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STABILITY OF SLOPES WITH SEEPAGE

by

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ABSTRACT

STABILITY OF SLOPES WITH SEEPAGE

The effect of steady seepage on slope stability was based on laboratory tests on embankments having slopes of 2 to 1, 3 to 1, 4 to 1, and 5 to 1, and including sections with gravel toe, coarse central layer, coarse layer parallel to the surface, fine central layer, and alternating fine and coarse layers.

Computed stability numbers gave an indication of the change in location of the failure zone, as well as giving the cohesion values required for slope stability for frictionangles of 5, 10, and 20^o and for 0, 40, and 100 percent saturation above the phreatic surface.

Graphic correlations in three variables are presented by plotting stability numbers and the pore pressure parameter, Ru_{ave}. versus ratios of headwater and tailwater to embankment height. The possible contribution of tailwater to both surface and massive circular slope failures is clearly indicated. Also, an explanation of the shape of surface sloughing based on pore pressure distribution is presented.

Slope flattening does not reduce, but tends to increase the relative effect of steady seepage on the massive slope stability parameters of stability number and factor of safety. Such flattening in the presence of tailwater may increase the surface potential gradients tending to cause increased erosion and possible surface sloughing.

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INTRODUCTION

Modern earth moving equipment and construction techniques allow the engineer considerable freedom in shaping earth surfaces to fit his needs. However, every time a cut is made or a fill is placed on existing terrain, a problem in slope stability develops. The analysis of such problems is made difficult by the engineer's somewhat limited knowledge of soil shear strengths and the heterogeneous nature of most embankments. When flow of ground water is encountered or created by the impoundment of water, seepage forces and their accompanying pressures add complexity to the design of stable earth slopes. Consequently, steady state seepage forces and their effect on slope stability furnish the basis for this study. Steady seepage differs from the drawdown case associated with the upstream slope of an earth dam. The difference is that the water inflow controls and maintains the ground water surface independent of the permeability of the embankment material.

Slope failures in which steady seepage forces have a significant role can be divided into two basic types: (a) the massive movement of earth along a slip surface, and (b) progressive sloughing or piping of the slope surface. Of these, the massive movement type has received the most attention, since many engineers associate slope failure with the design of earth dams. In such designs, seepage is generally minimized and confined within the downstream slope by means of impervious cores and rock toes, thus eliminating the need to consider surface failure on the downstream slope. Upstream riprap protection limits surface deterioration. Unfortunately, in much engineering construction, seepage must be allowed to penetrate embankment slopes. In these instances, the second type of failure is possible and may result in local failures or trigger considerable material displacement.

In any engineering design, the engineer should be cognizant of the variables involved and have at his disposal the tools for evaluating their effect on his works. To provide tools for such analysis of earth embankments, stability numbers have been introduced in the literature. While much effort has been expended in evaluating these stability numbers for the no seepage and instantaneous drawdown cases, more information on the steady seepage case is needed. In designing systems of drainage canals, knowledge of the influence of steady seepage is needed. Here, the engineer is faced with the two types of failure previously mentioned, and needs to know when and to what magnitude the stability of a slope is affected by various seepage conditions. Also, if flow in the drainage canal is controlled by weirs or other devices, one must know the effect of tailwater on slope stability. This latter item is not covered in the literature, but an appraisal of the standard computational methods indicates that tailwater could adversely affect stability by reducing friction forces through buoyant action, or by forcing a concentration or change in the potential pattern near the surface. Although the informational needs noted above are discussed in terms of drainage canals, it is obvious that they are needed for many other applications as well.

Because of the needs expressed above, the purpose of this study is to provide the design engineer with information on the potentials and forces associated with steady seepage, and insight into their effect on slope stability. This purpose will be achieved by investigating the effect of various seepage patterns on the stability numbers of several selected embankments. Additionally, the pattern of potential distribution and zones of high head loss will be delineated.

The first decision in planning this study was to base it on experimental data. Consequently, a testing program was carried out in the hydraulics laboratory at Colorado State University. Before further discussion of these tests, the writers would like to call attention to their basic purpose of providing knowledge of velocity potential distributions. Therefore, the laboratory studies were designed to model the hydraulic parameters involved, rather than the mechanism of slope failure. Later in the study, the hydraulic forces determined were used in computations selected to show the magnitude of their effect on slope stability parameters.

Laboratory experimentation for this project utilized a specially constructed tank having a test section 10 ft long, 4 ft high and 2 ft-8 in. wide in which sloping sand embankments were placed. Sand was used as the test medium in order to facilitate the establishment of steady flow. The flows were varied by altering the headwater and tail-water elevations. Pore pressures at up to fifty locations were measured by manometer probes placed in the embankment. This procedure was followed for bank slopes of 2 to 1, 3 to 1, 4 to 1, and 5 to 1 as well as for five different-layered systems. Results of the tests on homogeneous slopes were checked by repetition using a coarser plasterer's sand.

PROCEDURE

This section discusses acquisition of experimental data for this study.

A. Apparatus

The apparatus used in the study consisted of a rectangular tank 10 ft long, 4 ft high, and 32 in. wide. The floor and walls were of 3/4-in. aluminum plate with the exception of an 8 by 4 ft test observation section of 3/4-in. plexiglass. Porous concrete blocks extending the height of the tank were placed in the remaining 2 ft of length. The blocks served to still the water flowing into this part of the tank and to support the vertical sides of triangular test embankments. Provision for the introduction and withdrawal of water consisted of 2-in. valved outlets near the top and bottom of each end of the tank. Bulkhead fittings for manometer connections were installed in the aluminum back of the 8-ft test section. A bank of fifty-three 3/8-in. rigid plastic manometers was attached to a board covered with graph paper calibrated to 1/10 of an inch and fixed to the back of the tank. The manometers were connected to the bulkhead fittings by flexible plastic tubing. Inside the tank, 16-in. long semi-rigid plastic manometer leads extended from the bulkhead fittings. These leads were wrapped with tape to form 1/4-in. collars at the third points, and the ends were covered with fiberglass insulation to prevent clogging by sand flow.

Dimensions of length and height were chosen to give the maximum visible test section using a standard 8 by 4 ft sheet of plexiglass and to provide stilling of water. A width of 32 in. allowed the use of two rows of concrete blocks, provided sufficient width for manual access, and limited the quantity of material movement to a reasonable amount.

The use of long semi-flexible manometer leads extending from the bulkhead fittings eliminated wall effect in the determination of pore pressures, and gave flexibility to the points at which pressure could be determined.

B. Materials

In order to overcome the problem of non-uniform compaction and to expedite the development of steady seepage, two sands were used as the test material in determining potentials. Using two sands allowed the introduction of stratification and provided a check on the reproducibility of results.

The first of these sands, referred to as sand number one, or the fine sand, was a white sand commonly used in flume studies. Properties of this sand include a uniform gradation, a dry rodded unit weight of 100.4 lbs/ft^3, an apparent specific gravity of 2.64, and a coefficient of permeability of about 1.3 ft/hr.

The sand labeled sand number two and sometimes referred to as the coarse sand in this study was a locally obtained plasterer's sand from which it was necessary to remove a small amount of fine material by washing. Other properties are a dry rodded unit weight of 101 lbs/ft^3 , an apparent specific gravity of 2.64, and a coefficient of permeability after washing of 6.9 ft/hr.

C. Test Embankments

Embankments of both fine and coarse sand were tested for the following cases:

2 to 1 slope with a height of 47 in.,

3 to 1 slope with a height of 30 in.,

4 to 1 slope with a height of 24 in., and

5 to 1 slope with a height of 18 in.

In addition, five configurations with a total slope height of 47 in. and 2 to 1 slope with stratification as follows were tested:

Configuration 1. Plasterer's sand with a 6-inch thick horizontal gravel toe.

Configuration 1a. As above with a protective layer on the slope.

Configuration 2. Plasterer's sand with a 4-inch thick horizontal layer of roof chips. Placed at an intermediate level in the embankment.

Configuration 3. Plasterer's sand with a 4-inch thick layer of roof chips parallel to the slope and placed at a shallow depth below the embankment surface.

Configuration 4. Plasterer's sand with a 6-inch thick horizontal layer of fine sand. Placed at an intermediate level in the embankment.

Configuration 5. A system of alternating horizontal layers of fine and coarse sand.

To check scale or size effect an embankment of fine sand with 2 to 1 slope and height of 24 in. designated as Model Section was used.

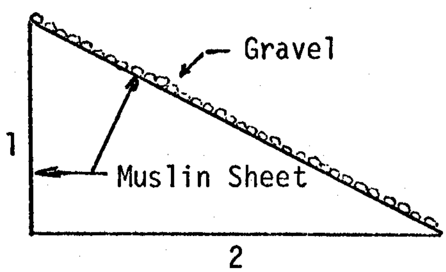
For surface inter-layer movement studies, a 3 to 1 embankment with a height of 28.33 in. was used.

D. Surface Cover

As the test embankments were unstable with regard to surface sloughing, the following stabilizing weights were used for flow out of the slope:

Homogeneous embankments:

2 to 1 slope, Tests 18, 19, 21, 2 in. of coarse sand and 1 in. of roof chips over a muslin sheet.



Tests 20, 22, 23, 24, 25, and 26, 5 in. of 1/4 in. pea gravel over a muslin sheet. (See sketch). Test 29, no cover. All other tests, 2 in. of roof chips over a muslin sheet.

3 to 1 slope, 2 in. of roof chips, and muslin sheet.

4 to 1 slope, 1 in. of roof chips and muslin sheet.

5 to 1 slope, no stone, but covered with a loose muslin sheet.

The test material was separated from the stabilizing weight on the slope surface of the test embankment by a muslin sheet extended to cover the face of the porous concrete blocks to prevent loss of sand through cracks.

All configurations, 1 in. roof chips and 2 in. stone. Also, in the configurations the stone, roof chips, and sand were separated by window screening.

The porous muslin sheet was used to protect the white sand from infiltration by the plasterer's sand. When tested for porosity, the sheet passed a relatively high flow of water without noticeable hindrance, while held under a water faucet.

E. Test Procedures

1) Construction of the Test Sections.

The initial step in constructing the test sections was the establishment of grease pencil grade lines for the sloping surface of the embankment. These lines were established on the sides of the tank by meter stick measurements. After establishment of the test section boundaries, the test material was introduced in layers and hand packed in place. If present, large stone was separated from the sand by screening. Simultaneously with material placement, the manometer leads were wrapped with fiberglass heat pipe insulation and placed at strategic locations. This placement of leads or ends was done by trenching into the sand at manometer positions from above and locating the leads by measurement from reference points established on top of the tank. After rough shaping of the largest test section, the tank was slowly filled with water from the bottom and slope side (seepage was allowed to develop toward the vertical side until equilibrium was established). After filling the tank to above the embankment surface, the tank was drained to allow final shaping and checking for movement of the manometer leads or ends. The tank was then again filled as previously and allowed to sit overnight.

2) Sequence of Testing

Test sections with flatter slopes were constructed in sequence by removing material from previously tested steeper slope. At this time the manometer lead locations were checked and re-located by trenching and measurement.

The sequence in which the test sections were constructed was as follows:

a) Fine sand, all standard size, homogeneous embankments defined earlier except the section for Tests 20, 22, 23, 24, 25, and 26.

b) Plasterer's sand, all standard size, homogeneous embankments.

c) Configurations in the order previously listed.

d) Half-scale fine sand model section.

e) Fine sand section for Tests 20, 22, 23, 24, 25, and 26.

f) 3 to 1 plasterer's sand model, previously mentioned, for surface washing study.

3) Pore Pressure Determinations

Following construction of the test embankment, the water level was allowed to rise and stabilize near the top of the tank. Next, the manometers were checked for response, uniformity of reading, and air bubbles, removed by surging the water in them. This surge was induced by introducing alternating positive and negative pressures at the top of the manometer tubes by the use of an ear syringe. When all manometers were operating satisfactorily, seepage into the slope was initiated by lowering the water level on the vertical face approximately 6 in. (3 in. for the half scale 2 to 1 test embankment). Inflow, provided by a small pump, and outflow were then adjusted until equilibrium occurred. Steady seepage flow within the embankment was indicated by stability in the manometer readings. The time needed to develop steady seepage flow within the test embankments was seldom a problem. This was because adjustment of flow outside the embankment, for desired head and tailwater elevations, generally took one hour - longer than for flow adjustment within the embankment. When the desired steady flow was attained, the manometers were then read and the process repeated. After the minimum vertical water was investigated, the head on the embankment slope was lowered 6 in. and the process repeated. However, at various times the water level was allowed to rise in order to check values on a previous test and to provide a rising level case to check the possibility of an effect due to the direction of water level movement. None being found, the procedure of lowering the water level was preferred to aid in maintaining manometer operation by not introducing air at negative pressures.

Upon completion of the seepage tests for flow into the slope, the embankments were tested visually for need of protection against surface sloughing. The protection detailed earlier was then placed on the slope and the procedure for flow into the slope repeated for at least one case to detect any effect of the pore pressure readings. Such values were recorded for one test with flow out of the slope. Next, the tests for flow out of the slope were conducted as for flow into the slope with the water elevations reversed. This procedure was followed until all required data were obtained. Later, data were verified using a simplified electrical analogy.

4) Dye-Tracing

To help judge the equipotential patterns a blue dye was injected into the test section adjacent to the plastic wall in four tests and the traces photographed for use as data check. Injection of this dye was accomplished by means of small plastic tubes pushed down into the test embankment next to the plastic viewing section. Since it took considerable time for the dye trace to form completely, a tendency for fluctuation in flow made it difficult to obtain other than qualitative lines for fine sand, but excellent results were easily attainable in the coarse sand.

5) Surface Sloughing Observations

Visual observations for surface failure were made in connection with all full size homogeneous test sections used in this study. Two procedures were used for these observations. First, the water elevation on the slope was lowered, while the head on the vertical face was maintained constant until movement on the slope surface was seen. Then the head on the vertical face was lowered to a desired level and again held constant while the water elevation on the slope surface was lowered until instability of the slope surface was apparent. Secondly, the head on the vertical face was raised while maintaining the water level between 6 and 12 in. against the embankment slope surface. In addition, a series of tests to determine the required difference in head required for embankment failure to start was conducted. For Configuration 3 tension cracks in the surface were noted for two cases. The first case had a 42 in. water level on the vertical face, and an 18½ in. tailwater elevation (rising). The second case had a 42 in. water level on the vertical face, and a 27 in. tailwater elevation (falling). These two cases represent apparent incipient surface failure for a rising and a falling tail-water elevation, respectively. Subsequent to the majority of tests for this study, the writers were able to observe surface sloughing in connection with a short series of tests attempting to cause failure below the tailwater level when seepage was out of the slope. These tests utilized a silt (stockpiled at the Colorado State University Engineering Research Center Hydraulics Laboratory) and a section with a 2 to 1 embankment slope.

Both a homogeneous section and one with a buried zone of coarse material were observed for surface failure. This zone was approximately 6 in. square and extended horizontally through the slope at the level of the toe. Also observed were several embankments in which the test embankment consisted of a triangular element placed on a rectangular base of the same material. The maximum height of the base was approximately 18 in., the width 32 in., and the length 92 in.

6) Determination of the Need for Protective Layer Gradation Control to Guard Against Surface Material Movement

A series of tests was conducted to determine the need for surface gradation control, to prevent the movement of bank material through the protective layer due to steady seepage.

The embankment for these tests consisted of fine sand having a 3 to 1 slope and a height of 28.33 in. Downstream from the toe a 2 in. x 4 in. wood baffle was placed in front of the outlet to catch any washed out material. Tailwater depths of 4 and 12 in. were used in conjunction with the maximum permissible headwater elevation resulting in a differential head of 16 to 24 in. The test pattern was to place a protective layer (detailed at the end of this paragraph) on the slope surface, and initiate the desired seepage out of the slope, taking care not to over-extend the headwater and cause washing. This seepage rate was then maintianed for periods up to 12 hours for each tail-water, unless observations through the plexiglass side indicated no hope for embankment movement. If examination below the toe indicated no washed material, a rapid draw-down test was made. Finally, the material near the toe was examined to see if any of the fine white sand was in the sand and water trapped by the baffle. This check was made by running the trapped material through filter paper. The protective layers used were as follows:

a) ½, 1, and 2 in. layers of coarse sand retained on a No. 14 sieve.

b) 1 and 2 in. layers of ¼ in. pea gravel retained on a No. 14 sieve.

c) 1 and 2 in. layers of roof chips retained on a No. 14 sieve.

d) 2 in. layer of large stone (1½ in. maximum).

e) 2 in. layer of a random mixture of all the materials mentioned above.

SUMMARY AND CONCLUSIONS

A. Summary

In the study, 145 laboratory tests to determine equipotential lines within a triangular embankment for various combinations of tailwater and headwater depth were conducted. Embankment slopes of 2 to 1, 3 to 1, 4 to 1, and 5 to 1 were studied using homogeneous embankments of fine and coarse sands. Five stratified embankments having a common slope of 2 to 1 were also tested. Based on these tests, plots of equipotential lines were prepared for all cases.

The equipotential plots made available by this study were used with the modified equations of Bishop and Morgenstern. The modification was accomplished by transforming the slice height to give an equivalent slice weight, using the dry unit weight, rather than the moist unit soil weight to compute embankment stability. Based on the method just described, the following computations were made to study the effect of seepage on embankment failure along a circular failure plane:

1) Location of the center of the critical circular failure path without seepage was found by mapping procedures, combined with a locus line derived from the geometry of the test embankment.

2) For the above critical centers, manual calculations of the stability numbers $(c/\gamma_d H)$ were computed for all

embankment tests, using a friction angle $\phi = 10°$, dry unit weight of soil $(\gamma_d) = 100$ pcf, saturated unit weight of soil $(\gamma_{sat}) = 125$ pcf, and 40% saturation above the phreatic surface.

3) Manual calculations of the average pore pressure parameters Ru_{ave} were made for all the tests, using a friction angle $\phi = 10°$, dry unit weight of soil $(\gamma_d) = 100$ pcf, saturated unit weight of soil $(\gamma_{sat}) = 125$ pcf, and 40% saturation above the phreatic surface.

4) Calculations corresponding to the above manual calculations were made with the aid of a digital computer, using the average pore pressure parameter Ru_{ave} and a straight line approximation of the phreatic surface.

5) Similar calculations using a digital computer were made for the stability number $(c/\gamma_d H)$, with and without pore pressure included, and for the average pore pressure parameter (Ru_{ave}), using a friction angle $\phi = 10°$ and its corresponding circular failure path. Percent of saturation above the phreatic surface = 0, 40, and 100%, and factors of safety against massive failure = 1, 2, and 3 were used for the above calculations, with a friction angle $\phi = 10°$.

6) Calculations similar to those in item 5 above were made for flow out of the embankment slope, based on these conditions: A critical circular failure path corresponding to $\phi = 5°$ and a friction angle $\phi = 5°$; critical circular failure paths corresponding to $\phi = 15°$ and $\phi = 20°$ for

homogeneous test embankments with a slope of 2 to 1 and a friction angle $\phi = 20°$; and circular failure paths passing through the crest and toe of the embankment, with friction angle $\phi = 20°$ for all test embankment slopes.

7) Using a friction angle $\phi = 10°$, calculations to determine the lateral movement of a critical circular failure path were made for two cases.

8) Using the circular failure paths passing through the crest and toe of the embankment, factors of safety against massive embankment failure were calculated and tabulated for friction angle $\phi = 26.6°$ and $40°$, corresponding to stability numbers $(c/\gamma_d H) = 0.025$, 0.050, and 0.075.

9) Three-variable plots of stability number with pore pressure included (N_d) , versus the ratios of headwater and tailwater elevations to embankment height, were presented for a factor of safety against massive failure for the following:

a) For a friction angle $\phi = 5°$, embankment slopes = 2 to 1, 3 to 1, and 4 to 1, with 40% and 100% saturation above the phreatic surface;

b) For a friction angle $\phi = 10°$, embankment slopes = 2 to 1, 3 to 1, and 4 to 1 plus Configurations 2, 3, and 4 with 40% and 100% saturation above the phreatic surface;

c) For a friction angle $\phi = 20°$, embankment slope = 2 to 1 using a critical circular failure path corresponding to $\phi = 15°$, embankments with slopes = 2 to 1, 3 to 1, and 4 to 1 using a circular failure path passing through the crest and toe of the embankment (toe circles), for saturation of 40% and 100% above the phreatic surface.

10) Three-variable plots of average pore pressure parameter (Ru_{ave}), versus the ratios of headwater and tail-water elevations to embankment height, were presented for the cases delineated in item 9 above.

11) The variation of the factor of safety against massive failure with headwater and tailwater elevations is illustrated by three variable plots of factor of safety versus ratios of headwater and tailwater elevation to embankment height. These plots are based on a friction angle $\phi = 26.6°$, failure circle passing through the crest and toe of the embankments, embankment slopes of 2 to 1, 3 to 1, and 4 to 1, with saturation above the phreatic circle = 0, 40, and 100%.

In addition to studying the massive failure case, a number of visual observations about the pattern of surface sloughing were made and discussed. The testing program included a series of tests using a 3 to 1 slope to determine the penetration of embankment surface material into several coarse protective filter layers.

B. Conclusions

Based on the work summarized above and on experimental observations, the writers feel that a number of conclusions are valid.

1) General

a) The common assumption that tailwater is always beneficial to embankment slope stability has been too often relied upon by the design engineer. This study has shown that tailwater is a cause of surface sloughing, and that if the tailwater and headwater elevations approach each other (submergence), the probability of massive failure may increase. This latter decrease in embankment stability phenomena is apparent with tailwater and headwater elevations up to 30% embankment height for 2 to 1 embankment slope, and with tailwater and headwater elevations equal to the total height of the embankment for a 5 to 1 embankment slope.

b) Embankment slope flattening does not in itself eliminate the effect of steady seepage on slope stability. Flattening of the embankment slope for soils with the same shear strength will increase the factor of safety for massive failure, compensating for a reduction in factor of safety due to the introduction of steady seepage into the embankment. However, if the shear strengths of two soils are different, with one requiring a flatter slope for embankment stability without seepage, the introduction of steady seepage into the embankment may cause a decrease in the factor of safety against massive failure. In addition, the flatter slopes with tailwater present have been shown to be potentially susceptible to erosion and surface sloughing.

c) The stability numbers and average pore pressure parameter (Ru_{ave}) values given in this study, along with the data required to convert them to different soil weights, are based on experimental data and currently accepted methods of slope stability determination. The design engineer concerned with massive slope failures will therefore have information previously unavailable to him. In addition, the equipotential plots given will allow the designer concerned with plane failure of surface sloughing to locate zones with critical potential gradients and to determine needed values of pore pressure.

d) Stability numbers, $(c/\gamma_d H)$, computed with and without pore pressure, along with those for different saturation percentages above the phreatic surface, provide an indication of their relative importance in the evaluation of slope stability.

e) Verification of the feasibility of using an average value of the pore pressure parameter, of approximating the phreatic surface with a straight line, and of using a simplified electrical analogy will allow the engineer to use these aids with confidence.

2) Surface Stability

The surface stability of a slope undergoing a steady seepage is a complex problem, the solution of which would involve random variables such as packing, point porosity, and local gradation. Taking an overall view, the following can be concluded:

a) The seepage breakout point can satisfactorily be located by the use of an equation developed by L. Casagrande for the flow out of the slope.

b) Tailwater has no significant effect on the point of seepage breakout when the tailwater elevation is below the normal breakout point. For higher tailwater elevation, the elevation at the breakout point appears to coincide with the tailwater elevation. Briefly, the reason for this is that the parabola with the maximum drop or head loss passing through a given point and exiting an embankment slope tangent to that slope, is a function of the geometry of the embankment, rather than of the tailwater level.

c) The presence of tailwater causes an upward flow, tending to exit normally to the surface of the embankment. This causes the equipotential lines near the embankment surface to become parallel to the surface. This results in a zone of high pore water pressure just below the embankment slope surface in the vicinity of the tailwater intersection with the slope. This condition becomes more pronounced for flat slopes, indicating that flatter slopes may have less surface stability when subjected to steady seepage in the presence of tailwater.

d) Bishop's equation, solved for cohesion equal to zero and verified by another method, yields an expression, which when solved for a given factor of safety, defines the limiting stable embankment angle slope for any point in the embankment. In addition, the limiting stable embankment slope, being expressed in terms of the pore pressure parameter (Ru), explains the variable slope surface failures observed in this study.

e) Material migration from a slope surface, due to seepage forces alone, is not critical, and can be prevented by a protective layer considerably coarser than the requirements for an inverse filter. In this study, no migration of fine sand into a layer of material with diameter size in excess of ¼ in. was observed.

3) Massive Circular Failure

The following conclusions were drawn concerning the effect of steady seepage on embankment failure, due to massive earth movement:

a) A partly submerged slope (headwater and tailwater elevations equal) may be less stable than a dry embankment. For a friction angle $\phi = 10°$, and embankment slope of 2 to 1, this decrease in stability will occur for headwater and tailwater elevations up to approximately 30% of the embankment height. Further, the above reduction in stability will occur with higher ratios of headwater and tailwater elevation embankment height, for flatter embankment slopes and high friction angles (ϕ).

b) The increase in the required stability number ($c/\gamma_d H$) for embankment stability, due to steady seepage, is significant for both flat and steep slopes ranging from near 50% for a 2 to 1 embankment slope, to several hundred percent for a 5 to 1 embankment slope.

c) With constant cohesion and friction angle ϕ, the factor of safety against massive failure will decrease with steady seepage.

d) Solutions using a straight line approximation of the phreatic surface proved successful. This was because the points at which major error could be introduced had a small moment arm, and thus had little effect on the moment activating the failure mass.

e) Except for cases where both the headwater and tailwater elevations were high, use of the average pore pressure parameter Ru_{ave}, examined for accuracy in this study, introduced very little error in the determination of stability number $(c/\gamma_d H)$. The exceptions can be minimized, because for these cases, the effect of pore pressure is small.

f) Due to the pore pressure increase caused by steady seepage out from an embankment, the center of the critical circular failure path will tend to move downward, since the effect of increasing pore pressure is similar to reducing the friction angle ϕ.

g) The presence of tailwater will cause a slight lateral movement of the center of critical circular failure path from the locus line toward the peak of the embankment.

h) The presence of tailwater (for flow out of the embankment slope) did not cause a smaller circular failure path of similar shape, located in a zone above a horizontal line established by the tailwater elevation, to be a more critical failure path. The smaller circular failure path did not become critical, because the stability number $(c/\gamma_d H)$ decreased linearly with the size of the circular failure path, while decreasing slowly with increasing tailwater elevation. Pore pressures are a significant item in the computation of the required stability numbers $(c/\gamma_d H)$ for embankment stability. This significance was determined by comparing stability numbers $(c/\gamma_d H)$ computed without pore pressure but including the additional weight due to seepage, with stability numbers $(c/\gamma_d H)$ computed including both the added weight and pore pressures introduced by steady seepage.

4) Miscellaneous

a) Except for the gravel toe, the stratifications studied had little effect on the equipotential patterns with tailwater elevations below 6 in., in that part of the embankment extending from a vertical line through the seepage breakout point on the embankment slope, to the embankment toe. This feature was due to the fact that the equipotential lines had to intersect the surface of the embankment slope at an elevation equal to the value of the equipotential lines. Thus, a control point for the equipotential lines existed on the embankment slope.

b) A coarse layer parallel to the surface of the embankment slope (Configuration 3) caused an increase in the pore pressure parameter, Ru , for headwater elevation above the elevation of the intersection of the coarse layer and the embankment's vertical face, when tailwater was present.

c) A horizontal coarse sand layer in fine sand (Configuration 2) caused a more uniform variation of the average pore pressure parameter, Ru_{ave}, with headwater elevation, for flow into the embankment slope (tailwater elevation greater than headwater elevation).

d) A fine horizontal sand layer in coarse sand (Configuration 4) caused higher values for the average pore pressure parameter, for headwater elevation above the fine layer, by inhibiting upward flow.

e) A simplified electrical analogy can be used successfully in predicting equipotential patterns.

f) The stability number $(c/\gamma_d H)$ and average pore pressure parameter (Ru_{ave}) can be converted for use with soils having different unit weights.

RECOMMENDATIONS

The following recommendations are made on the basis of this study:

A. Test Procedure

1) In further testing, it would be beneficial to use float-actuated valves to maintain constant head. These valves would allow the use of less responsive manometer ends, which would yield negative readings. Also, long term stability of the seepage pattern would facilitate the determination of flow rate.

2) The manometers should be placed so as to reduce horizontal interpolation of equipotential.

3) A slab of porous concrete should be placed in front of the downstream face of the concrete block to reduce the concentration of water and material flow through the joints.

B. Further Study

1) As a continuation of this study, stability numbers should be developed for greater slopes, using test embankments with a berm.

2) Equipotential lines need to be established for failure planes dropping below and beyond the toe of a test embankment.

3) The effect of buried pockets and non-continuous stratification, based on geological probability, needs

further study. In this type of non-homogeneity, the surface will be less likely to control the potential pattern.

4) An interesting study would be to investigate the stability of slopes during a development of steady seepage. For instance, a sudden rise in the water table behind an embankment would initiate a seepage wave which would have its initial effect on the failure mass in the zone of high activating moments.

5) The most challenging future study involves the slope surface. Not only is more instrumentation needed here to trace the potential in this vicinity, but the effect of weight placed on the embankment slope surface, which inhibits bulking of the surface, needs consideration. Erosion of the slope might be studied by tightening the tank, stabilizing the surface with air pressure, simulating rainfall on the surface, and observing deterioration for various material with and without seepage. A slope flatter than 2 to 1 should be used in this study.

6) An interesting computer problem of determining, by relaxation, the equipotential lines for various embankments, could be developed by using the technique of the University of Texas Computer Center. The technique is described in Chapter 20 of Non-linear Problems of Engineering, W. F. Ames (ed.), published by Academic Press.

7) The test apparatus employed in this study can be used to study the effect of steady seepage on embankments having odd shapes, such as a partially parabolic embankment face.

NOTATION

Symbol	Description	Units
c	Unit cohesion	F/L^2
H	Height of embankment	L
N_d	Stability number after Taylor based on unit dry weight	1
Ru	Pore pressure parameter	1
γ_d	Dry unit weight of soil	F/L^3
γ_s	Saturated unit weight of soil	F/L^3
ϕ	friction angle	degrees

Publications:

Muir, C. D., Stability of slopes with seepage, Ph.D. Dissertation, December 1968.