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Problems with interpretation of sand state from cone penetration test

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Considerable attention has been given to the inference of sand density from indirect tests, particularly the cone penetration test (CPT). Data from tests performed in large-scale chambers have demonstrated that for a given sand there is an approximately unique relationship between CPT tip resistance, density (or void ratio) and effective stress level. Data have been presented to support the supposition that CPT tip resistance, if normalized by division by the mean effective stress, is uniquely related to the difference between the current void ratio and the void ratio at the steady state at the same mean stress level. The Paper presents a study of chamber test data for the Ticino sand and demonstrates that there is no such unique relationship for this sand. Use of published correlations that fail to recognize this and other potentially important factors could result in interpretations of sand state that, if carried through to design, could in some circumstances be catastrophic. A series of flow slides that occurred during the construction of an hydraulically placed subsea sand berm at Nerlerk, in the Canadian Beaufort Sea, highlights these difficulties and provides an opportunity to compare field performance with laboratory data.

KEYWORDS: cone penetration test; sands; state parameter; liquefaction.

On a beaucoup étudié la détermination de la densité du sable à l'aide d'essais indirects, particulièrement à partir de l'essai de pénétration au cône. Des données obtenues au cours d'essais effectués dans des chambres de grande capacité ont démontré qu'il existe une relation à peu près unique entre la résistance à la pointe du cône, la densité (ou l'indice des vides) et le niveau effectif des contraintes. On a présenté des données à l'appui de l'hypothèse que si la résistance à la pointe est normalisée en la divisant par la contrainte effective moyenne elle est reliée de façon unique à la différence entre l'indice instantané des vides et cet indice pour l'état stationnaire et pour le même niveau moyen des contraintes. Cet article étudie les résultats d'essais effectués dans de telles chambres sur du sable du Tessin et démontre qu'il n'existe aucune telle relation dans le cas de ce sable. L'emploi de corrélations publiées qui ignorent ce facteur entre d'autres aspects d'importance potentielle pourrait conduire à des déterminations de l'état du sable qui seraient catastrophiques pour la construction dans de certaines circonstances. Ces difficultés sont soulignées par une série de glissements par liquéfaction qui eurent lieu lors de la construction d'une risberme mise en place sous la mer par moyen hydraulique dans la Mer de Beaufort (Canada) et qui donnent l'occasion de comparer les performances sur place avec les données de laboratoire.

INTRODUCTION

The behaviour of sand is sensitive to small differences in void ratio. The accuracy with which sand void ratio can be measured directly in the field can be low in relation to this sensitivity. The problem is that it is extremely difficult to recover a sample of sand with any certainty that its void ratio has not changed during the sampling process. This is not a new problem and it has led to many attempts to measure in situ density indirectly by correlation to the results of in situ tests. Early work concentrated on the standard penetration test SPT (e.g. Gibbs & Holtz, 1957). Since then increased attention has been paid to the use of the self boring pressuremeter (e.g. Hughes, Wroth & Windle 1977) and the cone penetration test (CPT) (e.g. Schmertmann 1970, 1977; Baldi, Bellotti, Ghionna, Jamiolkowski & Pasqualini, 1982). This Paper deals with the CPT, which is favoured by many workers because it is widely available and standardized, it does not rely on minimizing disturbance during insertion, it provides a continuous profile of the measured parameters, and there is a large body of literature concerning its interpretation.

Modern CPT equipment can make several measurements. The primary measurement is the cone tip resistance pressure q_c. Most instruments also measure the friction on a sleeve located above the cone tip. More sophisticated *instru-*

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ments allow the measurement of pore pressure close to the tip and the lateral stress on the instrument. Correlations between sand density and CPT results have concentrated on the tip resistance measurement.

CPT—DENSITY RELATIONSHIPS

Various workers have used large-scale chamber tests to determine relationships between sand density, or void ratio, effective stress level and CPT tip resistance (Schmertmann, 1977; Villet & Mitchell, 1981; Baldi *et al.*, 1982; Parkin, Holden, Aamot, Last & Lunne, 1980). These test chambers have ranged in size from 0·76 to 1·2 m dia. and generally allow the lateral and vertical effective stresses to be varied independently. Procedures have been developed that allow samples of sand to be prepared at various densities with reasonable uniformity. The importance of chamber size and boundary conditions has been recognized (Bellotti, Bizzi, Ghionna, Jamiolkowski, Marchetti & Pasqualini, 1979; Parkin & Lunne, 1982) and correction factors have been developed to allow data from different sized chambers and varying boundary conditions to be compared with field conditions (Been, Crooks, Becker & Jefferies 1986). The larger the chamber the smaller these correction factors, and intuitively, the more reliable the chamber test results are likely to be. Although different workers have used different sands, almost all published chamber tests have been performed on clean (no silt or clay size) medium sands in a dry state. Data available for the Ticino sand (Baldi, Bellotti, Ghionna, Jamiolkowski & Pasqualini, 1986) were obtained in a large chamber and are the most extensive and complete set that have been published. For these reasons, Baldi's data have been adopted for discussion purposes in this Paper.

For a given normally consolidated sand there is found to be a reasonably unique relationship between sand void ratio, vertical effective stress and CPT tip resistance q_c. That is, in a plot of any one of these three parameters against a second, contours of the third can be constructed. Normally consolidated sand is defined as sand that has been prepared to a given density and then loaded under conditions of zero lateral strain. Void ratio has traditionally been expressed in terms of relative density.

The value of K_0 increases with overconsolidation ratio. For overconsolidated sand there is no unique relationship between q_c, density and vertical effective stress. Depositional mode can influence K_0 even in normally consolidated sands. If mean effective stress, $p' = (\sigma_v' + 2\sigma_h')/3$ is used as the stress parameter, however, it has been shown that the relationship

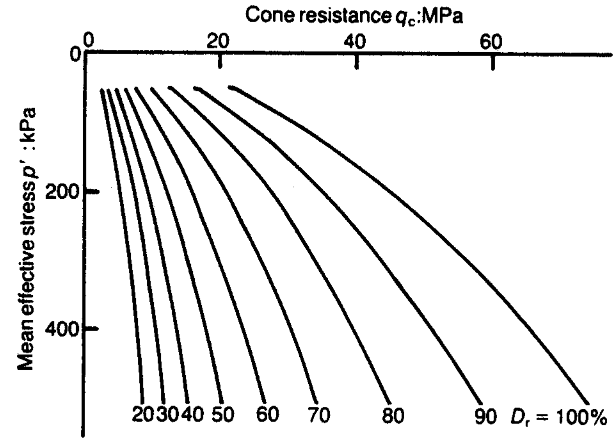

Fig. 1. The relationship between q_c, D_r and p' derived from chamber testing of normally and overconsolidated Ticino sand, from Baldi *et al.* (1986).

between q_c, density and effective stress is approximately unique for a given sand whether normally consolidated or overconsolidated (Baldi *et al.*, 1986). Baldi *et al.* have presented a relationship between relative density D_r, q_c and p' which can be rewritten as

$$D_r = 38{\cdot}3 \ln q_c - 21{\cdot}1 \ln p' - 199 \qquad (1)$$

where D_r is in percent and q_c and p' in kPa. This relationship is shown in Fig. 1, in which contours of relative density are shown in a plot of q_c against p'.

There is some evidence that tip resistance is more strongly dependent on horizontal effective stress than mean stress (Baldi *et al.*, 1986, Houlsby & Hitchman, 1988). Nevertheless, for the Ticino sand, the above expression, which was derived through a regression analysis of experimental data, correlates reasonably well with the chamber test results. Values of relative density predicted by the above expression are within ±14% of the actual value, nine times out of ten. That is within ±0·05 in terms of void ratio. This error band could be considered to be the limit of accuracy of any method of interpreting CPT data that only considers mean effective stress and tip resistance. For sands with less experimental data than for the Ticino sand, greater potential error could be anticipated.

Potential problems arise when applying relationships such as equation (1) to field conditions. Firstly, there is no direct evidence to prove that data obtained in a large chamber are directly relevant to field conditions even for the sand studied in the chamber. Such factors as depositional mode, fabric and ageing could affect CPT field performance. Secondly, it is not usually possible to measure the horizontal effective stress. Thirdly, it is not known if a relationship, developed for one sand, is applicable to any other sand, particularly to a variable deposit.

There are two aspects to this latter problem. Can the relationship between D_r, q_c and p' be expected to be unique for all sands and will two different sands with the same relative density necessarily behave in the same manner? While there is some evidence to suggest that the D_r, q_c, p' relationship may be reasonably unique for clean medium grained quartz sands, it is not known how this relationship is affected by fines content and other natural variables. There is considerable evidence to support the view that relative density is not a reliable index of behaviour for comparing various sands (e.g. Tavenas, 1973).

CPT–STATE RELATIONSHIPS

The state of soil in relation to the critical state line is potentially more useful as an index of soil behaviour than is relative density. This state can be represented on a plot of void ratio against the logarithm of mean effective stress, although it is not known if mean effective stress is the appropriate stress parameter for comparing general stress states. The soil state governs its propensity for contraction or dilation during shear. On the simplest level, soil whose initial state lies above the critical state line will undergo a net contraction when sheared to the critical state, whereas if the initial state lies below the critical state line, there will be a net dilation. Roscoe & Poorooshasb (1963) concluded that any two samples of a soil will behave in a similar manner provided the difference between the initial void ratio and the void ratio at the critical state at the same normal stress is the same for each sample. Cole (1967) and Stroud (1971) have presented considerable experimental evidence to support this principle of similarity of behaviour for dilatant sands.

For practical purposes the critical and steady states can be considered to be the same (Sladen, D'Hollander & Krahn 1985a). Techniques, to measure steady state conditions, developed for liquefaction analysis (Castro 1969, Castro, Enos, France & Poulos, 1982) are the only well established method of determining the critical state line for sands. This involves performing undrained triaxial tests on very loose sands whose initial state lies above the critical or steady state line. Tests on sands that are denser than the critical state can not generally be used because of the tendency of dilatant sands to develop nonuniformities of void ratio.

The difference between void ratio and void ratio at the steady state at the same mean effective stress has been termed the 'state parameter'. Been & Jefferies (1985) have correlated various behaviours to the state parameter. Sladen *et al.* (1985a) have shown that the behaviour of very loose, potentially liquefiable sands, including undrained brittleness index, can be rationalized by consideration of initial state in relation to the critical state line.

In order to evaluate the state parameter of a sand it is necessary to know its void ratio e and the position of the steady state line. Steady state lines are generally linear in e-log p' space so two constants (e_1 and C_{ss}) are necessary to define its location i.e.

$$e_{ss} = e_1 - C_{ss} \log p' \tag{2}$$

where e_{ss} is the void ratio on the steady state line at mean effective stress p'. The constant C_{ss} is the slope of the steady state line and e_1 is the void ratio at the steady state for unit p'. The state parameter ψ is given by

$$\psi = e - e_{ss} = e - e_1 + C_{ss} \log p' \tag{3}$$

Provided that the void ratio is known, or can be estimated from a relationship such as equation (1) and that laboratory tests have been performed to evaluate e_1 and C_{ss}, then ψ can be estimated.

Because of the importance of state parameter to sand behaviour, the possibility of correlating state parameter directly to CPT tip resistance is of considerable interest and has been explored by Been and his co-workers in a series of papers (Crooks, Shinde & Been, 1985; Been *et al.* 1986; Been, Jefferies, Crooks & Rothenburg, 1987b). They have proposed that, for a given sand, normalized tip resistance is a unique function of state parameter. Normalized tip resistance is defined as $(q_c - p)/p'$ where p is the mean total stress and $p = p'$ for dry sand. Generally q_c is much greater than p so that normalized tip resistance is nearly equal to q_c/p'.

In order to investigate this matter further, Been *et al.* (1987b) have obtained samples of the various sands for which chamber test data are available, have carried out undrained triaxial tests to determine steady state parameters (e_1 and C_{ss}) and have re-plotted void ratio–stress–q_c data from chamber testing conducted by others (after correcting for size and boundary effects) as normalized tip resistance against state parameter. As a result, Been *et al.* suggest that unique linear relationships exist between the logarithm of $(q_c - p)/p'$ and state parameter. Therefore for any given sand they suggest

$$(q_c - p)/p' = k \exp(-m\psi) \tag{4}$$

where k and m are constants.

Mean relationships for various sands, as published by Been *et al.*, are shown in Fig. 2. Values of m (the negative gradient of the lines in Fig. 2) are in a fairly narrow range of 9·9–11·7. Values of k (the intercept on the $\psi = 0$ axis) vary from sand to sand. Been *et al.* suggest that the

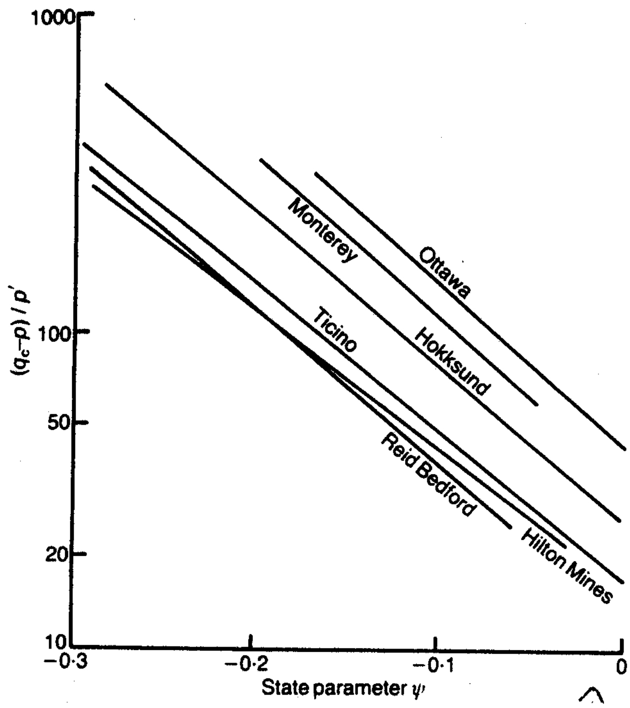

Fig. 2. The mean relationships between normalized tip resistance and state parameter for various sands, from Been *et al.* (1987)

values of k and m can be uniquely related to C_{ss} for all sands.

Equation (4) essentially imposes a restraint on the form of the relationship between q_c, void ratio and p'. It suggests that in a plot of void ratio against the logarithm of p', contours of normalized tip resistance must be parallel to the steady state line. The validity of equation (4) is investigated in the next section.

UNIQUENESS OF CPT–STATE CORRELATIONS

Figure 3 shows a plot of $(q_c - p)/p'$ against state parameter for the normally consolidated Ticino sand. This figure is based on the raw data of dry density, effective stress and tip resistance from chamber tests published by Baldi *et al.* (1986) and the steady state line for Ticino sand published by Been *et al.* (1987b). Only data for 3·57 cm dia. cones, the standard size, are presented. Correction factors for boundary conditions have not been applied because their absolute value is speculative and for the Ticino data they are always small and their application would not significantly affect any of the conclusions drawn. Also shown is the mean relationship (equation (4)) published for the Ticino sand by Been *et al.* (1987b).

Considerable scatter is evident in this plot. For some values of $(q_c - p)/p'$ the range of state parameter is greater than 0·15. Recognizing that the vertical axis is a logarithmic scale, the range of $(q_c - p)/p'$ for a given value of state parameter varies approximately by a factor of 3. For example, for a state parameter of −0·1 the range of $(q_c - p)/p'$ is about 30–100. This is a greater scatter than can be observed in the raw data values of q_c for a given void ratio and mean stress. This suggests that the scatter is not entirely random but is the result of some systematic trend that is not directly obvious from the method of data presentation adopted.

The data for the Ticino sand were obtained for a series of vertical stress levels. The value of K_0 varied from about 0·65, for loose states to about 0·45 for dense states. Hence the data can be grouped into a series of fairly narrow ranges of mean stress level as shown in Table 1.

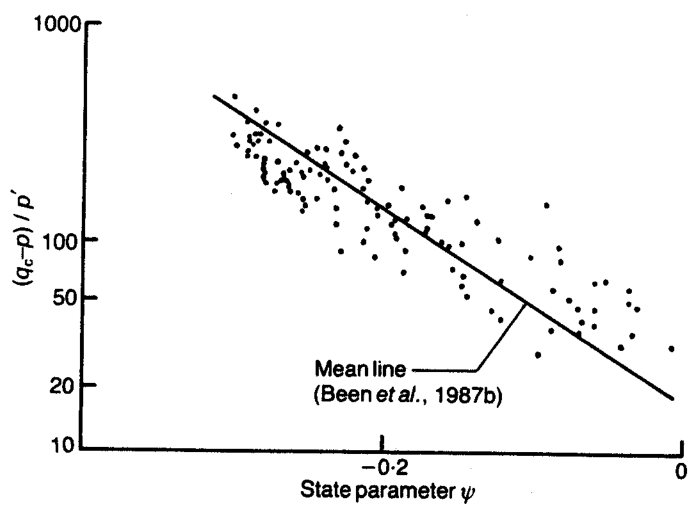

Fig. 3. Normalized tip resistance against state parameter for normally consolidated Ticino sand. Based on chamber test data presented by Baldi *et al.* (1986) and the steady state line for Ticino sand presented by Been *et al.* (1987b). Also shown is the mean relationship for this sand from Been *et al.* (1987b)

Table 1. Summary of chamber test data on normally consolidated Ticino sand grouped according to mean stress level

Group	Mean stress p'		Number of chamber test	Best fit	
	Average: kPa	Range: kPa		k	m
1	27	25–28	6	63	6·2
2	41	37–47	18	36	8·1
3	73	68–83	40	30	8·0
4	130	129–131	2	–	–
5	199	189–237	22	34	6·1
6	329	316–368	9	24	6·9
7	451	442–458	5	16	8·3

It is informative to plot the data in Fig. 3 according to stress range group, and this is done in Figs 4(a) to 4(f). Also shown are the linear regression lines for each group where there are sufficient data for a trend to be well defined. Fig. 5 shows each of these lines and for comparison the mean line for all stress levels published by Been *et al.* (1987b). The following observations can be made.

(*a*) For a given stress level there is a reasonably linear relationship between the logarithm of $(q_c - p)/p'$ and state parameter.
(*b*) The relationship is not unique for all stress levels—rather it varies systematically with mean stress level.
(*c*) The slope of the series of linear relationships is reasonably constant and is always flatter than that of the mean line.
(*d*) The intercept k of the projection of these lines on the $\psi = 0$ axis decreases with increasing stress.
(*e*) Even for a given range of mean stress level there is a scatter in experimental data that may in some cases be significant.
(*f*) There is a dearth of experimental data for low stress levels and high values of state parameter. Owing to this, the scatter of data for all stress ranges (Fig. 3) may be misleadingly low. For example, if the trends revealed by Fig. 5 can be extrapolated to higher values of state parameter, the range of state parameter for a value of $(q_c - p)/p'$ of 50 may be as great as 0·2 for stress levels between 25 and 450 kPa.

Based on the above, the parameter m in equation (4) is reasonably constant, for constant values of p', for Ticino sand (albeit significantly less than would be inferred from the mean line) but the parameter k varies significantly and systematically with stress level. Best fit values of k and m for the stress range groups are given in Table 1. Values of m are in the range 6·1–8·3; values of k are 16–63. These can be compared with the mean values of $m = 10{\cdot}5$ and $k = 17$ published by Been *et al.* (1987b).

It can also be observed that the difference in terms of state parameter between the mean lines for the data for the lowest stress level and the highest is about 0·15. This is close to the scatter of data in Fig. 3. This scatter is not entirely random but can largely be explained when differing stress level is taken into account. The systematic nature of this scatter is consistent with the observation that for a given void ratio and stress level, the value of q_c is reasonably unique. Indeed it can be pointed out that an approximate logarithmic relationship between $(q_c - p)/p'$ and ψ for a given value of p' could be inferred directly from inspection of equations (1) and (3).

In Fig. 6 the value of k is plotted against mean stress. A clear trend of reducing k with p' is evident. The parameter k represents the value of normalized tip resistance that separates positive from negative values of state parameter. The figure demonstrates that its value can vary by a factor of about four times for a single sand, within the mean stress range 25–450 kPa.

In Fig. 7, contours of normalized tip resistance, calculated from equation (1), for the Ticino sand are plotted in $e - \log p'$ space. It is not necessary to know the steady state line to draw these contours, they are simply another representation of the relationship shown in Fig. 1. Also shown is the mean steady state line for the Ticino sand, reported by Been *et al.* (1987b). If normalized tip resistance were a unique function of state parameter, these contours should be parallel to the steady state line. This is not the case.

ACCURACY OF THE DETERMINATION OF STEADY STATE LINES

To estimate state parameter from a known void ratio and stress level it is necessary to have determined the steady state line for the sand. This introduces three further potential problems with

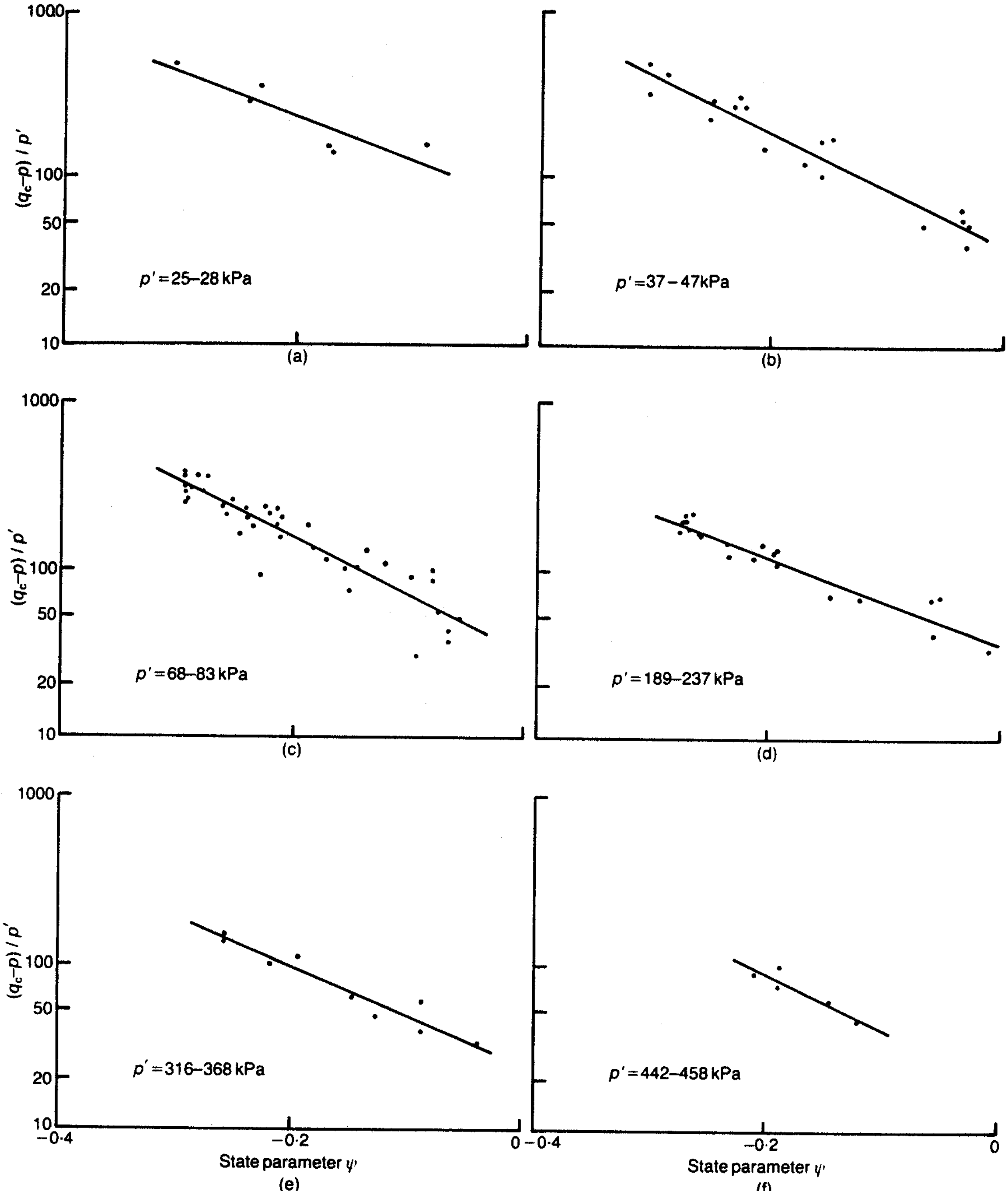

Fig. 4. Normalized tip resistance against state parameter separated according to mean stress level

the state parameter approach to CPT interpretation. Firstly, there can be significant errors in the determination of steady state parameters, particularly for silty sands, if standard techniques are adopted (Sladen & Handford, 1987). Errors in the estimation of void ratio and hence of state parameter of up to 0·15 have been reported for a sand with a silt content of 5–10%, smaller errors are likely for cleaner sands. Secondly, there is considerable evidence that the exact location of steady state line is sensitive to minor changes in sand gradation (Poulos, Castro & France, 1988) and particularly to fines content (Sladen *et al.*, 1985a). Thirdly, it is not known if steady state lines determined in the triaxial apparatus and expressed in terms of mean effective stress are unique in general stress states, in which the intermediate principal stress does not equal the minor principal stress. Each of these factors should be carefully considered before applying laboratory data to design analysis.

IMPLICATIONS FOR DESIGN

The potential error associated with applying a single relationship, such as equation (4), to design could be significant. The consequences of an error will vary from project to project. If, for example,

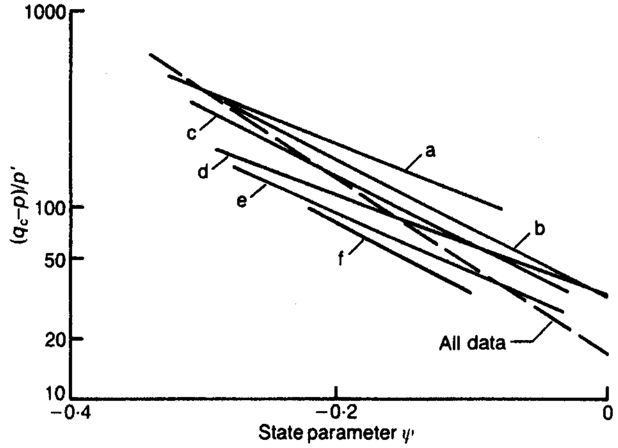

Fig. 5. Linear regression relationships between the logarithm of $(q_c - p)/p'$ and ψ for various mean stress levels compared, from Fig. 4(a) to 4(f). Values of p' corresponding to each line are: (a) 25–28 kPa; (b) 37–47 kPa; (c) 68–83 kPa; (d) 189–237 kPa; (e) 316–368 kPa; (f) 442–458 kPa. Also shown is the relationship for all data, published by Been *et al.* (1987b).

the CPT interpretation is being carried out to aid assessment of static settlement of foundations, the potential error may not be of major importance. If, conversely, the aim were to evaluate susceptibility to liquefaction it could be potentially catastrophic.

The magnitude and direction of the error in assessment of state, resulting from ignoring the effect of mean stress level, would vary with stress level and density. For low stress levels and densities, the tendency would be to underestimate state parameter, which is generally unconservative. If the trend shown by Fig. 5 can be extrapolated beyond the range of available data, then Ticino sand exhibiting values of $(q_c - p)/p'$ of as high as 50 could have positive state parameters (i.e. contractive) at mean stress levels up to about 30 kPa, even without allowing for potential errors in laboratory testing and other uncertainties associated with the application of chamber test data to field conditions. The mean overall trend would suggest a negative state parameter, i.e. dilatant. The potential error in terms of void ratio would be of the order of 0·1–0·15. On the other hand, at intermediate stress and density levels the mean relationship could be approximately correct while at high stress levels and densities it would tend to overestimate state parameter.

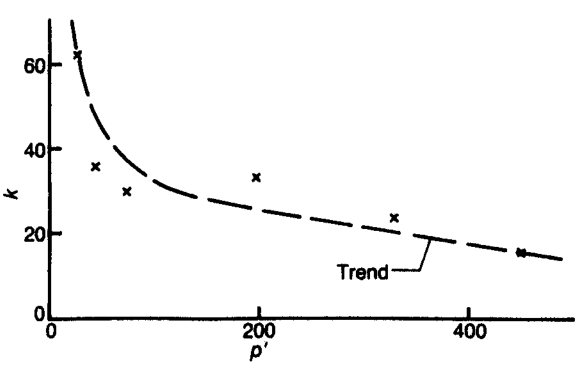

Fig. 6. *k* against mean stress level for Ticino sand

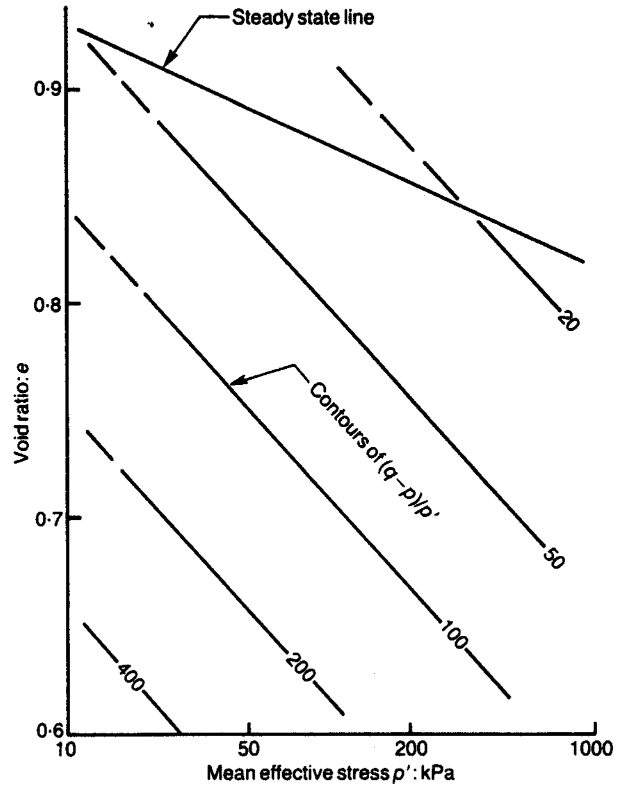

Fig. 7. Contours of normalized tip resistance in $e - \log p'$ space, data replotted from Fig. 1; also, steady state line for Ticino sand presented by Been *et al.* (1987b)

It is not possible currently to quantify the likely magnitude of total error that could result from all uncertainties, but a total error in terms of void ratio of about 0·2 could not be ruled out in some cases, that is more than 50% in terms of relative density. There are few projects where an error of this order of magnitude would be acceptable.

Any engineering correlation based entirely on laboratory testing, such as all of those discussed, should be applied to design with caution until there is field evidence to support or otherwise calibrate it. Even where field evidence is available, care should be taken in extrapolating beyond it. For example, data obtained from medium dense sands at intermediate stress levels could be misinterpreted as supporting the mean relationship.

NERLERK CASE HISTORY

Opportunities for field calibration of CPT—density relationships are rare but one such has been provided by the Nerlerk case history

(Sladen, D'Hollander, Krahn & Mitchell, 1985b; Mitchell, 1984). Nerlerk was a subsea berm intended to be used as a base for a hydrocarbon exploration structure in the Beaufort Sea. It was constructed with hydraulically placed sand. Before completion, construction was abandoned as a result of five large-scale liquefaction flow slides.

It is generally accepted that a state parameter of +0·02 or greater is required for liquefaction (Sladen *et al.*, 1985a; Been, Colin, Crooks, Fitzpatrick, Jefferies, Rogers & Shinde, 1987a). Back analysis of the failures led to the conclusion that the state parameter before failure must have been in the range +0·05–+0·15 to explain the high undrained brittleness index exhibited by the slides. Cone penetration tests had been performed before failure. The mean normalized tip resistance for the failed sand was in the range 40–200. The mean stress level was in the range 0–100 kPa, averaging about 30 kPa. Fig. 8 shows the profiles of mean q_c $(q_c - p)/p'$ and p'. Generally lower normalized tip resistances are associated with higher mean stress levels.

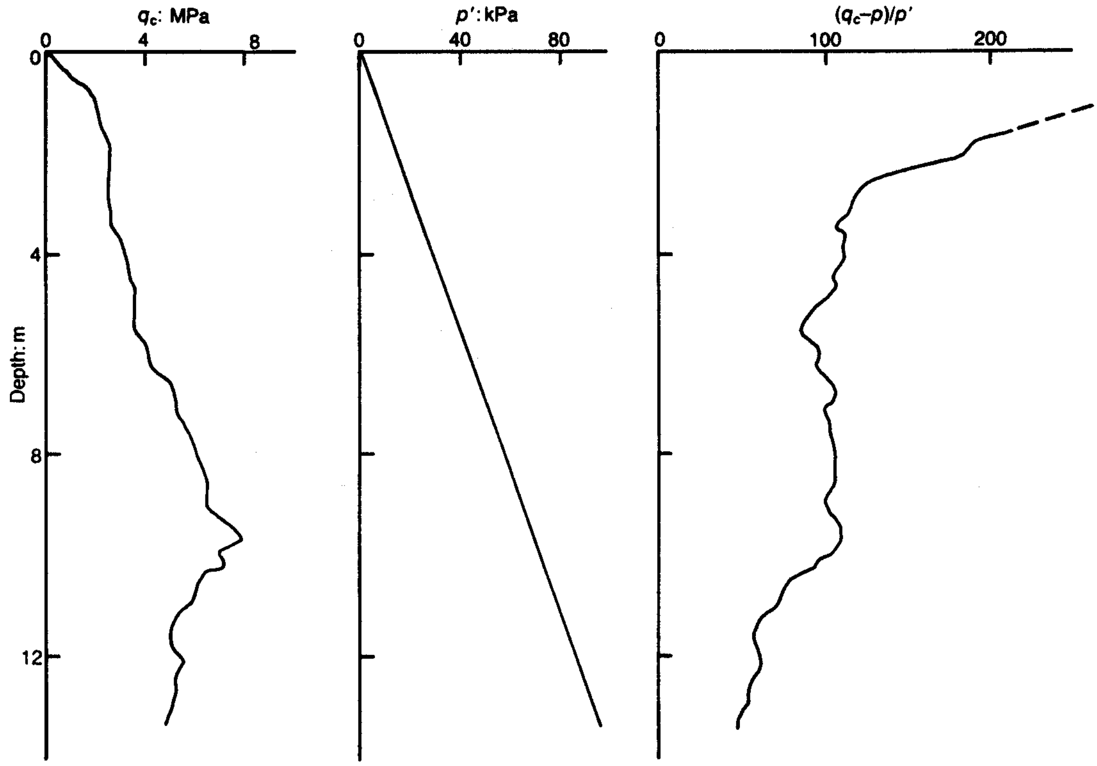

Fig. 8. Profiles of mean q_c, $(q_c - p)/p'$ and p' in Nerlerk sand at Nerlerk. This sand was involved in 5 major flow slides. Data replotted from Sladen *et al.* (1985b)

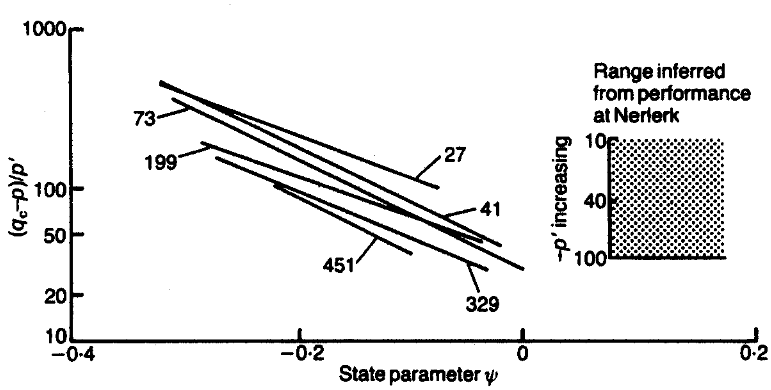

Fig. 9. Normalized tip resistance versus state inferred from the Nerlerk slides. Mean effective stress was higher for lower values of normalized tip resistance; values of p' corresponding to the various values of $(q_c - p)/p'$ are shown at side of shaded box. Also shown for comparison are the relationships developed for the Ticino sand, Fig. 5

In Fig. 9, the state of the Nerlerk sand inferred from the failures and CPT data is compared with the CPT–state relationships derived for the Ticino sand. The same trend of reducing normalized tip resistance with increasing mean stress is evident. The data cannot be compared directly as no Ticino sand data with positive state parameter are available. In general, however, for a given mean stress higher values of normalized tip resistance are implied for the Nerlerk case history for a given mean stress than for Ticino sand. This is in no way surprising. There is no reason to expect different sands to exhibit similar values of the parameter k, as is illustrated by the mean lines for various sands in Fig. 2.

There is also no evidence that linear regression lines for the Ticino sand can be extrapolated into the positive state parameter domain. Further it may be that the values of k for the Ticino sand are too low if a systematic error in the determination of the steady state line has been introduced. There are other potential uncertainties in the application of chamber test data to the evaluation of in situ conditions.

CONCLUSIONS

The following conclusions can be drawn from the points considered.

(*a*) There is an approximately unique relationship between q_c, void ratio and p' for a given sand in chamber tests; a mean relationship can predict void ratio for a given q_c and p' within about $\pm 0{\cdot}05$, provided sufficient chamber test data are available for the sand.

(*b*) A unique relationship does not exist between normalized CPT tip resistance and state parameter, rather the relationship varies significantly and systematically with stress level. Even allowing for variations in stress level there is scatter in the experimental data.

(*c*) There is currently no reliable way of comparing chamber test data for one sand to field situations for a different sand.

(*d*) At the present state-of-the-art any correlation between CPT tip resistance and sand state should be treated with caution. The use of some previously published correlations could in some circumstances be potentially catastrophic. Particular care should be exercised before extrapolating from the existing data base.

(*e*) If a unique mean relationship between normalized tip resistance and state parameter were assumed in design analysis, an error in the assessment of in situ void ratio of more than 0·2, that is more than 50% in terms of relative density, could not confidently be ruled out.

These conclusions may appear to be negative. However, they show that there is a pressing need to develop reliable methods of interpreting sand state from in situ tests. In these circumstances there is a natural tendency uncritically to adopt apparently simple solutions to a complex problem. It is hoped that the Paper will stimulate a renewed research effort. Opportunities to compare field and laboratory conditions, in particular, should be vigorously pursued. While the CPT is ideal for providing a qualitative profile in variable deposits, it may be that future research should be directed towards other tools, better suited to provide more direct quantitative measures of in situ density, such as advanced samplers or nuclear methods.

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