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Partially saturated tailings sand below the phreatic surface

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An opportunity to re-examine the liquefaction potential of hydraulically placed tailings sand has been provided by the Canadian Liquefaction Experiment (CANLEX). As part of this experiment, undisturbed samples of tailings sand were recovered after freezing the tailings in situ. Examination of undisturbed cores of frozen tailings sand clearly showed that the specimens were not fully saturated. This was confirmed by both physical measurements and laboratory tests in which gas was recovered from thawing specimens and analysed by gas chromatography. The gas was mainly air although a small amount of microbial gas was also present. Cryogenic scanning electron microscopy and confocal laser scanning microscopy were used to further confirm the existence of occluded gas bubbles. Triaxial undrained compression tests were carried out on undisturbed tailings specimens that were not back-saturated prior to shearing, in order to preserve the in-situ degree of saturation. Occluded air bubbles within the tailings sand, even if only in very small percentages by volume, are shown to have a marked effect on the response to undrained loading of the pore pressure within the tailings specimens. It is suggested that the liquefaction potential of tailings sand that could be expected to be contractive under undrained loading may be reduced by the occurrence of occluded gas bubbles within the voids. While it is not possible to quantify these effects accurately until further laboratory testing of both unsaturated and saturated loose tailings specimens has been conducted, this attribute could modify present engineering design. In this respect, obtaining undisturbed samples of granular soil is an important component of evaluating the liquefaction susceptibility of a specific deposit.

KEYWORDS: ground freezing; liquefaction; microscopy; partial saturation; pore pressures; sands

L'Expérimentation Canadienne sur la Liquéfaction (CANLEX) nous a donné l'occasion d'examiner à nouveau le potentiel de liquéfaction de résidus sableux mis en place par méthode hydraulique. Dans le cadre de cette expérience, des échantillons non perturbés de résidus ont été utilisés après congélation sur le terrain. L'examen des carottes non perturbées a montré clairement que les spécimens n'étaient pas entièrement saturés. Ce fait a été confirmé par des mesures physiques et des essais en laboratoire au cours desquels le gaz a été extrait des spécimens en décongélation et analysé par chromatographie gazeuse. Le gaz s'est révélé être principalement de l'air bien qu'une petite quantité de gaz microbien ait été également décelée. Nous avons utilisé la microscopie électronique à balayage cryogénique et la microscopie laser à balayage à foyer commun pour confirmer l'existence de bulles de gaz occlu. Des essais de compression triaxiale non drainée ont été effectués sur des spécimens de résidus non perturbés qui n'avaient pas été rétro saturés avant le cisaillement de façon à préserver le degré de saturation existant sur le terrain. Nous montrons que les bulles d'air occlu dans les résidus sableux, même s'il ne s'agit que d'un infime pourcentage en volume, ont un effet prononcé sur la réponse au chargement non drainé de la pression interstitielle dans les spécimens de résidus. Nous suggérons que le potentiel de liquéfaction des résidus sableux qu'on peut s'attendre à être contractifs en cas de chargement non drainé, peut être réduit par l'apparition de bulles d'air occlu dans les vides. Bien qu'il ne soit pas possible de quantifier avec exactitude ces effets avant que des essais plus poussés ne soient effectués en laboratoire sur des spécimens de résidus meubles non saturés et saturés, cette caractéristique pourrait modifier l'ingénierie conceptuelle actuelle. A cet égard, l'obtention d'échantillons non perturbés de sol granuleux est une composante importante pour évaluer la susceptibilité à la liquéfaction d'un dépôt spécifique.

INTRODUCTION

The Canadian Liquefaction Experiment (CANLEX), which is a collaborative effort between industry, engineering consultants and university participants, provided an opportunity to test new methods of sampling and of testing (both in the laboratory and in the field) of loose tailings sand. The Syncrude tailings dyke was one of three sites chosen in Canada for the initial sand characterisation phase of the project (Robertson *et al.*, 1995).

Syncrude Canada Ltd, located in Northern Alberta, Canada, produces about 75 million barrels (12 million m^3) per year of crude oil from the Athabasca Oil Sands. This is achieved by surface mining approximately 150 million tonnes of oil sands annually, separating the bitumen using a froth flotation process, and upgrading the bitumen to light sweet oil for shipment to refineries in North America. Approximately 300 000 tonnes of tailings solids are produced daily. The tailings slurry is discharged into two areas: a fine tailings settling basin and a sand storage site. Upon discharge the tailings naturally segregate. The coarse tailings settle out quickly, and since start-up in 1978 about 900 million m^3 have been deposited to date. The fine tailings runoff is contained in the settling basin to densify and release water for reuse in the bitumen separation process. Thickened fine tailings are pumped to a storage area in the mined-out pit (List & Lord, 1996).

Field investigations soon after start-up revealed that, in certain zones of the perimeter dykes of the fine tailings settling basin, the relative densities of sand deposited below water were lower than desirable and could be a potential liquefaction risk when the structure reached full height. The CANLEX project has produced improved techniques for the recovery of undisturbed specimens of loose tailings from below the phreatic surface, which may then be tested in the laboratory. Findings from this work that may impact on the liquefaction susceptibility of the Syncrude tailings dyke are the subject of the remainder of this paper.

SYNCRUDE TAILINGS SAND

The coarse tailings consist of a uniform quartz fine sand typically having a median size of 150 μm. The tailings slurry comprises process water, sand, silt, fine clay particles and trace amounts of unrecovered hydrocarbons. Construction of the fine tailings settling basin perimeter dykes was completed in 1995 using a modified form of upstream construction, as illustrated in Fig. 1. The compacted outer shell was built by sluicing the tailings into construction cells that were typically 50 m wide by

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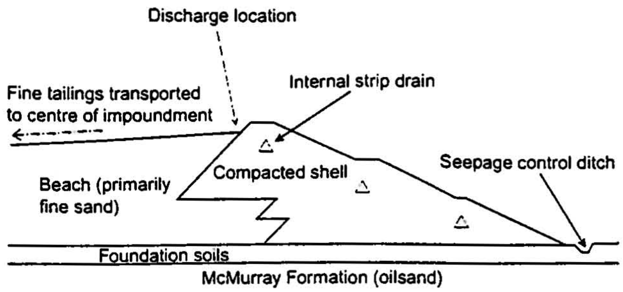

Fig. 1. Typical cross-section of tailings impoundment

700 m long, oriented parallel to the centreline of the dam (Handford, 1988). During sluicing operations the sand was spread by dozers and typically attained a relative density of about 60%. In winter the tailings were discharged upstream of the compacted shell to form a beach deposit. Upon deposition into the settling basin, significant particle segregation occurs, with most of the sand settling out in the vicinity of the discharge point. The fine tailings (<22 μm), which are approximately 50% fine to medium silt and 50% clay size particles, constitute about 12% of the solids fraction that accumulates in the centre of the impoundment and is allowed to settle over time. Beach construction may be either sub-aqueous or sub-aerial. If the coarser particles settle under sub-aqueous conditions, which may occasionally occur during construction, a relatively high void ratio results. Deposits of loose sand may thus occur in pockets within the dyke. These pockets are subsequently covered by later construction of compacted sand cells that are essentially medium dense sand deposits.

Recognising the potential occurrence of looser deposits, an initial screening programme was conducted at the Syncrude site in 1993 to find a suitable location to test new methods of sampling and laboratory and in-situ testing of fine sand. A location was identified that comprised approximately 27 m of dense clean fine sand that had been deposited sub-aerially overlying a zone between depths of 27 and 40 m where the sand was found to be looser, probably owing to sub-aqueous deposition. The phreatic surface was located at a depth of 21 m. A typical grading curve of the tailings sand recovered at this location is given in Fig. 2.

CHARACTERISATION OF SYNCRUDE TAILINGS SAND BY IN-SITU FREEZING, CONTROLLED THAWING AND IN-SITU TESTS

One of the aims of the CANLEX project was to develop the process of in-situ ground freezing to obtain undisturbed specimens of sand with a view to testing whether the tailings were potentially dilative or contractive. Undisturbed sampling of sands has long been recognised as a difficult process, and laboratory testing has thus usually been carried out on disturbed tube samples or reconstituted specimens. Based on field testing conducted as part of the CANLEX project during 1993, a process was refined that had the ability to 'target freeze' the ground at a particular depth and location. A number of undisturbed frozen core specimens from depths of 27 to 37 m were recovered from the Syncrude site referred to in the preceding section. This was achieved using a single, central freeze pipe through which liquid nitrogen was circulated. A column of ground approximately 1 m in diameter and 10 m long was frozen, and cores were recovered from within this zone using a 100 mm diameter Cold Regions Research Engineering Laboratory (CRREL) core barrel. A comprehensive description of the in-situ ground freezing programme is given by Hofmann *et al.* (1994).

Having developed a technique, at some expense, to recover undisturbed sand specimens from depth, it was necessary to develop a protocol for thawing the specimens prior to shearing that would retain the void ratio and structure that had been so carefully preserved. Hofmann *et al.* (1996) compared a range of techniques for thawing and consolidating the frozen specimens prior to shearing. Fig. 3 shows results from two of these techniques. One technique allowed multidirectional thawing (i.e. both axially and radially) under the application of a small (35 kPa) isotropic effective stress, and the other involved unidirectional thawing under the application of 90% of the calculated in-situ effective stresses. Fig. 3 shows that the smallest void ratio change occurred when frozen specimens were thawed using the unidirectional technique. In this method, the in-situ effective stresses were calculated from knowledge of the depth at which a particular specimen was sampled, the depth of the phreatic surface at that point, and a measure of the coefficient of at-rest earth pressure (K_0) that was derived from self-boring pressuremeter tests carried out at the site. These tests gave a K_0 value of 0·5. Rather than apply the calculated values of effective stress, it was decided to use 90% of these values to account for inaccuracies in determination of the parameters that were used in their calculation, such as depth of phreatic surface, density of sand and method of K_0 measurement. Rather than risk stressing the specimen beyond its in-situ stresses, and thus possibly causing consolidation during the thawing process, it was decided to thaw the specimens unidirectionally under reduced total stresses but under the in-situ pore pressure, resulting in applied effective stresses that were 10% less than the calculated effective stresses. From the results given in Fig. 3, this appears to have been a sound decision since void ratio changes during thaw and consolidation were of the order of 0·02.

With the ground freezing technique outlined above, it is possible to retrieve specimens of a loose sand from the field and test them in the laboratory from an initial state that is very close to that which exists in situ. Crucially, the initial void ratio of the laboratory specimen is almost identical with that which existed in the field.

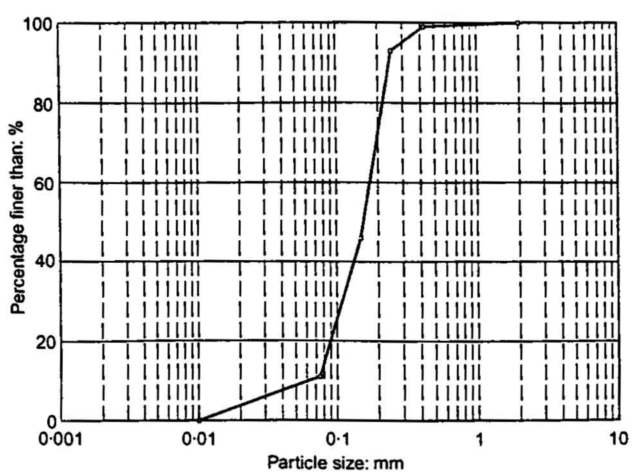

Fig. 2. Typical grading curve of Syncrude tailings from Phase I test location

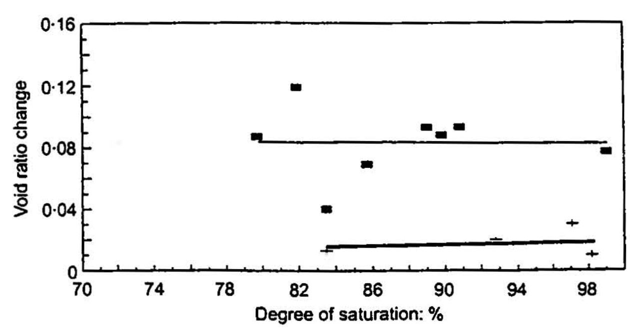

Fig. 3. Effect of thawing procedure on void ratio change during thawing and consolidation (after Hofmann *et al.*, 1996). Thawing technique: ■, multidirectional; +, unidirectional

Condition of frozen specimens

Calculations of the degree of saturation of the frozen specimens based on measurement of overall volume and mass of the specimens, mass of solid particles and specific gravity of the solids indicated that the specimens were partially saturated. This observation appeared questionable based on the depth below the phreatic surface of the specimens (between 6 and 16 m), and further work was deemed necessary to investigate whether or not the frozen specimens were indeed partially saturated. This work, and the potential impact on pore pressure response to undrained loading, are discussed in the following sections.

INVESTIGATIONS OF DEGREE OF SATURATION OF FROZEN SPECIMENS

Prior to setting up a frozen specimen in the triaxial cell for thawing and consolidation, the specimens were measured and weighed, to give the overall volume, V_f, and mass, m_f. The ice content, w_i, was determined from frozen shavings obtained during the specimen-trimming process. After shearing, the specimens were oven-dried and the mass of dry soil measured. Using a specific gravity, G_s, of 2·63, the degree of ice saturation, Sr_i, may be calculated according to

$$Sr_i = \frac{(m_f - m_d)/\rho_w}{V_f - [m_d/(G_s \rho_w)]} \tag{1}$$

where ρ_w is the density of water and m_d is the mass of dry soil.

When soils freeze, disturbance of the in-situ void ratio or fabric may result from the pore water freezing in place (and perhaps enclosing gas bubbles that are present in the voids) and undergoing a 9% volume expansion when freezing is undertaken too rapidly. As a freezing front passes through a soil, the conditions that develop near the front depend on a number of factors. Water may be either expelled from or attracted to the freezing front, depending on the soil type, stress level and rate of freezing (McRoberts & Morgenstern, 1975). In fine-grained soils such as clay or silt, water tends to be attracted to the front, while in sands or gravels the water tends to be expelled in advance of the wetting front (Hofmann *et al.*, 1994). As the freezing front passes through a sandy soil, 9% of the free pore water volume is expelled away from the front. Provided that drainage around the zone in which in-situ ground freezing is being undertaken is unimpeded, and that the soil is frozen slowly enough compared with the permeability of the soil to allow for expulsion of pore water, there is little or no disturbance of the in-situ void ratio or fabric. Many workers, including Yoshimi *et al.* (1978) and Seed *et al.* (1982), have shown that the undrained static and/or cyclic shear strength of sand was unaffected by a freeze–thaw cycle provided that disturbance did not occur owing to freezing with impeded drainage. The specimens tested in this study were obtained by freezing a 1 m radius column of sand unidirectionally from a central freeze pipe through which liquid nitrogen was circulated. This method allows for unimpeded drainage of pore water in advance of the freezing front, and changes in volume of the soil are thus unlikely. The effect of the freezing process on the change in volume of gas present in the voids is at present not well understood. The change in temperature during freezing may have some effect, although the in-situ temperature prior to freezing was below 6°C. The change in temperature may also cause the movement of gas into or out of solution in the pore water, but once again this effect is likely to be small, given the small temperature difference between in-situ soil before and after freezing. Drainage or diffusion of gas out of the zone being frozen is possible, although it is unlikely given the difficulty of flushing air out of undisturbed laboratory specimens with applied backpressures in excess of 400 kPa (Hofmann, 1997).

While it is thus difficult to quantify the change in void gas volume that may occur during the freezing process, the precautions taken during the in-situ freezing were thought to have minimised this effect, and it was thus assumed that the degree of saturation measured on the frozen specimens was approximately equal to the in-situ degree of saturation. Using this technique, the calculated degree of saturation was less than unity in all cases, with degrees of saturation as low as 0·85 for some specimens being estimated.

Controlled thawing of frozen specimens, collection and analysis of liberated gas

A water bath with an outflow spout was filled with deionised water. The bath was filled to the lip of the outlet: thus submergence of a frozen soil core within the water displaced a water volume equivalent to that of the specimen. This gave another measure of the overall specimen volume. A glass funnel and pipette were assembled above the submerged, frozen specimen in such a way that any gas escaping from the specimen would enter the pipette. The pipette and funnel were filled with deionised water, prior to the introduction of a frozen specimen into the water bath, and the pipette was sealed at the top end with a rubber septum. The rising gas thus displaced the water within the pipette, and the volume of the released gas could be measured. To minimise slumping and spreading of the tailings sand as it thawed, the frozen sample was placed inside a large dish within the water bath. Once the specimen was thawed it was gently agitated with a paddle, in order to liberate as much gas as possible. Although it is unlikely that all the gas present in the specimen would have been recovered using the technique outlined above, it appeared to provide a sound indication of whether or not gas was present in the frozen specimen as well as an estimate of the volume of this gas.

The gas was extracted from the pipette neck through the septum for analysis by gas chromatography. A flame ionisation detector and a Haysep N column were used to quantify the amount of carbon dioxide in the sample, and a thermal conductivity detector and a Molsieve 13 × column were used to quantify the oxygen and nitrogen. All the gases were compared with air concentrations. A definite but small methane component was observed in all of the gas samples: this was below the quantification limit, but significantly more than that found in air. A total of five frozen Syncrude tailings sand specimens were tested, and the results of the tests are summarised in Table 1.

The degree of saturation was calculated from the measured gas volume, measured specimen volume (= volume of water displaced when specimen submerged in water bath), measured mass of solids and specific gravity of solids. The percentage of the voids occupied by gas varies from 1% to 7%. These values were determined from the weights of the cores and the volume of the cores determined both by direct measurements and by using the water displacement volume. These values were in good agreement. The gas content in subsamples of the same core piece was found to be quite variable.

The frozen cores were thawed under atmospheric pressure, and the volume of air collected in the pipette was thus greater

Table 1. Measured gas volume and calculated degree of saturation of specimens

Specimen depth: m	Gas volume: ml	Gas as a percentage of specimen volume: %	Calculated degree of saturation: %
34·4	10·9	2·9	93
35·8	6	1·1	98·1
30·4	8	1·4	96·7
31·5	3·4	0·5	99
36·1	2	0·3	99·3

than that occupied by the same air within the in-situ tailings. However, some of the samples were from only 6 m below the phreatic surface, and furthermore the technique of gently agitating the thawed tailings in the water bath would not have liberated all the entrapped air. Hofmann (1997) found that to saturate samples of oil sand tailings fully prior to the preparation of reconstituted specimens required extensive boiling of the tailings. While the gas volumes listed in Table 1 may thus be a slight overestimate of the in-situ air volumes, it is shown later in the paper that even very small amounts of air (e.g. 1% of void space) are sufficient to influence the pore pressure response of tailings sand during undrained loading. The importance of the controlled thawing tests was thus not the measurement of exact volumes, but rather confirmation that air was indeed present in the tailings sand.

Table 2 summarises the carbon dioxide content of the core gas, relative to air. The majority of the gas entrained in the specimens was air. The carbon dioxide is most likely from biological activity, a speculation that is supported by the observation of noticeable but not quantifiable methane peaks in the gas chromatographs.

Microscopy

Microscopy was used to identify the gas pockets in the frozen core in order to confirm that the gases were not produced by a chemical reaction during melting of the core in the water bath. Two separate microscopic methods confirmed the presence of discrete gas bubbles.

Confocal laser scanning microscopy (CLSM). The microscopic examination of the frozen core samples was carried out using a Bio-Rad MRC-600 confocal imaging system attached to a Nikon Microphot 2 optical microscope. The instrument was equipped with a krypton–argon mixed-gas laser (15 mW) that could provide lines at 488, 568 and 647 nm. The use of suitable filters allowed the selection of one of these wavelengths or any combination. In this study, the reflectance mode was used to detect cavities (indicative of gases) in the core matrix.

The CLSM technique provides better detection of fluorescing organic species than scanning electron microscopy (SEM) and eliminates the problem of out-of-focus areas, which are usually a drawback in light microscopy (LM). In addition, the technique allows for simultaneous acquisition in the reflectance and fluorescence modes so that the association of organic and inorganic components can be studied. Confocal laser scanning microscopy combines some of the features of LM and SEM. Like SEM, which scans microscopic entities with an electron beam, CLSM scans the sample components point by point with a finely focused laser beam. The reflected or emitted (fluorescence) light from the specimen is detected by photomultipliers, digitised, and displayed on a monitor. The main feature of CLSM is that it removes out-of-focus information from the image by means of a spatial filter, which consists of an adjustable pinhole (iris) set before the detector. This allows the independent imaging of structures, permitting profiles, three-dimensional reconstructions, and quantitative measurements of height. Utilising CLSM it is possible to excite the fluorescence of some of the sample components with blue light (488 nm) and detect the fluorescence image in the green region (514 nm) while simultaneously detecting, in a second photomultiplier, other components that can show strong reflection of a longer wavelength (such as 647 nm). The screen of the image monitor is split during this mode of acquisition. Image processing techniques allow one to merge the two images in order to facilitate the association between the fluorescent and non-fluorescent sample components.

The microscopic examination of the frozen core samples was performed using a specially designed microscopic cell maintained at liquid nitrogen temperature to avoid changes in the morphology of the frozen core samples. The samples were broken, submerged in liquid nitrogen, and then transferred into the microscopic sample cell. The top surface of the cell was covered with silicon grease, used to form a seal between the holder and a glass window, which isolated the sample from the environment. The sample cell was in contact with liquid nitrogen to maintain the samples at temperatures close to −186°C. The external surfaces of the cell were insulated to prevent heat transfer, and during the microscopic examination a constant flow of nitrogen gas was directed to the surface of the window in order to prevent the formation of frost, which would reduce the transmittance of light to and from the sample.

Cryogenic scanning electron microscopy. The scanning electron microscope used was a Hitachi X-650 equipped with both energy-dispersive (EDS, 30 mm^3 Si(Li) detector; TN5402) and wavelength-dispersive spectrometers. The EDS on the Hitachi X-650 has a Z-max window, which allowed for the detection of carbon and oxygen in the samples. The SEM was also equipped with a Hexland DN302 cold stage used for examining frozen samples. By keeping the sample frozen on a cold stage in the electron microscope, it was possible to image the core sample and also to get compositional information from the X-rays emitted as the electron beam struck the sample. In samples with high water contents, such as the frozen Syncrude samples, it was possible to sublime away the water under controlled conditions, in order better to reveal the associations between the various components. The temperature of the cold stage in the electron microscope was maintained at −90°C by an Oxford ITC4 nitrogen heat exchanger and temperature-controller unit. Each sample was placed on a copper sample stub and immersed in liquid nitrogen. While frozen, the sample was fractured and subsequently transferred into the SEM chamber for observation. Secondary electron images of the samples were acquired at 15 or 20 kV and stored in a Tracor Northern TN8502 image analysis system.

Another consideration with sample handling and observation in this mode was the possibility of beam damage and creation of artefacts associated with the large amount of energy per area deposited on a sample when the electron beam was finely focused. This possiblity was minimised by using low beam currents, and in this case beam damage, even with long observation times, was minimal. Both secondary and backscattered electron imaging modes were used in order to distinguish more accurately between actual gas pockets and 'shadows' in the secondary electron images. The backscattered electron images have a brightness proportional to the average atomic number of the region being observed, so that the mineral components appear relatively bright compared with the water phase. The gas pockets then appear almost completely black.

The CLSM micrographs are three-dimensional representations, and require special glasses to be viewed properly. They are thus not reproduced here. When the micrographs were viewed with the required glasses, they clearly showed gas pockets, which appeared as hollows in the core surface. The CLSM technique is particularly useful because it shows the gas pocket surrounded by water and solids on all sides. Fig. 4 shows two cryogenic secondary electron SEM micrographs of

Table 2. Amount and percentage of carbon dioxide in specimens

Specimen depth: m	Carbon dioxide content: ppm	Carbon dioxide: %
34·4	4200	0·42
35·8	4850	0·49
30·4	n/a	n/a
31·5	600	0·06
36·1	500	0·05

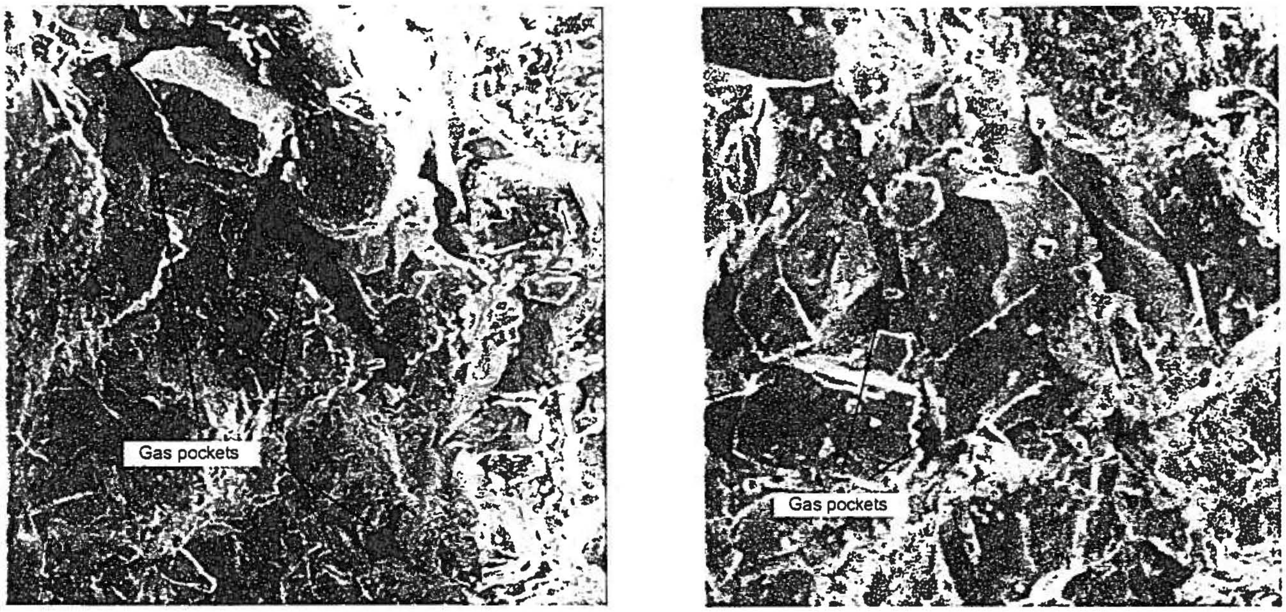

Fig. 4. Cryogenic scanning electron micrographs (secondary electron imaging) of the core samples showing several gas pockets (which appear as dark areas in the photographs). The image on the left is 400 microns across, the image on the right is 120 microns.

several gas pockets in a core sample. Fig. 5 shows a different field of view in both the secondary and backscattered imaging modes. The sand grains appear very bright in the backscattered electron image while the water phase appears grey. The gas pockets are very dark.

Although quantitative determination of the in-situ degree of saturation was not possible using the above techniques. the isolated pockets of gas encountered with the laser scanning confocal and cryogenic electron microscope positively confirmed that the sand deposit at the phase I test site was not fully saturated.

Evidence from previous field work

Further evidence that the degree of saturation below the phreatic surface of the Syncrude tailings sand is less than unity is given by the results of very careful fixed piston sampling reported by Plewes & Hofmann (1995). Samples were classified according to sample recovery. evidence of disturbance and condition of the sampling tube; only the best-quality samples were utilised for calculation of void ratio and degree of saturation. The results are summarised in Fig. 6. which shows that the degree of saturation once again appears to be less than unity.

POSSIBLE EXPLANATION FOR OBSERVED DEGREE OF SATURATION

Any of the above observations taken on their own would be insufficient to state unequivocally that the tailings sand was not fully saturated in-situ. However. when all the evidence is considered together, there can be little doubt that the sand is not always fully saturated. Since the tube samples were recovered

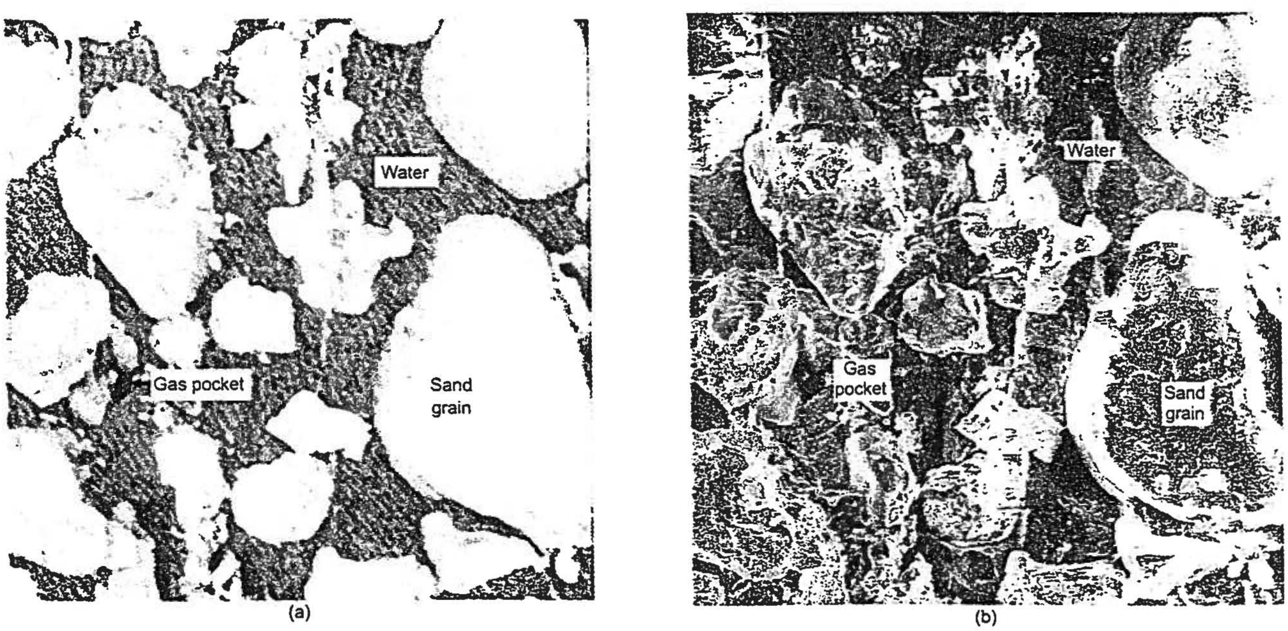

Fig. 5. (a) Backscattered and (b) secondary images of the same field of view. The gas pocket is very distinct in the backscattered imaging mode because this imaging method is sensitive only to sample density and not to topography. These imagess are 400 microns acroos.

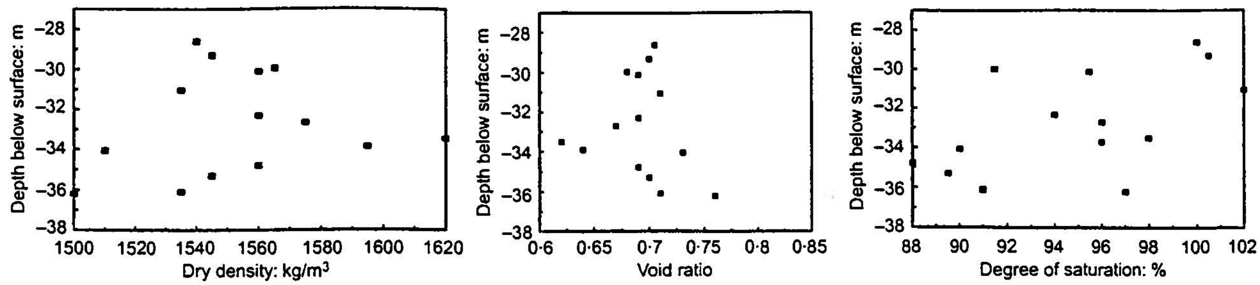

Fig. 6. Estimated in-situ dry density, void ratio and degree of saturation of intact Syncrude sand (after Plewes & Hofmann, 1995)

from depths below the phreatic surface of between 6 m and 16 m, the obvious question is what is the cause of this apparent anomaly. In a study by Foght *et al.* (1985), water samples were recovered from Syncrude's settling basin from depths of 0·5, 8, 12 and 15 m. Counts of aerobic and anaerobic heterotrophic bacteria were about 10^6/ml and 10^3/ml respectively, while counts of sulphate-reducing bacteria were 10^4/ml. Although methane was detected in their deepest sample, microbial activity was very low. The study concluded that an active microbial population existed throughout the depth sampled. The hydrocarbon-degrading capability of the shallow samples was superior to that of the deeper samples, which was attributed to the observed differences in species composition. In a more recent study, EVS Consultants (EVS, 1992) surveyed the microbial populations and their distributions with depth in the Syncrude tailings settling basin. The results are summarised in Fig. 7. The nitrate-reducing and iron-reducing bacteria were found to be the most plentiful.

The observed elevated carbon dioxide and detectable methane gas concentrations in the Syncrude specimens could be a consequence of activity of these bacteria. While these bacteria favour an anaerobic environment such as exists below the phreatic surface and could conceivably use nutrients such as nitrate, sulphate and residual hydrocarbons as an energy source, the concentration of biogas in the gas recovered from frozen specimens was not significant. As shown earlier, the gas was predominantly air. It is possible to speculate, but not prove conclusively at this stage, how the air came to be trapped in voids, below the phreatic surface. During tailings deposition the formation of preferential channels by the flowing slurry has been observed. Incision of these channels of up to 1·5 m into newly deposited tailings may occur. Furthermore, subsequent to completion of a deposition cycle, the tailings are allowed to drain under gravity. During this time air will enter some of the voids within the tailings sand. Subsequent tailings deposition above this partially saturated layer may not be able to dislodge all the air pockets, resulting in occluded air bubbles ultimately being trapped below the phreatic surface. Inspection of individual particles of Syncrude tailings sand under a microscope shows many of them to be highly pitted, with widespread

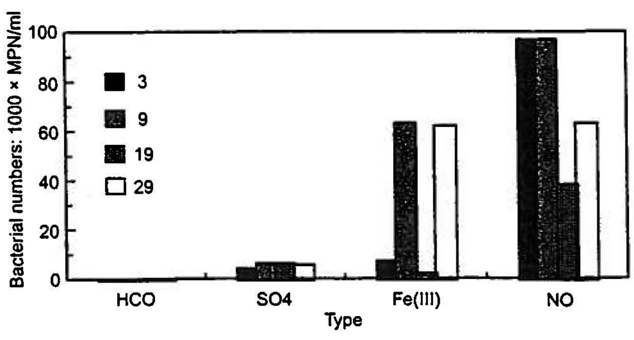

Fig. 7. Distribution of microbial populations in Syncrude's Mildred Lake Settling Basin in 1991 (after EVS, 1992). Populations of nitrate, iron, sulphate, and carbonate reducers are shown

occurrence of micro-fracturing. Air that is attached to features of this type may be particularly difficult to dislodge. Evidence of this are the tests on reconstituted specimens of Syncrude sand carried out by Sladen & Handford (1987), who found that it required backpressures of up to 690 kPa to achieve full saturation.

As described by Wheeler (1988), undissolved gas within the pores of a soil may take three different forms. In the first of these, the gas-filled voids are interconnected and the pore air pressure and pore water pressures are usually different. However, this usually occurs only if the degree of saturation decreases below about 85% (Wheeler, 1988). The second form, which is that investigated by Wheeler (1988) and Sills *et al.* (1991) amongst others, is discrete gas bubbles that are much larger than individual soil particles and which form distinct, large cavities in the soil. The third form, and that which applies to the Syncrude sand in this study, is occluded gas bubbles that are small enough to fit within the pore water in the soil voids. These small discrete gas pockets are indicated in Figs 4 and Fig. 5 and were clearly visible on the confocal laser scanning microscopy micrographs, which unfortunately may be viewed only with special viewing glasses.

The evidence gathered to date all points to the same conclusion: that is, the Syncrude tailings sand is not fully saturated. Although the degree of saturation is still high, and in many instances appears to be close to 98% or even higher, it is shown in the following section that even very low quantities of gas may have a significant impact on the undrained pore pressure response of a tailings specimen.

EFFECT OF DEGREE OF SATURATION ON RESPONSE OF PORE PRESSURE TO UNDRAINED LOADING

Liquefaction failures are primarily a concern in coarse-grained soils such as sands and some silts. Most sands, particularly those at depth, have a stiffness (usually defined in terms of the modulus of deformation, or Young's modulus) that is orders of magnitude higher than values for clayey soils. It is this relatively high stiffness that is of major significance when discussing the effect of a degree of saturation of less than unity on the liquefaction susceptibility of sands.

When carrying out laboratory triaxial testing of undisturbed specimens it is common practice to evaluate the degree of saturation by carrying out a so-called B test (Bishop & Henkel, 1962). Although a specimen is often considered fully saturated only when $B = 1$, it is common to accept values as low as 0·96 when testing compressible soils such as normally or lightly overconsolidated clays. However, with very stiff soils, the assumption that a B value of 0·96 represents a fully, or near fully, saturated state is invalid, as explained below.

For a fully saturated soil, Skempton (1954) has shown that the B value can be theoretically estimated from:

$$B = \frac{1}{\left(1 + \dfrac{nC_w}{C_d}\right)} \tag{2}$$

where n is the initial porosity of the soil, and C_w and C_d are the compressibilities of the pore fluid and the soil skeleton respectively.

The compressibility of the pore fluid (which is usually water) is much lower than that of the soil skeleton when the soil is saturated. Hence the value of B is close to unity. If air is present in dissolved form in the pore water it changes the compressibility of the water by an insignificant amount (Fredlund & Rahardjo, 1993). However, when air or gas is present in the voids of a soil, the pore fluid becomes more compressible, and as shown by Fredlund & Rahardjo (1993) the compressibility of the gas–water mixture is predominantly influenced by the compressibility of the free gas portion. In a clay, the soil skeleton is still usually substantially more compressible than the pore fluid, and hence the value of B is not too dependent on the degree of saturation. In a stiff soil, however, the presence of even a small amount of air increases the pore fluid compressibility sufficiently for it to become of the same order of magnitude as that of the soil skeleton. This has a major impact on the B value of stiff soils (and thus on their pore pressure response to imposed loads).

This is illustrated by the results in Fig. 8, which plots B against degree of saturation. The figure has been recalculated from data given in Black & Lee (1973) and shows results for three hypothetical soils: a soft clay, a medium stiff soil and a stiff soil. These three categories correspond to approximate Young's modulus values of 1 MPa, 12 MPa and 120 MPa respectively. The values of 12 and 120 MPa are similar to those for Syncrude sand at an effective confining stress of 300 kPa (which is typical of what exists in the field), and it is thus the curves indicated as 'medium' and 'stiff' that are of interest. It is clear that the pore pressure response of a medium to stiff sand will be extremely sensitive to changes in degree of saturation.

This has been borne out by B tests that were carried out at the University of Alberta (Hofmann, 1997) on Syncrude samples that had been thawed using the technique outlined earlier. Fig. 9 shows the results of these tests; with the exception of one outlier, there is a definite, rapid decrease of the B value with decreasing degree of saturation (which was computed using the method discussed earlier).

The effect of the degree of saturation on the response to loading of pore pressure in an unsaturated soil specimen is shown in Fig. 10. The data are from tests carried out by Hofmann (1997), and the figure is a plot of the change in pore pressure with axial strain for anisotropically consolidated, undrained triaxial compression tests on three Syncrude specimens that had similar initial void ratios. The dotted line is for an undisturbed (frozen) specimen that was thawed according to the protocol outlined earlier and then sheared without backsaturating (i.e. at the in-situ degree of saturation of about 96%) and with a cell pressure of 411 kPa. The second specimen ($e_i = 0{\cdot}734$) was prepared in exactly the same manner, except that it was saturated prior to shearing. The third sample ($e_i = 0{\cdot}71$) was reconstituted (using the sand from specimen no. 2) by a slurry deposition technique. The specimen was saturated prior to testing. The fabric of the first two samples was thus the same, but clearly different for the reconstituted specimen. The reconstituted specimen was also denser than the other two, undisturbed specimens, which probably explains why this specimen did not exhibit any initial positive increase in pore pressure during shearing.

The steady-state negative pore pressure developed in the two saturated specimens was similar and significantly higher than that in the unsaturated specimen, reaching a plateau at about −400 kPa. In the case of the reconstituted specimen, cavitation probably occurred at this pore pressure as the cell pressure used was only 315 kPa. For the saturated, undisturbed specimen, cavitation is thought to be unlikely because the cell pressure used was 411 kPa, although it cannot be fully discounted in view of the shape of the pore pressure plateau reached. Nevertheless, pore pressures in the range of −400 kPa developed for both saturated specimens. The unsaturated specimen developed far smaller negative pore pressures, and at a much slower rate, despite having dilation characteristics that were presumably similar to those of the other undisturbed specimen (because of the relatively similar initial void ratios). The volumetric expansion of this specimen was not completely prevented because some compression of air in the pore fluid was possible, and the

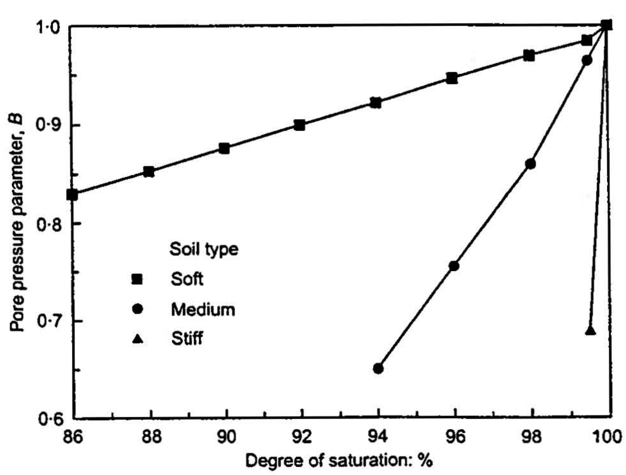

Fig. 8. Effect of degree of saturation on B value for different stiffness soils (after Black & Lee, 1973)

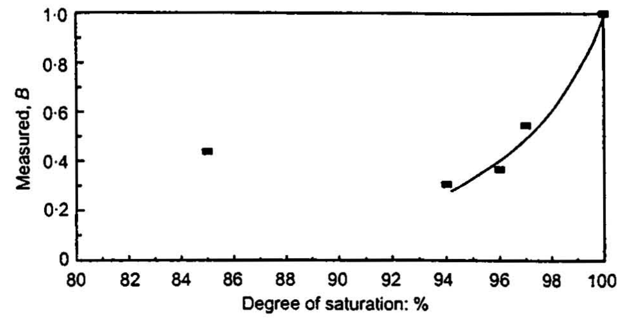

Fig. 9. Variation of B value with degree of saturation of undisturbed CANLEX specimens

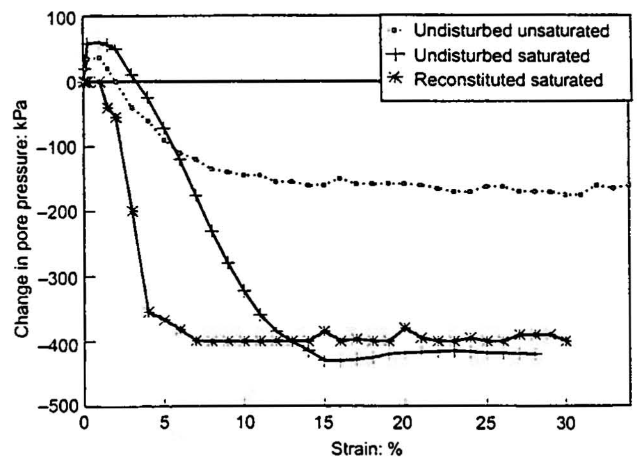

Fig. 10. Change in pore pressure during undrained triaxial compression of specimens of Syncrude tailings sand

pore pressure response was thus less than would occur if the specimen were fully saturated.

Chillarige *et al.* (1997) have shown that the presence of gas (in their case it was methane rather than air) within the Fraser River deltaic sediments may have been a contributory cause of submarine flow slides. They observed that the compressibility of the pore fluid (which was increased by the presence of dissolved methane) resulted in tide-induced changes in pore pressure being out of phase with the tides by about 1 h 25 min. During low tides, a residual pore pressure of 13 kPa was observed. This occurred because, as the sea level dropped, the total stress decreased and some dissolved gas came out of solution. The resulting tendency for the pore fluid to increase in volume increased the pore pressure.

IMPLICATIONS FOR EVALUATION OF LIQUEFACTION SUSCEPTIBILITY

The paper has highlighted a factor that may impact significantly on the liquefaction potential of a particular deposit, namely the in-situ degree of saturation. The existence of even a very small quantity of gas in the pores of a stiff sand, such as the Syncrude tailings, can substantially alter the pore pressure response of the sand to an applied load and thus its liquefaction potential.

The data presented in this paper support the conclusion that tailings sand may not necessarily be fully saturated below the phreatic surface. While it can be concluded that the liquefaction potential of such tailings may be significantly different from that of fully saturated tailings, it would be premature for engineers to incorporate this effect into their designs until a greater acceptance of this attribute is established. There is the obvious concern that the occluded gas bubbles will be flushed out of the tailings by seepage over a long period of time. However, the undisturbed Syncrude specimens tested in the present study are approximately 15 years old and, since the tailings are relatively permeable, it is likely that they have been flushed with many pore volumes of water since initial deposition. They nevertheless retain a detectable volume of air within their voids, which may in part be attributable to the nature of the Syncrude tailings sand.

There is additional evidence in the literature that the persistence of occluded air bubbles in soil below the phreatic surface affects the behaviour of such soil quite markedly. Sherard *et al.* (1963) describe a compacted earth dam in which air contents of 8% of total volume were found in undisturbed samples taken near the upstream slope after the dam had been in operation for 25 years. More recently, St-Arnaud (1995) discussed the effect of occluded air bubbles on the permeability characteristics of downstream filters in earth dams. While these two examples, like many others in the literature, discuss the occurrence of occluded bubbles in clayey materials, the existence in stiff, sandy deposits has not been reported. It is suggested that this may be primarily because of difficulties of taking undisturbed samples of these materials. Any air detected in disturbed samples could be attributed to the sampling process. With the advent of undisturbed sampling of sand by in-situ ground freezing, it is possible that more evidence of partially saturated sand deposits from below the phreatic surface may become available.

Given the impact that even a small amount of air within the voids of a sand may have on the pore pressure response of the sand, it is a topic that clearly requires further investigation.

CONCLUSIONS

Tailings sand sampled from below the phreatic surface at Syncrude's tailings settling basin were found to have degrees of saturation less than unity. This finding was based on physical measurements, collection of gas released during thawing of frozen specimens, microscopy, and measurements of the B value in triaxial tests on undisturbed specimens. It was also backed up by previous, very careful field sampling carried out by other workers. Occluded air bubbles within the tailings sand, even if only in very small percentages by volume, are shown to have a pronounced effect on the response to undrained loading of the pore pressure within the tailings specimens. The liquefaction potential of tailings sand under undrained loading may be reduced by the occurrence of occluded gas bubbles within the voids of these specimens. While it is not possible to quantify these effects accurately until further laboratory testing of both unsaturated and saturated loose tailings specimens has been conducted, this attribute could modify present engineering design. Soil improvement programmes such as deep blasting or dynamic compaction of deposits identified as potentially liquefiable may prove to be unnecessary or excessively large in scope in some cases.

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