Site Characterisation in Sands - Implications of Soil Variability

J.A. Howie, H.L. Giacheti, C.R. Daniel and R.G. Campanella
University of British Columbia, Department of Civil Engineering, Vancouver, Canada

ABSTRACT: Data are presented to illustrate the natural variability of deltaic sands. The implications of such variability are discussed with respect to delineation of site stratigraphy and the selection of representative soil properties. Soil variability and scale effects must be considered when using or developing field correlations for engineering design. Combined tests such as the Seismic Cone and Cone Pressuremeter reduce the impact of variability and may provide more reliable means of characterising soil behaviour.

KEY WORDS: Site characterisation, sands, variability, seismic cone, piezo-cone, self-boring pressuremeter, cone pressuremeter

1 INTRODUCTION

Site exploration for engineering design must delineate the stratigraphy at the site and determine the characteristic stress-strain behaviour of the soils. Where soil conditions permit, stratigraphic logging is best accomplished by the electronic piezo cone (CPTU) with limited drilling and sampling to confirm identification of soil type. After delineation of the stratigraphy, representative engineering parameters can be selected.

Two sand test sites were characterised by in situ testing and undisturbed sampling during the Canadian Liquefaction Experiment (CANLEX). The investigators (Robertson et al., 1998) were surprised to observe that the sand conditions were "*highly heterogeneous with large variations in density over short distances*" as "*the sites had been selected based on criteria of density and uniformity*". This paper presents data illustrating the natural variability at the sites and discusses the importance of such variability to stratigraphic logging and development or use of correlations between in situ testing results and design parameters.

2 TEST SITES

Two of the CANLEX test sites, Massey and Kidd2, are located on the Fraser River Delta near Vancouver, Canada. Both have similar stratigraphies consisting of surficial silts overlying Fraser River sands that in turn overlie extensive silt and clayey silt deposits. A detailed discussion of the geology and geomorphology is provided by Monahan et al. (1995). This paper focuses on the Fraser River sands.

3 SITE EXPLORATION

Detailed characterisation at each site was conducted on a circular area approximately 10 m in diameter after selection of a target zone from the results of vertical profiling by CPTU. High quality undisturbed samples were obtained by coring a 1 m diameter frozen zone in the centre of the target zone (Hoffman et al., 1997). Detailed in situ testing was carried out around the circumference of the test zone.

In situ test data presented in this paper were obtained by CPTU, Seismic CPTU (SCPTU) and Self-Boring Pressuremeter (SBPM) testing. In CPTU testing, tip resistance, q_t, sleeve resistance, f_s, and pore pressure, u, were recorded at 25 mm depth intervals as the cone penetrated the ground. The data were interpreted using conventional methods (Robertson and Campanella, 1983, 1988) to give soil type and layering, and engineering parameters.

The SCPTU consisted of an accelerometer package mounted behind the CPTU to detect the arrival of shear waves generated at the surface during pauses in penetration. Shear wave velocities, V_s, were calculated over 1 m depth increments (Robertson et al., 1986). The small strain shear modulus, G_{max}, was calculated using $G_{max}=\rho V_s^2$, based on elastic wave propagation theory

The SBPM consisted of a rubber membrane mounted on the outside of a hollow cylinder. The probe was drilled into the ground behind a cutting shoe with soil removed up the inside of the hollow cylinder. After installation, the membrane was inflated against the soil and the pressure vs. expansion curve was recorded. The expanding section was 445 mm long, 74 mm in diameter, and membrane expansion at mid-height of the expansion section was measured using strain arms (Da Cunha, 1994). Estimates of shear modulus, G_{ur}, were obtained from the slope of small unload-reload cycles carried out during expansion, and the Limit Pressure, p_L, was obtained by extrapolating the pressure-expansion curve to infinite strain using the method of Ghionna et al. (1990).

4 RESULTS

Typical CPTU profiles for each site, including the interpreted soil profile, are presented in Figure 1. Values of q_t have been corrected for pore pressure effects on unequal end areas. The soil layer beneath about 5 m at each site, Fraser River Sand, classifies as sand to silty sand. This interpretation has been confirmed by sampling.

In Figure 2(a) and (b), q_t, f_s, G_{max}, and G_{ur} measured in all holes within the test zone at each site are shown. Values of p_L interpreted from the SBPM tests are also plotted. Figures 3(a) and (b) show the q_t data plotted as an average ± one standard deviation for each site. Although not statistically valid, this approach allows elimination of extreme values. Values of Relative Density (D_r) were calculated using void ratios measured on the undisturbed samples after careful thawing and consolidation (Vaid et al.,1997). Measured values of $e_{max}=1.1$ and $e_{min}=0.7$ for Fraser River Sand were used to calculate D_r.

5 DISCUSSION

5.1 Stratigraphic Logging

Conventional site exploration in sands is based on the Standard Penetration Test (SPT). SPTs are typically carried out at 1.5 m depth intervals, providing a 450 mm disturbed soil sample and a penetration resistance based on the blow count (N-value) for the final 300 mm of penetration. The N-value is very dependent on details of test equipment and procedure and variations in N can occur independent of any variations in soil properties.

CPTU testing allows near-continuous, reproducible q_t, f_s and pore pressure data to be obtained. Soil can be classified and engineering parameters derived for each line of data obtained. As the data are independent of the operator, lateral and vertical variations in measured parameters mainly reflect soil variability. To reduce the volume of data, it is common to perform some form of averaging during interpretation. However, it is not sensible to average data either laterally or vertically until the soil stratigraphy has been delineated, as small but significant layers or zones may go undetected. Indeed, even without averaging, the minimum thickness of soil layer that can be detected depends on the size of the cone tip and the variation in stiffness of the layers. The measured q_t will not represent the full range of strength and stiffness of layers in interbedded deposits with stiff layers thinner than 20 cone diameters(D) and soft layers thinner than 5D, (Robertson and Campanella, 1983).

In Figure 2, the variations in q_t and f_s represent changes in grain size, grain size distribution, density and stress history. Both vertical and lateral variability were observed to be greater at Kidd2 than at Massey. At each site, the depths at which peaks and troughs in q_t and f_s occurred were generally consistent, but the magnitudes of the values at these features varied. Although q_t and f_s

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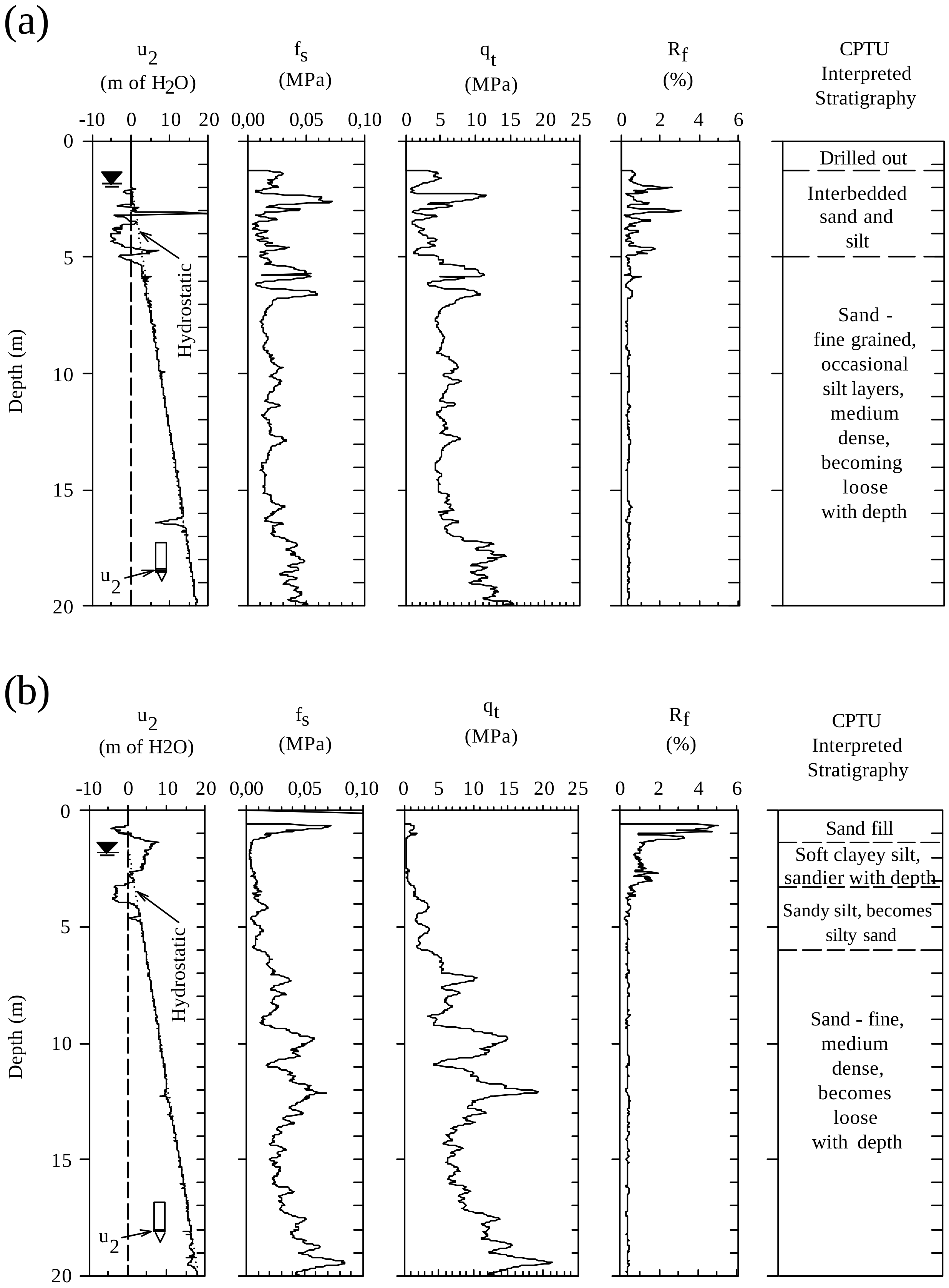

Depth Increment: 0.025 m

Max. Depth: 21.20 m

Figure 1: Typical CPTU profile for (a) Massey (b) Kidd2.

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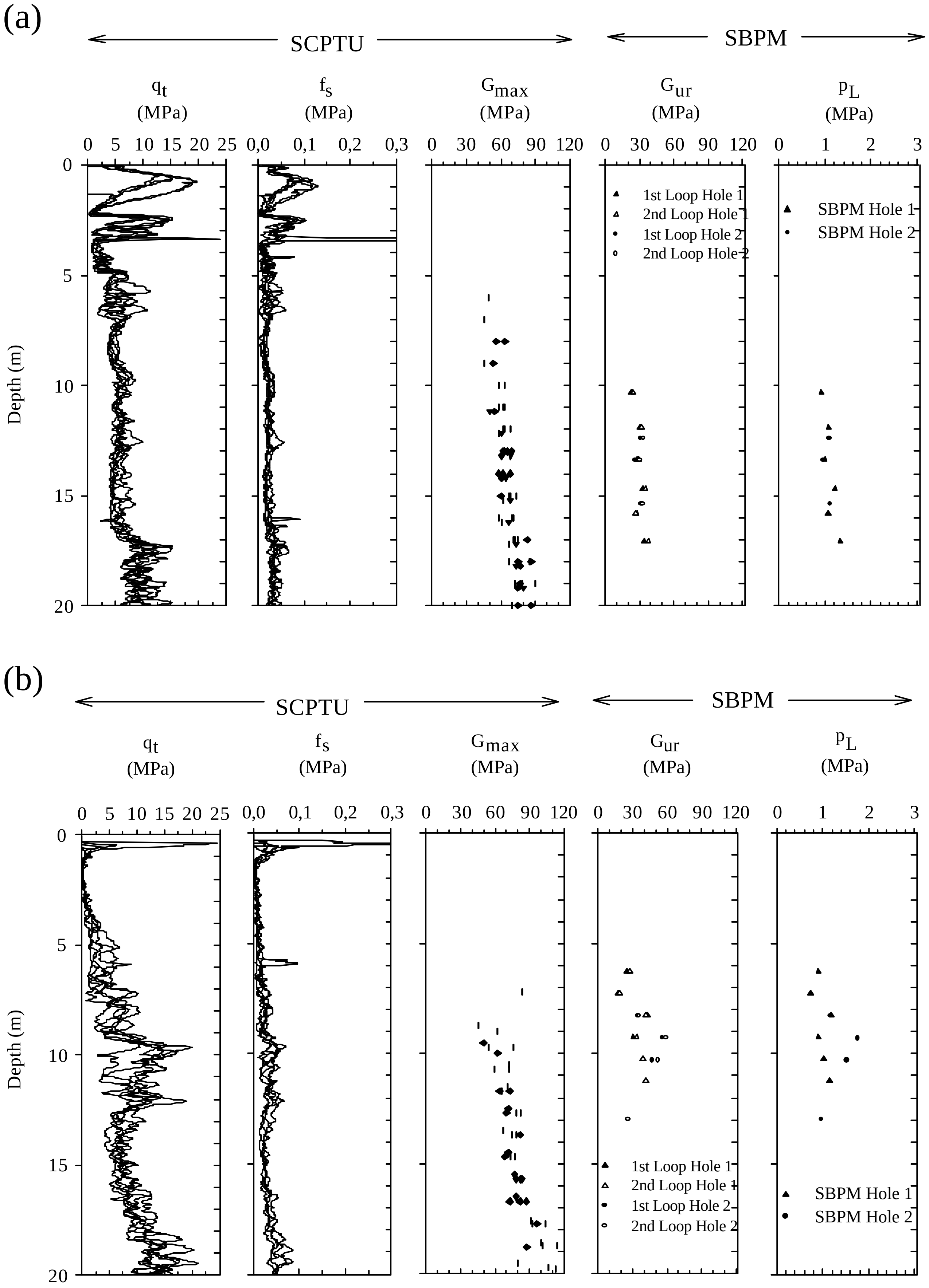

Figure 2: Compilation of CPTU, SCPTU and SBPM data obtained at (a) Massey (b) Kidd2

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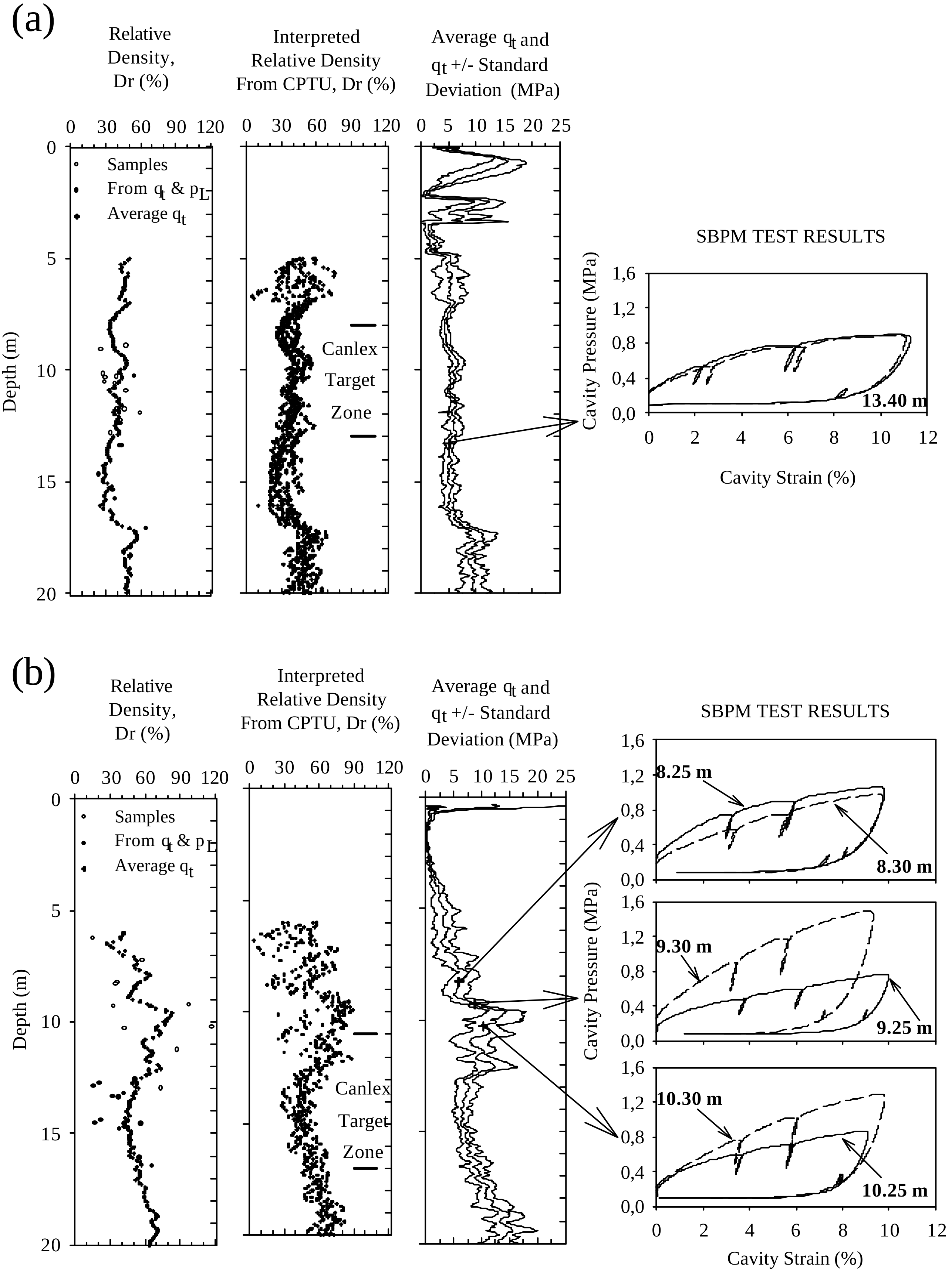

Figure 3: Effect of variability on data interpretation (a) Massey (b) Kidd2

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varied, the friction ratio, $R_f = (f_s/ q_t)*100$ remained constant. Such variations did not greatly affect the soil classification but may have a considerable influence on the selection of design parameters.

5.2 Selection of Representative q_t

Engineering parameters for sands are typically estimated from q_t based on correlations developed from chamber tests on similar sands. Variability is eliminated in chamber tests by careful sample preparation. For field data, variability is accommodated by some form of averaging, with the appropriate approach left largely to engineering judgement. The zone over which averaging is carried out should reflect the zone of influence of the foundation considered and the design method to be followed. For example, the pile design approach of de Ruiter and Beringen (1979) recommends averaging over a zone 4.0 pile diameters (D) ahead of and 0.7D behind the proposed pile tip elevation.

For the CANLEX sites, averaging over depth intervals varying from 40 to 80 cm in individual soundings made less than 10% difference to the calculated $q_{t,ave}$ except in zones where q_t was varying rapidly. However, lateral variations in measured values were typically ±20% of the average at Massey and ±40% at Kidd2. Thus, lateral variability within the test zone was much more important to the selection of a representative q_t value than any consideration of vertical variations within a given layer. This has important implications for correlations between penetration resistance and other parameters measured in adjacent boreholes.

5.3 Correlation to Engineering Behaviour

In Figure 3, values of D_r derived from all CPTU data points (Bellotti et al., 1985) are compared to D_r from the undisturbed samples at each site. At Massey, the CPTU data and measured values agree closely. At Kidd2, the agreement is not as good but the values are in a similar range. However, the true range in void ratio cannot be inferred from the data as it is not known which profile of q_t is representative of the measured void ratios. The true relationship between D_r and q_t at each depth could only be derived from a CPTU sounding at the exact location of the sampling. However, as the void ratios were obtained from 60 and 70 mm diameter samples trimmed from 100 mm diameter frozen cores, the zone of soil stressed by the cone tip was greater than the sample size. The interpreted D_r profile would likely be different from that measured due to the effects of soil variability.

One alternative approach is to obtain a profile of $q_{t,ave}$ by averaging q_t at each depth, The distribution of D_r for each site estimated from the $q_{t,ave}$ is also shown in Figure 3. The scatter plot using all the values would appear to be more representative of site conditions than the single profile based on $q_{t,ave}$.

The effect of variability on the SBPM data is illustrated in Figures 3(a) and (b). The pressuremeter expansion curves obtained for pairs of tests carried out at the same depth but in different boreholes are shown. The test depths are indicated on the q_t profiles. The pressure expansion curves are of the same general shape but there is considerable variation in the maximum pressures attained, particularly at around 9.3 m and 10.3 m at Kidd2, Figure 3(b). These are the depths of greatest variability in q_t values. At 9.3 m, q_t is changing rapidly with depth and also varies considerably in a lateral direction. More consistent SBPM curves would likely have been achieved if the locations of the PM tests had been selected within zones of consistent q_t values, as was the case at Massey (Figure 3(a)).

Simple cavity expansion theory suggests that at the maximum cavity strain of 10%, the SBPM expansion would have created a plastic zone about 10 to 17 diameters wide and 6 diameters high. This is equivalent to about 20 to 34 cone diameters and is likely similar to or slightly larger than the zone stressed by the cone. This suggests that the SBPM curves should reflect a similar degree of variability to the q_t data. The p_L values in Figures 3, do suggest greater variability at

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Kidd2 than at Massey. Stiffness will also vary over short distances. The appropriate stiffness values will depend on the magnitude of strains to be experienced and the scale of the foundation. G_{max} values from the SCPTU represent the average small-strain stiffnesses over 1 m depth intervals. This represents a larger soil volume than influences q_t and should result in a greater degree of averaging of the rapidly varying soil properties. The variability in G_{max} values in Figures 3(a) and (b) indeed show less contrast between Massey and Kidd2 than is indicated by the CPTU and SBPM data.

The G_{ur} values represent the stiffness of soil at a larger strain level and different stress level than the G_{max} values shown. G_{ur} values are consistently less than G_{max} and show more variability again comparable to the trends shown by q_t.

5.4 Implications for the Development of Combined Tests

Wroth (1984) used arguments based on theoretical soil mechanics and homogeneous soil properties to illustrate that different in situ tests loaded the soil along different stress paths and should give different values of interpreted soil parameters. A combination of in situ test methods in the same soil stratum may therefore give more insight into the characteristic behaviour of the soil than a single test. Combined tests such as the SCPTU and Cone Pressuremeter (CPM) allow more than one in situ test to be carried out in the same sounding.

The CPM consists of a pressuremeter module mounted behind a piezo cone. Schnaid and Houlsby (1990) showed that combinations of q_t and p_L obtained by CPM could be used to interpret values of horizontal stress and D_r in chamber tests. However, there have been few demonstrations of successful use of these techniques in natural deposits (Powell and Shields, 1998). Many attempts to validate the CPM concept have involved pressuremeter (PM) tests in boreholes adjacent to CPTU soundings, e.g. Schnaid (1994), and thus require the q_t profile used in any correlations to be representative of the soil stressed by the PM test.

D_r values for the CANLEX sites estimated using the Schnaid approach with $q_{t,ave}$ are shown in Figure 3. The results show similar scatter to the laboratory and CPTU data for Massey but greater scatter for Kidd2. Selection of another q_t profile would change the calculated relationship substantially making firm conclusions on the applicability of the method difficult . A further source of inaccuracy is the method of obtaining p_L. q_t is a measured quantity but p_L is interpreted by extrapolation to infinite strain. While this can be done in a consistent manner, the values obtained depend on details of the pressure-expansion curve, which for SBPM tests typically attains maximum cavity strains of only 10%. In order for the CPM concept to be validated in sands, the PM should be mounted behind a cone, the test zone should be selected based on the cone profile, and the method of obtaining p_L should be carefully considered. Similarly, correlations to G_{max} should be based on SCPTU testing.

6 CONCLUSION

Determinations of D_r from undisturbed samples obtained from a single borehole by coring of frozen ground have illustrated the natural variability of natural water-laid sands. The ability of a given in situ technique to sense such variations depends on the relationship between the volume of soil stressed by the test and the degree of variation. CPTU testing was shown to be very sensitive to soil variability allowing very detailed delineation of soil stratigraphy. The data gathered suggests that lateral variability is more critical than vertical variability in delta deposits. The CPTU data should not be averaged until the site stratigraphy has been interpreted as important detail could be missed.

The selection of design parameters from and the development of correlations to in situ test data should consider the effects of variability on the in situ parameter to be used as an index, the respective sizes of the

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stressed zones and the appropriate stress and strain levels. Correlation between parameters from adjacent holes can be unreliable. Combined test methods such as the Seismic Cone and the Cone Pressuremeter reduce variability effects as all parameters are measured in the same hole. The CPM concept shows promise but validation of methods of interpretation should be based on field tests with all parameters measured in the same sounding.

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