Proceedings of the Hydraulic Fill Structures '88, ASCE, Geotechnical Specialty Conference, CSU, Fort Collins, CO, D. J. A. Van Zyl and S.G. Vick, August 14-17, pp. 956-970. 1988

LATERAL MOVEMENTS AND MATERIAL PROPERTIES OF A POTASH TAILINGS PILE IN SASKATCHEWAN CANADA

D.E. Pufahl*
and
D.G. Fredlund**

Abstract

Saskatchewan Potash mines store enormous quantities of tailings and saturated brine, within earthen dykes, on the surface of the ground adjacent to the mine sites. The tailings consist of approximately 90% NaCl, 2% to 3% KCl, and 8% insolubles and other trace minerals. Grain size analyses indicate that the tailings have a gradation corresponding to a uniform medium to coarse sand. Direct shear and triaxial compression tests yield angles of shearing resistance of 45° or greater. Deformation moduli determined from laboratory triaxial tests indicate values of 115 to 700 MPa depending on the initial density and confining pressure. Poisson's ratio has an average value of 0.34.

General limit equilibrium analyses that have been used to assess the short term stability of the piles indicate that the properties of the foundation soils and the pore fluid pressures existing in the foundations are more likely to control the stability of the piles rather than the properties of the tailings.

Long term lateral movements were studied by instrumenting a tailings pile with piezometers, thermistor sensors and slope indicator access tubes. Plane strain finite element analyses using assumed material properties established a best-fit simulation of the deformations measured using the slope inclinometers. Deformation properties obtained in this manner are one to two orders of magnitude lower than those obtained from laboratory tests.

The results indicate that most of the lateral movement occurs in the upper portion of the pile, within the freshly placed tailings. The movements in the pile appear to correlate with temperature, apparently increasing with increasing summer temperatures. However the movements are not large and presently are not reason for concern.

The present tailings disposal methods tend to trap deposits of unconsolidated slimes within the pile. Since the slimes are of low permeability and high compressibility their presence may represent some threat to the stability of the piles.

---

*Professor of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 0W0

**Professor of Civil Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 0W0

Introduction

Saskatchewan potash mines have generated approximately 250 M tonnes of tailings since they began operating in 1962, all of which are stored in piles on the surface of the ground adjacent to the mine sites. In addition, the nine producing mines in the province continue to generate approximately 30 M tonnes of tailings per year. With ore reserves that have been conservatively estimated to last at least 100 years, the projected quantity of tailings is indeed enormous.

The mining companies would like to construct these piles as high as is practicable in order to minimize the storage area. The need for prudent engineering becomes more important as the height of the piles exceed 50 m. A massive failure of one of these piles could rupture the dykes surrounding the brine ponds which in turn would release large quantities of saturated brine to the environment.

A study was undertaken to ascertain the stability of the tailings piles both in the short and long term periods (Chiu and Fredlund, 1986). The short term stability was addressed by applying general limit equilibrium methods of slope stability analysis to establish the factor of safety for the future geometry of the piles as predicted or anticipated by the mine operators. A variety of potential failure surfaces and piezometric conditions were investigated. Based on preliminary results, the stability of the piles in terms of a sudden or catastrophic failure depends largely on the characteristics of the foundation soils and the pore fluid pressures in the foundations rather than on the properties and the behavior of the tailings themselves. As will be seen subsequently, the tailings are a strong and competent material, capable of sustaining high shear stresses at least in short term loading conditions.

Previous investigations of the behavior of potash tailings indicated that creep under sustained stress could constitute a substantial amount of the total deformation of samples loaded in the laboratory (Pufahl, 1982). Furthermore, potash ore can undergo large deformations under constant stress (King and Acar, 1970). This background suggested that continuous movements within the tailings pile caused by sustained shearing stresses could be an important consideration in assessing the long term stability.

As a result, a tailings pile some 22 m in height was instrumented with slope inclinometer access tubes, thermistor cables to monitor temperatures, and piezometers to measure pore fluid pressures. This instrumentation which was installed near the edge of the pile extended throughout the entire depth of the pile and down into the foundation soils.

This paper describes the lateral movements in the pile as determined from the results of the field instrumentation. Some physical and chemical properties of the tailings are provided as well as some of the mechanical properties. A plane strain finite element program employing linear elastic theory was used to establish a best-fit simulation of the results obtained from the slope inclinometer data. The deformation properties corresponding to the best-fit simulation are compared to those obtained from triaxial tests that were performed on laboratory samples.

Site Description

The tailings management site that was selected for the study is the Potash Corporation of Saskatchewan Mining Ltd., (PCS), Lanigan Division, Potash Mine. This mine, which is located approximately 100 km east of Saskatoon, Saskatchewan on No. 16 highway, has been in operation since 1967. In excess of 20 M tonnes of salt tails are presently being stored on the surface of the ground adjacent to the refinery and other surface facilities. This waste disposal site is located on a 270 hectare area of flat to gently undulating fluvial lacustrine terrain consisting of sand, silt and clay which is underlain by thick deposits of clay till (Goodall et al. 1983). Figure 1 shows an aerial view of the site.

Figure 1 Aerial view of waste disposal area
(Courtesy PCS Mining)

After refining; the halite and the slimes are delivered to the disposal area through a pipeline in the form of a brine slurry. The coarse fraction of the slurry is deposited near the exit of the pipe while the finer fraction settles out as the slurry proceeds down the slope of the tailings pile to a settling brine pond. The discharge pipes are moved around the disposal area and low tailings dykes are occasionally built with a crawler tractor and dozer so as to confine the slurry to small areas or cells. This procedure is a combination of the upstream and center-line method of construction. The tailings are pushed over the side of the pile and typically form a natural angle of repose of approximately 35° to the horizontal (Fig. 2).

Figure 2 Potash tailings; Angle of repose

The natural slope formed on the surface of the tailings pile is approximately 4% to 5% in the upper portion of the pile and as little as 0.5% as the slurry, consisting primarily of slimes, proceeds down the slope to the settling brine pond (Tallin and Pufahl, 1983). Even though the total percentage of slimes within the tailings is on average less than 10% to 12%, these disposal methods may cause layers of slimes of substantial thickness to be deposited within or adjacent to the piles which may then be covered with additional tailings. The extent to which these layers of slimes influence the stability of the pile has not been determined.

During the period of monitoring, the tailings discharge pipe was generally located in the northeast quadrant of the pile where tailings had previously been deposited to a height of 22 m or more above the surface of the ground.

Material Properties

The potash tailings typically consist of 85% to 90% $NaCl$, 2% to 3% KCl, 1% to 2% $MgCl_2$ and 5% to 12% water insolubles. The tailings have a texture and gradation that is equivalent to a uniform medium to coarse sand (Fig. 3). The relative density (specific gravity) of the individual particles ranges from 2.100 to 2.186. The in situ density at the surface is approximately 1.50 Mg/m^3, 1.65 Mg/m^3 at 1 m of depth and increases to about 1.95 Mg/m^3 near the base of the pile (Pufahl, 1983).

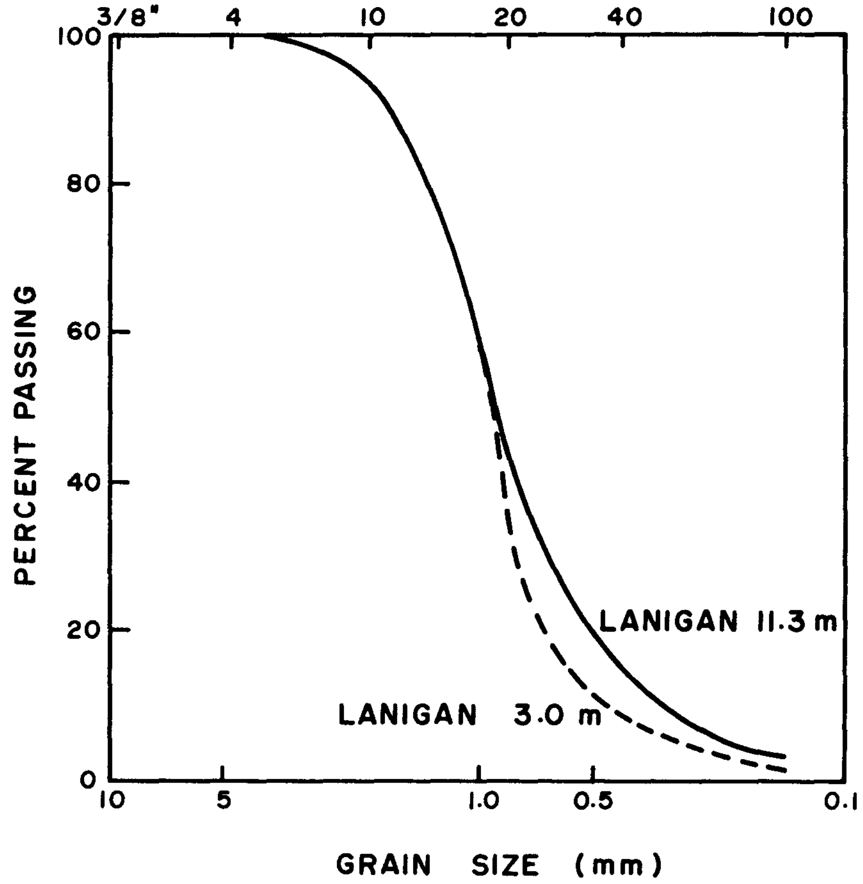

Figure 3 Gradation of potash tailings

In situ infiltration studies have been performed on this tailings pile using brine as the infiltration fluid. The results indicate that the saturated permeability varies from about 1.5 x 10^{-5} m/s to 4.0 x 10^{-5} m/s (Wong and Barbour, 1985). The low values of permeability were obtained from shallow pits while the larger values were established from large diameter bore holes (0.6 m in diameter x 1.5 m deep). The difference may be caused by the predominantly lateral flow from the bore holes compared with the predominantly vertical flow from the shallow trenches indicating a substantial degree of anisotropy with respect to permeability within the tailings pile.

The strength characteristics under short term loading were evaluated by using both direct shear and triaxial compression tests (Figs. 4 and 5). The material exhibits a large angle of shearing resistance (i.e., greater than 45°). This infers a shearing resistance greater than the normal stress applied to the sample. Such behavior is characteristic of extremely dense, angular, granular soils, where the component of strength caused by interlocking and crushing is substantial.

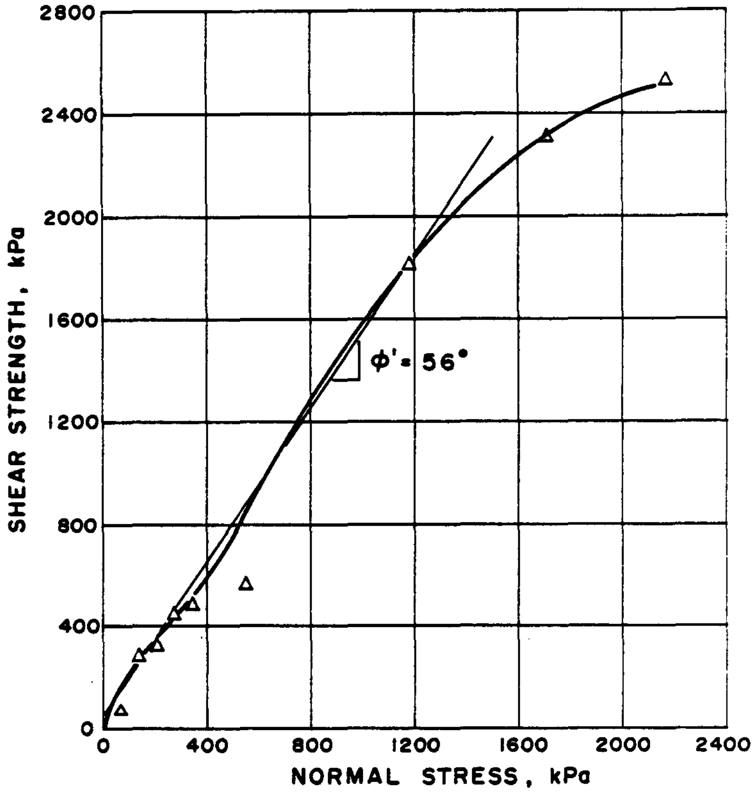

Figure 4 Direct shear test results

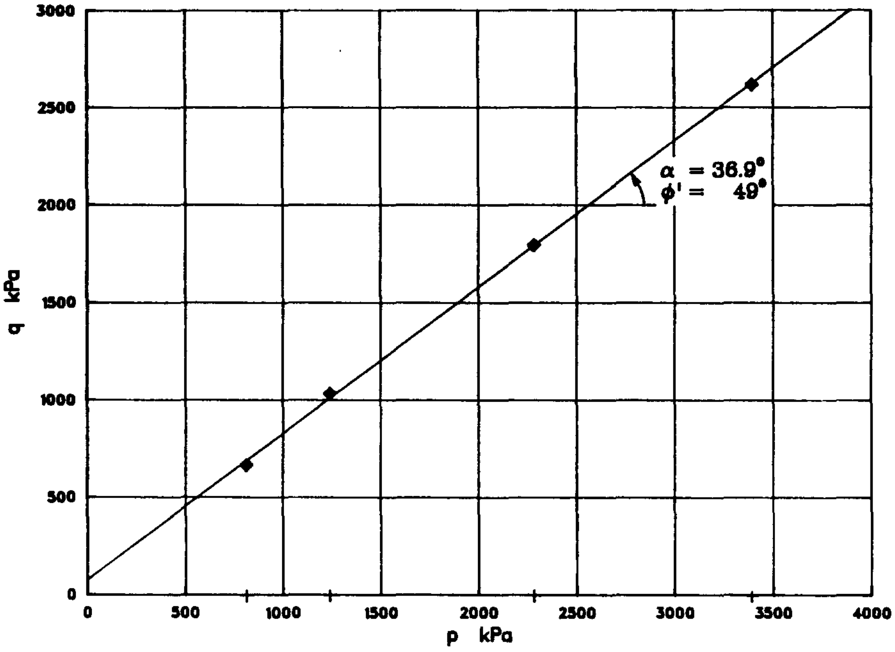

Figure 5 Triaxial test results

Drained triaxial tests were performed in order to evaluate the deformation modulus and Poisson's ratio. Figure 6 shows a typical stress-strain relationship for this material. The stiffness of the tailings, as with any granular material, depends upon the initial density and the confining pressure. In addition, significant cementation occurs between the salt particles which further contributes to the rigidity of the material, especially at low strains.

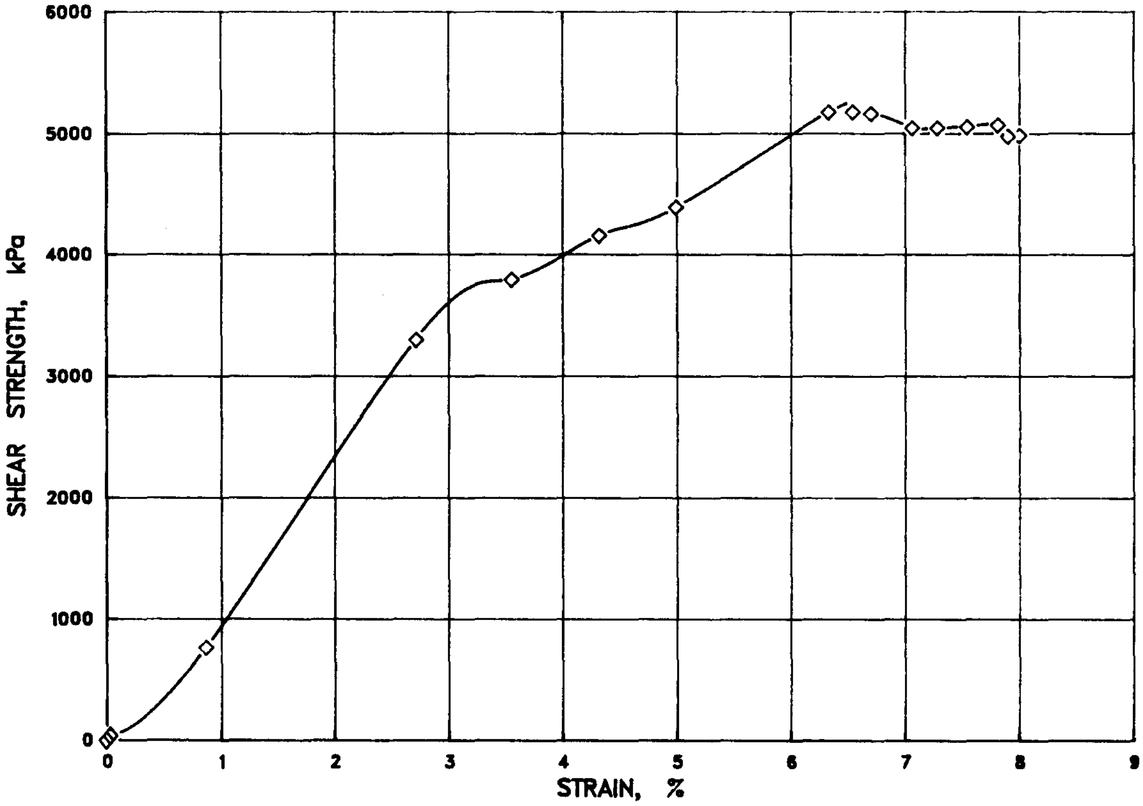

Figure 6 Stress vs strain: Potash tailings

In determining the stress-deformation characteristics of the tailings, it is important to be aware that the tailings undergo substantial creep under sustained loads. Therefore, the rate of loading has important implications in establishing the deformation modulus. The results presented in Figure 6 were obtained from a sample that was brought to failure over a period of six to eight hours representing a strain rate of approximately 1.3×10^{-2}%/min. Values of Poisson's ratio were obtained by measuring the volume of brine expelled from the sample in the initial stages of loading. By assuming uniform lateral deformation, the Poisson's ratio was computed. The density and confining pressure also determine the volume change behavior of granular materials. It is only at small strains where volume change is negative (i.e., decreases) that the results are meaningful in terms of elastic theory. The values for deformation modulus and Poisson's ratio are tabulated in Table 1. It is likely that the low values of Poisson's ratio are more realistic for short term loading conditions where elastic conditions are likely to apply.

Table 1: Tailings Properties from Laboratory Triaxial Tests

Sample Number	Density Mg/m^3	Deformation Modulus MPa	Poisson's Ratio
R-3	1.50	115	0.46
R-13	1.60	635	0.33
R-14	1.54	575	0.25
R-15	1.57	705	0.26
R-16	1.55	588	0.39
Average	1.55	524	0.34

Instrumentation

Figure 7 shows a plan view of the field instrumentation. Instrumentation consisting of piezometers, slope inclinometer access tubes, and thermistor cables was installed in the fall of 1982. The slope inclinometer access tubes and a number of piezometers were placed approximately 2 m from the edge of the pile. The thermistor cable and another set of piezometers were installed toward the center of the pile, approximately 165 m in from the crest. The position of the thermistors relative to the slope indicator access tubes prevents a complete understanding of the temperatures at the slope inclinometer access tubes.

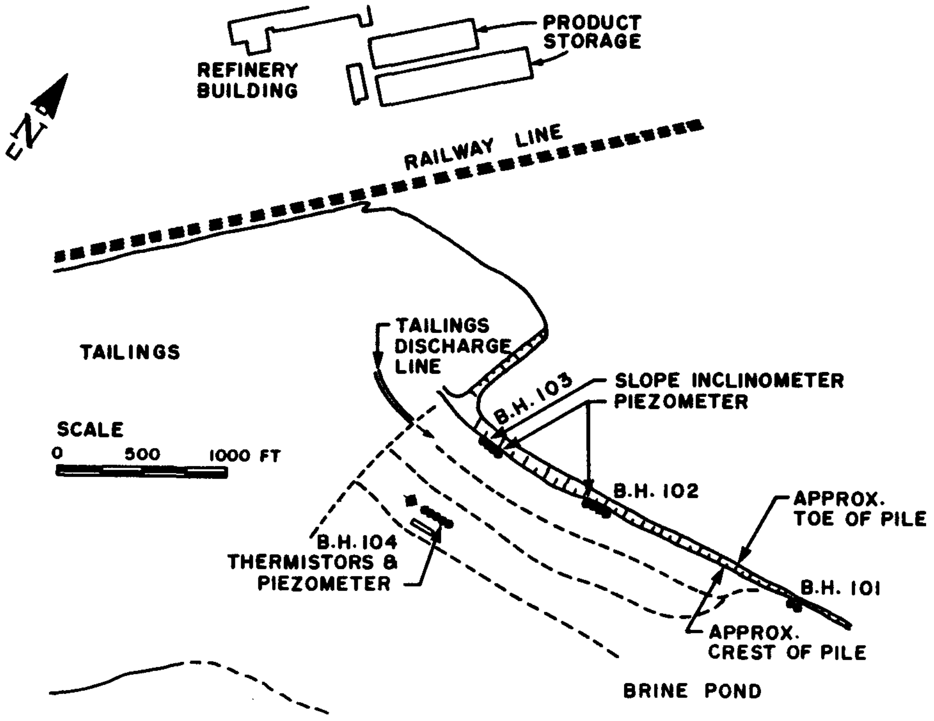

Figure 7 Plan view of instrumentation location

An initial set of slope indicator readings was taken on November 16, 1982. Regular monitoring began in May 1983 when readings were taken monthly to December 1983. Readings were discontinued at that time because excessive deflections of the access tube would not allow passage at the inclinometer sensor. Additional inclinometer access tubes were installed at the site in November of 1984 and monitoring was undertaken until January 1985.

Presentation of Data

Figure 8 shows the profile of deflections perpendicular to the strike of the slope that occurred over the period of a year. The contour of maximum deflection occurs at a depth of approximately 3 m to 8 m decreasing to the lesser value with increasing time. Figure 9 indicates the temperature profiles that were established from the thermistor readings (Chiu and Fredlund, 1986).

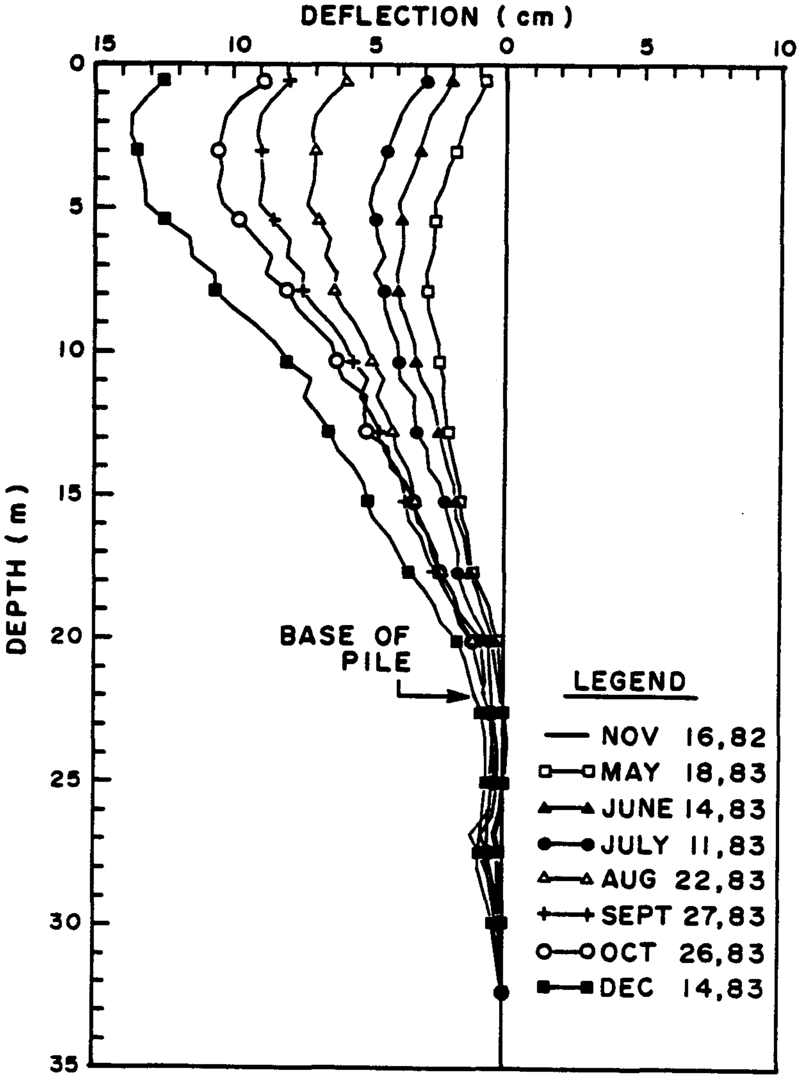

Figure 8 Deflections from slope inclinometer results

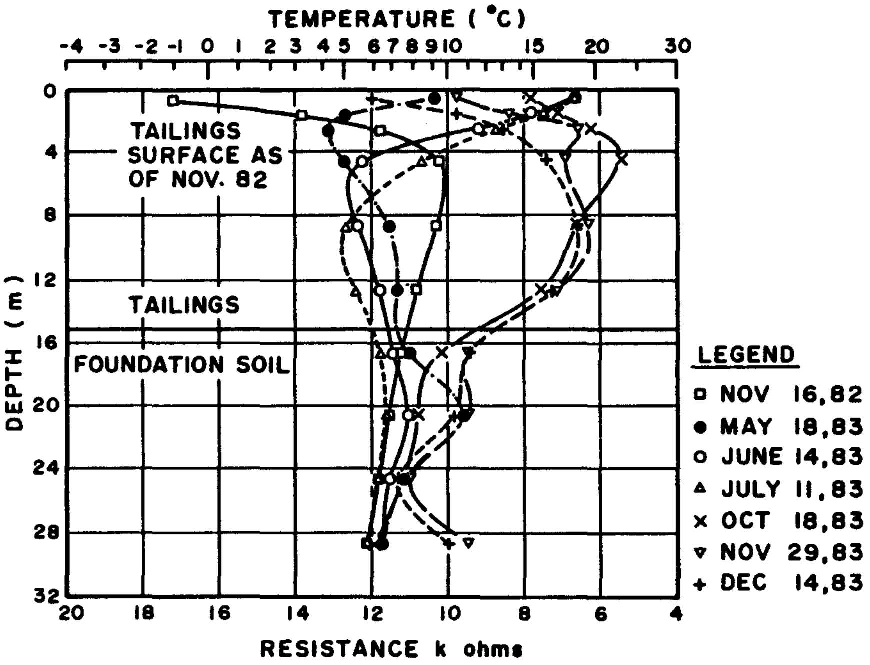

Figure 9 Temperature profile of tailings pile

Figure 10 shows the deflections and temperature at the 5 m depth with time.

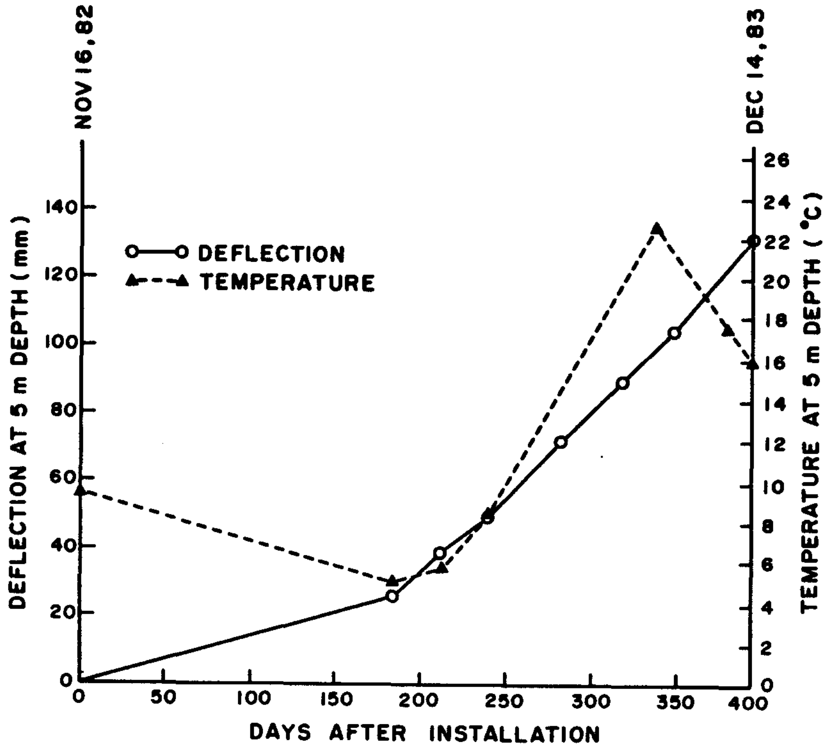

Figure 10 Deflection and temperature vs time at 5 m below surface

Figure 12 shows the schematic cross-section of the tailings pile. The pile was divided into 4 identifiable layers and different properties were assigned to each layer. Layer 3 and layer 2 represent the original tailings pile prior to installation of the instrumentation. Layer 3 is assigned a density and stiffness larger than layer 2 because it was deposited a number of years ago and field measurements indicate that it is denser than the upper part of the pile. However, the analysis assumes that deformation due to the self weight of layers 2, 3 and 4 is complete and that additional deformation is caused by the surcharge load applied by layer 1. Accordingly, the density of layers 2, 3, and 4 is assumed to be zero and only the deformation modulus and Poisson's ratio are of relevance.

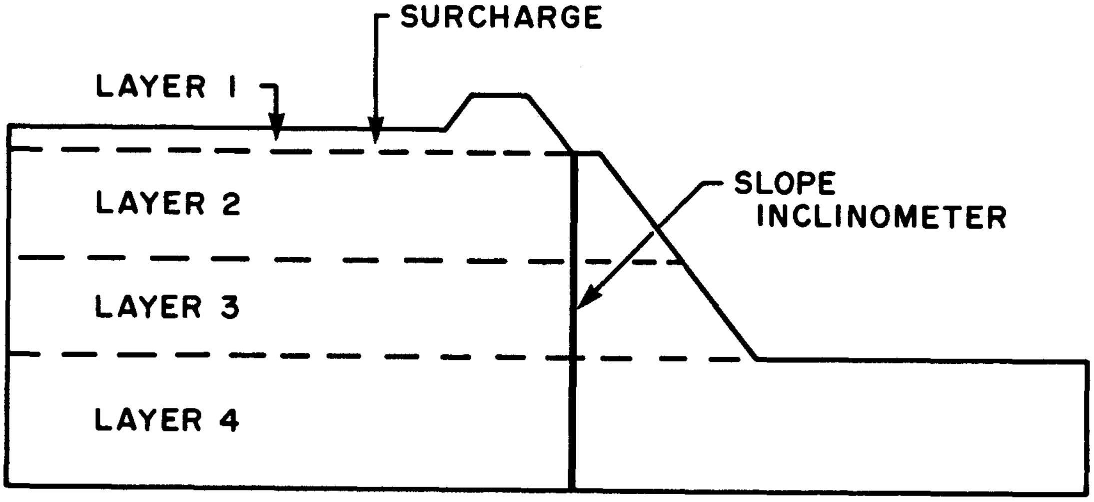

Figure 12 Schematic cross section of tailings pile

By varying the material properties over reasonable limits within each zone, a best fit relationship was established. The final selection of material properties is tabulated in Table 2. The comparison between the best-fit simulation and measured values of deflection is presented in Figure 13. Other combinations of material properties were used in the analysis (Chiu and Fredlund, 1986); however, only the best-fit results are reported here.

Table 2: Properties of Tailings Layers

Material	Density	Deformation Modulus	Poisson's Ratio
Foundation Soil	0	30 MPa	0.3
Potash Tailings			
Layer 3	0	6 MPa	0.4
Layer 2	0	3 MPa	0.4
Layer 1 Surcharge	1.60 Mg/m^3		

The rate of deflection over the winter months (1982-1983) is extremely small; however, the deflections begin to increase in a more or less linear fashion from April through to December 1983. Assuming the load has remained essentially constant with time, the steady increase in deflection with time appears to bear a relationship with the increase in temperature with time.

Analysis and Deformation Properties

A numerical analysis consisting of a two-dimensional, linear elastic, plane strain finite element program using a constant strain triangular mesh was used in an attempt to model the lateral deformations that had been measured by the slope inclinometer. It is recognized that potash tailings will creep under sustained stress (Fig. 11) and, therefore, the input parameters to the finite element program are pseudo-elastic parameters because they implicitly contain a function of time. The stress analysis requires only the density of the tailings, a deformation modulus and Poisson's ratio as input. The density is input only for the layers of tailings which are applying a load that is producing the deformations being measured. The density is known from field and/or laboratory measurements, but the deformation modulus and Poisson's ratio can be varied so as to obtain the best-fit between the analytical analysis and the observed behavior in the field.

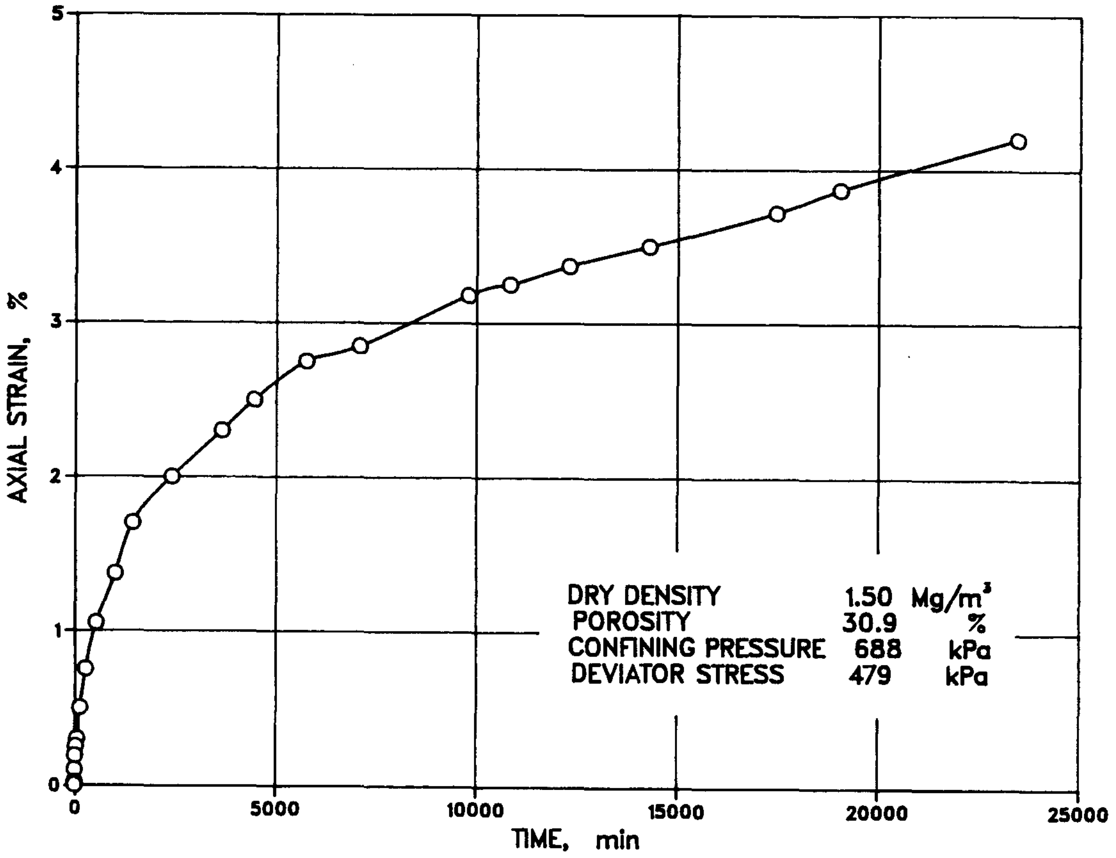

Figure 11 Creep under constant deviator stress

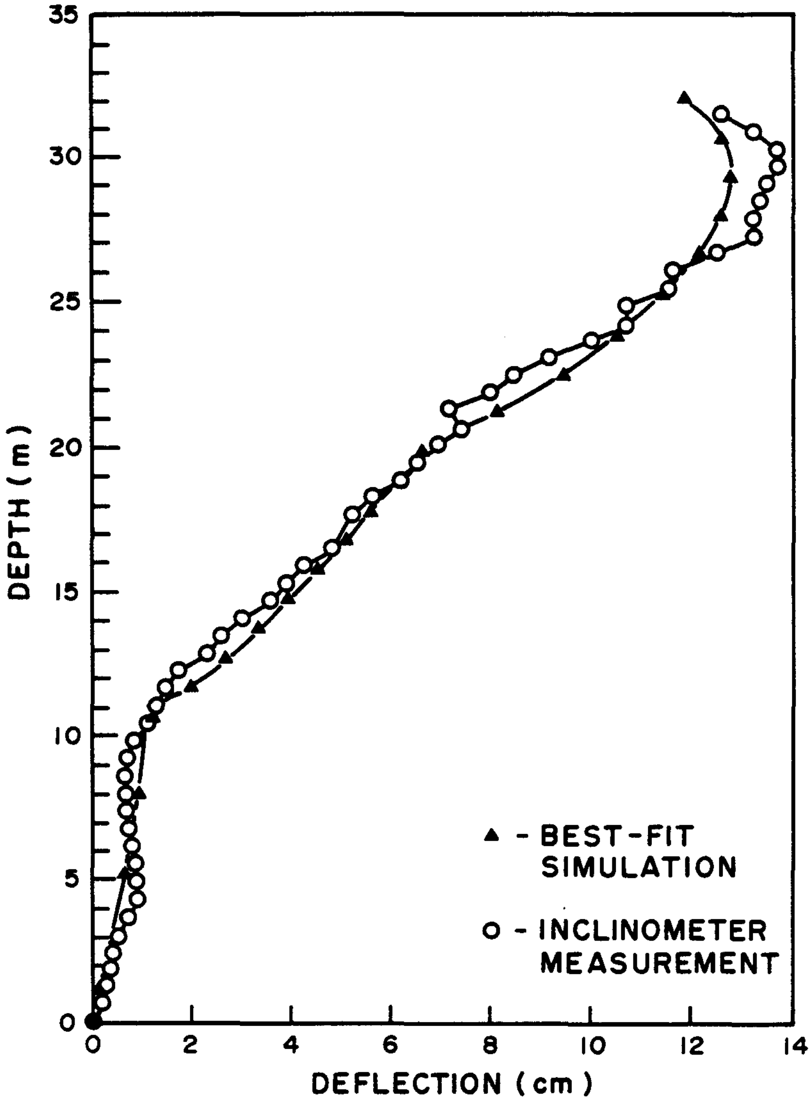

Figure 13 Comparison of best-fit simulation and measured deflections

Discussion and Conclusions

A large disparity, as much as two orders of magnitude, exists between the deformation modulus obtained from laboratory triaxial tests, tabulated in Table 1, and those used for the best-fit simulation of the measured deflections. The laboratory tests were performed using confining pressures in the order of 900 kPa. The magnitude of this pressure is well in excess of that acting in the tailings pile around the inclinometer access tubes and represents a value associated with a depth of 85 to 100 m of tailings. These triaxial tests were performed to obtain data for a somewhat different application, and that is the reason that such high confining pressures were used. As stated previously the stiffness of granular materials is dependent on the level of confining pressure. Therefore, the modulus obtained from the laboratory tests would be expected to be in excess of that obtained in the field. Moreover, the rate of loading of the laboratory samples was large compared to the field situation which also has the effect of increasing the modulus. However, the comparison is useful because the data emphasize the extremely large range of values that may be anticipated under different conditions of loadings.

Poisson's ratio measured in the laboratory varied from 0.25 to 0.46 with an average value of 0.34. This average value is somewhat lower than the value of 0.4 that was selected for the analytical study. As indicated earlier, Poisson's ratio is also somewhat influenced, for a given density, by the level of confining pressure. The smaller values of Poisson's ratio tend to be associated with the higher values of confining pressure because the tendency for dilation in the sample is suppressed.

The extent of the field data does not permit a complete appraisal of the deformation characteristics and the movements in the tailings pile that was investigated in this study. However, a number of observations can be made.

i) The movements are relatively small. The maximum deformation measured over the period of a year was approximately 130 mm.

ii) The movement is apparently caused by creep under constant deviator stress.

iii) The depth below the surface of the pile at which maximum movements are occurring is quite shallow, approximately the upper 1/3 point of the pile. This infers that the maximum safe height of the pile should not be governed by this type of movement.

iv) The rate of movement appears to be related to the temperature, with increases in rate occurring with increases in temperature.

v) The rate of movement did not decrease with time over the period of measurement as might be expected. Further readings could not be taken because of the slope inclinometer access tubing collapsed.

vi) Precise records of loading associated with the tailings disposal activity in the vicinity of the instrumentation were not established over the period of measurement. As a result, the observations contained in items ii), iv) and v) may have been affected by the addition of tailings and/or of brine to the pile near the instrumentation.

vii) Additional studies could provide information on the correlation of temperature changes with deformation rate. Precise measurements of deposition rate and other details of tailings disposal activity would be required over the monitoring period.

The amount of creep or lateral deformation in the tailings pile measured in this study does not appear to be alarming. Most of the movement occurs in the freshly deposited tailings and it seems to decrease as the tailings age and become denser.

Perhaps of greater concern in determining the stability of the tailings piles is the effect of deposits of slimes that can collect within or adjacent to the piles. The slimes, consisting mainly of silt size particles with traces of chemicals used in the refining process have low permeabilities and relatively high compressibilities. This combination of material properties indicates that consolidation and the concommittant gain in strength will occur rather slowly when they are loaded with additional tailings (Pufahl, 1987). Until more information is acquired regarding the properties of the slimes and how they affect the stability of the piles, definitive statements regarding the stability of the piles are not possible.

Acknowledgements

The authors express their appreciation to the Potash Corporation of Saskatchewan for the financial and field support in obtaining this data and for their permission to allow publication.

References

Chiu J. and Fredlund D.G. 1986. The analysis for the stability of potash tailings piles. University of Saskatchewan research report for Potash Corporation of Saskatchewan, Saskatoon, Saskatchewan.

Goodall D.G., Fredlund D.G., Lamb K.N. 1983. Methods and implications of a state of the art geotechnical field investigation of potash tailings near Lanigan, Saskatchewan. Proceedings, First International Potash Technology Conference, Saskatoon, Saskatchewan. pp. 787-792.

King, M.S. and Acar, K.Z. 1970. Creep properties of Saskatchewan potash as a function of changes in temperature and stress. Third Symposium on Salt, Northern Ohio Geological Society, Inc., Vol. 2, pp. 226-235.

Pufahl, D.E. 1983. Properties of potash tailings for tailings pile stability analysis. Proceedings First International Potash Technology Conference, Saskatoon, Saskatchewan, pp. 787-792.

Tallin, J.E. and Pufahl, D.E. 1983. Waste management schemes of potash mines in Saskatchewan. Proceedings, First International Potash Technology Conference, Saskatoon, Saskatchewan, pp. 755-760.

Wong, D. and Barbour, S.L. 1985. Studies of the infiltration and migration of brine in salt tailings. Proceedings, Canadian Society for Civil Engineering, Annual Conference, Saskatoon, Saskatchewan, pp. 357-374.