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Phase I Penetration Testing of CANLEX: The Results of Seismic Piezocone Testing and Energy Measured SPT Programs at Syncrude's Mildred Lake Tailings Facility

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ABSTRACT
The penetration testing site characterization at Syncrude's Mildred Lake Settling Basin in support of the phase I of CANLEX Project is described in detail. The results presented and discussed include preliminary screening tests to establish the target depth and location and detailed stratigraphic logging and shear wave velocity profiling with seismic piezocone and SPT with energy calibration. The soil at the 27.5 to 40.0m target depth with ground water table 20m below ground is a reasonably homogeneous, free draining, uncemented, medium dense sand.

RÉSUMÉ
Des tests in-situ servant à la caractérisation du bassin de dépot du lac Mildred de Syncrude en appuis à la phase I du projet CANLEX sont décrits en détail. Les résultats présentés et discutés incluent les tests préliminaires de reconnaissance qui ont servi à établir la profondeur et la location cible. Sont aussi inclus la coupe stratigraphique détaillée ainsi que le profilé de la vitesse d'onde de cisaillement mesurée à l'aide de piézocones et de la méthode SPT avec calibration d'energie. Le sol, à la profondeur cible de 27.5 à 40.0m, est un sable dense, plutôt

consistant, drainé naturellement et non cimenté. La nappe phréatique est à 20m sous la surface du sol.

INTRODUCTION

The piezocone (CPTU) and seismic piezocone (SCPTU) have been used in the Phase I CANLEX investigations at Syncrude Canada Ltd.'s Mildred Lake Tailings Facility as part of both the screening and detailed characterization efforts. The screening was carried out in order to locate optimal testing locations for the detailed characterization programs. Optimal location was deemed to occur where there was relatively uniform sand material at depth with at most moderate density. The screening program consisted of seven CPTU soundings and the detailed program five (Fig. 1). In addition, two energy measured Standard Penetration Test (SPT) boreholes were completed as part of the detailed characterization program.

For both the screening and detailed characterization programs, pre-drilling through dense, unsaturated tailings was necessary. The low phreatic surface, 20m below ground surface, and the 27 m to 35 m depth to "target zone materials" presented a relatively unique testing situation for conventional CPTU penetration set up configurations. For both the screening and detailed investigation programs, pre-drilling through the majority of the unsaturated dense overlying tailings was required. For the screening program, a track-mounted auger drill rig with approximately 10 tonnes of effective pushing force was used. For the detailed program, a specialized CPTU vehicle with roughly 18 tonnes of pushing force was used.

This paper presents a summary of the Phase I penetration testing programs. The overall results are summarized and problems with using penetration technology at such depths are discussed within the context of the programs carried out. The discussion will include the energy calibrated SPTs.

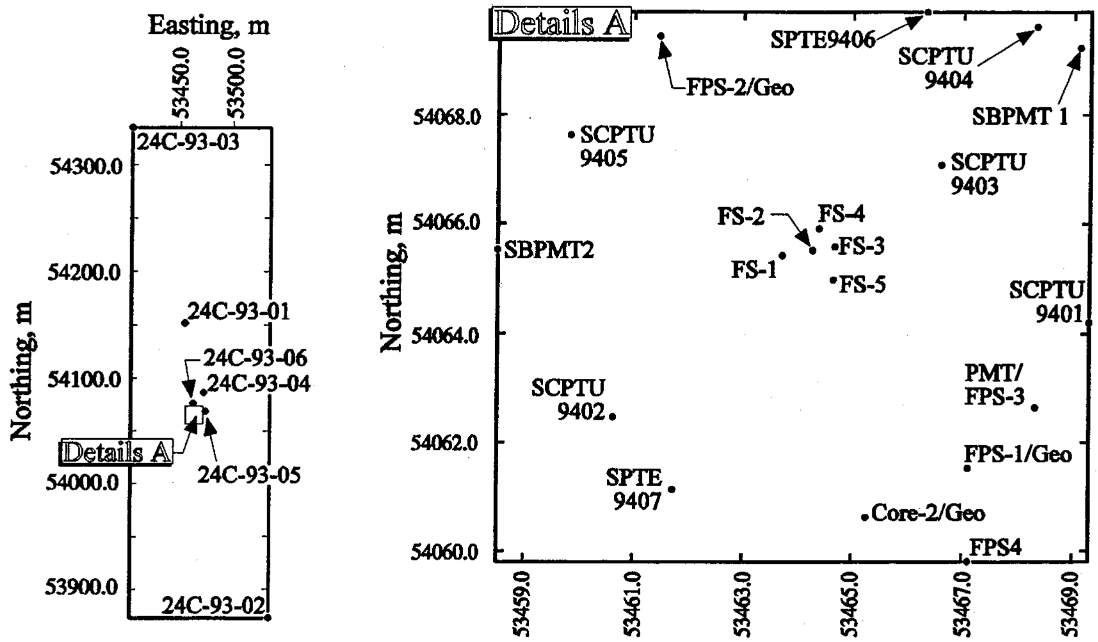
FIELD PROGRAMS

Screening Program

The initial screening work was carried out by Conetec Investigations Ltd., Vancouver, B.C., in June, 1993. A track-mounted BOA 10 M drilling rig operated by SDS Drilling Ltd., was used for predrilling and pushing the Piezocone. A total of 6 Standard Cone Penetration Test (CPTU) and one Seismic Cone Penetration Test (SCPTU) were carried out to a maximum depth of 46m. Five CPTU and one SCPTU were performed in Cell 24 and one CPTU was carried out in Cell 27 of the Mildred Lake Tailings Basin. Full details of the screening program are given by Robertson et al., 1994.

The first CPTU sounding (24C-93-01) was carried out to evaluate the upper compact sand deposit and to develop an optimum procedure for obtaining piezocone penetration data for locating the stratigraphic units of lower density for future detailed investigation. The first sounding encountered refusal at a depth of 11m primarily due to a large tip resistance of 60 MPa.

For the subsequent sounding (24C-93-02) a small diameter (60mm) hole was drilled using mud rotary technique with a tricone bit. Predrilling was taken to 33m depth and CPTU was performed to 35m depth. The maximum tip resistance at the termination of sounding was 40 MPa. To increase the speed of operation, the procedure was modified and only the relatively loose zone underlying the near surface compact zone was targeted. In soundings 24C-93-03 through 06 (Cell 24) and 27C-93-01 (Cell 27) predrilling was taken down to approximately 30m. Subsequently, SPTs were carried out at about 3m intervals until the less compact zone was



a. Location of Soundings in Screening Investigation

b. Location of Soundings in Detailed Investigation

Abbreviations Used:	SPTE: Standard Penetration Test with Energy Calibration
SCPTU: Seismic Piezocone Penetration Test	FPS: Fixed Piston Sampling
SBPMT: Self Boring Pressuremeter Test	Geo: Geophysical Logging
PMT: Pressuremeter Test	FS: Frozen Sampling

Fig. 1. Testing and Sampling Program at CELL 24 of the Syncrude Site

reached. Seismic CPTU measurements were carried out in sounding 24C-93-05. A hammer and beam at surface was utilized as the seismic source and a seismometer in the cone was used as the receiver.

Detailed Program

The detailed characterization work consisted of regular (CPTU) and seismic piezocone (SCPTU) penetration tests and energy calibrated SPT in rotary advanced boreholes. The field work was carried out between May 19 and May 22, 1994 inclusive. A total of one CPTU and four SCPTU soundings were carried out to maximum depths of just over 39 metres. SPTs were also carried out at two locations, 9406 and 9407. Fig. 1b shows a detailed plan for the Phase I test and sampling locations.

The CPTU/SCPTU work was carried out using the BCMOTH specialized in-situ testing vehicle that had a gross vehicle weight for the project of approximately 18 tonnes. The SPT work was carried out with the assistance of Elgin Explorations Ltd who supplied a rubber tired Acker drill rig. Elgin also was used for pre-boring the majority of the CPTU/SCPTU sounding locations to the starting depth of approximately 28 metres.

The detailed CPTU program rates of production were somewhat better than experienced by the screening work carried out for the project in the fall of 1993. The better weather and the use of the heavy 18 tonne BCMOTH cone truck are likely responsible for the improved progress for this portion of the work.

PIEZOMETER CONE PENETRATION TESTING

The initial sounding, 9401, was pushed from ground surface to determine if the heavy vehicle would be able to attain the target zone from approximately 28 to 37 metres without the need for pre-drilling as was required in the screening investigation. Unfortunately, penetration was refused at a depth of 20.4m with cone tip resistance reaching 60MPa. Therefore, the remainder of the soundings were initiated with a pre-bored 60 to 75 mm guide hole to a starting depth of about 28m.

Equipment and Procedures

The program used a mix of UBC and Hogentogler cone equipment to provide protection against potentially biased results. Soundings 9401, 9402 and 9403 all used the cone UBC9 which had pore pressures measured behind the tip and behind the friction sleeve, respectively. The use of the Hogentogler cone was also selected for its high signal to noise ratio geophone versus the accelerometer in the UBC cone.

For all but 9401, the procedure for each hole involved aligning the BCMOTH vehicle over the pre-bored hole and then lowering the cone and cone rods to the base of the pre-bored hole. Caving of the holes was minimal so considerable time was spent in lowering the rods to avoid "dropping" the complete string. Extra care in leveling the drilling rig and the BCMOTH vehicle was taken to ensure that verticality was achieved prior to pushing due to concerns with rod bucking and deflection of tip during penetration.

Upon reaching the base of each hole, the push was initiated and continued at 2 cm/sec for each rod segment. The Piezocone data were digitally acquired using a 486 field computer and UBC's proprietary data acquisition program, GEODAS. The digital record was assembled every 25mm.

At each rod break, either at 0.5 metre or 1.0 metre intervals depending upon the depth selected, the pore pressure dissipations and seismic testing were carried out. For the seismic testing, a wooden plank with metal inserts at each end was placed beneath the front jack-pads of the BCMOTH vehicle and this plank was used as the energy transfer medium. The energy was generated manually using a sledge hammer. The seismic data was collected as four hits per depth and recorded digitally on a Nicolet 4094 digital oscilloscope. Arrival times were determined in the field using visual picks and by using the cross-over method where possible. Later the shear velocity was more rigorously determined by means of cross-correlation methods (Campanella and Stewart, 1992).

Baseline values were determined prior to lowering the rods and upon extraction from the ground following a sounding. None of the soundings, regardless of cone used, showed baseline shifts of more than 0.5% of full-scale which gave added confidence to the measured results. Verticality for all soundings was measured to never be more than about $\pm 3^{o}$, which is negligible.

RESULTS

The CPTU performed for the screening program indicated a free draining material. The tip resistance in the target zone from 27 to 37m varied between 28 and 35MPa and the friction ratio was slightly lower than 1 percent. The shear wave velocities were between 214 and 263m/s with no clear increasing trend with depth. A summary of CPTU is given in Fig. 2.

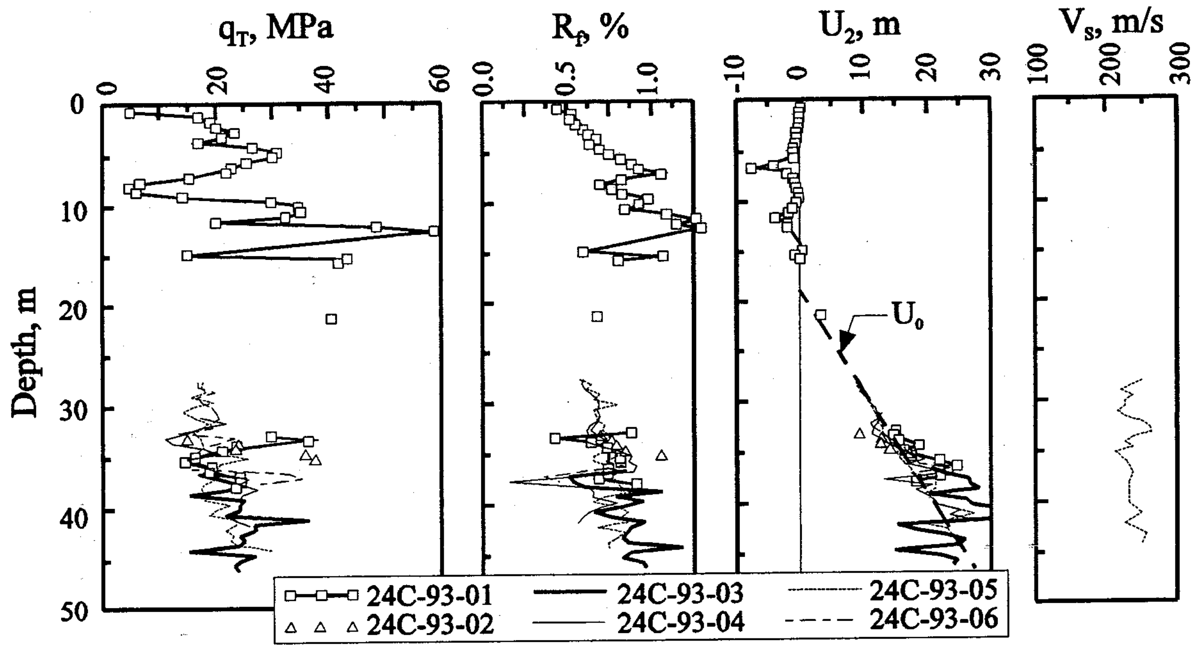


Fig. 2. Details of the Seismic Piezocone Soundings in Preliminary Investigation

Refusal came on a very dense, granular material assumed to be of either fluvial or till margin origin. The push from surface, 9401, was not limited by the weight of the BCMOTH vehicle as much as by the hydraulic systems. The refusal pushing pressure exceeded 2200 psi which was causing bypass on the main feed valves. Calculations indicated that the pushing pressure did mobilize nearly 95% of the roughly 18 tonnes total vehicle weight available for pushing. Fig. 3 shows the SCPTU results for the detailed program from 25 to 40m.

Soundings 9402, 9403 and 9404 are all similar with little variation in the tip stress and essentially identical friction ratios. The largest variation in tip resistance occurred in 9404 at a depth between 33 and 34 metres where the presence of a significantly looser zone is evident. For sounding 9405, a somewhat higher friction ratio over some depth ranges but quite similar tip stress profile was encountered. The difference in friction ratio is relatively minor but also likely accurate as the same cone (Hogentogler) was used in both 9404 and 9405 with identical baseline values. Fig. 3 shows that 9405 was far enough from the rest of the soundings to have some potential depositional variations at over specific depth ranges. For the most part, however, use of 9402, 9403 and 9404 produces a section directly through the frozen core sampling zone and, with a SBPMT directly adjacent to 9404, these three soundings are those that we recommend be used for the general characterization conclusions to produce correlations to laboratory and other in-situ test results.

As noted earlier, soundings 9402 through 9405 were SCPTU soundings. The shear wave velocity profiles determined for each sounding are also presented in Fig. 3. The arrival time was estimated using the precise cross-correlation method. In general, there is some variation in the shear wave velocities in the target sampled zone with values approximately constant with depth and ranging from about 200 to 300 m/s.

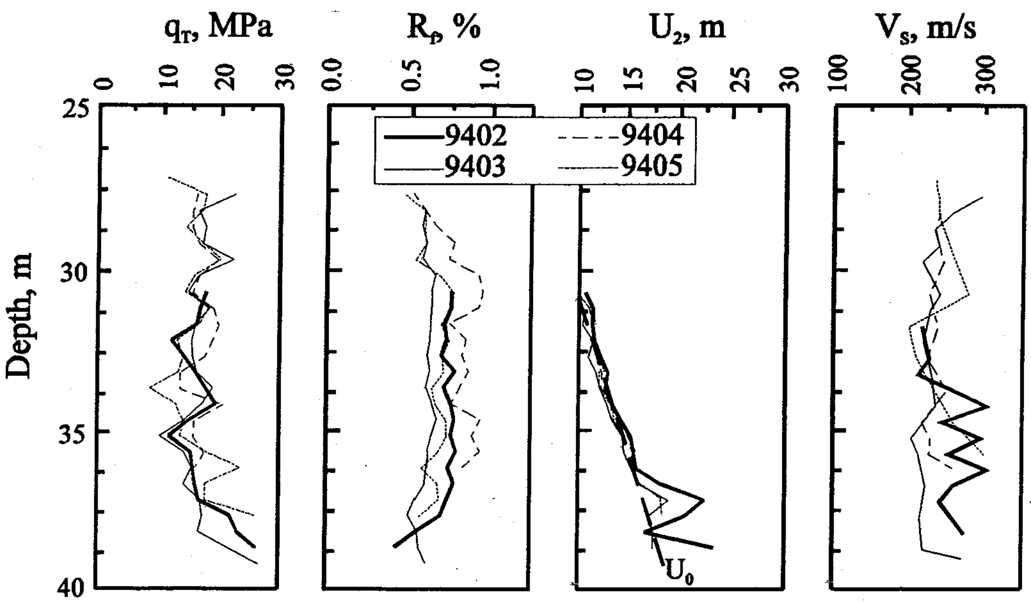


Fig. 3. SCPTU Results From Detailed Investigation

STANDARD PENETRATION TESTING

The SPT work was carried out within two mud-rotary advanced boreholes. The equipment and procedures used are typical of that used by the geotechnical community in Canada. Not as common in Canadian practice, although ever-increasing, is the use of energy calibration devices to determine the percentage of the theoretical maximum input energy during the SPT. This project carried out SPT energy calibrations for both boreholes using the two methods most often cited in literature as providing the true rod-input energy.

Equipment and Procedures

The boreholes were advanced using a 4½ inch tricone bit and AW drill rods. The drill rods were assumed to have a unit mass of 2.18 kg/m. Casing was required in the upper 1.5 metres to prevent caving of loose surface material. Mud circulation was used to maintain borehole integrity. Two different safety hammers were used in the program (denoted as hammer 1 and 2). Both of these hammers were reported as being recently weighed and adhering to the established 63.5 kg (140 lb.) standard weight. The hammers were operated via a rope and cathead system. The rope was relatively new hemp rope and was not wetted during the testing. One and a quarter turn of rope on the cathead was used for driving the sampler. The SPT-N values were determined by summing the number of blows to penetrate the final 300 mm of a 450 mm penetration depth. Soil liners were not used even though there was space for them behind the core catcher. Other relevant details specific to the boreholes and the SPT tests are given by In-Situ Testing Group, University of British Columbia (1994).

To carry out the energy calibration, which determined the percentage of the theoretical maximum energy for the 63.5 kg (140 lb.) weight falling unrestricted through a height of 760 mm (30 inches), an instrumented rod of 0.5m length was used at the top of the drill-rod string to measure the force and velocity imparted by a blow. The instrumentation included two load cells and an accelerometer. The load cells were used to record the time histories of the force delivered blow and the accelerometer signals were processed to obtain the corresponding velocity-time histories during each hammer blow. The high speed data recording system allowed the energy to be measured for every blow up to a maximum of 41 blows for each test depth.

The through-put energy actually being transferred to the drill-rods was determined using the "force-squared" (F^2) and the "force-velocity" (FV) methods. Complete details for each method can be found in ASTM D 4633-86 and in Sy and Campanella (1991), respectively.

Table 1 summarize the results of the energy calibration carried out on the SPT's in boreholes 9406 and 9407. The results from both analytical methods, F^2 and FV, indicate that the energy delivered varied around an average value of between roughly 65% and 70% for both boreholes. This average value is typical for safety hammers and is usually higher than the value of 55% used for donut hammers. The N_{60} values tabulated in Table 1 represent the 60% energy level. The depth of these tests and the resulting stress levels require special consideration as to the actual energy that should be adopted for comparative purposes to a database that is largely established at stress levels roughly 1/3 to 1/2 or less of those encountered here. Nonetheless, the results summarized in Table 1 indicate that relatively constant energies were experienced over two different days with different hammers. In 9406 and 9407, the difference in the computed energy using the F^2 and FV methods was less than 8% of the FV values.

DISCUSSION OF RESULTS

No excess pore water pressure developed during the SCPTU soundings within the target zone between 27.5 and 40.0m. The interpretation of the cone bearing and sleeve friction data based on Robertson and Campanella (1986) classifies the soil unit in the target zone as clean sand.

Table 1. SPT Energy Calibration Data from CNLX 9406

Hole ID	Mean Depth m	Raw Blow Count in (blow per last 300mm)	% Theoretical Energy		Difference (% of FV)	N_{60} from FV Method	Std. Dev. in Energy	
			F^2	FV			F^2	FV
9406	27.7♧	41	73.6	70.6	4	48	7.1	5.7
	29.3♧	26	63.5	64.8	2	28	5.3	4.1
	30.8♧	45	65.6	68.4	4	51	5.3	3.4
	32.3♧	34	74.8	71.0	5	40	6.1	3.9
	35.3♧	30	76.7	74.0	4	37	6.0	4.4
	38.4◇	62	64.3	62.5	3	65	7.8	5.4
	41.5◇	52	67.5	65.9	2	57	8.2	6.9
	44.5◇	54	76.3	70.4	8	63	6.6	3.0
9407	27.7◇	36	67.0	68.7	3	41	3.6	2.6
	29.3◇	31	67.5	67.8	0	35	6.9	3.9
	30.8◇	34	67.1	65.0	3	37	5.5	3.6
	32.3◇	34	67.6	67.1	1	38	4.8	3.2
	33.8◇	44	58.6	57.4	2	42	4.0	2.4
	35.4◇	41	66.3	65.3	2	45	6.9	3.9
	36.9♧	69	61.5	57.4	7	66	4.1	4.4
	39.9♧	69	68.1	62.9	8	72	5.0	7.1
	43.0♧	92	68.1	67.8	0	104	6.2	4.4

Note: ♧ Hammer No. 1 ◇ Hammer No. 2

SUMMARY

This report has presented the results of the Phase I CANLEX general site characterization program carried out at the end of May, 1994. A total of five CPTU/SCPTU soundings and two rotary drilled boreholes with energy calibrated SPT profiles were carried out in the program. The results indicate a large degree of consistency across the detailed sampling area if the test results can indeed be considered representative across the materials between each sounding.

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