THE STABILITY OF TAILING STRUCTURES - PORE WATER PRESSURE DISTRIBUTION AND MONITORING

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ABSTRACT

The stability of tailings dams is governed by the height of the embankment, the unit weight of the fill, the gradient of the slope and to a major extent by the water pressure distribution within the dam and its foundation. For a given dam geometry and construction material the only variable affecting the stability of the dam is then the pore water pressure distribution.

This paper describes the results of a study which was carried out to analyze the stability (factor of safety) of three tailings dykes of various heights. The effect of five flow conditions on the factor of safety were also investigated. Recommendations are also made regarding monitoring the dams for water pressures and deformations.

INTRODUCTION

Several failures of tailings structures in the recent past have caused world-wide attention, mainly because they involved extensive property damage and loss of human lives (e.g. Aberfan in 1966; and El Cobra tailings dam failures in Chile in 1965). Many more failures were unreported due to their remote locations. The ones which received the attention of the professional community and were back analyzed for stability showed that shear strength prior to failure had been drastically altered by induced high pore water pressures. These changes were either brought about by changes in hydraulic conditions or by seismic forces. Whatever the cause, it is now generally accepted that most problems of instability of tailings structures are due to seepage forces and liquefaction of the tailings material.

The papers reports on the results of a study were three slope geometries and five dams were investigated, each case was subjected to five different hydraulic groundwater conditions which one could expect in real life situations. The hydraulic conditions will be discussed in detail in the following sections.

A brief discussion is included regarding monitoring of the performance of these structures with respect to seepage conditions and movements.

Recording and analysis of pore pressure and movement data will furnish valuable information to provide assurance that the design criteria were satisfied and for use in future design work.

GEOMETRY OF TAILINGS DAMS

Most tailings impoundment structures in Canada are of low or medium height, that is, in the range from 5 to 30 metres. From this observation three slope geometries and five dam heights were investigated for stability and were considered to represent most practical cases. The heights of embankments which were studied were 5, 10, 15, 20 and 30 metres. For each height three different slope gradients were considered, namely 3 horizontal to 1 vertical, 2.5 to 1 and 1.75 to 1. Throughout this study the soil properties were kept the same for all cases. The slope geometries are shown in Figure 1.

SEEPAGE CONDITIONS

As was pointed out earlier for a given geometry and soil properties, the major factor affecting the stability of a tailings dam is the intensity and direction of the seepage forces. Classical effective stress slope stability analysis mainly rely on ratios of the hydrostatic porewater pressure distribution to evaluate the effect of groundwater flow in an impoundment structure. Porewater pressures are evaluated from the height of the water column (piezometric surface) by an expression of the form:

$$u = \gamma_w h_w \quad \alpha \qquad [1]$$

where u = porewater pressure
γ_w = unit weight of water
α = coefficient of proportionality between the true water column height and its effective height

In many cases it is more convenient to express the porewater pressure as

$$u = r_u \gamma h \qquad [2]$$

where r_u = a coefficient of proportionality between the effective porewater pressure and the total vertical stress
γ = total unit weight of soil
h = height of soil column

In both of the above methods of determining porewater pressures, a constant coefficient describes a uniform groundwater distribution and flow condition. The direction of seepage flow is considered to be either horizontal or subparallel to the groundwater table. Those conditions are rarely observed in nature. A tailings structure located on flat ground may have a strong downward water flow. A cross-valley dam located on a pervious stratum may experience an upward gradient (discharge area). Such a condition would explain the strong artesian pressures measured at many sites usually accompanied by a discharge from the underlying aquifer.

In this investigation five possible groundwater flow types were considered as follows:

(1) hydrostatic or horizontal flow
(2) flow parallel to the slope of the dam
(3) actual seepage flow in a homogeneous dam
(4) downward flow to a previous stratum underlying the tailings dam, and
(5) artesian upward flow at the toe of the dam.

These five flow conditions are shown in Figure 2.

COMPUTER PROGRAMME

A computer programme was developed mainly in response to needs expressed by various consultants and researchers faced with stability problems with low to medium high tailings dams. The programme which evolved, is based on different existing programmes, such as SSBM, LEASE, ICES and SLOPE. Two versions were developed, a Fortran programme edited on H-level of an IBM360/365 computer, and a second more limited version using a Texas Instrument TI-59 programmable mini-calculator with a printout. The programmes were extensively tested and compared to other programmes. Deschamps [1] gave a detailed description of each version and their range of applicability. Briefly the programme calculates the factor of safety according to Bishop's method of slices for a series of failure arcs passing through the downstream slope of the dam. The programme's main advantage is its flexibility in handling non-uniform porewater pressure distributions and their strength parameters. In this particular study constant strength parameters of $\phi'=33°$ and $C'=10$ kPa were chosen to present the property of the tailings. Most tailings exhibit a slight cohesion due to the fine grain sizes present.

PRESENTATION OF RESULTS

A total of 75 cases were investigated and the lowest factor of safety was determined for each case. In order to facilitate comparison between the different slope geometries and groundwater conditions on the stability of the respective slopes, the tailings material was considered to have constant strength and weight properties. Figure 3 summarizes the effect of groundwater conditions on the stability of slopes having different heights but the same slope ratio of 1.75 horizontal to 1 vertical. In an increasing order of stability the groundwater conditions can be classified as follows: (1) upward flow of water from an underlying aquifer as shown in Figure 2(e). (2) The second least stable condition assumed hydrostatic groundwater conditions with horizontal flow lines, as depicted in Figure 2(a). (3) Parallel flow with flow lines being parallel to the slope of the dam. (4) Normal seepage conditions, that is, the top flow line or phreatic surface exits at the toe of the dam. The top flow line was determined by the method discussed by Bauer [2]. (5) Downward flow towards an underlying aquifer seems to be the most stable condition for a tailings structure. Similarly, Figures 4 and 5 show the variation of factor of safety with regard to dam height and hydraulic conditions for slope ratios of 2.5 to 1 and 3 to 1, respectively. The order of stability with the five different groundwater conditions for these two slope geometries is the same as shown in Figure 3 and as discussed above. As can be expected the factor of safety decreases with slope height and increases with flattening the slopes. The confined aquifer with an upward flow gradient will generate the lowest stability for any geometry considered. This uplift excess hydrostatic pressure will in the extreme case generate zero effective normal stresses which would result in deep failure surfaces which are uncommon in tailings dam failures.

MONITORING FOR PORE PRESSURES AND MOVEMENTS

The preceding sections have shown the vital effect the occurrence and direction of seepage forces have on the stability tailing structures. Therefore, the groundwater conditions at a dam site should be monitored over several seasons prior to the construction of the dam in order to assess the proper hydraulic conditions. Monitoring for porewater pressures should be continued during and after construction of the dam to determine if the design assumptions were met and to verify the stability analysis. This definite need to gather quantitative data to analyse stability problems and movements of tailings dams should be an integral part of the overall project and should be included in the planning from the outset. For low and medium high tailings dams the minimum requirement for measurements will consist of the determination of the porewater distribution within the dam and the underlying material and the assessment of movements. The measurement of the magnitude, rate and distribution of vertical and horizontal movements may be of a major concern if the structure is founded on compressible material.

There are a variety of instruments readily available to fill the needs of almost any situation. The description and application of the various instruments is beyond the scope of this paper. There are many excellent publications which deal explicitly with this topic and the reader is referred to references [3] and [4] for example. The simplest device for groundwater observation are open boreholes which are readily available during an investigation of a particular site. A particular disadvantage of this system is that artesian pressures can occur in a specific layer that may be interconnected by the borehole so that recorded water levels may be of little significance. The writer was involved in many instrumentation projects over the last fifteen years and the more successful systems for water level monitoring consisted of pneumatic and electric piezometers. These two types have many advantages such as: (a) practically immediate response to changing groundwater conditions, (b) remote sensing and therefore minimum interference with construction, (c) stability and longevity, (d) simple to install and to operate, and (e) possibility of automatic recording and transmission of data. The data acquisition and processing methods can range from visual recording of an individual sensor to the most sophisticated and completely automatic operation where the data is collected by a central terminal.

There are also a variety of instruments on the market which are applicable to monitor vertical and horizontal movements in dams. For a detailed description of these devices the reader should consult references [3] and [4]. Generally for low and medium high tailings dams movements are not of prime concern unless the structure is founded on compressible soil. A device which is simple and sufficiently accurate for most practical cases is the "Settlement Probe" [5] which is able to measure both vertical settlements as well as horizontal movements. There is no general rule regarding the type, number and location of instruments in tailings dams, each problem is different and has different requirements. In all cases where a monitoring system is considered adequate time in planning is required in order to establish the proper type, location and number of instruments and to develop an adequate recording technique.

CONCLUSIONS

This parametric study has shown that the stability of tailings dams is largely influenced by the groundwater hydrology and by the height of the dams. Seventy-five cases have been investigated and for each case the minimum factor of safety was determined. The results are presented as graphs, factor of safety versus dam height, for various dam geometries (Figures 3, 4 and 5). These graphs can be used as guides for initial design purposes to choose a trial cross-section of the dam. A proper analysis necessitates an adequate investigation of the site for the existing groundwater conditions prior to the construction of the dam. This is turn points to the necessity for monitoring the site and the structure proper for porewater pressures and vertical and horizontal movements.

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4. Wilson, S.D. and P.E. Mikkelson, Field Instrumentation, Ch.5 of Landslides, Analysis and Control, Special Report 176, Transportation Research Board, National Academy of Sciences, Washington, D.C. U.S.A., 1978.

5. Information available from the Slope Indicator Company, 3668 Albion Place North, Seattle, Washington, U.S.A.

LIST OF FIGURES

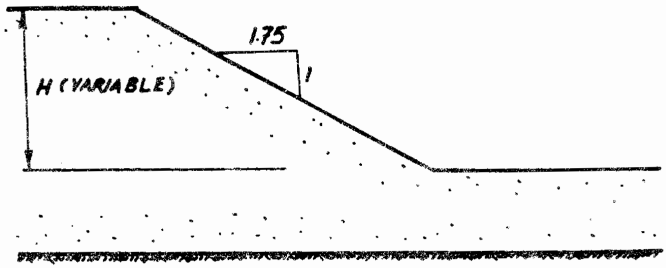
Fig. 1. The Three Slope Ratios Investigated

Fig. 2. Different Hydrolic Flows Through Dam

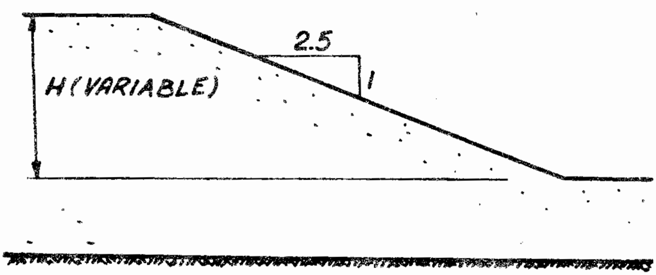
Fig. 3. Variations of Factor Safety /Slope Ratio 1,75 to 1/

Fig. 4. Variations of Factor Safety /Slope Ratio 2,5 to 1/

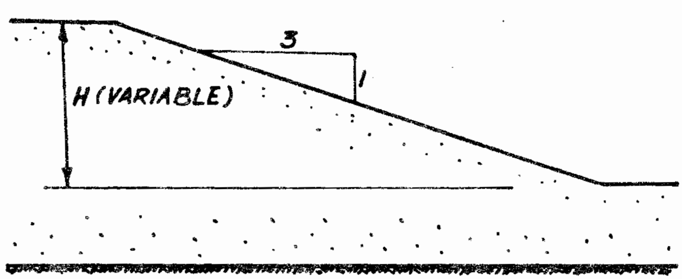
Fig. 5. Variations of Factor Safety /Slope Ratio 3 to 1/



(a) Slope Ratio 1.75 to 1

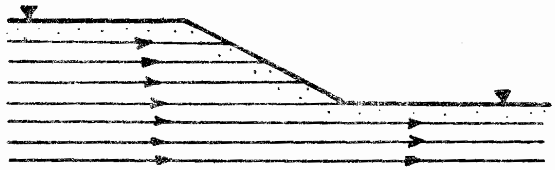


(b) Slope Ratio 2.5 to 1

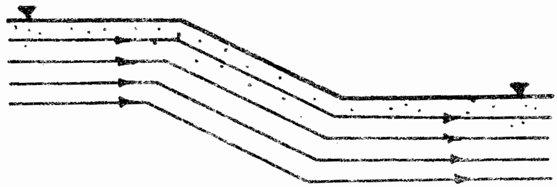


(c) Slope Ratio 3 to 1

FIG. 1. The Three Slope Ratios Investigated

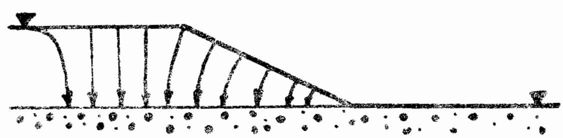


(a) Horizontal Flow (Hydrostatic Condition)

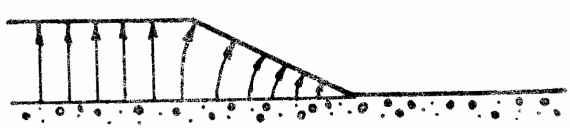


(b) Flow Parallel to the Slope Surface

(c) Actual Seepage Flow



(d) Downward Flow into Previous Stratum



(e) Artesian Upward Flow

FIG. 2. Different Hydrolic Flows Through Dam

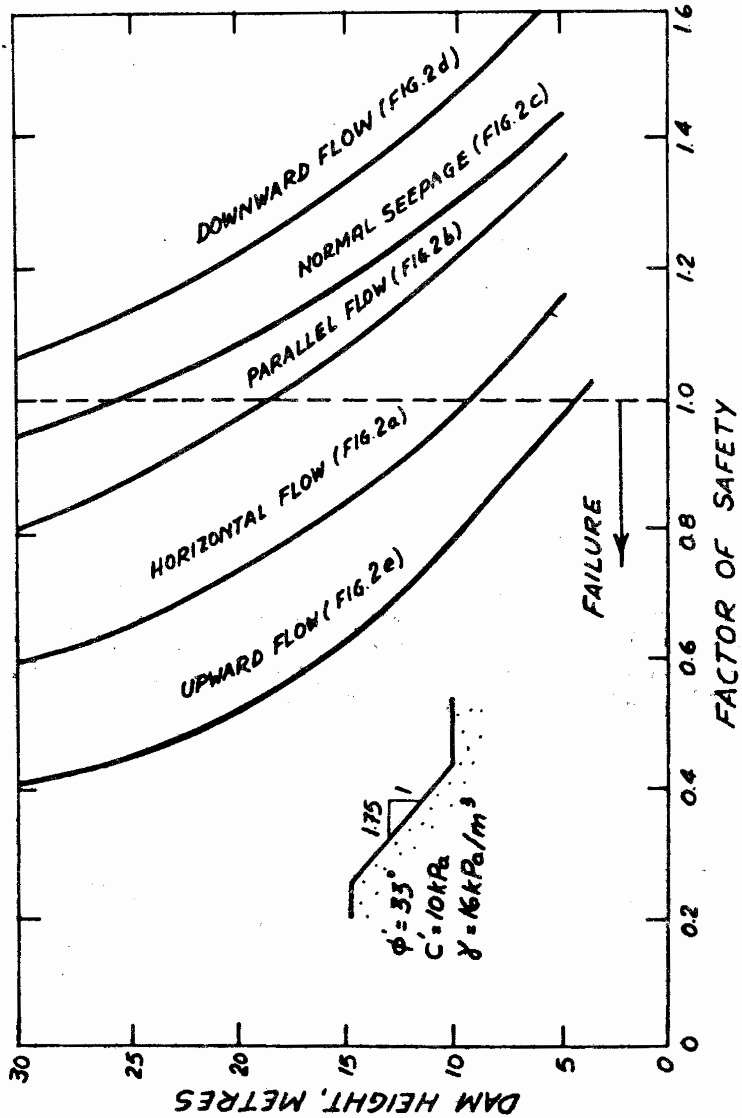


FIG. 3. Variations of Factor Safety (Slope Ratio 1.75 to 1)

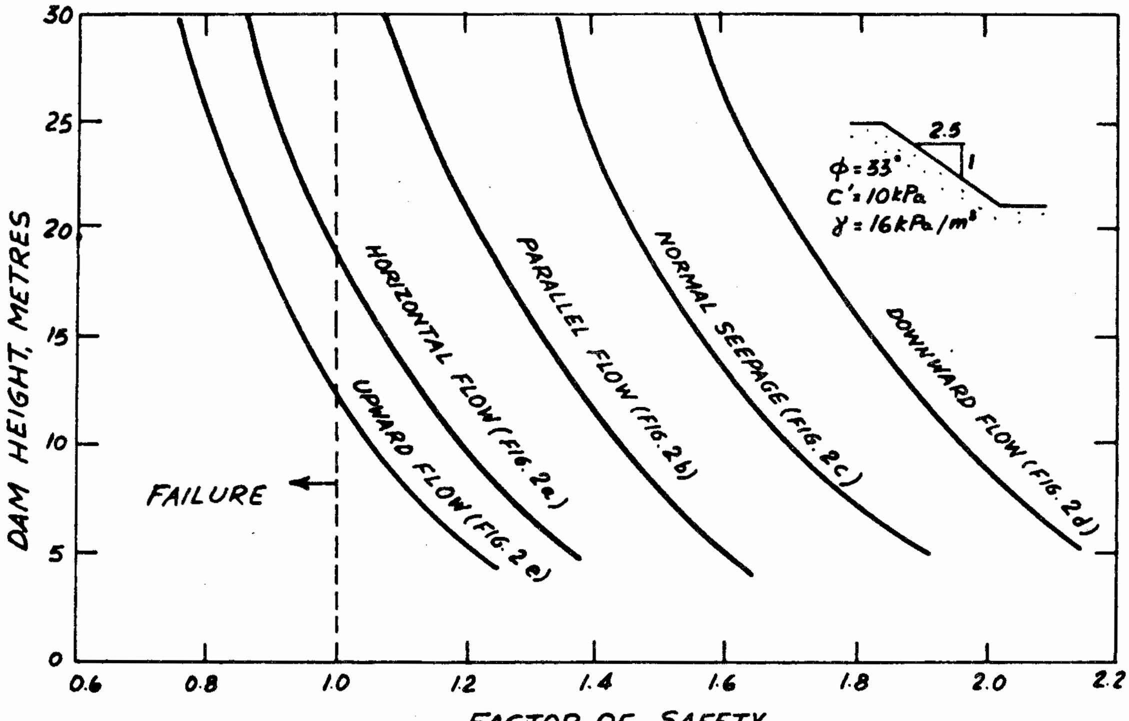


FIG. 4. Variations of Factor Safety (Slope Ratio 2.5 to 1)

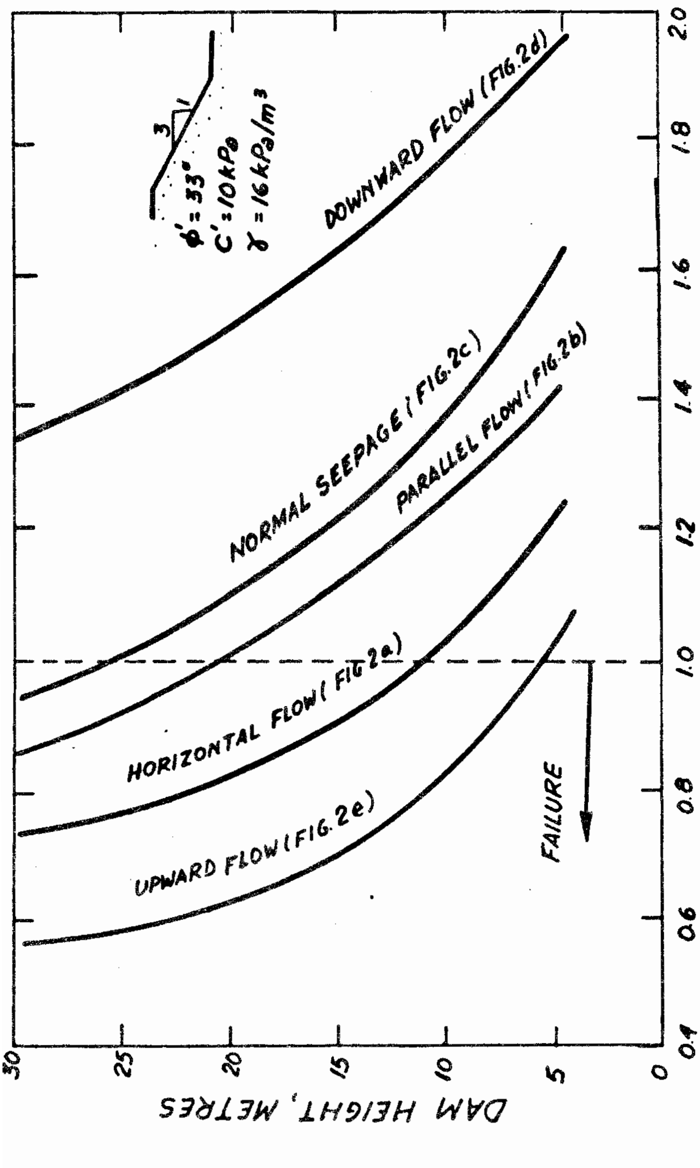


FIG. 5 Variations of Factor Safety (Slope Ratio 3 to 1)