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A simple understanding of the liquefaction potential of sands from self-boring pressuremeter tests

La compréhension du potentiel de liquéfaction du sable en utilisant un pressiomètre auto-foureur

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ABSTRACT: Although the conventional Menard pressuremeter can be used in sands, disturbance from stress relief during the formation of the pocket for the pressuremeter can significantly influence the results. However, a self-bored pressuremeter can readily be deployed in loose or dense sands in such a manner that the disturbance is limited. As shown in the paper, the data from this tool can provide some insight into the state of the deposit. Unlike cone data, which can be interpreted only in an empirical manner, pressuremeter data can be interpreted with little recourse to empiricism.

RÉSUMÉ: Meme si le Menard pressiométre conventionelle pout etre utilisé dans le sable, l'influence du trou construit dourant l'installation du pressiométre peut significatirement influencer les resultats. Cependant, un pressiométre auto-foureur minimezer l'influence causé par l'installation. Contrairement aux resultats d'un cone qui ne peutqu'etre interpreté de façon empiricale, les resultats du pressiométre peut etre interpreté sans utiliser des correlations empiricale.

1. INTRODUCTION

Although the conventional Menard pressuremeter can be used in sands, disturbance from stress relief during the formation of the test pocket for the pressuremeter can significantly influence the results. However, a self-bored pressuremeter can readily be deployed in loose or dense sands in such a manner that the disturbance is limited. The data from this tool can provide some insight into the state of the sand. Unlike cone data, which can be interpreted only in an empirical manner, pressuremeter data can be interpreted with little recourse to empirical correlations. The usefulness of these tests in determining the state of the sands is the objective of this paper.

The Canadian Liquefaction Experiment (CANLEX) research project was set up exclusively to consider the most suitable methods of assessing the liquefaction potential of sands. In this study, six sand sites have been examined in great detail. Two of these sites were at the Syncrude Canada Ltd. Mine in Northern Alberta. At the J-pit location, the sand was intentionally deposited in a loose state as a foundation for a trial embankment. The Cell 24 site was at a high tailings dam, over 40 m in elevation. At all of these sites, self-boring pressuremeter tests (SBPMTs) were performed. This paper outlines the salient results of pressuremeter tests at the two Syncrude sites in a very simplistic, "broad-brush" manner. From the results of this overview, the major features of the behaviour of the sand can be determined. These findings are consistent with the results of the laboratory tests conducted on samples obtained by exceedingly expensive freezing techniques.

2. SITE DESCRIPTION

Cell 24 is situated in the 40 m-high Syncrude Tailings Dam at Fort McMurray, Alberta. The tailings are essentially free-draining, angular to sub-angular fine quartz sand, obtained by extraction of crude petroleum from naturally-occurring oil sand. The tailings were deposited by hydraulic means in a settling basin inside a compacted perimeter dyke. Details on the site characterization in the test zone from 28-38 m can be found in Campanella et al. (1995). A typical cone tip profile through this cell is presented in Figure 1A.

At a nearby location, J-Pit, a very loose foundation of Syncrude tailings, approximately 12m thick, was constructed. The foundation was carefully constructed by underwater deposition of the same sand as that used at Cell 24. On the top of this foundation, an embankment was constructed. The upstream side of the embankment was rapidly loaded with the objective of creating a static liquefaction slide through the loose foundation. Details of the field investigation at Cell 24 and J-Pit are outlined in Hoffman et al. (1996). The details of the full scale flow liquefaction tests and some of the preliminary conclusions regarding the limited movement during loading are contained in Robertson et al. (1996). The cone tip profile data, obtained at the J-Pit location CPT20, within 5 m of the pressuremeter tests, are presented in Figure 1B.

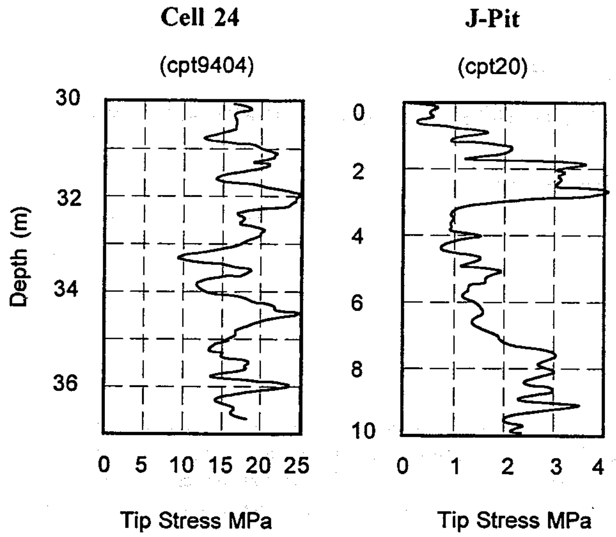
3. RELIABILITY AND REPEATABILITY OF SBPMT

The general quality of the pressuremeter data is probably best described in terms of its repeatability in a sand that is in a fairly uniform state as measured by the variation in the cone tip stress. An indication of the repeatability of the data can be seen in the pressuremeter tests at 35.0, 35.8 and 36.6 m depth, in the same hole, at cell 24, (Figure 2) and the three tests, in different holes 4 m apart, but at the same depth of 4.5 m at J-pit (Figure 3). The SBPMTs, particularly at J-pit, lie in a very narrow band. These results are very consistent with the cone tip resistances measured at J-Pit. At Cell 24 the spread of the SBPMT data is slightly larger. However, that is consistent with the variation in the cone data

Therefore, it would appear that the self-boring pressuremeter data is consistent with the cone data in reflecting the variation of the behaviour of the sand.

4 FUNDAMENTAL DATA PROVIDED BY SBPMT AND THE CONE

At any depth the pressuremeter test provides a complete curve of deformation behaviour, defined by (in many cases) several hundred points. Hence, the pressuremeter provides many data sets which relate the pressure to a particular strain. In contrast,



1 a 1 b

Figure 1. Typical cone tip stress profiles at Cell 24 and J-Pit

the cone at any particular depth gives only one data set relating a tip stress to some average strain. Hence, mathematically speaking, with several data sets, there is the possibility of determining the state of the sand, whereas with one data set there is only the possibility of estimating the state of the sand through empirical correlations.

Since the cone tip stress is affected by many material parameters, it is difficult to be certain of the state of the sand determined from this one number alone. For instance, sands with the same tip stress could have different densities, depending on the relative compressibility and stress history of the sand. Therefore, the cone tip stress alone, no matter how accurately it is determined, can be used to determine only an indication of the state of the sand.

5 DETERMINING THE STATE OF SAND FROM SBPMT

A simple "broad-brush" approach is adopted in this presentation to illustrate the usefulness of SBPMT. The simplest approach to infer the state of the sand is to compare the field SBPMT data to the ideal pressure-expansion curve which would be generated if the sand deformed at the critical state friction angle, φ_{cv}, (Gibson and Anderson, 1961). At this state the sand would deform in drained loading at constant volume. Hence, if the field curve is above this ideal line, then additional energy or work is required to shear the sand. In contrast, if the field curve is at or below this line, an unstable situation could occur, in which the sand could collapse on shearing.

In its simplest form, this ideal line can be generated by four simple assumptions:

1. The sand is initially in a k_o stress state.
2. Initially, shear occurs under elastic conditions until the stress ratio reaches the critical state. An average secant elastic modulus, from zero shear stress up to the stress ratio that the critical state is reached, is required. (If the data is well defined, the average elastic secant modulus is determined from the initial slope of the pressuremeter curve, or it is taken to lie between 0.3 to 0.5 times the modulus derived from the unload-reload loop).
3. At the critical state stress ratio, as defined by the critical state friction angle, φ_{cv}, the sand is assumed to shear at constant volume.
4. The deformation of the centre of the instrument is assumed to be approximated by plane strain conditions.

Applying this procedure to the SBPMT data from the two sites at Syncrude, it is clear that at the Cell 24 (Figure 2) additional energy over and above that required to shear the sand under constant volume (Poissons ratio=0.5) is necessary to shear the soil. In contrast, the sand at 4.5 m depth at J-Pit is close to the critical state line and hence, would be very close to an unstable state (Figure 3)

With the slightly more complex model proposed by Carter et al. (1986), the effect of elastic sand compressibility on critical state is easily included by considering Poisson's ratio to be a function of compressibility. Included in Figures 2 and 3 are the ideal pressure-expansion curves for Poisson's ratio of 0.5, (the Gibson and Anderson solution) and a possible lower limit for sands of 0.0, giving a practical band for constant volume behaviour. (In compressive silts the apparent Poisson's ratio can actually be modelled by a negative value.)

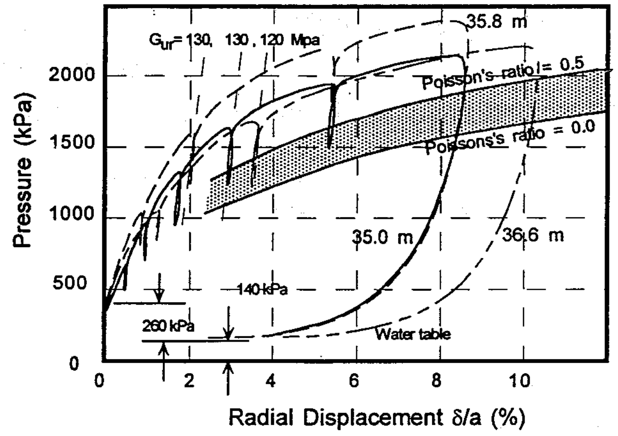


Figure 2. SBPMT data at Cell 24 compared with ideal pressuremeter curve for constant volume deformation

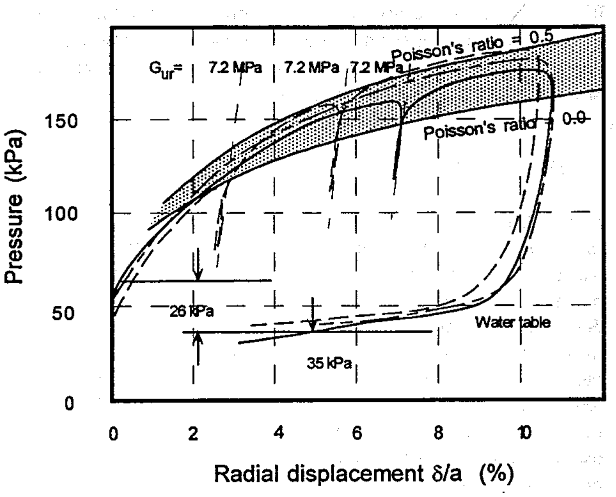


Figure 3. Pressuremeter tests at 4.5 m depth at J-Pit compared with ideal pressuremeter curve for constant volume deformation

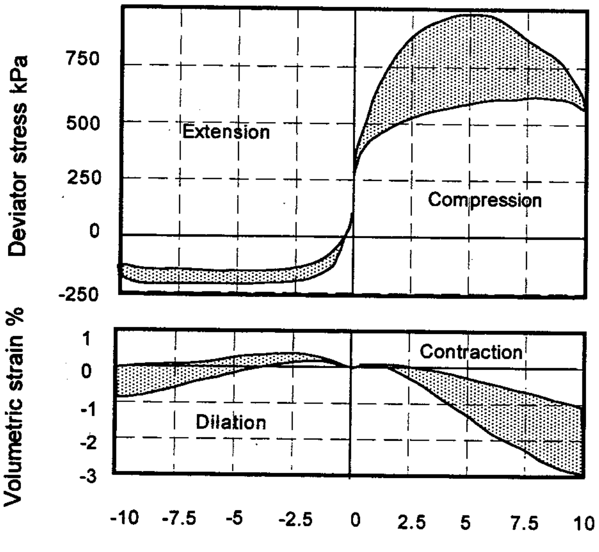


Figure 4. Range of laboratory triaxial drained test data for Cell 24 (undisturbed frozen samples 30 to 35 m depth)

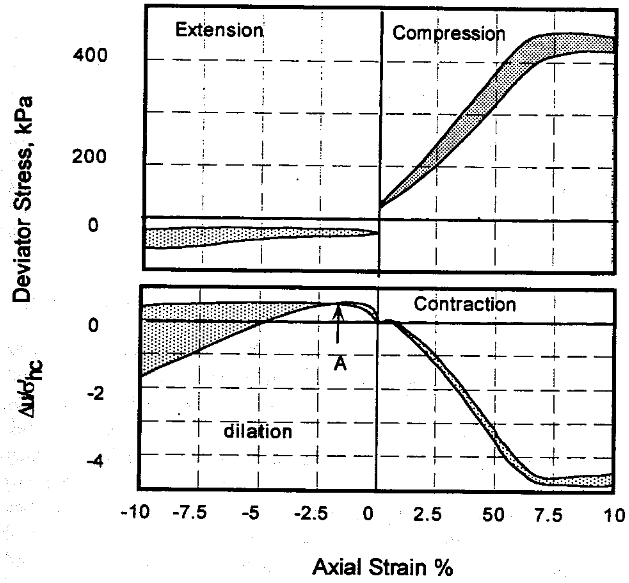


Figure 5. Range of laboratory triaxial undrained test data for J-Pit (undisturbed frozen samples 3.5 to 4.75 m depth)

6. LABORATORY TEST DATA

Several undisturbed samples extracted by ground freezing from Cell 24 and J-Pit have been tested in the laboratory (Konrad and Saint-Laurent, 1995; and Vaid et al., 1996). Figures 4 and 5 present the range of response in triaxial compression and extension tests for samples from Cell 24 (drained tests) and J-Pit (undrained), respectively. After thawing at a small confining pressure, the samples were consolidated anisotropically to the estimated in-situ state of stress.

The laboratory tests show that, in triaxial compression, both sites exhibit dilative behaviour on shearing. In contrast, in extension tests the Cell 24 data shows a tendency to dilate after an initial contraction, whereas at J-Pit the results are much less certain and are possibly representative of a material which is close to deforming at a constant volume.

In these natural samples the in-situ fabric will have been retained. As a result of the vertical deposition, there is a significantly greater grain contact in the vertical direction rather than the horizontal direction. In general, the volumetric behaviour of granular material is dominated by the relative direction of the major principal stress to the direction deposition.

Hence, for tests in triaxial compression, in which the major principal stress and the direction of deposition coincide, the dilation effects are larger than for extension tests, in which the principal stress is normal to the direction of deposition (Vaid et al. 1990). This behaviour is clearly evident with the tests at the 35m level at Cell 24. The volumetric strain in triaxial compression is far greater than for extension. However, after about 2.5% strain, both tests exhibit a positive dilative behaviour.

In a self-boring pressuremeter test the shear planes are vertical, normal to the direction of grain deposition. Hence, the triaxial extension (rather than triaxial compression) test data is more indicative of the behaviour of sand tested by the SBPMT.

7. CONCLUSIONS

With the use of a very simple model, a clear qualitative indication of the state of the sand can be obtained from a visual inspection of the relative position of the field pressuremeter curve to the constant volume pressure-expansion curve. With a slightly more complex model, with only one more variable, the dilation rate (v), the distance from the critical state line to the field curve can be defined in terms of the volume change which is required to shear the soil under drained conditions (Hughes et al., 1977). This, as pointed out by Yu et al. (1994), can then be directly related to the state parameter.

The general "broad brush" approach to the determination of the state of the sand, as to whether it was in a dilative or contractive state is in agreement with the laboratory results and was obtained at a fraction of the cost. For projects of larger areas, a few well-done self-boring pressuremeter tests could provide the reference data needed to develop empirical correlations with cone data at the SBPMT locations. In this way, the more productive CPT could be used throughout the site to provide stratigraphic detail and indicate locations of concern or where additional testing and analyses would be required.

8. ACKNOWLEDGEMENTS

The CANLEX project, initiated by P. K. Robertson, has become an excellent vehicle for evaluating currently available testing techniques and methodologies to determine the in-situ state of granular soils.

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