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# PORE WATER PRESSURE CONDITIONS IN TAILING DAMS

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## ABSTRACT

Typically, effective stress slope stability analyses of tailing dams are performed assuming a location for the phreatic surface with hydrostatic pore water pressures calculated below this surface. Depending on numerous factors including tailing properties, deposition-raise rates and boundary conditions, these assumptions may be either conservative or unconservative. Pore water pressure conditions within several tailing dams at a copper mine in the southwestern United States are examined with respect to the factors listed above. For the structures considered, the assumption of hydrostatic pore water pressures was found to give conservative results with respect to calculated factors of safety.

Pore water pressure conditions within several operating dams at the site have been monitored for many years using an extensive piezometer system which includes open well and isolated tip piezometers. It was found that the pore water pressures below the phreatic surface are less than hydrostatic, a result of the favorable drainage conditions and the relatively slow loading rates experienced by these dams.

The methods used to measure pore water pressures and the observed conditions are presented. Characteristics of the tailing dams including size, historic raise rates and subsurface conditions along with tailing properties (index and engineering properties), are also presented to give an overall understanding of these structures, the materials of which they are comprised and the observed behavior of the structures in terms of observed pore water pressures.

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## INTRODUCTION

The complexity and variability inherent in tailing dams makes prediction as well as evaluation of the performance of these structures difficult. Many factors are found to influence the performance of tailing dams including: geologic and topographic setting; dam geometry; tailing properties; deposition methods and operation of the dam. Nelson, Shepherd and Charlie (1977) have investigated operation and construction factors and their affect on the stability of tailing dams. Modeling of seepage through tailing dams has been investigated by Van Zyl and Harr (1977) as well as many others. The purpose of this paper is to evaluate the performance of several tailing dams where data are available that reflect the behavior of these structures during normal operation. Given this understanding, important aspects of tailing dam behavior can be addressed when assessing the performance of existing or proposed dams.

Four upstream method tailing dams and one rockfill dam are currently used for tailing deposition at this mine. The behavior of the upstream method tailing dams is monitored by an extensive system of piezometers, movement markers and staff gauges installed in each of the dams. This paper presents a description of the tailing dams and examines their behavior as indicated by pore water pressure conditions within the dams.

## PHYSICAL DESCRIPTION OF TAILING DAMS

Operation of the mine began in the late 1960's when construction of the original tailing dams was initiated. Since that time new tailing disposal facilities have been constructed as needed. The crest lengths of the tailing dams currently range up to 2 1/2 miles (4 km) and the dam heights range between about 130 feet (40 m) and 250 feet (76 m) with ultimate planned heights approaching 400 feet (122 m).

The tailing dams are located in the topographic expression of a fault-bounded structural trough. The dams are founded primarily on Bolson Fill that is derived from materials eroded and transported by water from the surrounding mountains. The Bolson Fill consists of relatively clean to clayey and silty sands with gravelly and cobbly lenses. In valley bottoms, the Bolson Fill is overlain by up to about 20 feet (6 m) of alluvial materials consisting primarily of relatively clean to slightly silty sands and gravels.

Tailing production at the mine is generally about 40,000 to 50,000 tons per day. Tailing deposition is normally restricted to one dam at a time, and deposition is rotated from dam to dam to provide alternating periods of deposition and rest on each dam. Recently, deposition periods have been on the order of two to six

months, and rest periods on the order of six months. Raise rates for the tailing dams have varied and have typically been relatively high during the first few years of deposition on a dam. Raise rates for the smaller dams have recently been on the order of 10 feet per year (3 mpy), and for the larger dams on the order of 3 to 5 feet per year (1 to 2 mpy).

The tailing dams are raised using the upstream method of construction with tailing deposited by cycloning. Tailing is currently delivered to the dams by pumping the tailing slurry in a 30-inch (76 cm) diameter delivery pipe that extends across the dam on a bench constructed on the downstream slope. The tailing is deposited using 12-inch (30 cm) diameter cyclones spaced about every 52-feet (16 m) along the dam. Tailing is fed to the cyclones by a 6-inch (15 cm) diameter line that is extended as needed to raise the dam. The tailing delivery pipe is raised about every 45 to 50 feet (14 to 15 m) of dam raise. The cyclone underflow, coarser tailing, is deposited in cones that form the "sand beach" or downstream portion of the dam, and the cyclone overflow, finer tailing, is deposited using lines that extend upstream from the cyclones into the storage area. A schematic cross-section is shown on Fig. 1, and a photograph of deposition on Fig. 2.

The whole tailing slurry is typically about 45 percent solids by weight. The typical range in grain size distributions for whole tailing, underflow tailing and overflow tailing are shown on Fig. 3. The percent passing the No. 200 sieve for whole tailing ranges from about 50 to 70, for underflow tailing from about 20 to 45, and for overflow tailing from about 63 to 88 percent. Atterberg limits for tailing materials are also shown on Fig. 3. The whole tailing and cyclone overflow tailing classify as either a ML, CL-ML or CL, and the cyclone underflow tailing is generally non-plastic and classifies as an SM according to the Unified Soil Classification System.

## DESCRIPTION OF MONITORING SYSTEM

Many elements comprise the monitoring system utilized on these tailing dams. The following is a description of the piezometer and staff gauge systems, the two elements that are pertinent to this study.

Piezometers are strategically located at study sections established on each of the tailing dams. Two types of piezometers are used: open well and isolated tip piezometers. The open wells are slotted essentially along the entire length of the piezometer so that they reflect the uppermost water level intercepted by that well. Isolated tip piezometers are designed to measure water pressures at the tip location; both porous and pneumatic isolated tip type piezometers are used. The piezometers have been installed in



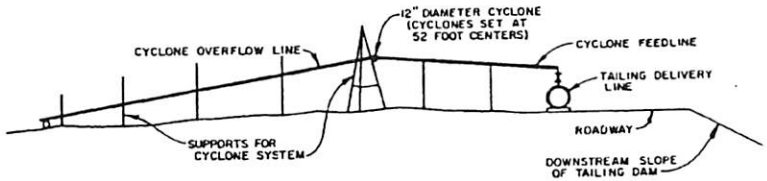



Fig. 1. Typical Cyclone Setup

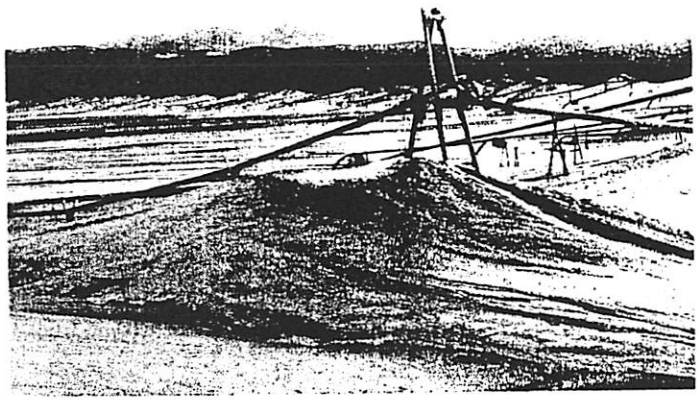
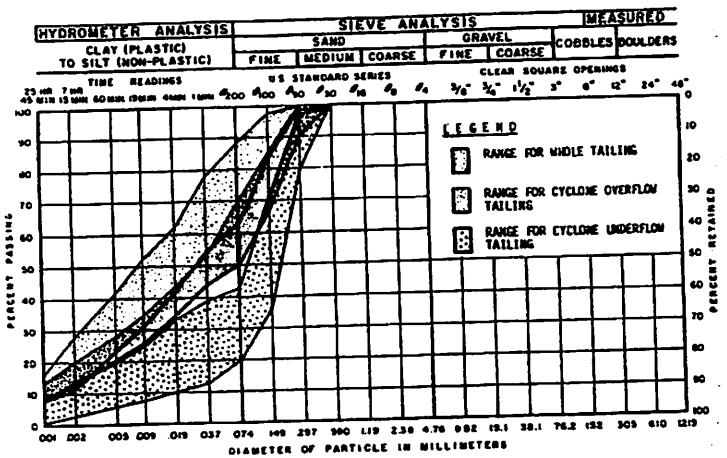


Fig. 2. Photograph of Cyclone in Operation

groups, each group typically including one open well and one or more isolated tips. The piezometers are grouped in areas along the study sections between the toe and crest of the dam, generally at each bench. In addition, isolated pneumatic tip piezometers are located at varying distances and elevations upstream of the crest in the storage area.

A total of about 20 to 110 piezometers are used to monitor internal water conditions in each dam. The piezometers are typically read every one to two weeks. Computerized data management systems are used to facilitate timely review of these data.




GRADATION ANALYSIS

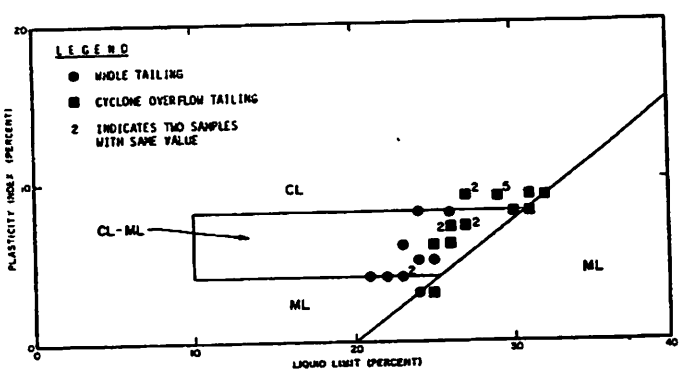



Fig. 3. Typical Grain Size Distributions and Atterburg Limits for Tailing Materials



Staff gauges in the storage areas are used to monitor the tailing level in each dam. The gauges are typically secured in the natural ground at several locations around the perimeter of the storage area. These gauges, along with records of tonnage of tailing deposited, allow for accurate monitoring of dam usage and raise rates.

## EXAMINATION OF PIEZOMETER DATA

Piezometer data offers a means of assessing the performance of a tailing dam during operation of the dam. Interpretation and analysis of these data provides a reasonable basis for modification of operation of the dam to optimize deposition while maintaining an acceptable margin of safety. Monitoring of the dams is accomplished by comparing measured water levels to design assumptions and to threshold water levels that have been established for the piezometers.

Following is a presentation of the piezometer data from one study section located near the maximum section on one of the tailing dams. This section was selected because it is well instrumented and illustrates many of the important aspects related to pore water conditions in the dams. The height of this dam is about 200 feet (61 m) and the crest length about 9600 feet (2900 m). Fig. 4 shows the cross-section including piezometer types and locations as well as water level readings for the piezometers. Additional isolated pneumatic tip piezometers located further upstream in the storage area are not shown.

As shown on Fig. 4, the water levels for isolated tip piezometers are in all cases lower than the water level measured in the adjacent open well for each piezometer group. The line of saturation or phreatic surface at this study section, and in general in the dam, is located about 20 to 40 feet (6 to 12 m) below the slope surface. Fig. 5 presents the piezometer data from the piezometer group at the first raise bench in a different form. The isolated tip piezometer readings are plotted as pore water pressures, and the open well reading is used to estimate the location of the phreatic surface. The pore water pressure profile corresponding to hydrostatic conditions (assuming the phreatic surface is located at the level indicated by the open well piezometer), and the actual pore water pressure profile are shown on Fig. 5. It is clear that the actual pore water pressures are less than hydrostatic, and approach zero at the base of the dam.

Fig. 6 shows pore water pressure contours on the same cross-section of the dam. The pore water pressure contours are based on piezometer data from all of the piezometers at this section. Examination of the pore water pressure contours indicates that pore water pressure conditions throughout the dam cross-section are less

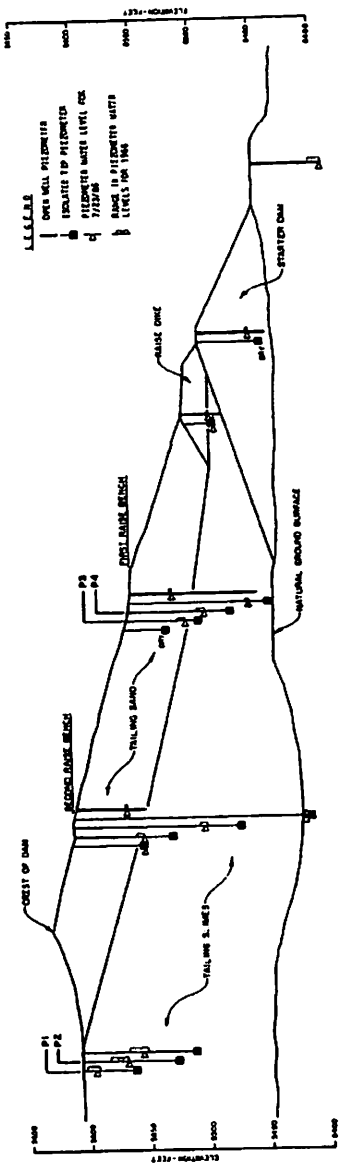



Fig. 4. Cross-Section of Study Section



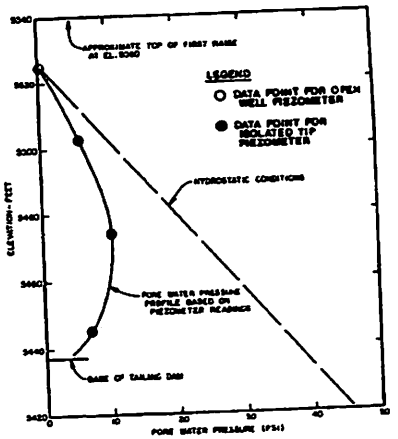



Fig. 5. Pore Water Pressure Profile at First Raise Bench

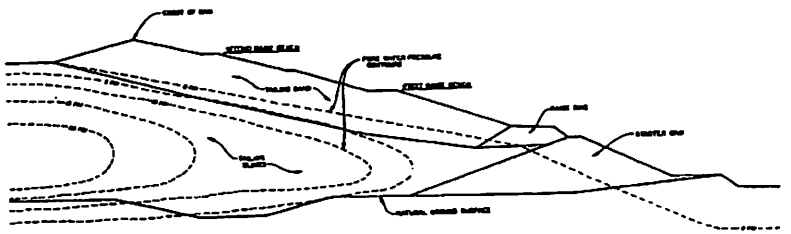


Fig. 6. Cross-Section Showing Pore Water Pressure Contours

than hydrostatic. These conditions result from the permeability of the underlying natural materials being greater than that of the tailing. Thus, the foundation materials act as a nearly free draining boundary. These drainage conditions are favorable from the standpoint of dam stability. The importance of this finding with respect to the stability of this dam is considered later in this paper.

Investigations that we have performed using piezometer cone penetration testing methods indicate that similar less than hydrostatic pore pressure conditions exist in other tailing dams. We found that the piezocone works quite well as an investigation tool for tailing dams; static pore water pressures can be measured by performing pore pressure dissipation tests that are relatively short in duration. Campanella, Robertson and Gillespie (1984) describe a piezometer cone investigation of tailing dams in British Columbia where equilibrium water pressures indicated a downward gradient of pore water pressures.

Data shown on Figs. 4, 5 and 6 correspond to one set of piezometer readings and thus represent the "static" pore water pressure conditions within the dam. The range in typical piezometer readings for each of the piezometers at this study section is shown on Fig. 4 using brackets. The ranges in water level readings are greater for piezometers upstream of and near the dam crest compared to those further down the slope. Increases in the piezometer readings generally occur in response to tailing deposition on the dam, while decreases in piezometer readings occur during rest periods.

Tailing deposition on the dam during the first six months of 1986 is illustrated graphically on Fig. 7. The only significant deposition during this time occurred over about a month long period in late January and early February. No significant deposition had occurred on the dam for about four months prior to this period. Examination of the staff gauge readings indicates that the average increase in the tailing slimes surface in the storage area as a result of this deposition was about 1.8 feet (0.5 m). Assuming an even distribution of tailing across the storage area and a total unit weight for deposited tailing of 90 pounds per cubic foot (14 kN/m$^3$), the total tonnage of tailing deposited during this period amounts to about 2.2 feet (0.7 m) thickness of tailing, a good agreement with staff gauge readings.

Examination of piezometer water level history plots indicates that the response of the piezometers to this period of deposition depends on location and type of piezometer. The response of two isolated pneumatic tip piezometers located beneath the first raise bench and two isolated pneumatic tip piezometers located beneath a point just upstream of the dam crest are shown on Fig. 8. It is clear that the piezometers located near the crest of the dam show an almost instantaneous and marked response to deposition on the dam. The total increase in water level is about 10 feet (3.0 m) with the highest water level occurring about one to three weeks after tailing deposition has ceased. Water levels for these two piezometers return to near the pre-deposition levels about two months after the peak reading. For the two piezometers located on



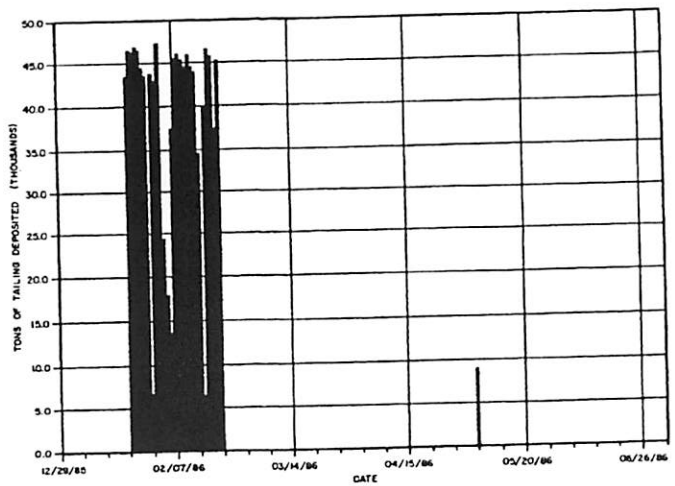



Fig. 7. Tailing Deposition on Dam

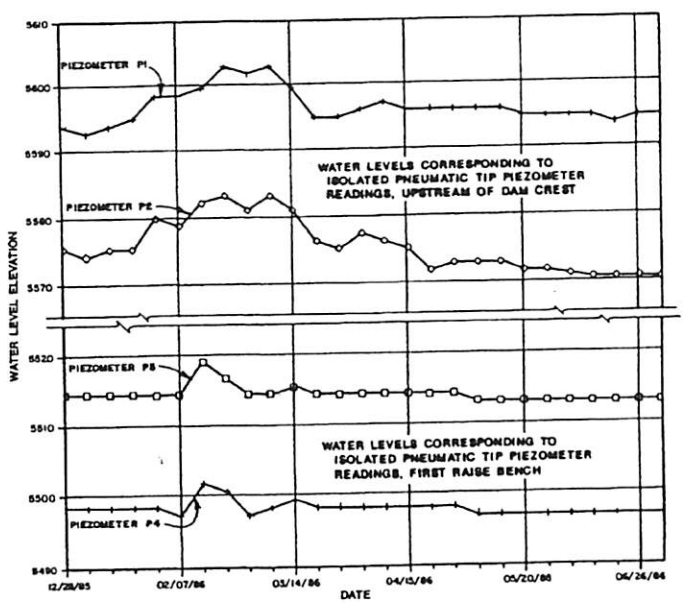



Fig. 8. Response of Piezometers to Tailing Deposition

ıe first raise bench, response begins about two weeks after :position was initiated, and the increase in water level was about feet (1.5 m) with the highest level measured occurring at about ıe end of the tailing deposition period. Water levels for these ıo piezometers return to near the pre-deposition levels about two :eks after the peak reading. The open well piezometers at this :ction generally showed one to two foot increases in water levels, ith gradual returns to pre-deposition levels.

The difference between the behavior of piezometers located up-:ream of the dam crest and those located beneath the downstream lope of the dam is explained in part by the fact that previously :posited tailing material upstream of the crest of the dam is (periencing an increase in load from the recently deposited ıiling. Initially this increased load generates excess pore water ·essures as shown on Fig. 8 (excess with respect to the static ıre water pressure). With time these excess pore water pressures issipate and the increased load is carried by the tailing ıterials. Based on estimates of the amount of tailing deposited ıbout 2 feet (0.6 m) thickness) and assuming a total unit weight ır the recently deposited tailing of 90 pounds per cubic foot 14 kN/m$^3$), this deposition corresponds to an increase in pore ıter pressure of about 3 feet (0.9 m) of water. This is about one ıird of the increase in water level readings observed for the solated tip piezometers located upstream of the crest as shown on ig. 8. This difference is probably caused by deposition in the icinity of these piezometers being greater than elsewhere on the ım, or by deposition of cyclone underflow sand over these iezometers.

As shown on Fig. 8, piezometers located beneath the downstream lope of the dam generally showed a smaller increase in response to ıe deposition. This response was probably generated in part when ıe excess pore water pressures generated beneath the deposited ıiling, as described above, began to dissipate. In addition, some f the water from the deposited tailing was probably flowing nrough the cyclone underflow sands beneath the slope of the dam. xamination of piezometer responses to longer deposition periods on nis dam and on other dams indicates that the phreatic surface eneath the downstream slope of the dam continues to rise during rolonged periods of deposition.

The pore water pressure response at one of the other study sec-ions on the dam during the same deposition period shown on Fig. 7 s illustrated by readings from three additional isolated pneumatic ip piezometers. These piezometers are located at varying depths ust upstream of the crest of the dam. The pore water pressure



profiles as indicated by the piezometer readings at four points in time are shown on Fig. 9. Hydrostatic pore water pressure conditions are also shown assuming that the line of saturation is at the tailing surface, generally a reasonable assumption at locations upstream of the crest. The pore water pressure profiles before deposition (1/7/86) and about five months after deposition (7/9/86) are about the same and appear to represent pore water pressure conditions during "resting" of the dam. The pore water pressure profile at the time when deposition has ceased (2/18/87) is approaching the hydrostatic line in the upper 40 feet (12 m) of the profile. The pore water pressure profile about one month after deposition has ceased (3/19/87) is somewhat higher and appears to be at about hydrostatic conditions in the upper 40 feet (12 m) of the profile.

While the fact that the highest pore water pressures are not observed until after tailing deposition has ceased is difficult to explain, this observation points out the importance of under-standing how the dam responds to tailing deposition periods of

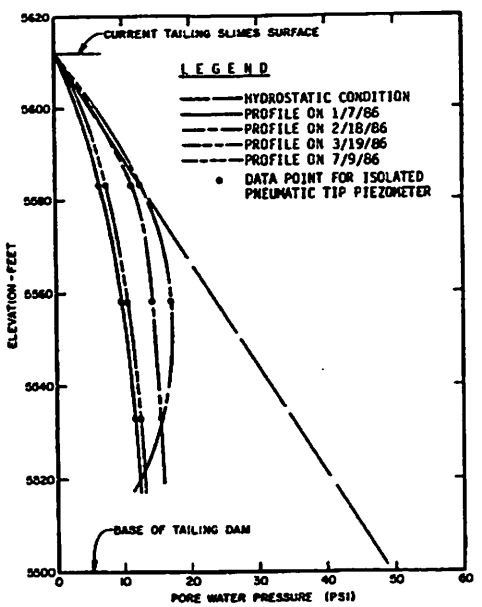



Fig. 9. Response of Pore Pressure Profile to Deposition on Dam

varying duration. This understanding can only be gained by instrumentation of the dams and analysis of piezometer data by personnel who are experienced in operation of these complex structures.

## SLOPE STABILITY CONSIDERATIONS

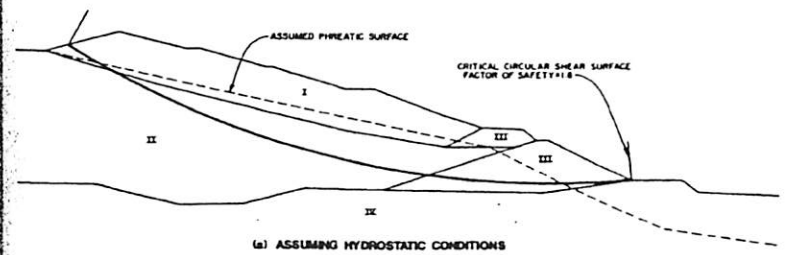
Given the understanding of pore water pressure conditions described above, stability analyses were performed to assess the importance of these conditions with respect to slope stability. The slope stability analyses performed were limit equilibrium analyses using effective stress strength parameters with pore water pressures defined as described below.

Tailing materials were modeled using two material types, one to represent the tailing sands (predominantly cyclone underflow materials), and the other to represent the tailing slimes (predominantly cyclone overflow materials). The width of the tailing sand (sand beach) was based on drill hole and surface sampling information and was generally about 200 feet (61 m).

Two definitions of pore water pressures were used for these analyses. For the first, the phreatic surface was located based on water levels measured in the open well piezometers, and the pore water pressures were calculated in the usual manner as depth below the phreatic surface times the unit weight of water. Pore water pressures defined in this manner are referred to as hydrostatic. For the second definition of pore water pressures, the contours shown on Fig. 6 were used. As discussed above, pore water pressures defined by these contours are less than hydrostatic. The same phreatic surface was used as a contour line along which the pore water pressure is zero, and pore water pressure data were input to define the other contours. Pore water pressures were assumed to be zero above the phreatic surface for both cases analyzed.

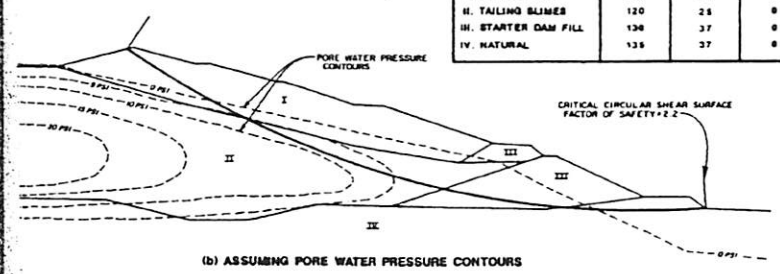
Results for the slope stability calculations assuming hydrostatic conditions, presented on Fig. 10a, indicate a factor of safety of 1.8. The critical circular shear surface passes through the entire slope height with a maximum depth of about 75 feet (23 m). Results for the slope stability calculations using pore water pressure contours, presented on Fig. 10b, indicate a factor of safety of 2.2. The critical circular shear surface again passes through the entire slope height with a slightly deeper maximum depth of about 90 feet (27 m). The difference in the two calculated factors of safety is about 20 percent in this instance. Similar analyses that we have performed for other dams where pore water pressures are less than hydrostatic indicate that the difference in factors of safety can range up to 50 percent.






(a) ASSUMING HYDROSTATIC CONDITIONS

| ASSUMED MATERIAL PROPERTIES | | | |
|---|---|---|---|
| MATERIAL | $\gamma$ (PCF) | $\bar{\phi}$ (DEGREES) | $\bar{c}$ (PSF) |
| I. TAILING SAND | 122 | 36 | 0 |
| II. TAILING SLIMES | 120 | 26 | 0 |
| III. STARTER DAM FILL | 130 | 37 | 0 |
| IV. NATURAL | 135 | 37 | 0 |




(b) ASSUMING PORE WATER PRESSURE CONTOURS

Fig. 10. Results of Slope Stability Analyses

Slope stability calculations described above indicate that the factor of safety calculated based on observed pore water conditions in this instance is about 20 percent higher that that calculated assuming hydrostatic conditions. It is important to point out, however, that the pore water pressure contours used for these calculations (shown on Fig. 6) represent conditions within this dam during "resting". The pore water pressures within the dam were observed to increase as a result of tailing deposition, and in the upper reaches of tailing material upstream of the crest, to reach hydrostatic conditions. Measured pore water pressure increases in the lower portion of the dam slope were less.

Results of slope stability analyses performed on these tailing ıms under normal operating conditions indicate that the assumption : hydrostatic pore water pressure conditions is conservative. ɔnsidering the complexity of observed pore water pressure condi- ions within these dams, and the difficulty associated with ɜasuring and modeling these conditions, the assumption of hydro- :atic conditions for slope stability analyses in this case makes ɔod sense. Analyses using pore water pressure contours, however, ·ovide further insight into the stability of these dams and in ɔme instances may be warranted.

## )NCLUSIONS

The complexity of pore water pressure conditions within oper- :ing tailing dams is clearly illustrated by examination of the iezometer data for these dams where an extensive piezometer system ıd a regular reading schedule have been implemented. The phreatic ırface is generally located about 20 to 40 feet (6 to 12 m) below ıe slope surface. Pore water pressure conditions within these ıms are found to be less than hydrostatic as a result of drainage ıat is occurring at the base of the dams and prudent operations of ıe dams (i.e., limiting raise rates and providing rest periods). ıe pore water pressure conditions at a given instant are found to ıry throughout the cross-section and to be dependent on the ɜposition history and characteristics of the tailing and founda- lon materials. Slope stability analyses performed for these dams ıdicate that with pore water pressures corresponding to actual ɜasured values (less than hydrostatic) the factor of safety was ɔout 20 percent higher than the factor of safety corresponding to ·drostatic conditions. These findings point out the importance of ɔnsidering drainage conditions and dam operation when assessing ıe performance and stability of tailing dams.

The writers wish to emphasize that the properties of the tailing ıd foundation materials at every mining facility are unique and ıat it would be improper to assume that conclusions presented in ıis paper are applicable to tailing dams in general. Each dam at ıch mine must be evaluated independently considering all factors ıat influence its behavior. It is also important to note that ɔor drainage at the base of a tailing dam can result in pore pres- ırres within the dam that are in excess of hydrostatic pressures. ırthermore, operation of the dams (i.e., raise rates and rest ɜriods) have major effects on internal pore pressures and slope tability as indicated by this study.

## :KNOWLEDGMENTS

The authors would like to thank the many individuals within ɔodward-Clyde Consultants who have contributed to this study.



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