Piezometer–friction cone investigation at a tailings dam

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Static piezometer–friction cone tests were carried out at the tailings dam at Brenda Mines, Peachland, British Columbia to evaluate soil characteristics and seepage conditions in the dam. Several types of electric quasistatic cones were pushed to depths of 40–70 m at various locations in the dam and on the beach. The cones used included both the Fugro electric friction cone and piezometer cone, and a University of British Columbia designed piezometer–friction cone.

Site conditions are described and typical cone logs of bearing, friction, friction ratio, and pore water pressure vs. depth are presented, interpreted, and discussed. The cone data is used to assess strength and relative density, and to assess gradational variations of the tailings and slimes on the beach, including the identification of ice inclusions.

Measurements of equilibrium pore water pressures with depth at three locations on the beach allowed a clear picture to be developed of the pore pressure gradients within the dam. Other problems and experiences concerning quasistatic cone logging for a tailings dam are also discussed.

Key words: in situ testing, static penetration testing, piezometer cone, tailings dam, tailings beach, seepage, strength, relative density, ice, pore pressures.

Des essais au piézo-pénétromètre statique ont été réalisés dans les aires de stockage des résidus de la mine Brenda à Peachland, Colombie Britannique, pour évaluer les caractéristiques géotechniques et les conditions d'écoulement dans le barrage. Plusieurs types de cônes électriques ont été foncés à des profondeurs de 40 à 70 mètres à différents endroits dans le barrage et dans les résidus. Les cônes utilisés comprenaient le cône à manchon de frottement et le piézocône de Fugro, et un piézocône à manchon de frottement développé à l'Université de Colombie Britannique.

Les propriétés du site sont présentées, et des profils typiques de résistance en pointe, de frottement, de rapport de pointe à frottement, et de pression interstitielle en fonction de la profondeur sont présentés, interprétés et discutés. Les données sont utilisées pour évaluer la résistance et la densité relative, ainsi que les variations de granulomètrie des résidus et des boues de même que la présence d'inclusions de glace.

Les mesures de pression interstitelle à l'équilibre en fonction de la profondeur à trois endroits dans l'aire de stockage ont permis d'établir une image claire des gradients de pression interstitielle dans le barrage. D'autres problèmes et expériences relatifs à l'utilisation du pénéromètre statique dans les barrages de résidus miniers sont également discutés.

Mots clés: essais en place, essai de pénétration statique, piézocône, barrage de résidus miniers, écoulement, résistance, densité relative, glace, pression interstitielle.

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Introduction

Static piezometer–friction cone penetration testing (CPT) was carried out at the tailings dam at Brenda Mines, Peachland, British Columbia, during the summer of 1980, to evaluate soil characteristics and pore pressure conditions in the dam and on the beach. This paper describes the CPT data and discusses the significant findings from the cone testing program.

Brenda Mines

Brenda Mines is situated on a mountain plateau west of Okanagan Lake in south-central British Columbia, approximately 65 km (40 mi) from Kelowna, British Columbia at an elevation of approximately 1400 m. The mine produces copper and molybdenum concentrates from a low-grade, open-pit operation with a capacity of approximately 28 000 Mg (28 000 tons) per day. For a planned mine life of 20 years, approximately 200 million Mg (200 million tons) of tailings must be safely stored.

The mine is situated at the headwaters of a stream flowing eastward into Okanagan Lake. Because the Okanagan Valley is one of the major tourist and recreational areas of southern British Columbia, it was made a basic requirement for development of the mine that the tailings wastes be completely self-contained.

The valley in which the tailings dam and tailings pond are situated has a steep gradient and is relatively narrow, requiring a high dam to provide the necessary storage volume. Figure 1 presents a plan and section through the

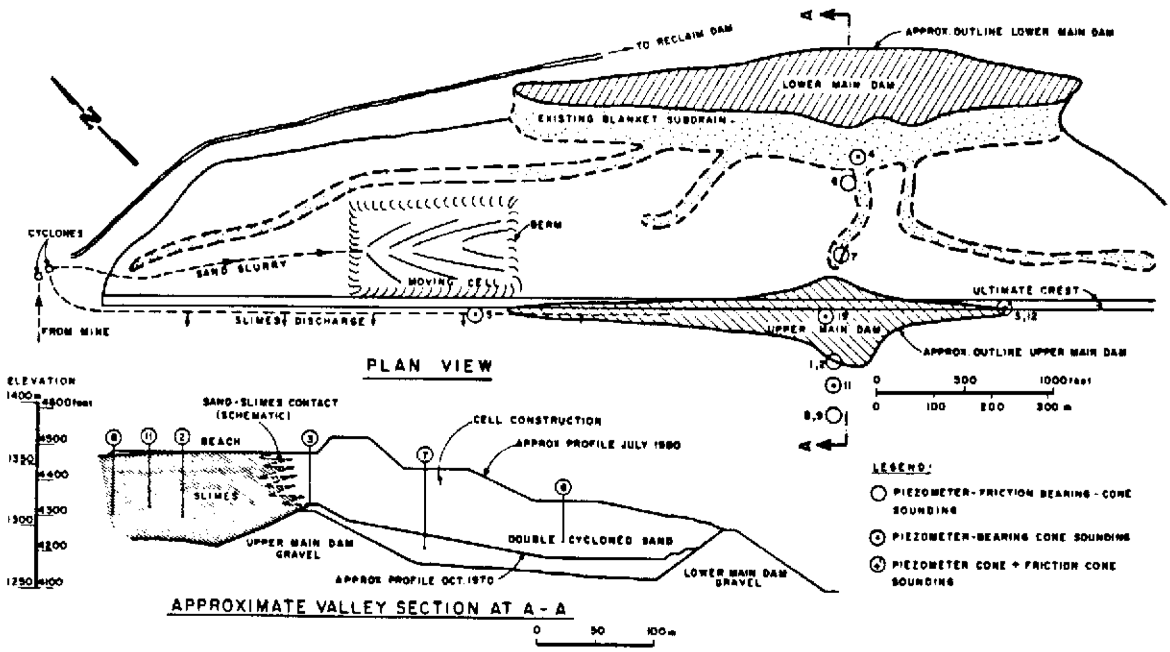

FIG. 1. Brenda Mines tailings dam, Peachland, B.C.

dam. The dam embankment is being constructed of double cycloned sand. A starter dam having a maximum height of 38 m (125 ft) was constructed of rockfill and impervious blanketing, designated in Fig. 1 as the upper main dam. The structure indicated in Fig. 1 as the lower main dam is a free-draining rock toe, about 53 m (175 ft) high, that provides confinement to the lower portion of the dam and serves to retain the embankment so that it could be sited close to the edge of a steeply dropping section of the valley. Underdrainage is provided by a blanket drain upstream of the rock toe together with finger drains extending up under the body of the sand embankment.

The currently proposed dam will have an ultimate crest length of approximately 2000 m (6500 ft), a maximum base width of approximately 550 m (1800 ft), and a maximum height above the downstream toe of about 167 m (550 ft). The dam is being raised by the centre-line method of construction, which produces a vertical upstream face of interfingered cycloned sand and slimes. The final downstream sand slope will be approximately 3.5 horizontal to 1 vertical. Total sand requirements will be approximately 25×10^6 m^3 (33 000 000 cu yd).

The Brenda tailings dam is located in an area of low seismicity with a predicted 100 year return acceleration of only 2% of gravity. The original design includes a large stabilizing rock toe fill, extensive underdrainage, and flat downstream slopes, and utilizes free-draining cycloned sand as a construction material. In effect, the ultimate tailings pond will be retained by a large mass of relatively loose, dry sand, and the lower portion of this sand mass will be buttressed by the large rockfill toe–dam. For this design, the high density of the cycloned sand is not considered critical, provided the sand is kept drained. The design includes an allowance in the freeboard requirement for any settlement that might occur owing to seismic shocks.

Water reclaim is by pump-barge, floating on the tailings pond. Seepage water passing through the main dam, and in particular the transportation water used for placement of the sands, is recovered at the reclamation dam downstream and returned to the tailings pond. No water from the tailings pond catchment or the tailings pond itself is allowed to pass beyond the reclamation dam.

The construction procedures currently being used to raise the dam are similar to those used for conventional hydraulic fill operations. Cells or paddies, 1.8–2.4 m (6–8 ft) deep, are constructed using bulldozers, and these cells are hydraulically filled with sand. The sand and water enter the cell at one end and the water is discharged through spillways at the other end of the cell and (or) seeps through the dam to the underdrains. The sand deposits as a beach on a slope of approximately 25:1. Filling starts at one end and continues across the entire length of the dam.

The cone tests reported herein represent only a small part of the overall geotechnical investigation to assess the suitability of the proposed embankment design for a final height of 167 m (550 ft). The overall investigation included, among other *in situ* tests, seismic methods, performance monitoring instrumentation, continuous

TABLE 1. Brenda Mines tailings dam—cone log summary

Hole No.	Location	Cone used	Parameters measured	Depth (m)
1	Beach, 112 m SW of crest	C10FPS-1UBC	q_c, f_c, u	21
2	Beach, 114 m SW of crest	Fugro F5CW-009	q_c, u	54.5
3	Crest, beside Piez 1-5	Fugro F5CK-225	q_c, f_c	42
4	Downstream, 11 m S of Piez 2-1	Fugro F5CW-009	q_c, u	42
5	Crest, 9 m S of Piez 4-5	Fugro F5CW-009	q_c, u	46
6	Downstream, beside Piez 2-2	C10FPS-1UBC	q_c, f_c, u	34
7	Downstream, beside Piez 2-4	C10FPS-1UBC	q_c, f_c, u	69
8	Beach, 173 m SW of crest	C10FPS-1UBC	q_c, f_c, u	49.5
9	Beach, 171 m SW of crest	C10FPS-1UBC	q_c, f_c, u	19.5
11	Beach, 142 m SW of crest	Fugro F5CW-009	q_c, u	45
12	Crest, beside Piez 1-5	Fugro F5CW-009	q_c, u	44.5
19	Crest, 12 m SW of Piez 2-5	Fugro F5CW-009	q_c, u	35

NOTE: standpipe piezometer (Piez) locations not shown in Fig. 1; q_c = cone bearing (60° cone on 10 cm^2 base area); f_c = friction sleeve stress (sleeve surface area 150 cm^2); u = water pressure (calibrated in metres of water pressure).

undisturbed sampling at the site, a broad range of laboratory testing including cyclic liquefaction assessment of undisturbed samples, and very extensive computer analyses for both static and seismic loading conditions. A detailed description of the overall geotechnical study is given by Klohn (1984).

Cone testing

Several types of electric cone penetrometers were pushed into the tailings at a constant rate of 2 cm/s for *in situ* logging of cone bearing, q_c, sleeve friction, f_c, and pore water pressure, u. A standard Fugro friction cone of 50 kN (5 ton) bearing capacity was used as well as a Fugro piezometer cone, also of 50 kN (5 ton) bearing capacity. A special high-capacity cone, 150 kN (15 ton), capable of measuring bearing, friction, and pore water pressure was designed and built at the University of British Columbia (UBC). The UBC cone was equipped with a slope sensor to indicate verticality with depth. Full details of the Fugro cones are given by de Ruiter (1971, 1982). Full details of the UBC cone are given by Campanella and Robertson (1981). The piezometer element on both the UBC cone and the Fugro cone was located immediately behind the cone tip.

The cone penetration testing was performed using the UBC *in situ* testing vehicle. A complete description of the vehicle and hydraulic and electronic controls is given by Campanella and Robertson (1981). The vehicle was designed as a low-cost, versatile vehicle for both research and teaching in the field. The enclosed truck has a pushing 'dead weight' capacity of about 80 kN (18 000 lb force). Outrigger reaction beams allow additional capacity by attaching weights or reacting against earth anchors. Steel plates were attached to the outrigger arms on the UBC vehicle at Brenda to increase the pushing capacity to about 150 kN (34 000 lb force). The deepest sounding at Brenda went to a depth of 70 m. The self-contained hydraulic power supply on the truck provided a constant penetration rate of 2 cm/s. The 4.5 kW generator on the truck provided a stable power supply for all electronic instrumentation, and continuous electronic recordings were taken of cone bearing, friction, and (or) pore water pressures with depth. All procedures and equipment were in accordance with ASTM Specification D-3441-79.

A total of 19 cone penetration tests was carried out at locations shown in Fig. 1. Several cone soundings were performed on the beach from a specially constructed access road (about 8 m wide) of compacted tailings sand about 1–2 m thick. The access road extended about 200 m southwest of the ultimate crest toward the pond at section A-A in Fig. 1. Section A-A is located in the deepest 'valley' section where the tailings dam has the greatest height above natural ground.

Table 1 shows a summary of the cone testing and indicates sounding or hole number, location, cone type used, parameters measured, and depth of sounding. Hole No. 10 was used for piston sampling next to hole No. 9. All cone sounding locations were accurately located by the Brenda Mines survey crew.

As shown in Table 1, five CPT holes were on the beach, four were along the center line of the dam along the ultimate crest location, and three were downstream of the crest in the main body of the tailings dam. Section A-A in Fig. 1 shows the depth and location of the cone soundings to scale in the valley section.

Pore pressure measurements were made in all holes except No. 3. Pore water pressures were measured continuously during penetration and allowed to dissipate at selected depths in order to measure the equilibrium values.

Interpretation of CPT data

Full details on cone penetration test interpretation are given by Robertson and Campanella (1983*a*, *b*). An estimate of soil type and gradation can be made using the cone bearing, q_c, and the friction ratio, FR, defined as $(f_c \div q_c) \times 100\%$ (Fig. 2). A high bearing ($q_c >$ 40 bars[1]) and a friction ratio generally less than 1% indicate a clean sandy soil. As the proportion of fines and plastic characteristics increases the bearing decreases and the friction ratio generally increases. Values of friction ratio greater than 3 generally indicate a clayey soil.

Significant improvements in soil classification, however, can be made if pore pressure, bearing, and friction are measured continuously (Campanella and Robertson 1981). The excess pore pressure (Δu) measured during penetration is a useful indication of soil type and provides an excellent means of detecting details in stratigraphy. For clean sandy soils, the excess pore pressures tend to dissipate almost as fast as they are generated. For silty and clayey soils, because of their relatively low permeability, significant excess pore pressures can be generated. Normally consolidated silts and clays tend to develop large positive excess pore pressures, whereas overconsolidated silts and clays tend to develop smaller positive or even negative excess pore pressures. Therefore, the measured excess pore pressures indicate both the relative permeability and volume change characteristics.

However, the measured pore pressures are very dependent on the details of the cone design, in particular the location of the pore pressure element (Robertson and Campanella 1983*b*). Because of the complex variation of stresses and strains around a cone tip, the location of the pore pressure element can significantly affect the measured pore pressure during cone penetration. In normally consolidated clays and silts, where large

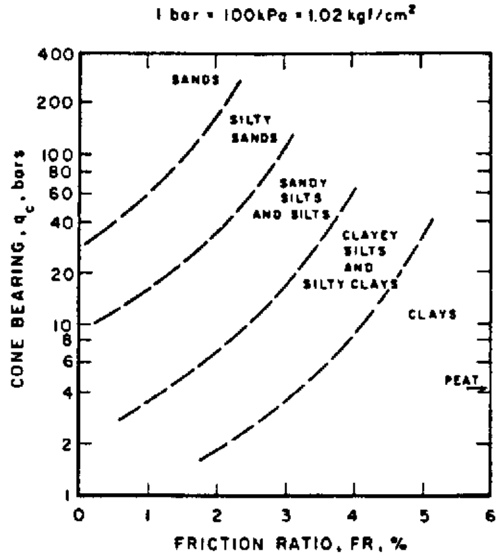

FIG. 2. Classification chart for electric cones. (Adapted from Douglas and Olsen 1981.)

positive pore pressures are generated during shear, pore pressures measured on the face of the tip are generally only 10–20% larger than pore pressures measured immediately behind the tip (Roy *et al.* 1982; Campanella *et al.* 1983). In overconsolidated clays and silts, and fine sands, where small positive or negative pore pressures are generated during shear, pore pressures on the face of the tip tend to be positive whereas pore pressures measured immediately behind the tip may be negative (Campanella *et al.* 1983). The reason is that the area along the face of the cone tip is in a zone of maximum compression and shear, unlike the area immediately behind the tip, which is in a zone of total stress relief. Pore pressures are generated in saturated soils because of increases in both normal stresses and shear stresses. Thus, the area behind the tip appears to measure a response dominated by the shear behaviour of the soil. Because of the stress relief experienced by a soil element as it passes behind the tip, the pore pressure element behind the tip encourages the measurement of low or negative dynamic pore pressures. Campanella *et al.* (1983) have shown that with the element located immediately behind the tip the dynamic or total pore pressure appears to be a more sensitive measure of stress history, since it tends to accentuate the soil behaviour during shear.

Campanella and Robertson (1981) have shown that complete saturation of the piezometer element is essential. It was also shown that glycerin works effectively as a saturating fluid that is miscible with water yet develops a high air-entry tension to prevent loss of saturation during use and penetration through soils above the water table. This was particularly

[1]NOTE: 1 bar = 100 kPa ≈ 1 kgf/cm² ≈ 1 ton/ft².

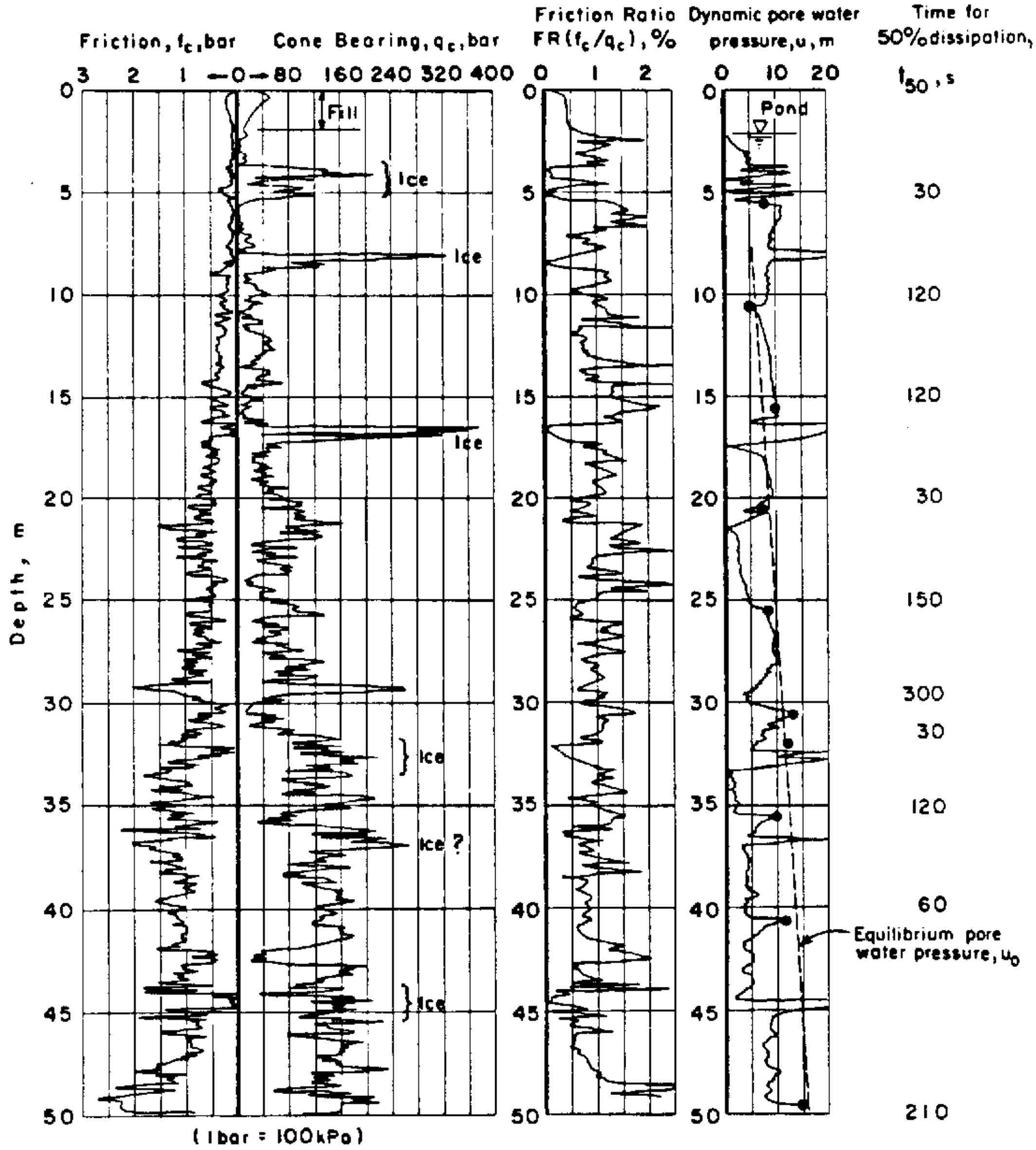

FIG. 3. Piezometer–friction cone sounding No. 8, on beach, 173 m from crest, Brenda Mines tailings dam.

important during cone penetration testing in the unsaturated sand in the main dam at Brenda. Further details will be given later regarding this problem.

Beach area

The objective of the cone testing over the slimes beach area was to evaluate the equilibrium water pressures beneath the pond and to assess the variation in strength of the tailings slimes. A summary of the cone penetration test data on the beach is given in Figs. 3–5. The location of these soundings is given in section A-A in Fig. 1.

Figure 3 shows the results of piezometer–friction cone sounding No. 8, located the furthest out on the beach, approximately 173 m from the crest center line. The record shows the friction, f_c, and cone bearing, q_c, plotted 'back to back,' the friction ratio, and the pore pressure, u_0. The pore pressure is in metres of water and the friction and cone bearing are in bars (1 bar = 100 kPa).

The cone bearing for sounding No. 8 (Fig. 3) shows very high bearing values, greater than 200 bars (>20 000 kPa), at 4, 8, 16.5, 29, 33, 37, and 45 m. The friction ratio values at some of these depths is almost

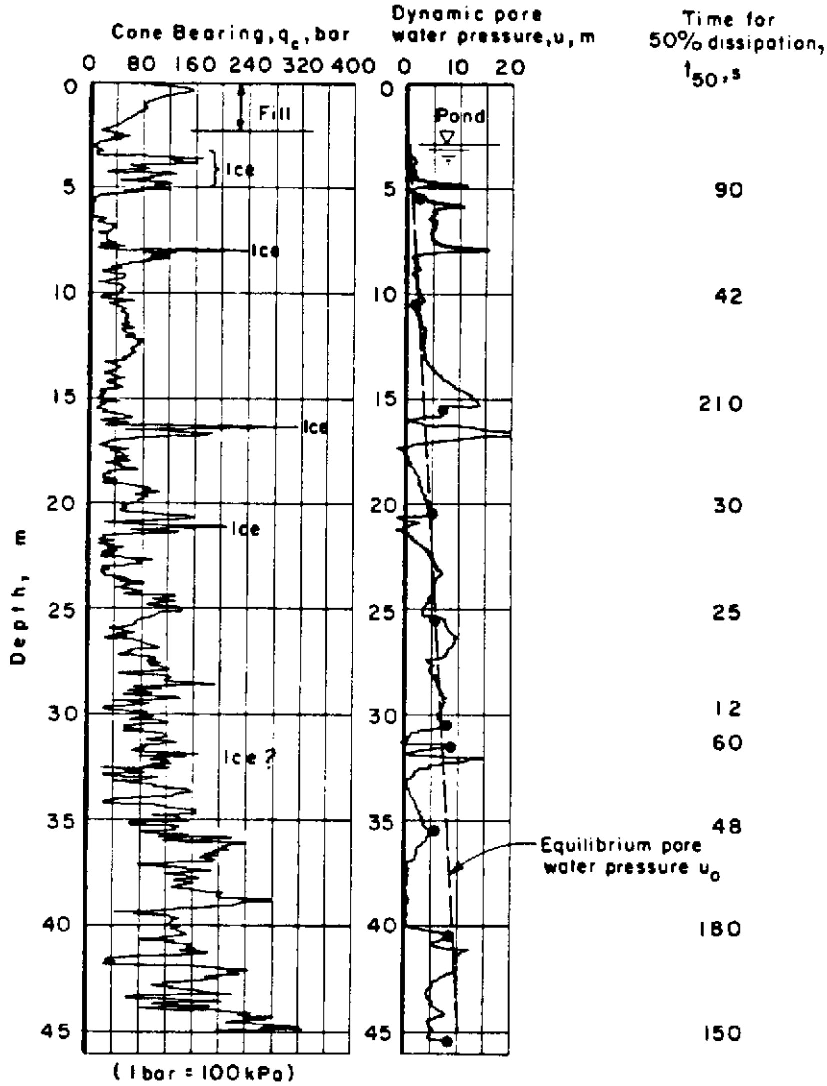

FIG. 4. Piezometer cone sounding No. 11, on beach, 142 m from crest, Brenda Mines tailings dam.

zero. The pore pressure values exceed 20 m of water pressure at some of these locations. At a depth of 37 m the measured water pressure was equivalent to 130 m of water (13 bars (1300 kPa)). It was suspected that many of these very large bearing values represent trapped ice. A thin layer of almost 'pure' ice would explain the very high bearing values combined with the almost zero friction ratio and very high pore pressure measurements. When the cone penetrates ice the bearing resistance would be very high, resulting in some pressure melting of the ice and a thin film of water developing around the cone. The water film would result in very small friction values as the friction sleeve penetrates the ice. However, as the tip penetrates and melts the ice to form a thin film of water the water is contained in an almost incompressible system of ice and extremely large pore pressures are generated. As soon as the piezometer element and cone penetrate through the ice, the pore pressures immediately return to their previous low value. The presence of ice layers within the tailings was demonstrated by a shallow excavation to expose the previous winter's snow and ice trapped 1–2 m beneath the existing ground surface with air temperatures almost 38°C. Subsequent piston sampling confirmed the existence of almost 'pure' ice lenses in the beach deposits. During winter operations ice on the pond is covered over by spigoted slimes at outfall locations. The cone data at depths of 4, 8, 16.5, 33, and 45 m clearly show all the above responses indicating ice layers or ice-rich soil. The data at 29 and 37 m are less conclusive but may indicate layers of soil with some ice (i.e., ice-poor soils). A similar response was recorded in holes 11 (Fig. 4) and 2 (Fig. 5).

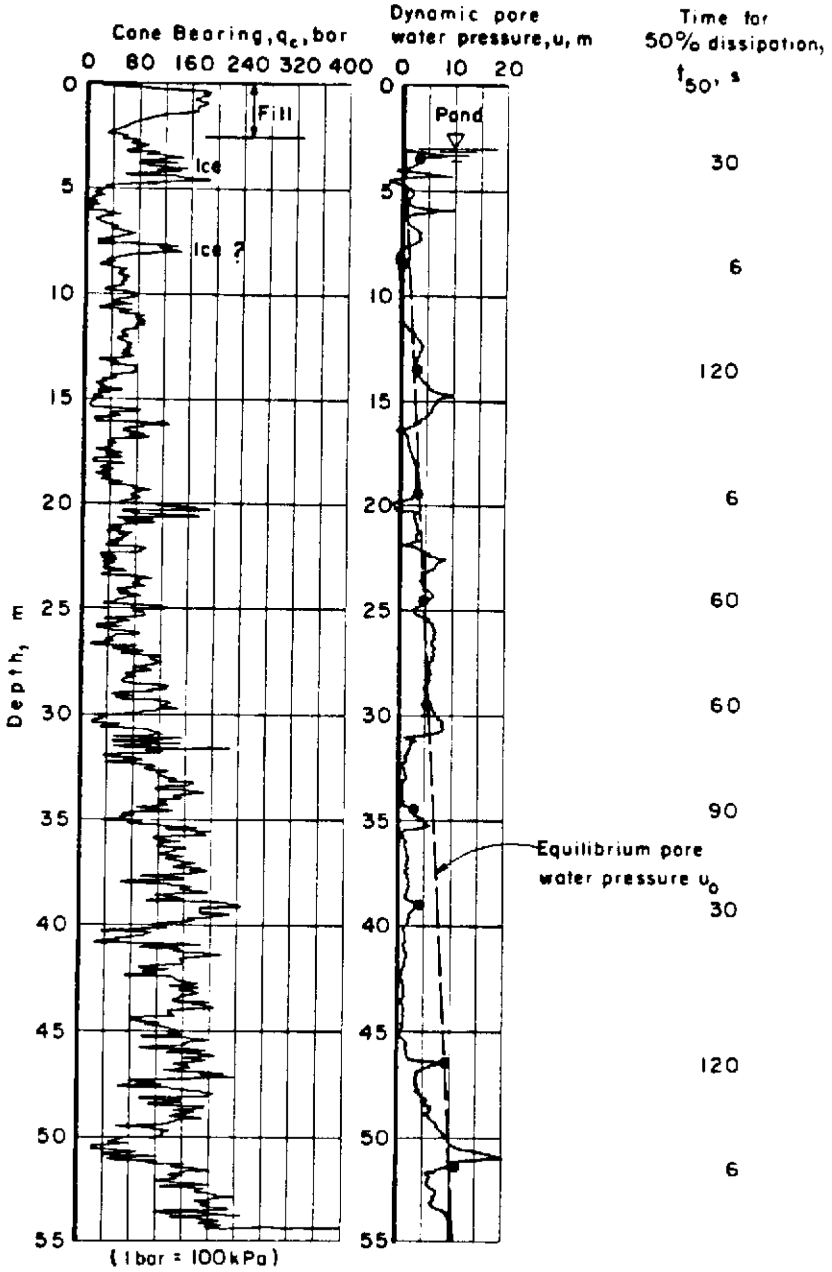

FIG. 5. Piezometer cone sounding No. 2, on beach, 114 m from crest, Brenda Mines tailings dam.

The ice appears to be irregular, noncontinuous inclusions. Holes 8 and 9 were located approximately 2 m apart. Some ice was encountered in both holes at the same depth, whereas other inclusions were not encountered in both.

The equilibrium water pressure indicates a slightly increasing water pressure with depth. The equilibrium water pressure is significantly less than those expected for a hydrostatic water regime. The slight linear water pressure increasing with depth in hole No. 8 indicates a downward gradient of about 0.7. A similar but steeper downward gradient existed in soundings 11 and 2.

The equilibrium water pressures recorded during the cone penetration testing clearly indicate a downward gradient of pore water pressures with gradients greater than 1/2 and close to 1 in sounding 2. The major source of water causing the downward flow was thought to come from spigoting along the crest toward the pond

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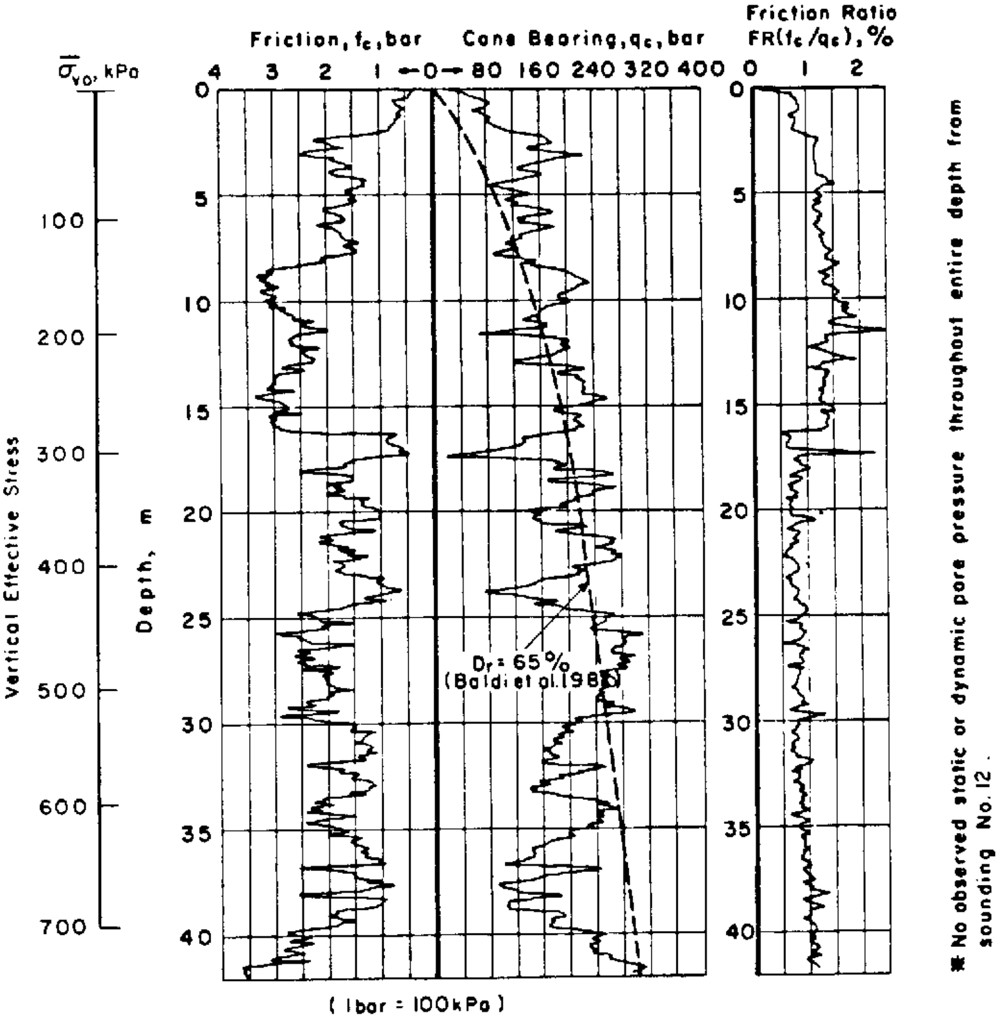

FIG. 6. Friction cone sounding No. 3, on crest, Brenda Mines tailings dam.

infiltration from surface runoff and rainfall, and the slimes pond itself. Unfortunately, the mine was temporarily shut down for maintenance during the cone investigation; hence there was no spigoting and the pond level was being lowered. Therefore, the actual seepage condition was very complex at the time of the piezometer cone investigation. However, the repeatability of the measured pore pressures from adjacent cone soundings, as well as the correspondence with permanent piezometers on the beach, lends credibility and confidence in the measurements. It is important to keep in mind that seepage conditions are rarely constant but change with varying boundary water conditions.

During a stop in penetration, excess pore pressures generated during cone penetration immediately start to dissipate. The time to reach 50% dissipation or t_{50} is a useful parameter for distinguishing stratigraphic types and indicating relative drainage conditions (Campanella *et al.* 1983). Figures 3–5 include t_{50} times listed on the right side of the profile. The rapid dissipation of excess pore pressures indicates a relatively high permeability and good drainage characteristics of a fine sand to silt.

The friction ratios, FR, in general vary from 0.5 to 2.5% except for the values below 0.5% through the ice. The FR values of 0.5% usually correspond to higher cone bearing values and indicate a sand. The FR values of 1.5–2.5% usually correspond to the low bearing values of less than 40 bars (<4000 kPa) and indicate a fine sand to a silt.

The dynamic pore pressures are generally less than the equilibrium water pressures, indicating a dilatant behaviour in the soil for the pore pressure sensing element behind the tip (Campanella *et al.* 1983). This, combined with the FR and q_c data, indicates a generally cohesionless soil. The variation of the FR, q_c, and pore pressure data clearly indicates a variable deposit of

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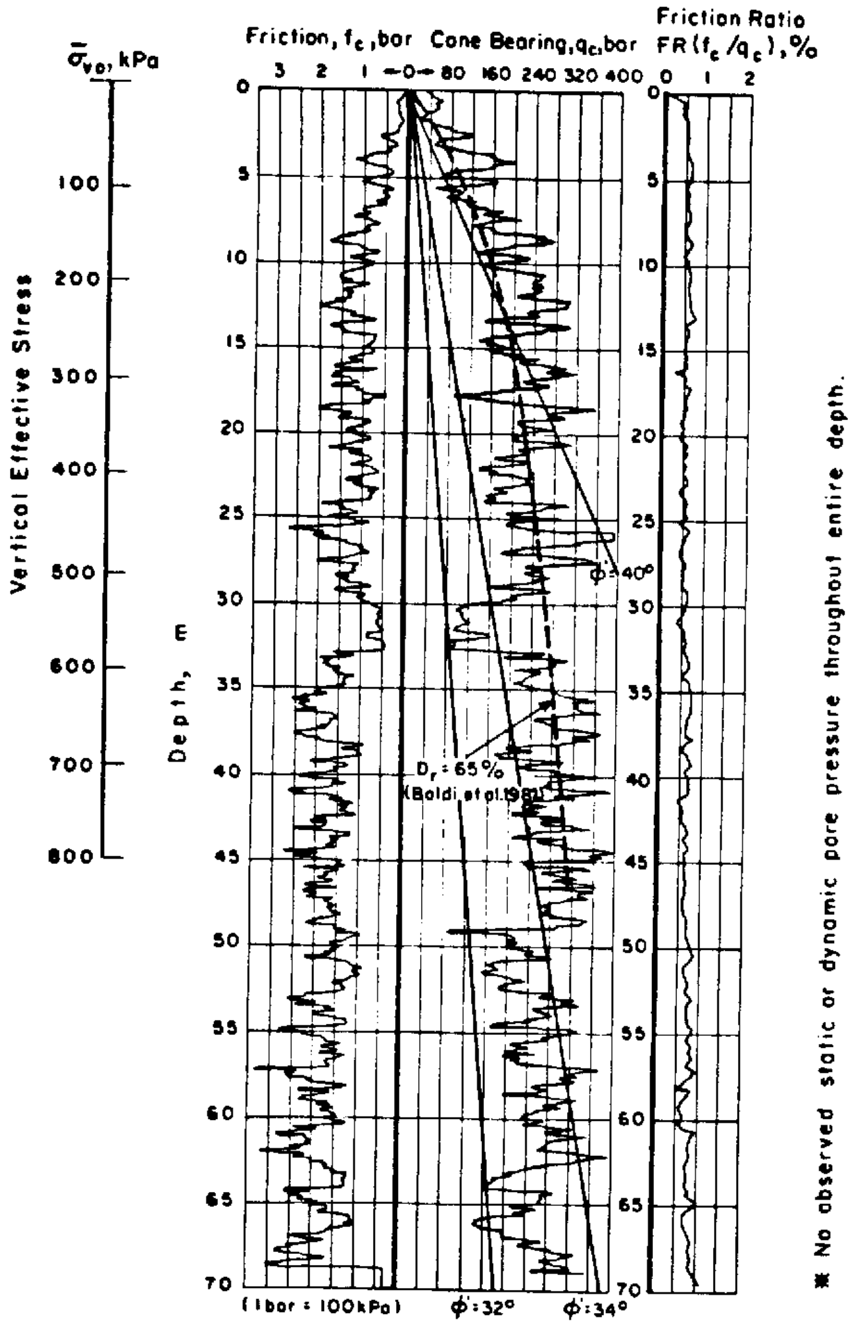

FIG. 7. Piezometer–friction cone sounding No. 7, downstream, 92 m from crest in body of Brenda Mines tailings dam.

sands and silts in the beach area. This is not unexpected considering the manner in which the tailings dam is constructed with interfingered cycloned sand and slimes upstream of the crest line (Fig. 1) with the bulk of the fines staying in suspension and settling out in the central pond area.

If a line is drawn through the low points of the cone bearing profile and corresponding highest friction ratio values in Fig. 3, it would indicate a linear increase in strength for the slimes or finest grain sizes in the beach area. The c_u/σ'_{vo} ratio or change in undrained shear strength with effective overburden stress can be estimated from the line through the low points of cone bearing and using an N_K value of 15 (Robertson and

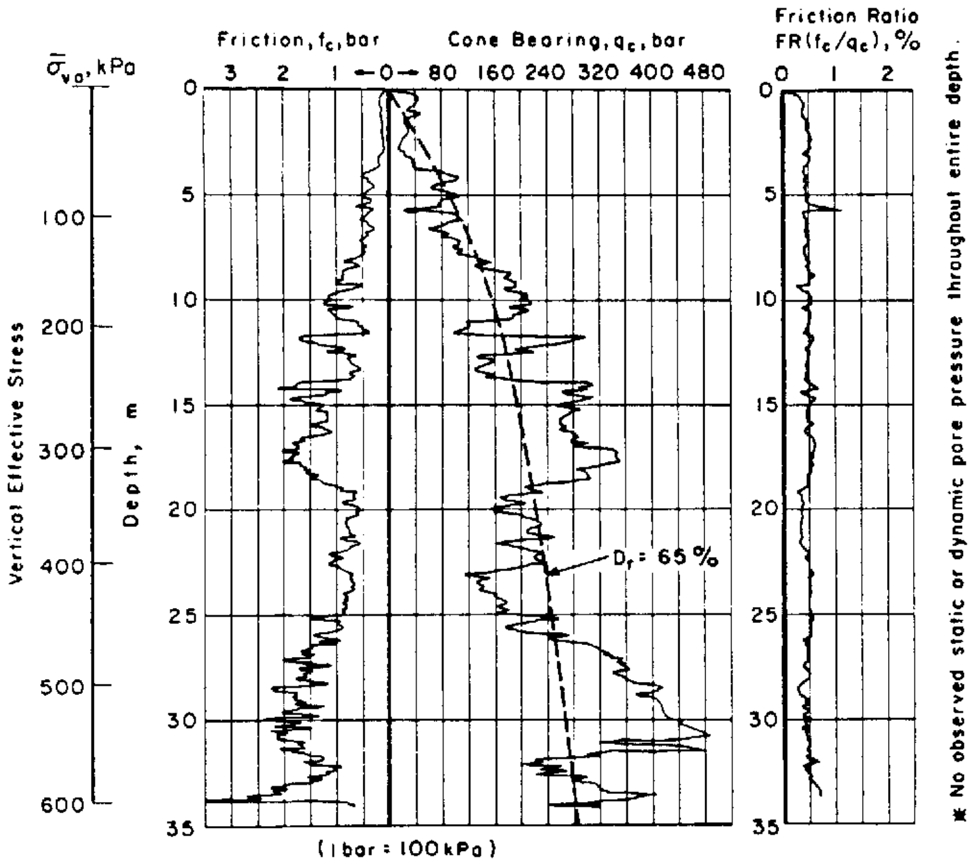

FIG. 8. Piezometer–friction cone sounding No. 6, downstream, ≈215 m from crest in body of Brenda Mines tailings dam.

Campanella 1983*b*). If the σ'_{vo} is calculated using an assumed hydrostatic equilibrium pore pressure profile the c_u/σ'_{vo} = 0.43. However, if the measured equilibrium pore pressure profile is taken, the c_u/σ'_{vo} = 0.26, which is a more realistic value for a normally consolidated low PI silty deposit.

The pore pressure measurements indicate that the cone penetration is predominantly undrained or partially drained. However, some zones appear to be close to a drained penetration (Fig. 3, 11–15 m and 26–28 m). If a drained penetration is assumed, the inferred drained friction angle of the deposit varies from about 30 to 34° (Robertson and Campanella 1983*a*). These values appear reasonable for a loose fine sand and silt deposit.

Main dam

The objectives of the cone testing in the main dam were to evaluate the character and uniformity of the tailings sand construction and to assess the seepage conditions. A summary of the CPT data in the main dam along section A-A is given in Figs. 6–8.

The most significant observation from the CPT data in the main dam is that no observed static or dynamic pore pressures were recorded. This is in agreement with the permanent piezometers installed within the dam and shows the effectiveness of the drainage system.

The effectiveness of using a fluid such as glycerin as a saturating medium for the pore pressure element was illustrated when water was encountered at a depth of approximately 40 m in sounding No. 5 along the crest. The very rapid pore pressure response indicated that a high degree of saturation was maintained in the measuring system. Confirmation of the reading was obtained from a nearby standpipe piezometer installed during the previous drilling program.

All the CPT data within the main dam shows the soil to be sand (see Fig. 2) in accordance with the construction procedure. Figures 6–8 include a constant relative density relationship by Baldi *et al.* (1982). This indicates the sand to have an average relative density of about 65%, although there are zones of looser sand. A review of calibration chamber test data (Robertson and Campanella 1983*a*) has shown that no unique relationship exists between cone resistance, *in situ* stress, and

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relative density. The relationships are significantly influenced by the soil compressibility. The soil compressibility is influenced by grain shape, size, and mineralogical composition. The curves presented by Baldi *et al.* (1982) represent a reasonable average for typical moderately compressible sands where the grain minerals are predominantly quartz. The Brenda Mine cycloned sand is predominantly quartz but the grain shape is very angular. The angularity tends to make the sand more compressible and so Baldi's relationship may slightly underestimate the true *in situ* relative density by about 5% (Robertson and Campanella 1983*a*).

It is generally recognized that the mobilized friction angle of a sand decreases with increasing confining stress. Using the friction angle correlation proposed by Robertson and Campanella (1983*a*), the CPT data show the friction angle to be generally greater than 40° above a depth of about 20 m, then decreasing to a value of about 33° at 55 m (see Fig. 7). This confirms the previous predictions of an approximately constant relative density with depth. The existence of sand with a low friction angle at depth can have a significant influence on any stability analysis.

Summary and conclusion

Probably the most significant finding from the CPT data was the fact that no pore water pressures in excess of hydrostatic were observed in any of the soundings. All the CPT soundings in the beach area indicate a downward gradient with almost constant equilibrium water pressure with depth. This high downward gradient is indicative of the effectiveness of the drainage facilities in the dam and has significantly contributed to the relatively high bearing of the slimes owing to increased effective stress. The existence of the downward gradient was confirmed by the permanent piezometer installations in the beach area (Klohn 1984).

Ice was encountered within the beach area. The ice appeared to be irregular, unpredictable, noncontinuous inclusions. It was found that very low friction ratios of the order of 0.25% or less together with correspondingly high local bearing values and high pore pressures were always associated with ice encounters.

The strength of the sand–silt slimes in the beach area, excluding the ice inclusions, generally increased approximately linearly with depth, indicating a normally consolidated deposit with a relatively high shear strength. The high shear strength is probably due to the very low water pressures and, thus, high effective stresses.

The CPT data in the main embankment show the dam to consist of a fairly uniform well-drained sand with an approximately constant relative density of about 65% with depth. The results of other relative density measurements including undisturbed sampling, SPT, and density logging indicate that the relative density in the main dam is at least 55%. The friction angle of the sand appears to decrease with depth owing to the large confining stresses.

Finally, the piezometer–friction cone investigation has demonstrated its effectiveness as an efficient economical *in situ* logging tool that provides most of the geotechnical data needed for stability analyses. Furthermore, continuous CPT logging clearly identifies 'zones of concern' where sampling and (or) additional testing may be required. Cone logging is well suited to mine tailings wastes grading from slimes to very coarse sands. The data and conclusions provided from this piezometer–friction cone investigation were subsequently confirmed by the very extensive additional field, laboratory, and office studies carried out to assess the seismic stability of the Brenda Mines' tailings dam (Klohn 1984).

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