LONG TERM STABILITY OF POTASH TAILS PILES

ON SOFT FOUNDATIONS

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Presented to
The Second International Potash
Technology Conference
KALI '91

Hamburg, Germany
May 26-29, 1991

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ABSTRACT

In Saskatchewan, Canada, the waste tails associated with the potash mining operation are piled on the ground surface. The piles cover many hectares and presently range from 50 to 100 metres in height. The piles are built using a spigotting technique. The foundation conditions in Saskatchewan always involve glacial deposits which are soft relative to the stiffness and strength of the crystallized tails. As a result, this produces some difficult analytical problems relative to the predicting the stability of the piles.

The proposed research paper will first summarize the results of extensive laboratory studies on the strength properties of the potash tails. In general, the friction angle for the tails are in excess of 45 degrees. In addition, the strength characteristics of the stratified and unstratified glacial deposits are also summarized.

The primary emphasis of the research paper is directed towards the question, "How can limit equilibrium analyses be used to assess the factor of safety of an extremely strong material (tails) over a relatively soft material (glacial sediments)?" A total of four potential modes of failure were analysed in a parametric manner. Each mode was also evaluated in the light of observed behavior on tails piles in Saskatchewan.

The study concludes that limit equilibrium analyses can be used to analyse conditions of an extremely strong material overlying relatively soft sediments. The research study also identifies deep-seated slip surfaces through the foundation soil as the most serious made of failure. At the same time, a number of additional questions are raised which require further study. These questions involve the evaluation of the insitu pile characteristics (e.g. honeycombing) and the prediction of pore-water pressures below the toe of the pile. These pore-water pressures were found to be crucial in the evaluation of overall pile stability.

KEY WORDS Slope Stability, Potash Tails Piles, Bearing Capacity, Shear Strength of Tails

INTRODUCTION

The mining of potash ore for fertilizer involves the removal of many tonnes of ore each year with the associated generation of almost an equal amount of waste. Underground mining commenced in the early 1960s in Saskatchewan. During the early stages of the mining operation, detailed attention was not given by way of engineering studies, into the long term handling of the waste products from the mining operation. Tailings were piled on the ground surface with an attempt to collect and control the movement of brine from the pile.

The tailings piles are built using a spigotting technique. The waste products are delivered to the pile in the form of a slurry. The coarse fraction is deposited near the exit of the spigot while the finer fraction settles out as the slurry proceeds down the gradual slope (i.e., a few degrees) to the brine pond. The spigot can be moved around the discharge area, and low tailings dykes are built with a crawler and a dozer so as to confine the discharge to cells. Using this technique or some variation thereof, the tailings piles can readily be built to heights exceeding 50 m. Figure 1 shows the cross-section of a typical tailings pile. The steep portion of the pile is generally about 37 degrees to the horizontal. The entire tailings area is generally contained within an earthfill dyke.

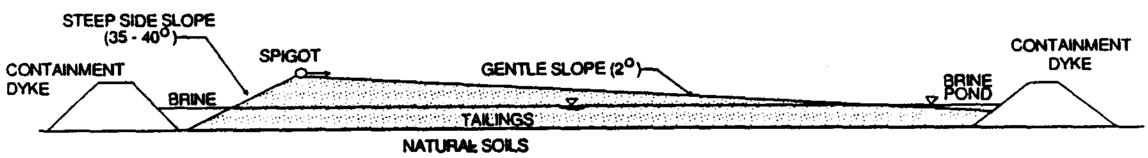


Fig. 1 Typical Cross-section of Tailings Pile

Figure 2 shows a typical areal layout of a waste containment site, this one being the PCS site at Lanigan. Also shown are the locations of slope inclinometer instrumentations used to study the deformation and stability of the tailings pile. About 20 million tonnes of tailings have been deposited in this 270 hectare tailings containment facility between commencement of operations in 1967 until 1983. Current annual tailings production is about 2.5 million tonnes. A typical stratigraphic sequence at the PCS site at Lanigan consists

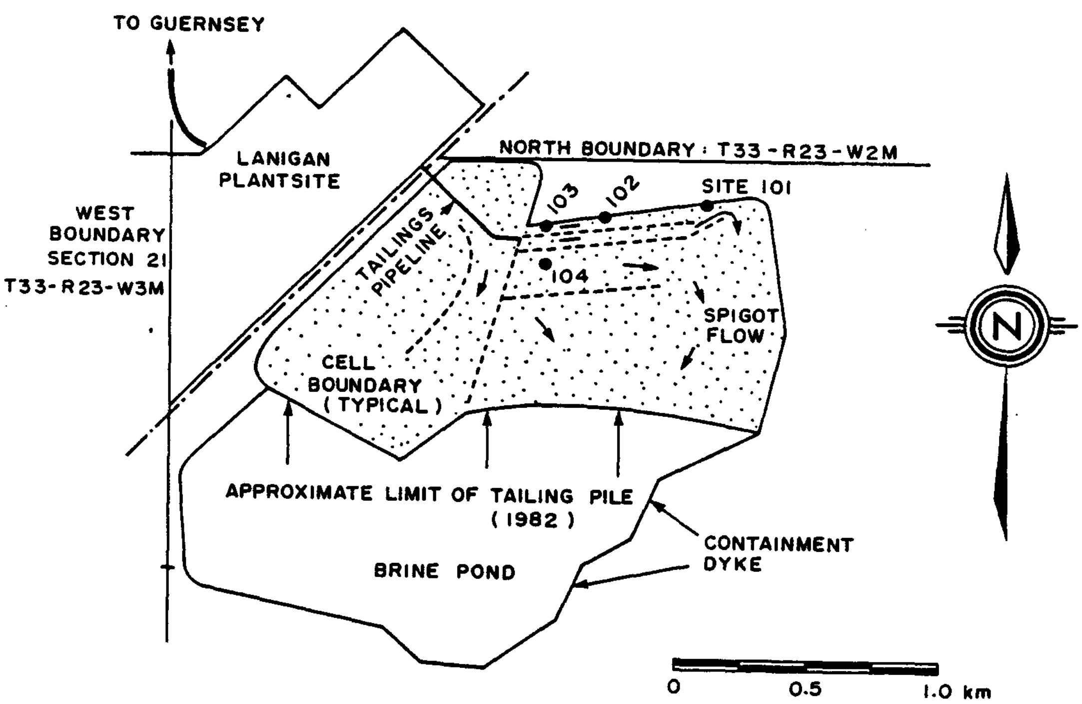


Fig. 2 Areal Layout of the PCS Waste Containment Facility at Lanigan, Saskatchewan

of relatively thin, surficial stratified drift being underlain by substantial thicknesses of till. The stratigraphy varies significantly from one site to another in Saskatchewan and is vitally important to the functioning of the waste containment area.

Figure 3 is a map showing the potash beds and mines in Saskatchewan. Presently the potash industry in Saskatchewan produces about 14 million tonnes of KCl product per year along with 28 million tonnes of salt tailings per year and 11 million cubic metres of brine. The tailings represent about 103 percent of the mined volume. The tailings not only cover a substantial area but represent a significant challenge as long term operation and closure of the mines are considered.

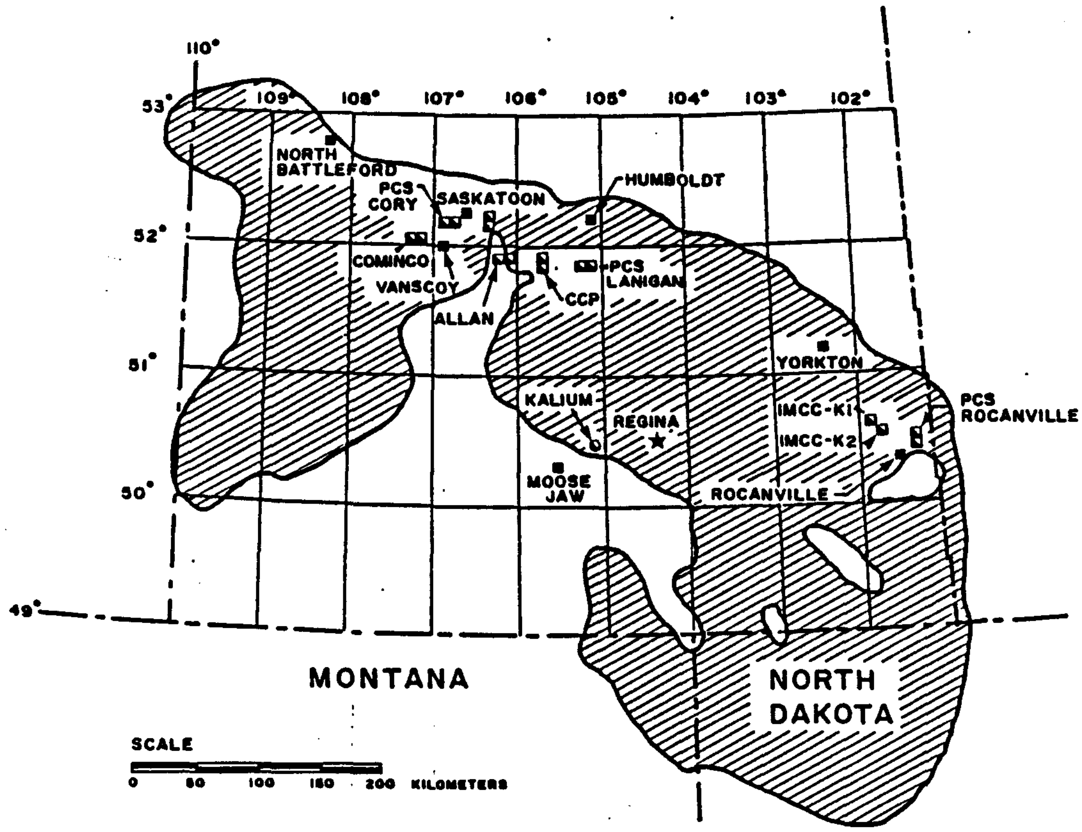


Fig. 3 Map of Province showing Potash Bed and Mines. (After Dunn, 1976 and Fuzesy, 1982)

At present, the tailings piles are generally in the order of 50 m in height but may someday exceed 100 m in height. The need for careful design and analysis becomes critical as the piles exceed about 50 m in height. In addition, there is need to be aware of problems in advance of their occurrence and be able to analytically model situations relevant to long term behavior and closure of the piles. Obviously, an important aspect of such analyses includes an understanding of the physical and mechanical behavior of the tailings.

The long term behavior of the containment dykes is also of concern since the brine may change the properties of the soil with time, thus affecting the stability of the dykes. While the stability of the dykes are of concern, the emphasis in this paper is on the long term behavior of the tailings piles.

This paper outlines some of the accomplishments to-date in the study of the tailings piles. It includes a brief outline of the history of investigations, a summary of relevant soil properties which have been studied along with their application to questions that must be addressed relative to the long term stability of the tailings piles. Several scenarios are presented which clarify the types of studies which should be conducted in the near future. Many questions can still be asked regarding the long term and closure, and these should be the focus of research studies.

HISTORY

Within approximately one decade of the commencement of potash mining in Saskatchewan, there arose concern about the stability of the tailings piles. The questions were not regarding the steepness of the piles (which was always about 37 degrees) but rather about the height to which the piles could be built. Failure of a tailings pile may result in the release of brine to the surface of the surrounding agricultural land or more rapid movement of brine into the soils below the tailings pile.

Little was known about the engineering behavior of the tailings and this necessitated laboratory studies on their strength properties. Early attempts at studying these properties revealed the difficulties associated with obtaining representative, undisturbed field samples. Secondly, the laboratory testing of tailings samples proved to be more difficult than anticipated. To-date, there has been a gradual accumulation of experience which has led to acceptable procedures for performing field investigations, obtaining undisturbed samples and performing laboratory tests.

FUNDAMENTAL SOIL PROPERTIES OF RELEVANCE

Studies on the long term behavior of tailings piles primarily involve an understanding of the shear strength parameters for the tailings. The soils underlying the tailings piles can, to a large extent, be studied using conventional soils mechanics procedures. The one exception with respect to the foundation soils relates to the physico-chemical changes which may occur over periods of time.

General Soil Properties

Before discussing the shear strength properties, let us consider some typical classification, identification, and other properties of the tailings. The specific gravity (relative density) of the individual particles generally ranges from 2.10 to 2.19. The insitu density near the surface of a pile is typically about 1.50 Mg/m^3 and may increase to 1.95 Mg/m^3 near the base of a pile (Pufahl, 1983).

Dry sieving of the salt particles indicates that the material can be classified as a fine gravel to a coarse sand. The insolubles contain silt and clay size particles which can be of medium to high plasticity. Insitu infiltration studies have been performed using brine as the infiltration fluid (Wong and Barbour, 1985). The results indicate saturated permeabilities in the range of 1.5×10^{-5} m/s to 4.0×10^{-5} m/s. The range in permeability in this study was related to anisotropy in the tailings pile.

Shear Strength Parameters

The strength characteristics under short term loading has been evaluated using both direct shear and triaxial compression tests. Figure 4 shows the results of direct shear tests on tailings from the PCS site at Lanigan. The best-fit angle of friction is 56°. Figure 5 shows the results of triaxial tests on a similar material. The friction angle is higher in the lower stress range and the best-fit angle for the entire stress range is 49°. Both tests exhibit a large angle of shearing resistance (i.e., greater than 45°). This infers a shearing resistance greater than the normal stress applied to the

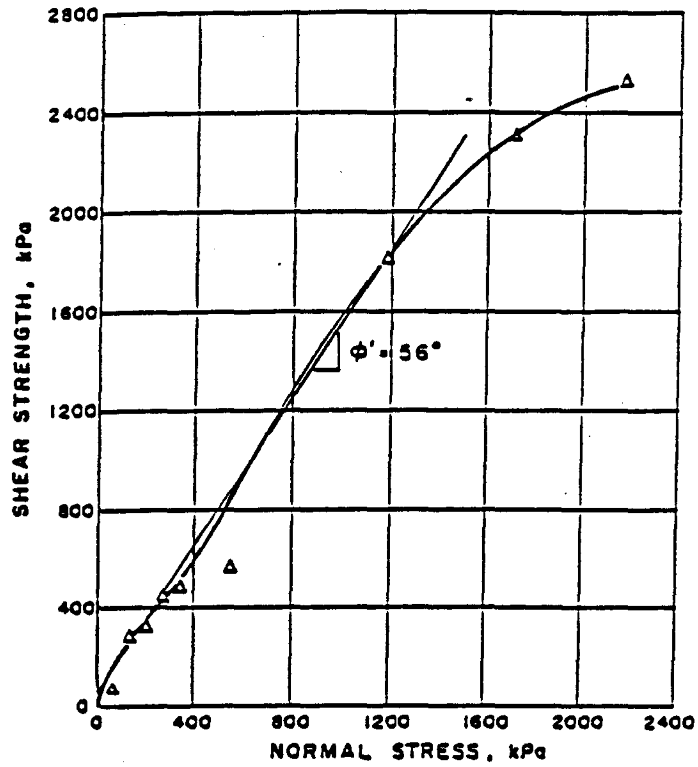


Fig. 4 Direct Shear Test Results on Tailings from Lanigan

specimen. Such behavior is characteristic of dense, angular, highly granular soils, where the component of strength caused by interlocking and crushing is substantial.

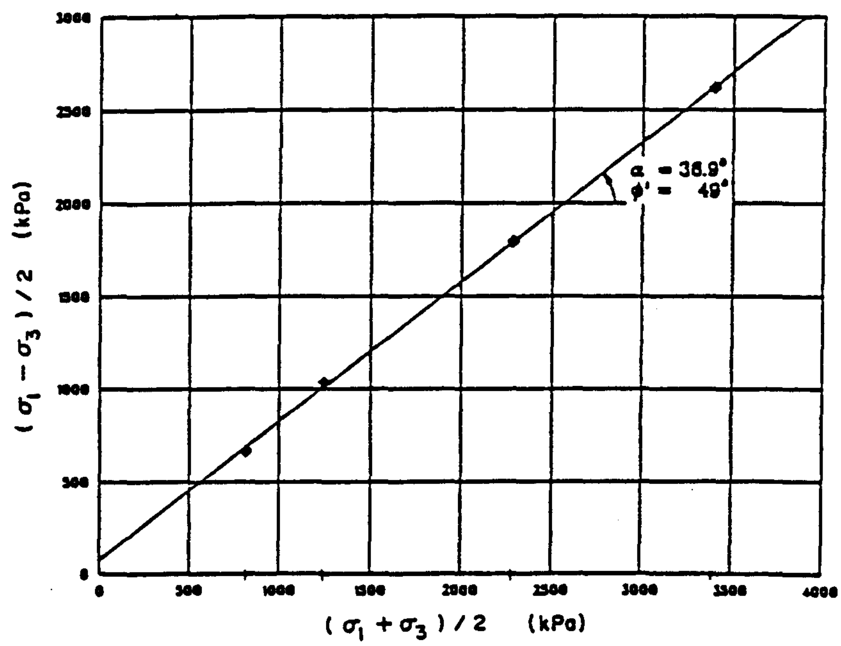


Fig. 5 Triaxial Test Results on Tailings from Lanigan

The implications of angles of friction greater than 45° must be carefully considered with respect to the stability of the tailings piles. Angles greater than 45 degrees imply that the higher the pile is constructed, the greater may be its stability. There appears to be a slight cohesion intercept and the shear strength of a granular material, τ, can be written as,

$$\tau = c' + \sigma_n \tan \phi' \qquad [1]$$

where:
σ_n = normal stress
c' = effective cohesion intercept
ϕ' = effective angle of internal friction

Values of ϕ' greater than 45° give rise to a value of ($\tan \phi'$) greater than 1.0 and subsequently an increase in strength more substantial than the increase in normal stress. From an engineering standpoint it could be questioned whether friction angles greater than 45° can ever be justified in an analysis of stability. To-date, friction angles used in practice have varied over a wide range.

Drained triaxial tests also give an indication of the deformation modulus and Poisson's ratio of the tailings. The stiffness of the tailings has been found to be strongly dependent upon their initial density and their confining pressure. This is typical of granular type behavior. In addition, significant cementation occurs between the salt particles which further contributes to the rigidity of the material, especially at low strains. The specimens also show a dilatant behavior when being sheared.

Figure 6 shows a typical multi-cycle direct shear test on tailings. The results indicate that there is a peak strength under low strains which is about 20% higher than the ultimate (or residual) strength value.

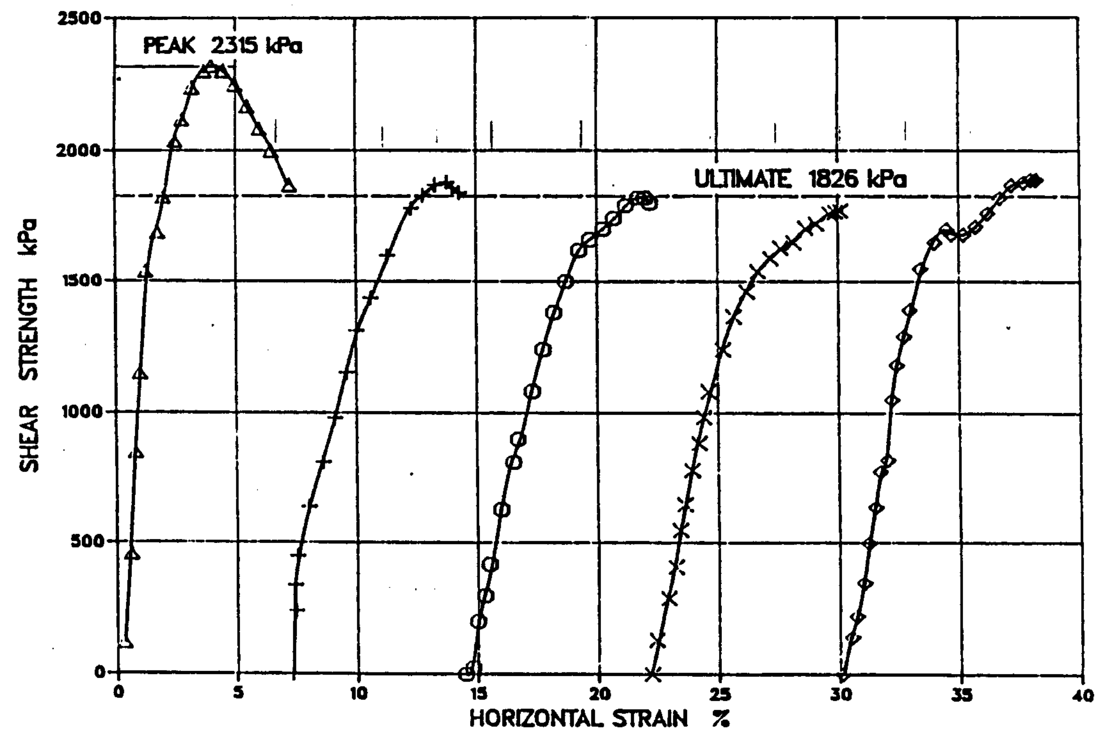


Fig. 6 Shearing Stress versus Deformation (Normal Stress 1710 kPa)

Direct shear tests have also been performed on the insolubles (silts and clays) and these reveal shear strength parameters substantially lower than those of the tailings. Figure 7 shows test results on the insolubles from the Cory mine site. The peak friction angle is 30° and the ultimate friction angle is 23°. Zones high in segregation insolubles can thus result in reduced shear strengths that have an effect on the stability of a tailings pile.

CLOSURE SCENARIOS AND RELEVANT QUESTIONS REQUIRING STUDY

There are many questions which arise when giving consideration to the long term stability and closure of the tailings piles. A few scenarios are described below.

Long Term Stability of the Tailings Pile with no Change in Properties or Geometry

The long term stability analysis of high piles (e.g., 100 m) still requires further study. Many questions have been answered regarding how to perform the stability analyses but other questions still remain unanswered.

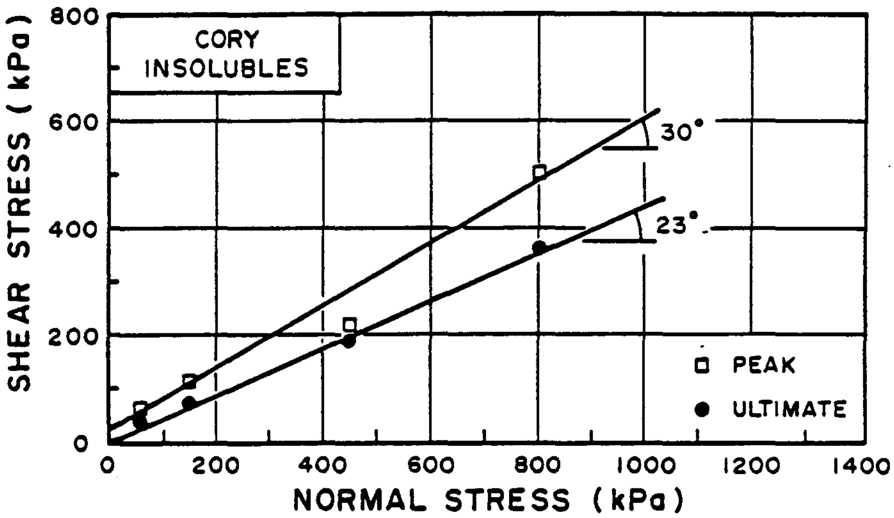


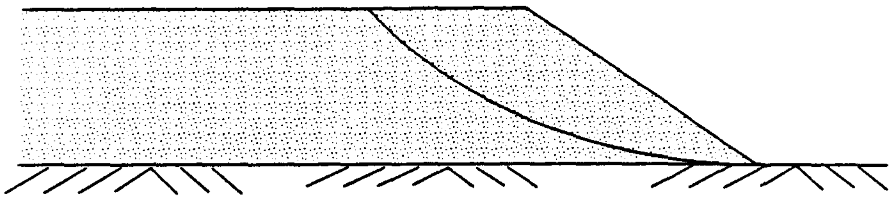
Fig. 7 Direct Shear Tests Results on Insolubles from Cory

For example, there is no assurance regarding the mode of failure which is most likely to occur. The studies by Chiu and Fredlund (1986) indicated several potential modes of failure (Figure 8). The first three modes primarily involve failure through the tailings. However, Mode 2 could either involve tailings or foundation soil along the composite portion of the slip surface. Mode 3 reflects one type of solutioning; namely, the dissolving of tailings from under the edge of the pile.

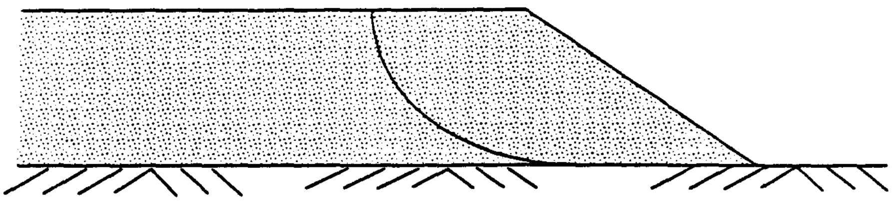
A range of soil and tailings shear strength parameters were assumed in the above study for calculating the factor of safety.

Mode 1: Figure 9 shows a plot of factor of safety versus the height of pile for the case where the failure surface is circular through the tailings. The results would indicate that this type of failure is essentially impossible due to the strength of the tailings.

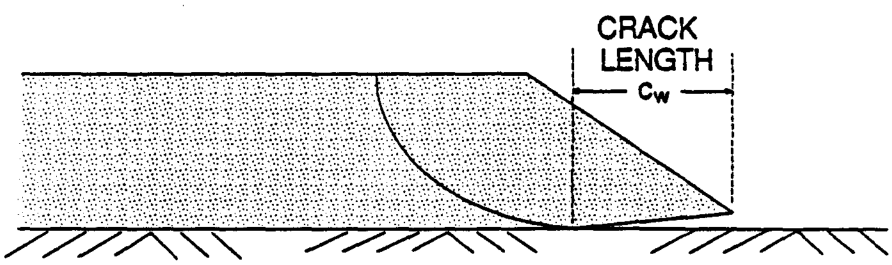
Mode 2: Figure 10 shows the effect of the failure surfaces being composite, through the tailings. Once again, it is essentially impossible to fail the tailings pile. Failure surfaces with the composite portion in the foundation soils could have a factor of safety which is reduced considerably depending upon the shear strength of the foundation soils.



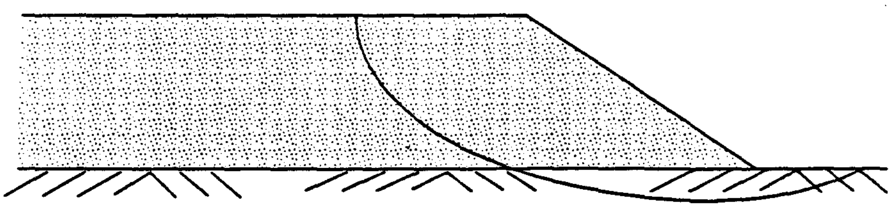
a) **Mode 1:** Circular Slip Surface Passing Through the Toe of a Pile



b) **Mode 2:** Composite Slip Surface Passing Through the Toe of a Pile



c) **Mode 3:** Circular Slip Surface Existing at the End of a Crack Through the Toe



d) **Mode 4:** Slip Surface Passing Through the Foundation

Fig. 8 Modes of Failure for the Slope Stability Study

Mode 3: The effect of solutioning is presented later.

Mode 4: Figure 11 shows the variation in factor of safety with respect to a failure surface through the foundation soils. Two situations are studied; which are, the case of no pore-water pressures in the soil and the case of pore-water pressures at the surrounding ground surface. Once again, the factors of safety appear to be well in excess of 1.0.

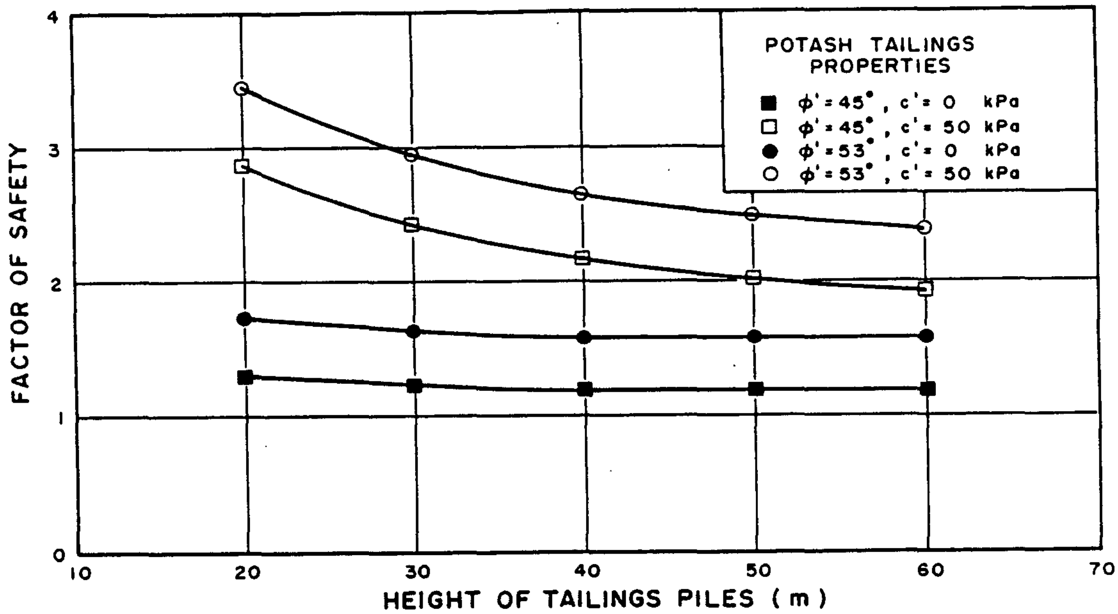


Fig. 9 Factor of Safety versus Height of Pile (Toe Failures Mode 1

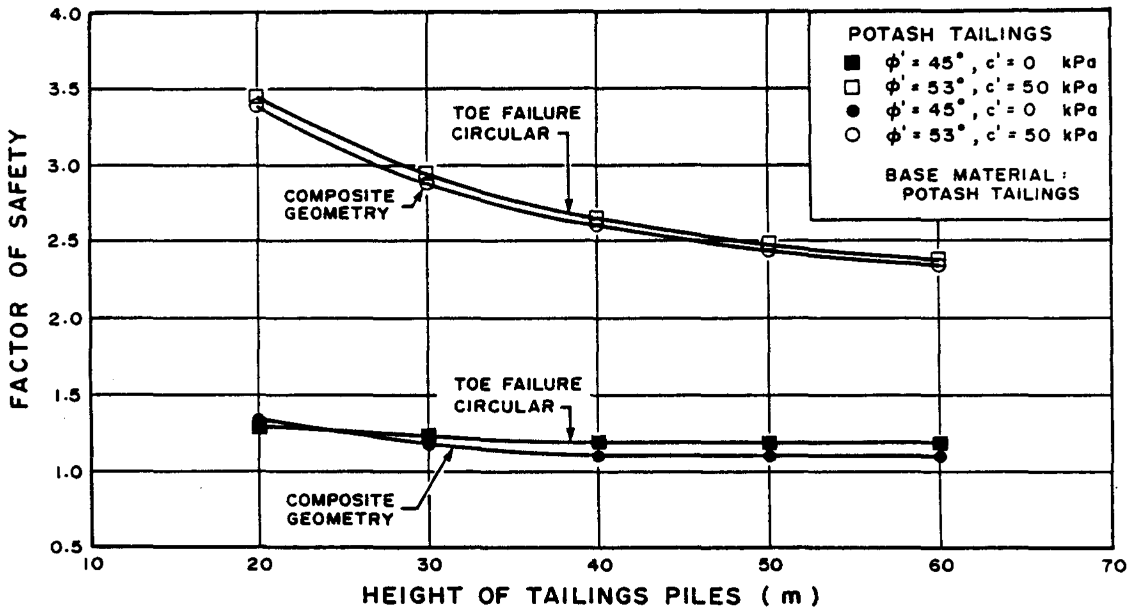


Fig. 10 Toe Failure and Composite Failure for a Failure Through the Tailings Pile

Figure 12 further considers a failure surface through the foundation soils but with increased pore-water pressures. The results indicate that pore-water pressure has a dramatic effect upon the factor of safety. For a tailings pile of 40 m, a pore-water pressure equivalent to one-half the height of the pile could precipitate instability. These results isolate pore-water pressures as a significant variable in assessing stability of tailings piles.

The effect of seismic activity was also studied by Chiu and Fredlund (1986) and shown to be a significant variable affecting overall stability. In other words, a small seismic activity substantially reduced the overall factor of safety.

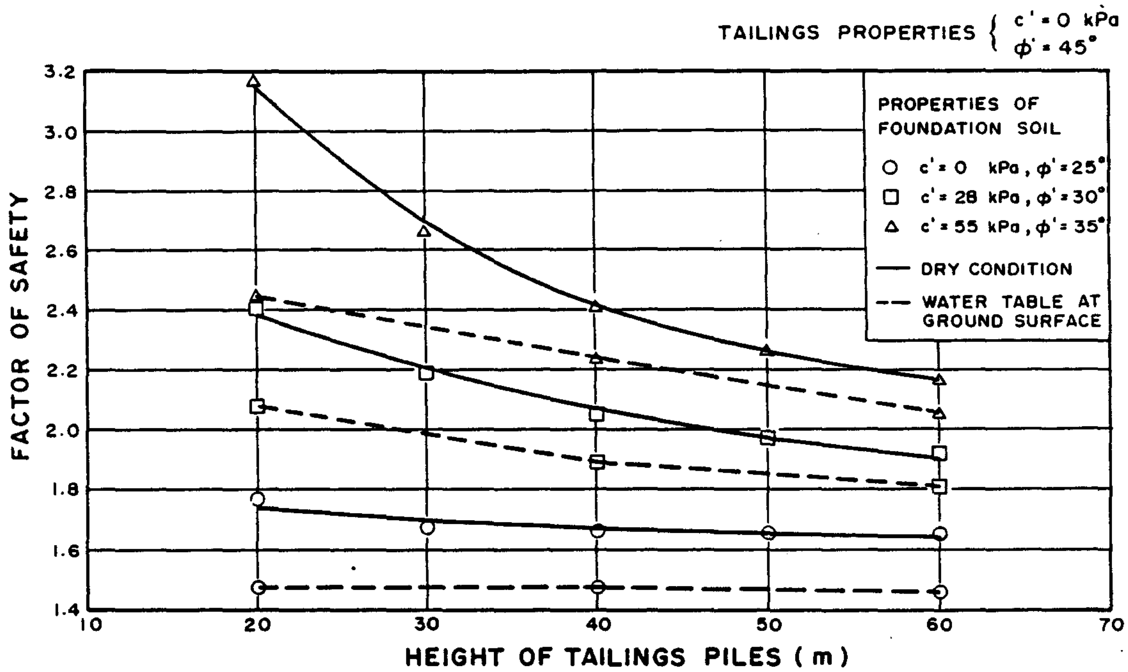


Fig. 11 Factor of Safety versus Height of Piles (Base Failure)

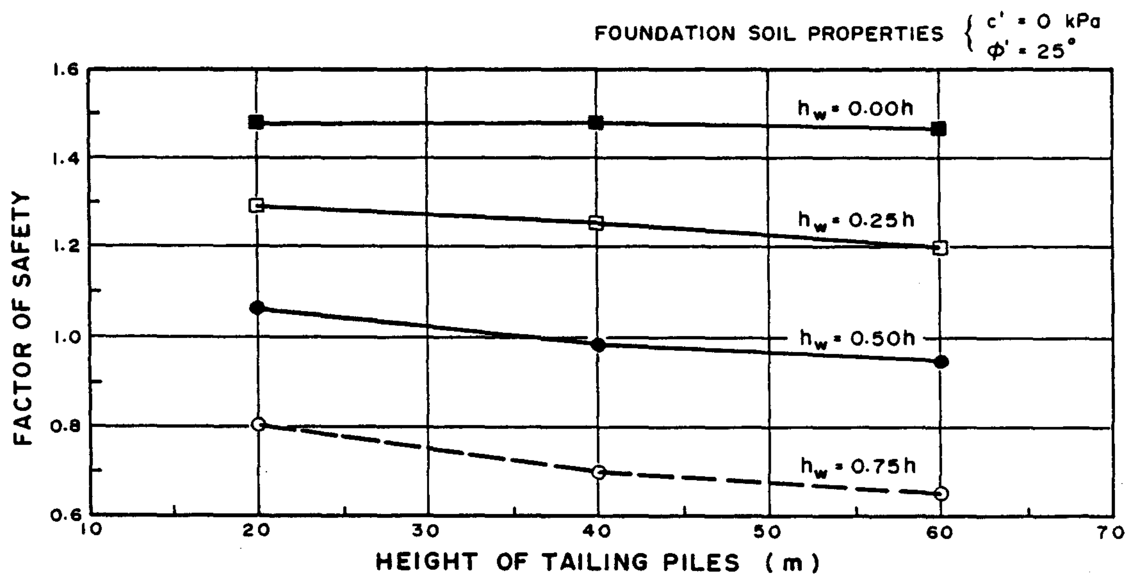


Fig. 12 Factor of Safety versus Height of Pile (Base Failure) for Different Ground Water Levels (c′ = 0 kPa and ϕ′ = 25°)

Comparison of Modes of Failure

Figure 13 shows a comparison of the modes of failure for a pile 100 m in height with the pore-water pressures decreasing to zero at the toe of the pile. First, the height of the pile does not appear to be significant since the failure surfaces appear to congregate at the toe of the pile. The same analysis was repeated using slightly higher pore-water pressures at the toe of the pile (Figure 14). The factor of safety results change significantly. The effect of pore-water

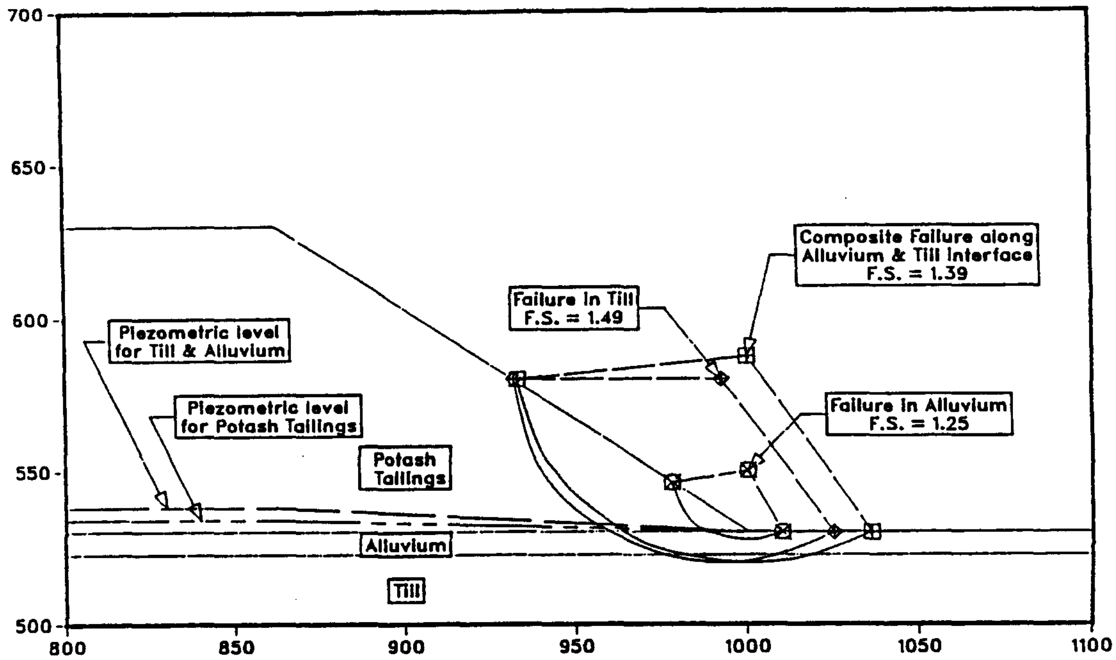


Fig. 13 Summary of Stability Analysis for the Case Study: Height = 100 mm (piezometric levels dropping off towards the toe of the slope)

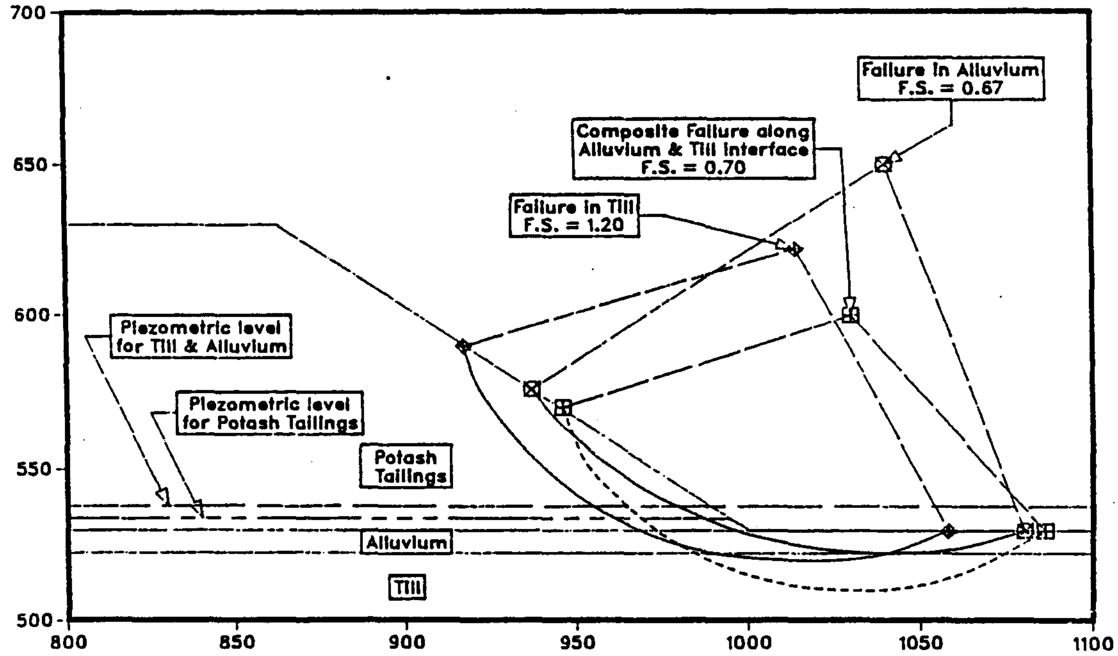


Fig. 14 Summary of Stability Analysis for the Case Study: Height = 100 mm (with no drop-off in the piezometric level)

pressures at the toe of the slope are very significant. This is a real possibility in practice and is a condition worthy of further study, both analytically and in the field.

Effect of Solutioning on Tailings Pile Stability

There is the possibility of solutioning of the tailings, both within the pile and around the edge of the pile. The former case (i.e., solutioning within the pile) has not been studied to-date but should be given consideration with respect to long term stability and closure. Let us assume that over a period of time the pile becomes honey-combed or karst in nature as shown in Figure 15. Many questions of relevance could be asked. For example, "How can the solutioning be taken into account analytically?" Or, "How can the solutioning be mapped and quantified insitu?" Or, "What type of subsurface exploration program can be carried out?" Even the possibility of solutioning of the pile with time is not a process which is understood. Much research could still be done on this subject.

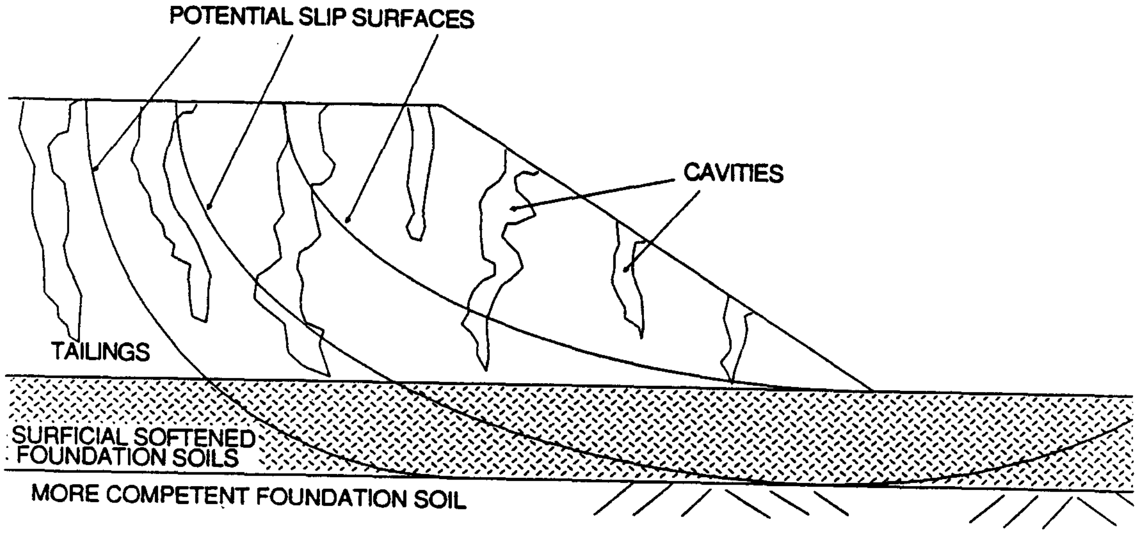


Fig. 15 Consideration of the Possibility of Solutioning within the Tailings Pile

The effect of solutioning around the edge of a tailings pile was studied by Chiu and Fredlund, 1986 (Figure 16). The factor of safety of the slope was shown to tend towards a vertical section of the pile breaking off at the end of the crack. Access of fresh water around the tailings has shown that this mode is a distinct possibility.

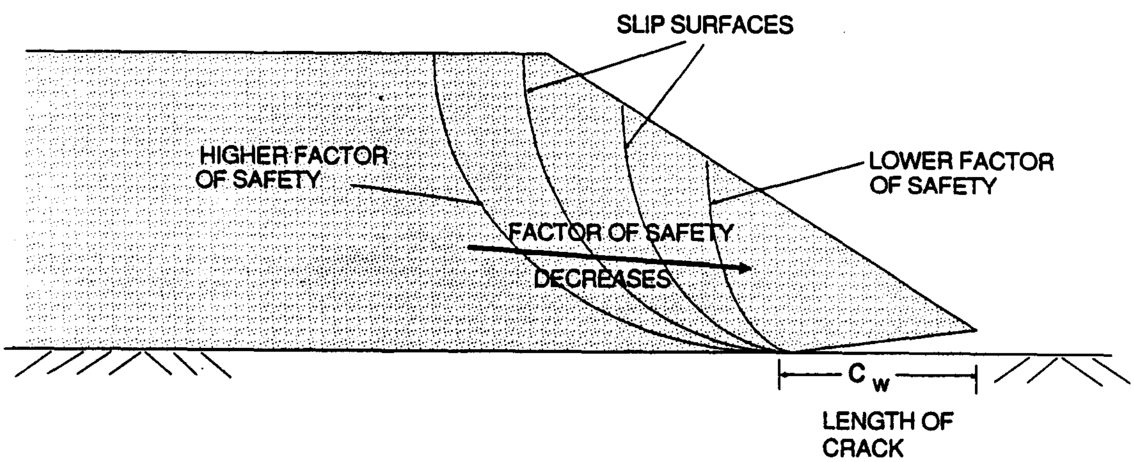


Fig. 16 Diagram Showing the Trend in Variation of Factor of Safety as the Slip Surface Tends Towards a Vertical Line

Figure 17 shows the reduction in factor of safety caused by edge cracks on the pile. The reduction in factor of safety is significant; however, such failures may produce more of a maintenance problem than a catastrophic type of failure.

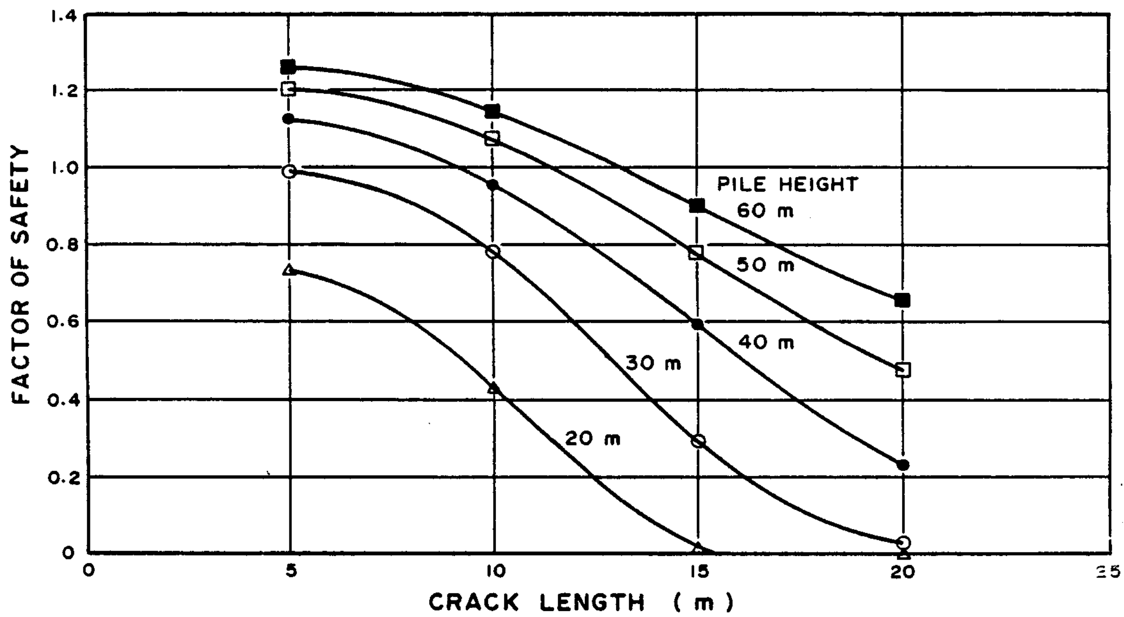


Fig. 17 Factor of Safety versus Crack Length for Different Heights of Pile

PORE-PRESSURE MIGRATION

The problem of pore pressure migration should be modelled using a saturated/unsaturated and a stress loading, pore pressure generation type of analysis.

In recent years there has been several embankment failures involving the phenomenon of "pore pressure migration". This involves the situation where high pore-water pressures build up below an embankment due to the placement of the fill. However, at this point the pore pressures do not produce instability. With time, however, the pore pressures dissipate horizontally towards the toe of the embankment. As shown previously, the pore pressures below the toe of the slope can substantially reduce the factor of safety. In other words, the failure through the foundation is delayed until some time in the future when the pore pressures are high below the toe of the tailings pile. It would be of value to study the potential of pore pressure migration producing long term instability of the tailings piles.

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