent to the embankment. Except for storm events, water is usually not impounded directly against the embankment or if impounded against the embankment is relatively shallow creating a window of water (Figure 1).

By taking the difference in permeability of fine and coarse refuse into account, it is possible to predict the phreatic surface for various ratios of permeability of coarse to fine refuse. Figure 4 shows the theoretical effect of slurry with permeabilities ranging from 1/100 to 1/1000 of that of the coarse refuse on the computed phreatic surface at various ratios of horizontal to vertical permeability of the coal refuse (the same anisotropy ratio was assumed for coarse refuse and for fine refuse).

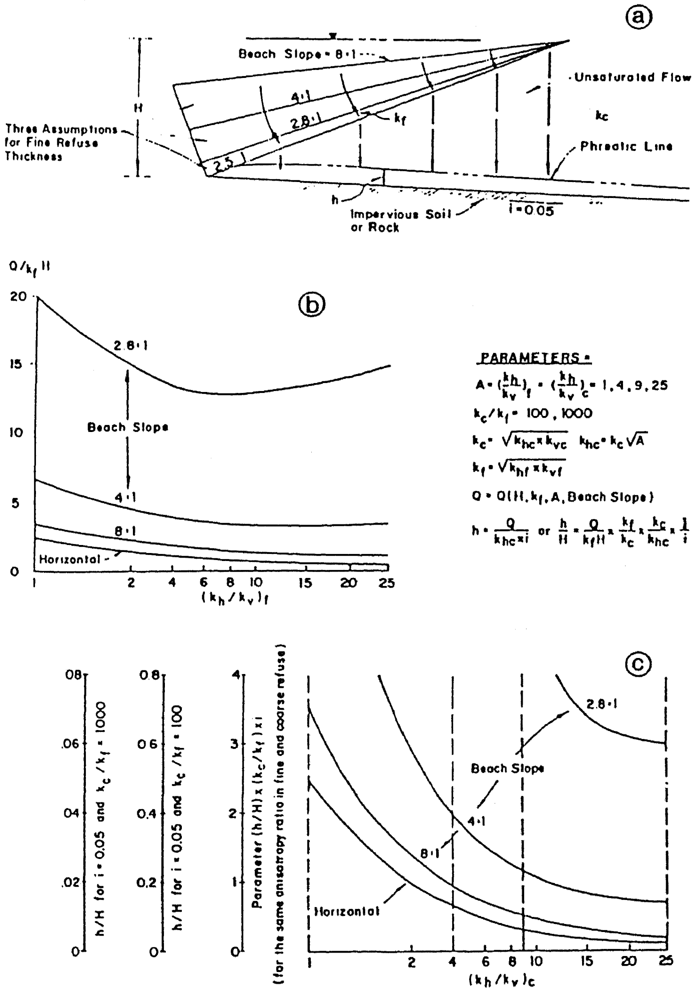


FIGURE 4. Relation of Beach Slope to Seepage

It can be seen that when the beach slope of the slurry is about 4:1 or gentler, an increase in the anisotropy ratio yields a decrease in the quantity of seepage. This is because the seepage flow is mainly a function of the vertical permeability of the fine refuse, K_{vf}, which decreases with anisotropy ratio when the equivalent isotropic permeability ($k_f = k_{hf} \times k_{vf}$) is assumed constant (Figure 4b).

Accordingly, the depth of saturated flow in coarse refuse, h, decreases with the anisotropy ratio. The decrease is greater than the decrease in the quantity of seepage, because the flow through coarse refuse is mainly governed by the horizontal permeability, k_{hc}, which increases with the anisotropy ratio when the equivalent isotropic permeability ($k_c = k_{hc} \times k_{vc}$) kept constant (Figure 4c).

It is apparent that the decision of whether to design the embankment as a water retention structure or as a coarse structure shell with an upstream "impervious" facing makes considerable difference in the calculated positions of the phreatic surface. The position of the phreatic surface and the amount of seepage dictates the design of any internal drainage and, thus, the initial capital cost of the project.

Typically, values of the ratio of coefficient of horizontal to vertical permeability used in design is required to be 9:1, and the presence of the slurry is ignored. The assumption of a ratio of 9:1 for k_h/k_v yields a fairly high position for the phreatic surface in homogeneous embankments and thus dictates the design of a relatively large drain in the embankment. The position of the drain is designed on the basis of the ratio of horizontal to vertical permeability, i.e., the larger the ratio of horizontal to vertical permeability, the longer the drain will need to be to yield a phreatic surface that is not too close to the downstream slope of the embankment. Obviously, by using too conservative a value of the horizontal to vertical permeability ratio, the drain is over-designed and becomes longer than necessary. The cross-sectional area of the drain is designed based on the actual value of permeability and the amount of seepage. This design becomes very conservative if the effect of the slurry on seepage is ignored.

DETAILS OF STUDY

The purpose of this study was to compare actual phreatic surfaces in "old" refuse dams to computer modeled surfaces taking into account the presence of the slurry as a less permeable part of the dam and utilizing various ratios of horizontal to vertical permeability. All of the embankments considered in the study are "old" embankments, and it can be said that steady-state conditions have been reached. By comparing the computer modeled surfaces to the actual phreatic surfaces, it is possible to determine the effect of the slurry beach on the seepage patterns in the coarse refuse embankments and to more accurately predict the ratio of horizontal to vertical permeability for the coarse refuse.

After the failure of Buffalo Creek in 1972, the then-existing refuse impoundments were required to be evaluated. The evaluation included the installation of piezometers for the determination of piezometric surface; as well as the determination of strength and other parameters. Some six (6) of those embankments have been chosen for presentation in this paper. All six (6) embankments were studied, and piezometers installed between 1975 and 1978. The phreatic surface has been continuously monitored in these embankments over a period of at least 14 years and the embankments range in age from 24 to 44 years. Thus, it can be safely said that the phreatic surfaces represent long-term, steady state seepage conditions and provide an adequate model for determination of the ratio of horizontal to vertical permeability of the coarse refuse and the long term effect of the slurry.

The classical seepage theory and the finite element computer program, SEEP, were used to model the phreatic surfaces for various assumptions. A ratio between permeabilities of coarse and fine refuse of 100 was used in this study. Using the program SEEP, the sections of the various embankments in question and the level of impounded water and/or slurry phreatic surfaces were developed for different assumed ratios of horizontal to vertical permeabilities. By comparing the developed phreatic surface modeled by the program SEEP to the actual long-term steady state phreatic surface, it is possible to determine which ratio of horizontal to vertical permeability most accurately models the actual phreatic surface.

EMBANKMENT DESCRIPTIONS

A list of the embankments and their locations, height, slopes, and depth of impounded water and/or slurry is given in Table 1.

TABLE 1

Embankment No.	Location	Height (ft)	Average Downstream Slope	Crest Elevation (ft)	Slurry/ Water Elevation (ft)	Ages Years	Date of Piezometer Installation
1	Fairview, WV	180	2:1	1276.0	1265.3	24	1978
2	Fairview, WV	102	2:1	1236.4	1219.0	44	1975
3	Shinnston, WV	138	2.5:1	1205.2	1197.5	34	1975
4	Granville, WV	160	2.5:1	1235.0	1205.0	34	1977
5	Maidsville, WV	160	7:1	1155.0	1128.0	24	1977
6	Blacksville, WV	28	2.5:1	1008.0	1002.5	24	1976

Table 1 shows the dates that the piezometers were installed in the embankments as well as the ages of the embankments. Readings of the piezometers have been taken on a weekly basis since the date they were installed. The information in Table 1 was utilized to develop the phreatic surface for each embankment. There is some variation in the phreatic surface seasonally due to storm runoff or additional impounded water or changes within the embankment. However, for purposes of comparison, the average readings in each of the piezometers for each of the embankments was taken to plot the position of the phreatic surface.

COMPUTER MODELING USING SEEP PROGRAM

The computer modeling was done using three (3) assumptions.

1. The entire section of the embankment is coarse refuse and there is no slurry, but the reservoir is filled with water to its final pool level with steady state seepage conditions developed. This is the assumption normally made in the design of these embankments and the computed phreatic surface is similar to those in Figure 3a.
2. There is no slurry in the reservoir, but the coarser refuse located near the toe of the dam acts as a drain. Figures 3b and 3c show the calculated phreatic surface for two (2) different assumptions regarding the extent of this drain.
3. The embankment is totally constructed from coarse refuse and there is finer material with a lower coefficient of permeability immediately adjacent to the embankment sloping at a 2.8:1, 4:1 or 8:1 slope out from the embankment (a thin layer of fine refuse over coarse refuse). In this assumption, the coarse refuse in the embankment will drain all seepage permitted by the fine refuse without saturation, and the computed phreatic surface is of the type shown in Figure 4.

These analyses were then all compared to the actual phreatic surface to determine the type of analysis that yielded the best fit with the actual surface. This analysis was done for various ratios between the coefficients of horizontal and vertical permeability for the fine and coarse refuse and a ratio of 100 between the permeabilities of the two materials.

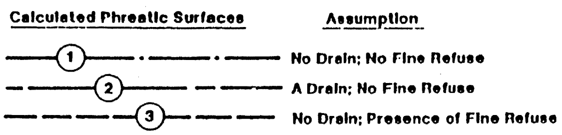
The following assumptions were made to compute different phreatic surfaces for the six (6) embankments studied.

1) an 8:1 beach slope,

2) a permeability anisotropy ratio of 4:1 for both fine and coarse refuse; and

3) a coefficient of permeability for coarse refuse 100 times greater than for fine refuse.

The phreatic surfaces computed in this manner are compared with the actual measured phreatic surfaces in Figures 5 through 10.



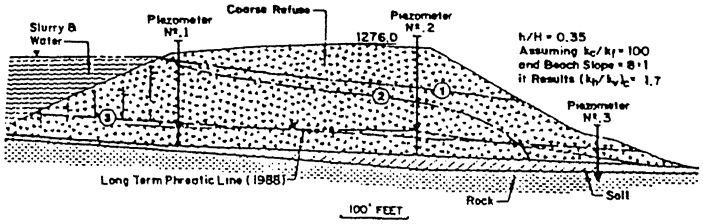


FIGURE 5. Case History #1

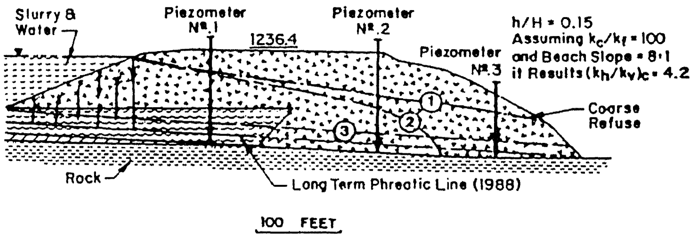


FIGURE 6. Case History #2

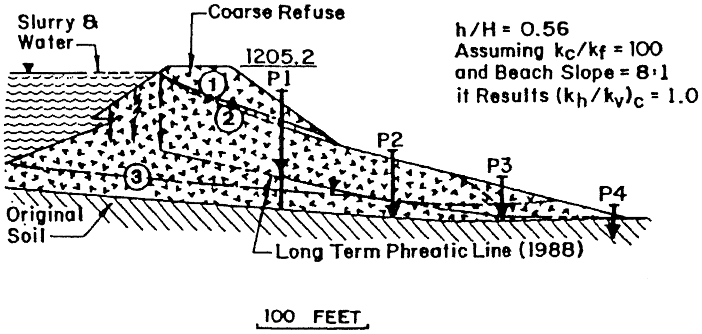


FIGURE 7. Case History #3

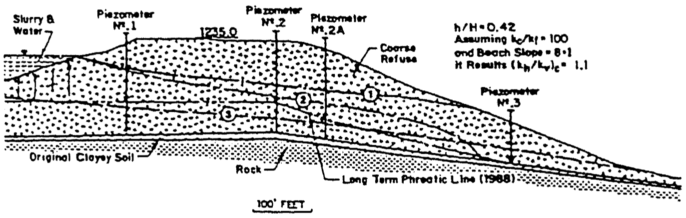


FIGURE 8. Case History #4

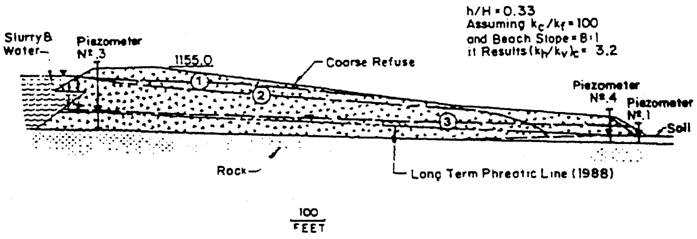


FIGURE 9. Case History #5

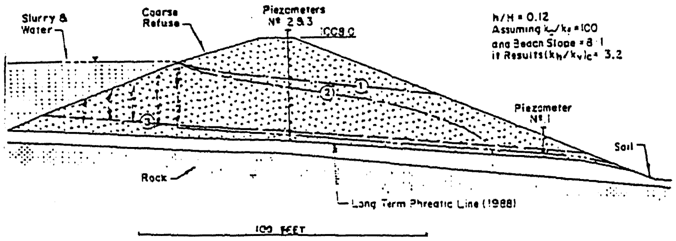


FIGURE 10. Case History #6

Among the calculated phreatic surfaces those corresponding to the assumption of fine refuse on the upstream face of the embankment fit best with the measured ones. The height of the phreatic surface, h, divided by the total water head, H, varies in the calculations between 0.11 and 0.30, as compared with 0.12 to 0.56 for the actual phreatic surfaces. Table 2 compares the values of h/H and lists the calculated anisotropy ratio for coarse refuse for the "best fit" assumption.

TABLE 2

Embankment No.	Average Slope of the Foundation Soil, i (ft/ft)	Calculated h/H for A=4, 8:1 Beach and kc/kf = 100	h/H as Measured	Anisotropy Ratio to Yield Calculated h/H Equal to the Measured One
1	0.05	0.20	0.35	1.7
2	0.06	0.17	0.15	4.2
3	0.08	0.13	0.56	1.0
4	0.08	0.13	0.42	1.1
5	0.033	0.30	0.33	3.2
6	0.09	0.11	0.12	3.2

CONCLUSIONS

1. Coarse coal refuse is a relatively free-draining material and maintains its drainage characteristics over a long period of time without the material breaking down.
2. All coarse coal embankments studied showed excellent drainage characteristics without the need for drains.
3. This study would suggest that coarse coal refuse acts as a drain and very little additional internal drainage is needed.
4. From this study, it is concluded that the fine refuse effectively acts as an upstream "impermeable" blanket.
5. The influence of the assumed anisotropy ratio on the computed position of the phreatic surface is small as compared with the effect of the ratio between the permeabilities of coarse and fine refuse. Lower anisotropy ratios give more conservative results if unsaturated flow is assumed below the slurry and

coarse refuse interface and in part of the coarse refuse shell.

6. Conventional seepage design of coarse refuse embankments based upon long term water retention structures is too conservative from a seepage viewpoint because of the upstream face slurry deposition.

7. Refuse disposal systems with the embankments constructed from coarse refuse should have the fine refuse slurried into the reservoir at the embankment face to enhance internal drainage characteristics.

8. The ratio of k_h to k_v used in design for coarse coal refuse should be between 1:1 and 4:1. The average value found in those dams studied showed a ratio of 2.4:1, however, in order to take into account the effects of compaction required in today's construction, a value of 4:1 is probably more appropriate. The anisotropy ratio of the fine refuse deposited in water is probably greater, but it is conservative to assume the same value as for coarse refuse.

9. The presence of a slurry beach at the face of the dam should be considered in the design of the embankment. Temporary rises of water above the slurry beach during storm runoff do not appreciably affect the long-term, steady state phreatic surface.

ACKNOWLEDGMENTS

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