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Detection of liquefiable sand layers by means of quasi-static penetration tests

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1 INTRODUCTION

This paper presents a contribution on the use of Dutch Cone Penetration Test (DCPT) and Flat Dilatometer Penetration Test (DMT) for detecting and evaluating liquefiable sand layers.

2 BACKGROUND

It has been pointed out by many researchers (e.g.Seed 1979,Lambrechts & Leonards 1978, Schmertmann 1978) that:

a. The resistance to liquefaction increases with relative density (D_r),in situ K_o, cementation,aging,prestressing,stiffer packing etc.

b. The factors listed in a. also increase soil stiffness.

c. The factors listed in a. also increase penetration resistance.

By combination of a. and c. various researchers concluded that "at least some useful degree of correlation" should exist between factor of safety against liquefaction and penetration resistance.

The direct use of penetration resistance to evaluate resistance to liquefaction can only be of an approximate nature,due to the not completely understood yet influence of each of the factors listed in a. on liquefaction properties and on penetration resistance.For similar reasons the "correlation error" of such correlations is still difficult to evaluate at present.Some partial considerations of some usefulness are however possible.For instance the "measurement error" (which sums up with the "correlation error")should not be excessive,i.e.the measurement should be reproducible.For example, Standard Penetration Test (SPT) N-values "are known to have a poor reproducibility and great variability between different operators and equipment,which can easily change N by 100%,resulting in equal changes in the interpreted factor of safety against liquefaction"(Schmertmann 1978).

DCPT(Baligh et al.1980) and DMT (see Fig.2 later in the paper) exhibit much better reproducibility and,from this point of view, are better suited for correlations with resistance to liquefaction.

Another important prerequisite of a penetration parameter for the use discussed here is its sensitivity to all factors listed in a.,known to affect liquefaction behaviour. The sensitivity of penetration resistance (e.g.Cone Resistance q_c or N_{SPT}) to factors such as in situ K_o and D_r is well documented. However the influence of other factors is less clear and less documented.One of these factors is prestressing.A major objective of the tests described in this paper was to study the influence of prestressing on penetration parameters.

3 LAMBRECHTS & LEONARDS EXPERIMENTS

This section summarizes tests performed by Lambrechts and Leonards (1978) that enabled these authors to formulate some evaluations on sensitivity of q_c to prestressing.

a. Two triaxial sand specimens were prepared and consolidated along the K_o line (path OP in Fig.1).

b.The second specimen was prestressed along the K_o line (path PM and back MP). After this prestress cycle both specimens were subjected to the same state of stress (point P in Fig.1),the only difference being that specimen No.2 had been prestressed.

c.The subsequent initial moduli were determined on both specimens,by a small increase of axial stress.

d.Both specimens were penetrated with a model cone,with σ_v and σ_h constant (point P in Fig.1) and the Cone Resistance q_c was measured.

Lambrechts and Leonards found that K_o prestressing to a "prestress ratio" (ratio between stresses at point M and point P) in

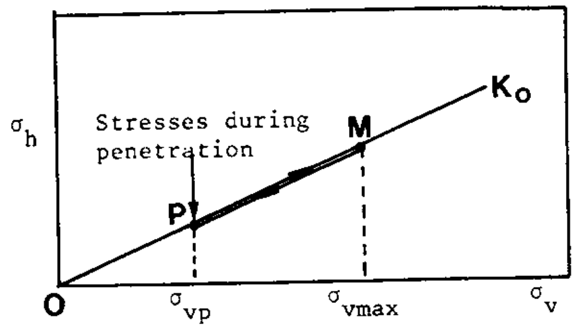

Fig.1 K_o prestressing along the K_o line (σ_{vp}=value of σ_v during penetration - σ_{vmax}=max σ_v reached during prestressing)

the range 2 to 3 increased by one order of magnitude the modulus of specimen No.2.However q_c in specimen No.2 was only slightly higher than in specimen No.1. Note that path PMP represents "pure" prestressing.The term"pure" is used to emphasize the distinction between this kind of prestressing and overconsolidation in nature due to erosion, causing,besides "pure" prestressing,an increase of horizontal stress.

Lambrechts and Leonards concluded that "increase in q_c after prestressing of a sand is due largely to the residual lateral stress.Prestraining,without residual lateral stress,has only a minor effect on q_c".

A possible explanation of q_c being an inadequate revealer of "pure" prestressing is that the improvement of the stress-strain curve due to prestressing is most notable in the early portion of the curve.This improvement may be not felt by q_c because the strains in the soil surrounding the Cone are higher than those at which the stiffening effect of prestressing is significant.

The Flat Dilatometer advances in the soil producing distorsions that various evidence suggests lower (Marchetti 1981) than those produced by conical tips.This poses the question whether DMT results (specifically the index K_D discussed in the next section) are more sensitive to "pure" prestressing.

4 HORIZONTAL STRESS INDEX K_D BY FLAT DILATOMETER

This section covers definitions and comments concerning K_D.

The Flat Dilatometer (Marchetti 1980) basically provides:

a. The horizontal total soil pressure p_o against the vertical side of the blade at the end of each penetration interval.This pressure p_o is larger than the original σ_h due to the insertion.The pressure p_o,normalized to σ'_v ,provides the "horizontal stress index" K_D,defined as follows

$$K_D = (p_o-u_o) / \sigma'_v$$

u_o is the pre-insertion porewater pressure (unaltered by the insertion in freely draining sands,the only sands considered in this paper).The index K_D is dimensionless and, for comparative purposes,more convenient to use than p_o.In dry sand the previous equation reduces to $K_D=p_o/\sigma_v$.

b.A modulus E_D inferred via the theory of elasticity from the pressure increment on the back of the flexible steel membrane (initially flush with the vertical side of the blade)required to move its center 1 mm against the soil (Eq.4 in Marchetti 1980).

In the field both p_o and E_D are measured at close depth intervals,usually 20 cm,obtaining a nearly continuous profile.

Fig.2 illustrates the high reproducibility of K_D(a few percent).The readings were taken in two soundings,a few meters apart, by four different operators (Cestari,Lacasse,Lunne and the writer) alternating with each other.

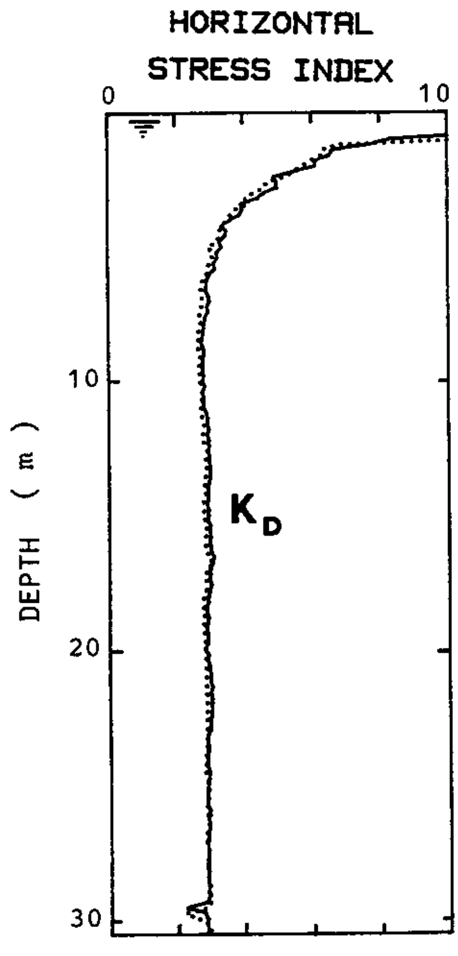

Fig.2 Reproducibility of K_D profiles (Onsøy,Norway)

Note that the K_D profiles in Fig.2 were obtained in clays,and are shown here only to illustrate reproducibility.(Only clay deposits can be so homogeneous that differences in two profiles may be attributed to imperfect reproducibility rather than to soil non-homogeneity).

Interestingly,the high reproducibility illustrated by Fig.2 is obtained with the current mechanical Dilatometer.The measurement of p_o by an electronic transducer would be an obvious alternative.However,in the writer's opinion,the (illusory) increase in resolution would not be worth the deterioration of the overriding feature "If a reading can be taken,this can only be the correct reading" that the mechanical Dilatometer possesses at present to a quite satisfactory degree.

5 TESTS WITH THE DILATOMETER IN THE CALIBRATION CHAMBER

"Two-stage" calibration tests with the Dilatometer were performed on dry sand specimens,both in the University of Florida and in the Enel-Milano calibration chambers. The qualification "two-stage" refers here to the penetration,arrested at mid-height of the specimen (first stage),then resumed and completed (second stage) after prestressing the specimen.The test procedure was the following.

a.Pluvial deposition of the specimen (dry).

b.Application of a NC K_o state of stress, path OP in Fig.1 (for all tests reported in this paper it was assumed K_o=0.45).

c.Penetration of the upper half of the specimen with the Dilatometer,at 10 cm depth intervals.

d.Application of a prestress cycle along path PM and back MP in Fig.1.After this prestress cycle σ_v and σ_h were both identical to those applied during the penetration of the upper half of the specimen,the only difference being that the lower half had been prestressed.

e.Completion of the penetration in the lower half of the specimen.

Since the boundary stresses σ_v and σ_h were the same during both stages of penetration, the midheight discontinuity of the DMT profiles reflects theoretically only the effects of prestressing.

Various information concerning the four chamber tests is summarized in Table 1.

Figs.4 to 7 show chamber test results in terms of the already mentioned "Dilatometer modulus" E_D,horizontal stress index K_D and of the constrained tangent modulus $M=1/m_v$ interpreted from E_D and K_D using Fig.13a or Eq.9 in Marchetti 1980.

Table 1. General information on the four chamber tests with the Dilatometer.

Test No.	Chamber	Sand	D_r %	Prestress σ_{vm}/σ_{vp} ††	I_D†
FL 1	Univers. Florida	Reid Bedford	26	2	2 to 3.5
MI 1	Enel Milano	Ticino Sand	54	3	~3
MI 2	Enel Milano	Ticino Sand	15	3	2.5 to 4.5
MI 3	Enel Milano	Ticino Sand	15	1.3 10 cycles	3 to 4.5

†I_D=Material Index (see p.303 and 312 of Marchetti 1980).

†† For all four specimens σ_{vp}= 1 bar,σ_{hp}=.45bar

1 bar=100 kPa=1.02 Kg/sqcm=1.044 tsf

The discontinuities of the DMT profiles should be examined in correspondance of the horizontal dashed line at mid-height of the chamber (i.e.at some distance from the top and bottom of the specimen) where "plateau" values are observed (Fig.3) when normal one-stage tests are performed.

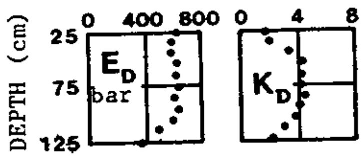

Fig.3 Typical profiles of E_D and K_D from normal (one-stage) DMT performed in the calibration chamber (Bellotti et al.1979)

5 RESULTS

Test FL1 (D_r=26%,Fig.4)

The most notable result is the significant increase of K_D after prestressing.A "prestress ratio" of two was reflected by an approximately twofold increase in K_D.

Another feature,somewhat unexpected,was the lack of increase in E_D despite the sure increase (not measured in these tests) in specimen stiffness caused by prestressing.

The constrained tangent modulus M,interpre-

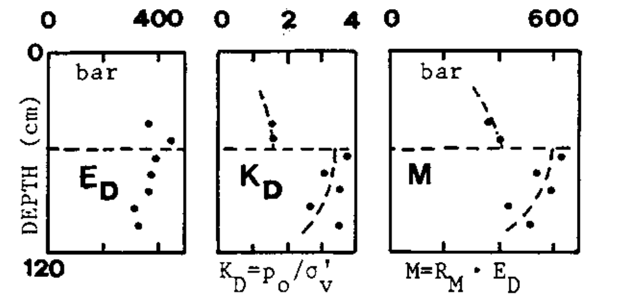

Fig.4 Effects of prestressing on DMT results. Chamber Test No.FL1,D_r=26%,Prestress ratio=2.

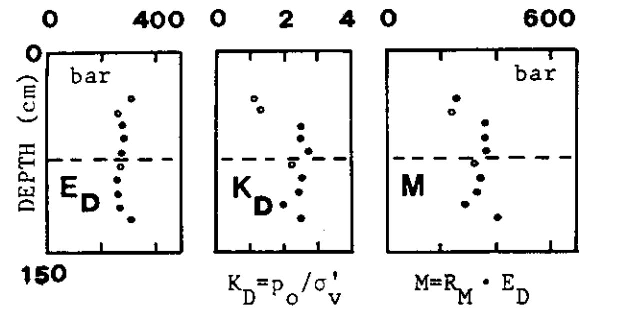

Fig.5 Effects of prestressing on DMT results. Chamber Test No.MI1,D_r=54%,Prestress ratio=3.

ted from E_D and K_D,increased considerably (this M increase is discussed later in section 7h.)

An interpretation of these results is offered hereunder.

Lack of increase of E_D.The distorsions caused by the advancing Dilatometer are still sufficient to "obliterate" the benefits of prestressing in the bulb of soil facing the membrane,leading to the same E_D when this bulb is loaded by the expanding membrane.

Sensitivity of K_D.The blade penetration is contrasted by virgin soil.The penetration mechanism is profoundly different from a "bearing capacity" type of failure (instead an advancing Cone,as noted by Schmertmann 1975:83,"shows the failure as primarily a compressibility-displacement,concentrated in the zone immediately below the Cone point"). The penetration of the Dilatometer resembles more to the opening of a fissure in the soil.The two sides of the fissure,pushed apart, induce strains in a relatively large volume of soil.Thus the pressure p_o opposed by the soil is determined even by elements far from the probe,where the strain level is low and the benefits of prestressing appreciable.

Another aspect to consider is that,when the two sides of the fissure are pushed apart,the "propensity" or "reluctance" of the sand to decrease in volume,for accomodating the probe,certainly play an important role in building up p_o.If the sand is "propense" to decrease in volume,p_o will be small and viceversa.Thus p_o would reflect sand resistance to a volume decrease.Since such sand resistance is very much related with resistance to liquefaction,this interpretation seems to support the use of p_o (or K_D) as an index of resistance to liquefaction.

Test MI1 (D_r=54%,Fig.5)
In this specimen,considerably denser than the previous one,K_D did not reflect prestressing. Apparently in this denser sand relatively few grains were ready to move into more stable positions and the less significant benefits of prestressing were not appreciated by the Dilatometer.(Note : the insensitivity of q_c to prestressing pointed out by Lambrechts and Leonards was noted on D_r=57% specimens. Cone resistance too might be more sensitive to prestressing at lower D_r.Unfortunately data of this type seem unavailable at present).

Test MI2 (D_r=15%,Fig.6)
In this quite loose specimen the "prestress ratio" equal to three was reflected by an approximately threefold increase in K_D,i.e. the "responsiveness" of K_D to prestressing was approximately one to one,as for test FL1. In test MI2 even E_D showed an appreciable increase.This increase may be due partly to the presumably higher benefits of prestressing in very loose sand,partly to the larger scatter of the profiles in loose sand.Incidentally,the lack of regularity of the K_D profiles suggests a significant nonhomogeneity of the supposedly homogeneous specimens (Fig.2 shows that when the soil is homogeneous,K_d is very continuous).

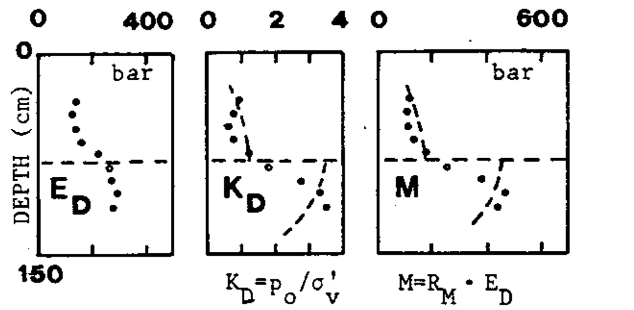

Fig.6 Effects of prestressing on DMT results. Chamber Test No.MI2,D_r=15%,Prestress ratio=3.

Test MI3 (D_r=15%,Fig.7)
This test differs from the previous one only in that the "treatment" on the specimen,

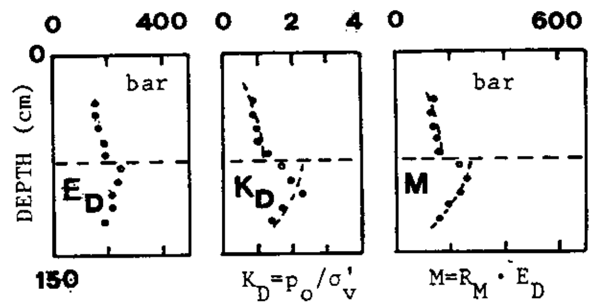

Fig.7 Effects of cyclic prestressing on DMT results.Chamber Test No.MI3,D_r=15%. Ten cycles of prestressing to prestress ratio=1.3

before penetrating the lower half,consisted in ten cycles of K_o prestressing,between σ_{vp}= 1 bar and σ_{vm}=1.3 bar.The effects of cyclic loading on E_D,K_D and M are similar to (though less marked than) the effects of prestressing.The increase in K_D caused by this type of cyclic loading was approximately twofold.It may be noted that the "pre-treatment" value of K_D approximately repeats the value 1.2 observed at the end of the first stage of test MI2 (before the second stage the two tests were identical).

7 ADDITIONAL COMMENTS

a. A previous series of chamber tests (Bellotti et al.1979) showed that an increase of K_o is reflected quite sensitively by K_D.In those tests,a multiplication factor applied to K_o was reflected by an increase by a similar factor in K_D.

b.The values of K_D observed in the previous series,in conjunction with the pre-treatment "NC" values of K_D reported in this paper, permit to evaluate the law of increase of K_D with D_r-only in NC specimens.

Table 2. Increase of K_D with D_r-only in NC triaxial specimens.

Source	D_r%	K_D
Tests MI2 & MI3 reported in this paper	15	1.2
Test FL1 reported in this paper	26	1.55
Test MI1 reported in this paper	54	2.5
Bellotti et al.1979 Tests Nos 43,44 and 47	65 to 70	4 to 4.5

These data are derived from tests on three different sand types,yet they appear quite consistent and illustrate clearly how considerably K_D increases with D_r.

c.Since K_D is sensitive to K_o,prestressing, D_r,cyclic loading,it is expectable that K_D is also sensitive to aging and vibrations, considering the similar effects produced. Cementation has also been observed to produce abnormally high K_D values (Marchetti 1978,though those results were observed in OC clays).

d.In conclusion K_D seems a sensitive revealer of the cumulative effect of the parameters listed in 2a. Note that a high K_D, though indicative of a high combined effect of factors such as D_r,in situ K_o,prestressing, possibly cementation etc.,does not permit in general to identify the responsibility of each factor.However a high K_D is generally beneficial,in liquefaction (or settlement) problems,regardless of its cause.On the other hand a low K_D indicates that none of the beneficial factors has acted (i.e.the sand is loose,uncemented,in a low horizontal stress environment etc.) so that the sand will settle considerably under vertical loads and may be a source of liquefaction problems.

e.Probably the most reliable way of establishing and evaluating correlations K_D vs resistance to liquefaction is the accumulation of K_D profiles in natural sands well documented from the liquefaction behaviour point of view.In fact various calibration chamber artifacts (different boundary conditions,different texture for a given D_r, dry vs submerged deposition etc.) render unjustified the direct transposition of chamber test results to natural sands.Indeed natural submerged sands with D_r=60 to 70% typically exhibit $K_D \simeq 1.5$,whereas chamber specimens deposited at similar D_r exhibit K_D=3 to 4.

f.The DMTs performed sofar in natural sands (with D_r estimates based on SPT or DCPT) have provided the following broad indications:

- In NC sands deposited underwater,with estimated D_r=60 to 70%,typically $K_D \simeq 1.5$
- In very loose sands (with estimated $D_r \simeq 20\%$),values of K_D as low as 0.6 are observed (K_D=0.6 is the minimum value observed sofar,after tens of tests in sand formations).

Thus,when K_D<1.5-1.6,the D_r is likely to be less than 60-70% and the sand may be a source of liquefaction problems.Incidentally, were these numbers combined with published correlations of Resistance to Liquefaction τ_{dy}/σ'_{vo} vs D_r,such as Fig.3 of Vaid et al. 1981,one would obtain $\tau_{dy}/\sigma'_{vo} \simeq K_D/10$.

g.An example of profile of K_D clearly pointing out a layer,source of potential liquefaction problems,is shown in Fig.8.These DMT results were obtained at a research site

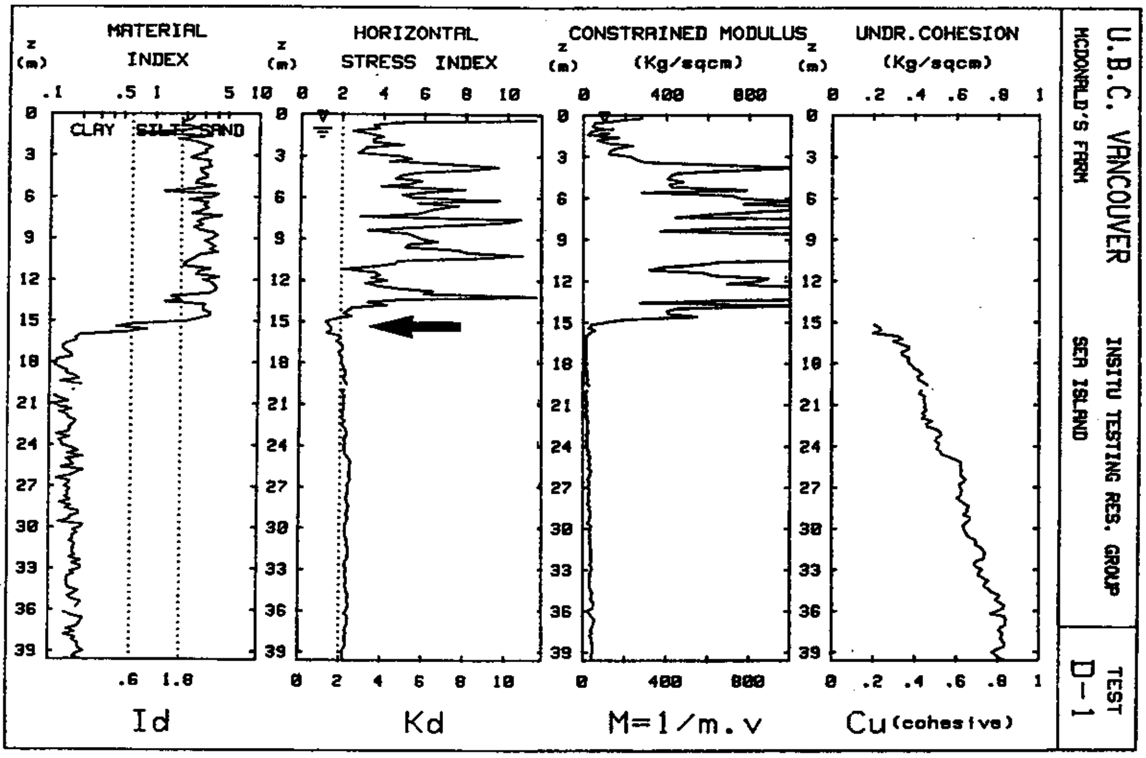

Fig.8 Results and interpreted parameters by DMT at Vancouver International Airport

near Vancouver, in cooperation with the University of British Columbia. The soil consists of approximately 15 m of sand, followed by NC clayey silt for more than 200m. The reader may note in Fig.8 the large difference in the interpreted constrained modulus M in the sand and in the clay, and the linear increase of the interpreted c_u in the clay. The K_D profile clearly points out the presence of a layer exhibiting a low K_D at approximately 15 m depth, suggesting that, in this layer, the resistance to liquefaction reaches a minimum. Fig.9 shows DCPT profiles of the friction resistance f_s and of q_c at the same site. At 15 m depth the friction resistance too exhibits a minimum, though the message is less clear than in the K_D profile (Note: f_s is proportional, in principle, to p_o-u_o). The same message is visible, though almost completely blurred, in the q_c profile.

h. The relative insensitivity of E_D to prestressing previously noted and the sensitivity of K_D to various agent, as discussed in section 7d., suggests an explanation of the empirically established correlation M vs E_D in the form $M=R_M \cdot E_D$, where the empirical factor R_M was found to increase with K_D (Fig.13a in Marchetti 1980). As already discussed, the distorsions due to penetration

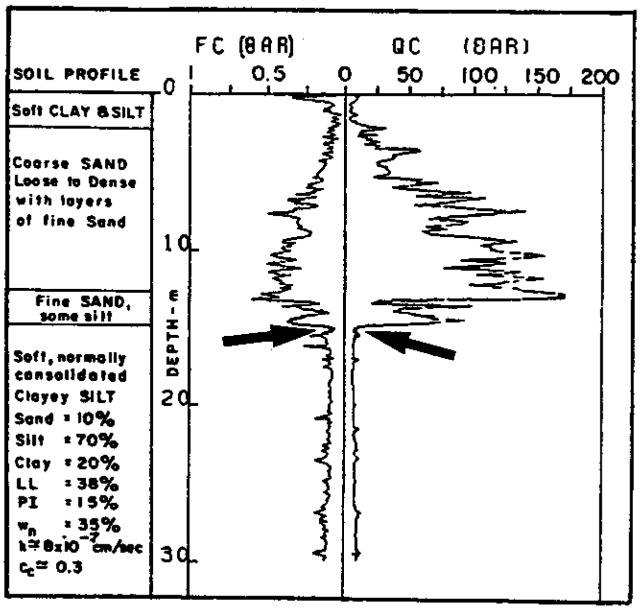

Fig.9 Soil profile and DCPT profiles of q_c and f_s at Vancouver International Airport

tend to obliterate, in the bulb of soil facing the membrane, the effects of prestressing, cyclic loading and presumably cementation, aging etc, which have improved the modulus but are not reflected by E_D. On the other hand the effects of these agents are caught up by K_D. Therefore to multiply E_D by R_M is a way of compensating the modulus deterioration due to the insertion. The higher K_D, the higher the deterioration. But the higher K_D, the higher will be the compensating factor R_M read from Fig.13a in Marchetti 1980. Note that, according to this figure, when K_D is very low (loose sand), R_M is less than 1. Indeed, in loose sand, the penetration may improve, rather than deteriorate, the modulus, explaining for these sands a compensating factor less than 1.

8 CONCLUSIONS

a. The results presented in this paper indicate that, in loose sands, the parameter K_D determined by DMT detects sensitively the effects of prestressing and cyclic loading, factors not easily detectable by other methods and having significant influence on liquefaction behaviour.

b. More in general K_D reflects quite sensitively D_r, in situ K_o, cyclic loading, prestressing and presumably cementation, aging and vibrations. When K_D is high, the cumulative effect of the reflected factors is high, though from the value of K_D alone it may not be possible to identify the individual responsibility of each factor. On the other hand, when K_D is low, then none of these factors has acted, i.e. the sand is loose, uncemented, in a low horizontal stress environment etc. and may be a source of liquefaction problems.

c. Besides sensitivity, K_D exhibits high resolution and reproducibility. Moreover its determination is fast and simple.

d. The results presented in this paper suggest that K_D is a parameter well suited for correlations with the safety factor against liquefaction.

e. The data available to the writer suggest that natural submerged sands having $K_D < 1.5$-1.6 are likely to have $D_r < 60$-70% and the liquefaction risk should be considered. The accumulation of K_D profiles in sands well documented from the liquefaction behaviour point of view is necessary for further evaluating and developing correlations and methods.

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