# THE FLAT PLATE DILATOMETER TEST
# FOR LIQUEFACTION ASSESSMENT

by

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The Flat Plate Dilatometer Test (DMT) was developed in Italy by S. Marchetti (1980). The dilatometer is a flat plate 14 mm thick, 95 mm wide by 220 mm in length. A flexible stainless steel membrane 60 mm in diameter is located on one face of the blade. Beneath the membrane is a measuring device which turns a buzzer off in the control box at the surface when the membrane starts to lift off the sensing disc and turns a buzzer on again after a deflection of 1 mm at the centre of the membrane. Readings are made every 20 cm in depth. The membrane is inflated using high pressure nitrogen gas supplied by a tube pre-threaded through the rods. As the membrane is inflated, the pressures required to just lift the membrane off the sensing disc (reading A), and to cause 1 mm deflection at the centre of the membrane (reading B), are recorded. Readings are made from a pressure gauge in the control box and entered on a standard data form. Full details of the test procedure are given in the Dilatometer Users Manual (Marchetti and Crapps, 1981).

The dilatometer is pushed into the ground at a constant rate of penetration of 2 cm/sec. Before and after each sounding the dilatometer is calibrated for membrane stiffness.

The dilatometer data (readings A and B) are corrected for offset in the measuring gauge and for membrane stiffness. Another small correction is required because of the configuration of the measuring system. A full discussion on corrections is given by Marchetti and Crapps (1981). Simplified expressions for the corrected data are:

$$P_o = A + \Delta A$$

$$P_1 = B - \Delta B \; .$$

$\Delta A$ is the vacuum required to keep the membrane in contact with its seating, since after several readings the membrane acquires a permanent outward curvature. $\Delta B$ is the air pressure required to cause a 1 mm deflection in free air.

Using the $P_o$ and $P_1$ the following three index parameters were proposed by Marchetti:

$$I_d = \frac{(P_1 - P_o)}{P_o - u_o} = \text{Material Index}$$

$$K_d = \frac{P_o - u_o}{\sigma'_{vo}} = \text{Horizontal Stress Index}$$

$$E_d = 34.6\ (P_1 - P_o) = \text{Dilatometer Modulus.}$$

where $u_o$ is the assumed in-situ hydrostatic water pressure and $\sigma'_{vo}$ is the in-situ vertical effective stress. The data is reduced using a computer program supplied with the instrument. Computer graphics facilities are used to generate the completed plots. An example of DMT results analysed and displayed by the computer are shown in Fig. 1.

The dilatometer equipment is extremely simple to operate and maintain. The simplicity and low initial cost of the equipment is one of the main advantages of the flat plate dilatometer as an in-situ test method.

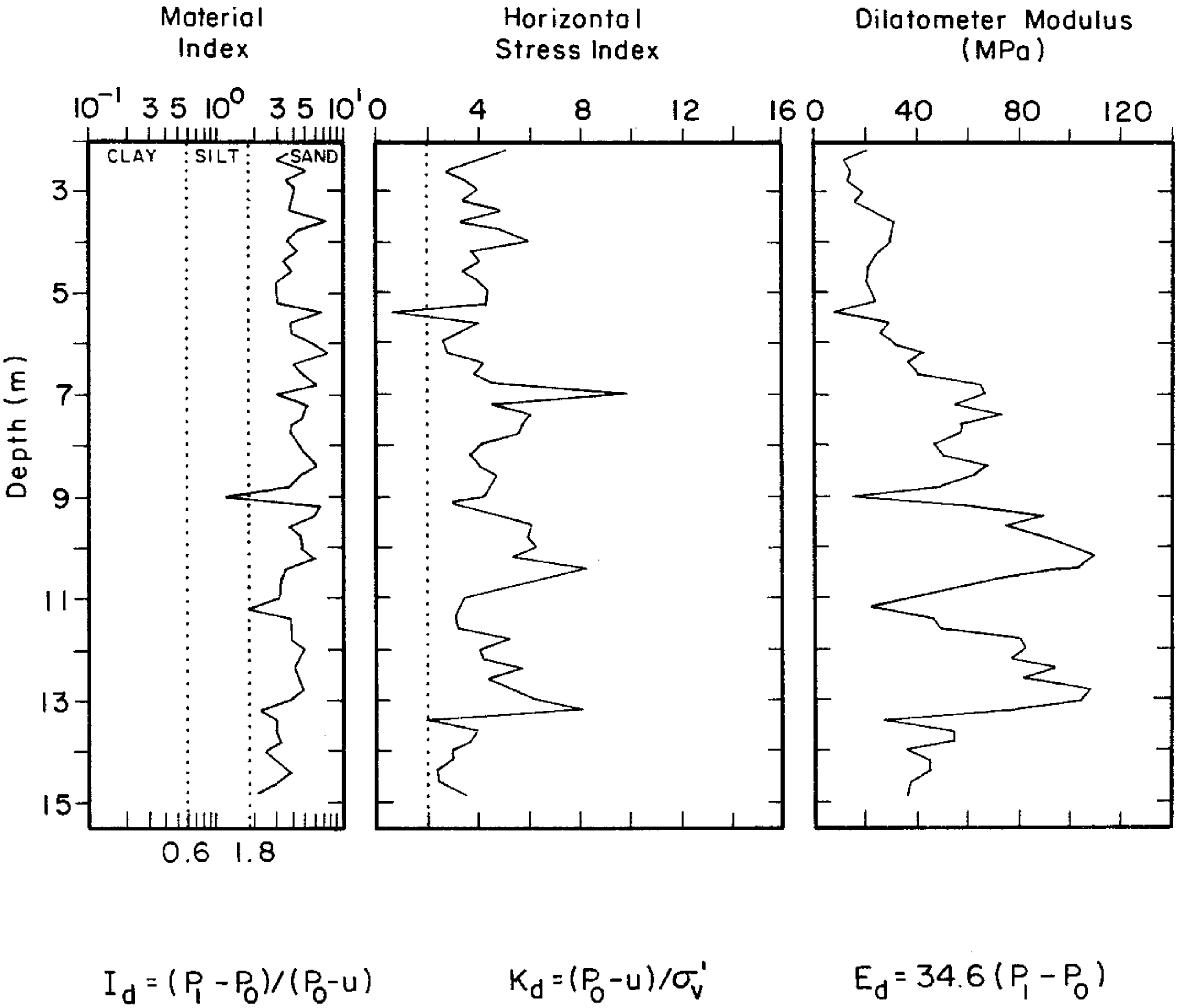

Figure 1. Typical DMT Index Parameters, McDonald's Farm Site, B.C.

Marchetti performed DMT at about 10 well documented sites in Italy and developed empirical correlations based on these results. Correlations were developed between the three index parameters, $I_d$, $K_d$ and $E_d$ and soil type, soil unit weight, $K_o$, OCR, undrained shear strength, constrained modulus and friction angle. All of the soil parameters were obtained from laboratory test results. The majority of the sites consisted of clay deposits with only two sites involving sand. At both sand sites the sand was very loose with relative densities around 30 to 40%. Details of the sites and the empirical correlations are given by Marchetti (1980).

The interpretation of the DMT results centers around the three index parameters, $I_d$, $K_d$ and $E_d$. The parameters, $I_d$ and $K_d$ require a knowledge of the in-situ water pressure ($u_o$) before penetration and the in-situ vertical effective stress ($\sigma'_{vo}$). The in-situ water pressure is assumed to be hydrostatic and the only data required is the depth to the ground water level. The in-situ vertical effective stress ($\sigma'_{vo}$) is calculated using soil unit weights obtained from an empirical correlation using $I_d$ and $E_d$ and using the assumed hydrostatic water pressure.

The correlations proposed by Marchetti (1980) were based on a limited amount of data. In his closure to his 1980 ASCE paper, Marchetti suggested that "the data base for all the correlations discussed in the paper will expand with the expanding use of the dilatometer test". Unfortunately, the writers believe that the development of the computer program to analyse and interpret the DMT results has tended to restrict the user and discourage improvements or modifications to the existing correlations as more experience is gained with the test. However, this problem will likely be minimized in the future with the recent addition of Dilatometer Digests by GPE Inc. which includes program updates.

## Liquefaction Assessment

Marchetti (1982) suggested that the horizontal stress index, $K_d$, could be used as a parameter to assess the liquefaction resistance of sands. $K_d$ appears to reflect the following soil variables:

i) Relative density, $D_r$;

ii) in-situ stresses, $K_o$;

iii) stress history and pre-stressing;

iv) aging;

v) cementation.

However, it is not possible to identify the individual responsibility of each variable. On the other hand, when $K_d$ is low, none of these variables is high, i.e. the sand is loose, uncemented, in a low horizontal stress environment and has little stress history. A sand under these conditions may be a liquefaction problem. Marchetti (1982) suggested a tentative correlation between the cyclic stress ratio to cause liquefaction $(\tau_\ell/\sigma'_{vo})$ and horizontal stress index, $K_d$, as follows,

$$\frac{\tau_\ell}{\sigma'_{vo}} = \frac{K_d}{10} \qquad \text{Marchetti (1982)} \qquad (1)$$

Chamber test results in sand (Bellotti et al., 1979 & Marchetti, 1982) using the DMT show that the horizontal stress index parameter, $K_d$, is related to relative density for normally consolidated ($K_o \simeq 0.40$), uncemented sand. Results presented by Bellotti et al. (1979) and Marchetti (1982) are shown in Fig. 2. Results from two sites presented by Marchetti in his ASCE 1980 paper are also included in Fig. 2. The relative density

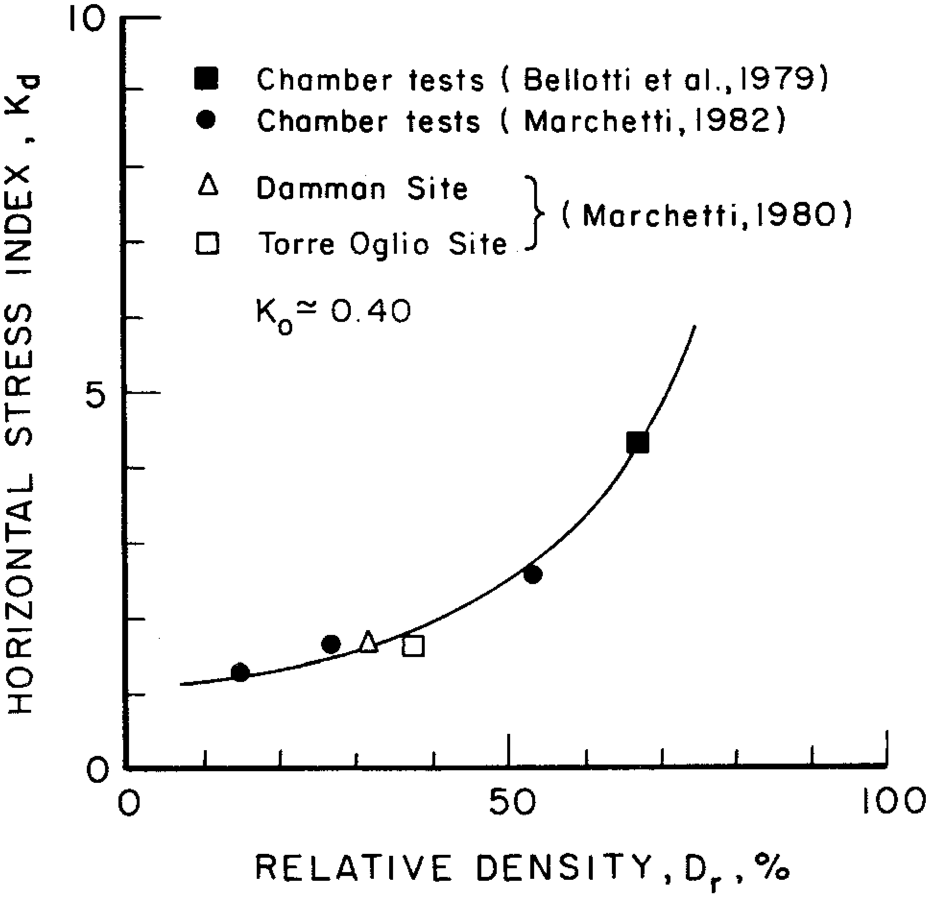

Figure 2. Correlation between Horizontal Stress Index from DMT and Relative Density for Normally Consolidated, Uncemented Sand.

values of the sand deposits presented by Marchetti (1980) were estimated by the writers using available CPT data.

If the relationship shown in Fig. 2 is combined with the field liquefaction resistance data produced by Christian and Swiger (1975) a liquefaction correlation with the DMT can be developed and is shown in Fig. 3. The liquefaction resistance curve by Christian and Swiger (1975) was chosen because it appears to represent quite closely the observed field liquefaction behaviour. The correlation proposed in Fig. 3 would predict cyclic stress ratios significantly lower than those predicted using the formula proposed by Marchetti (Equation 1).

Marchetti (1982) has shown that $K_d$ appears to increase with increases in $K_o$, aging, cementation, and stress history. Experience has shown that the liquefaction resistance also increases with these factors. Although the correlation shown in Fig. 3 is based on a $K_d$ - Dr relationship for normally consolidated, uncemented sands any increase in the above factors will produce an increase in apparent density and thus be reflected by an increase in liquefaction resistance.

The correlation proposed in Fig. 3 for DMT data is based on limited empirical data and requires considerable field verification. The DMT based method in Fig. 3 should be used in the same manner proposed by Seed et al. (1983) for the SPT based method. However, the DMT data does not require modification for in-situ effective overburden pressure since this is accounted for in the $K_d$ parameter.

The correlation shown in Fig. 3 is only applicable for testing in sands where penetration and expansion occur under drained conditions. Testing in silty sands or silts may generate significant pore pressures which would influence the measured $K_d$ values.

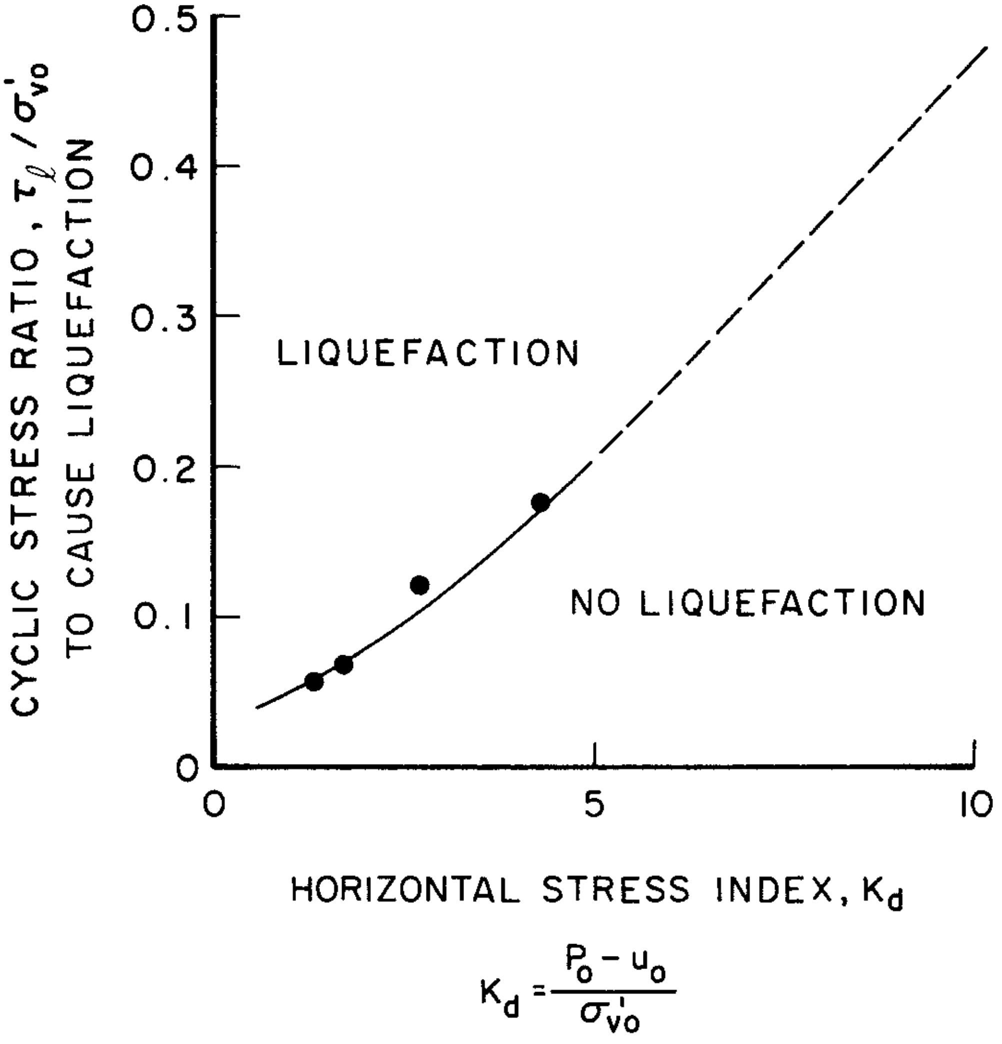

Figure 3. Proposed Correlation between Liquefaction Resistance Under Level Ground Conditions and Dilatometer Horizontal Stress Index for Sands.

## Preliminary Evaluation of Proposed DMT Correlation

To evaluate the proposed DMT liquefaction assessment curve shown in Fig. 3 data was obtained at the University of British Columbia (UBC) research site for in-situ testing near Vancouver International Airport. The site (McDonalds Farm) is located on the north side of Sea Island on Ministry of Transport, Canada land near the Municipality of Richmond. Sea Island is located between the North Arm and Middle Arm of the Fraser River on the north side of the main Fraser River Delta. The site is approximately level with the natural ground at elevation +1.6 m. Sea Island is contained by a system of dykes to protect against flooding from the Fraser River.

A summary of the soil profile based on sampling, laboratory and cone penetration testing (CPT) is shown in Fig. 4. The upper 2 m of soil consists of soft, compressible clays and silts. The sand from 2 m to 13 m was deposited in a turbulent environment and is therefore relatively non-uniform in density. In general however, the sand increases in density with depth as indicated by the constant relative density relationship by Baldi et al., 1982. The sand has medium to coarse grain sizes with thin layers of medium to fine sand and some lenses of silty sand. A thin transition layer of fine sand with some silt exists from 13 m to 15 m.

The sand is underlain by a thick deposit of soft, normally consolidated clayey silt. The clayey silt is estimated to extend to a depth of more than 300 m.

Groundwater is approximately 1 m below existing ground surface and groundwater pressures are approximately hydrostatic to the depth shown in Fig. 4.

A field and laboratory study was performed that included Cone

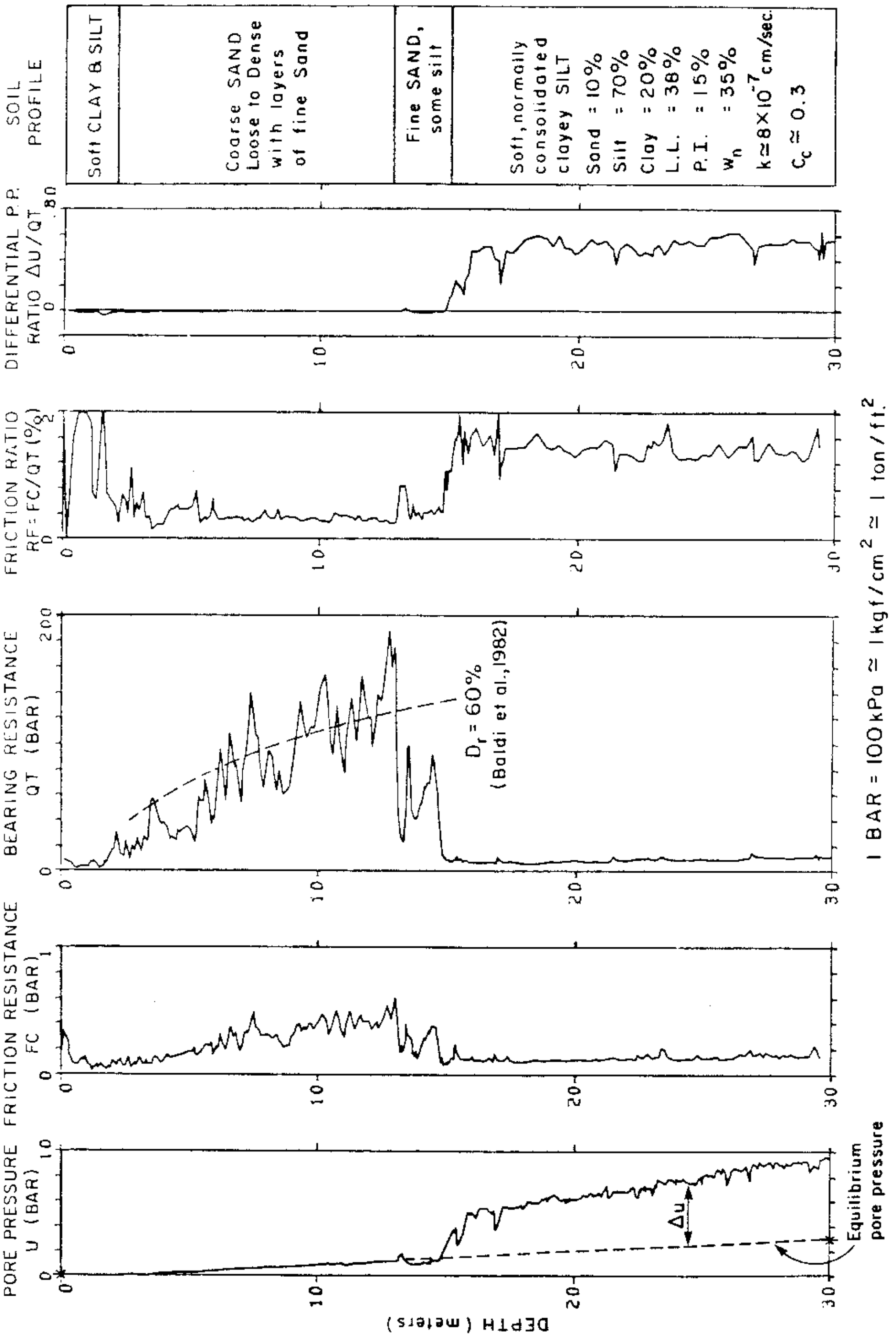

Figure 4. Soil Profile for Research Site at McDonald's Farm, B.C.

Penetration Tests (CPT), Standard Penetration Tests (SPT) and undisturbed sampling using a 86 mm I.D. (3-3/8 inch), thin walled, fixed piston sample tube. Laboratory cyclic triaxial tests were performed on the undisturbed samples.

The relative density of the sand at the research site (McDonald's Farm) was estimated from the DMT data using the correlation shown in Fig. 2. Densities predicted by the DMT and those measured from the samples in the laboratory are compared in Fig. 5. The DMT data appears to have predicted an average relative density around 70%, with a maximum of close to 10%. The CPT (Fig. 4) and laboratory data indicate a relative density of about 40% at a depth of 4 m rising to about 60% at a depth of 12 m.

The relationship between relative density and horizontal stress index, $K_d$, shown in Fig. 2 was based predominantly on data from chamber tests studies using Ticino sand. The grain characteristics (i.e. grain shape, size and mineralogy) of the Ticino sand is very similar to the sand at McDonald's Farm. Thus, a reasonable agreement would be expected. However, the dilatometer $K_d$ is more sensitive to changes in in-situ horizontal stress conditions than is cone penetration resistance. Therefore, the slightly higher relative density predictions from the DMT may be a result of slightly larger in-situ horizontal stresses (i.e. $K_o > 0.40$). The chamber test work by Bellotti et al. (1979) also included some tests where the sand was overconsolidated at the same density (i.e. $K_o > 0.40$). The chamber results are shown in Fig. 6 and indicate a proportionate increase in $K_d$ for an increase in $K_o$ for constant relative density. If the relative densities from both the CPT and the laboratory measurements are assumed approximately correct the DMT $K_d$ data, would indicate an in-situ $K_o$ of 0.55 in the sand at the McDonald's Farm site. This value of $K_o$ is

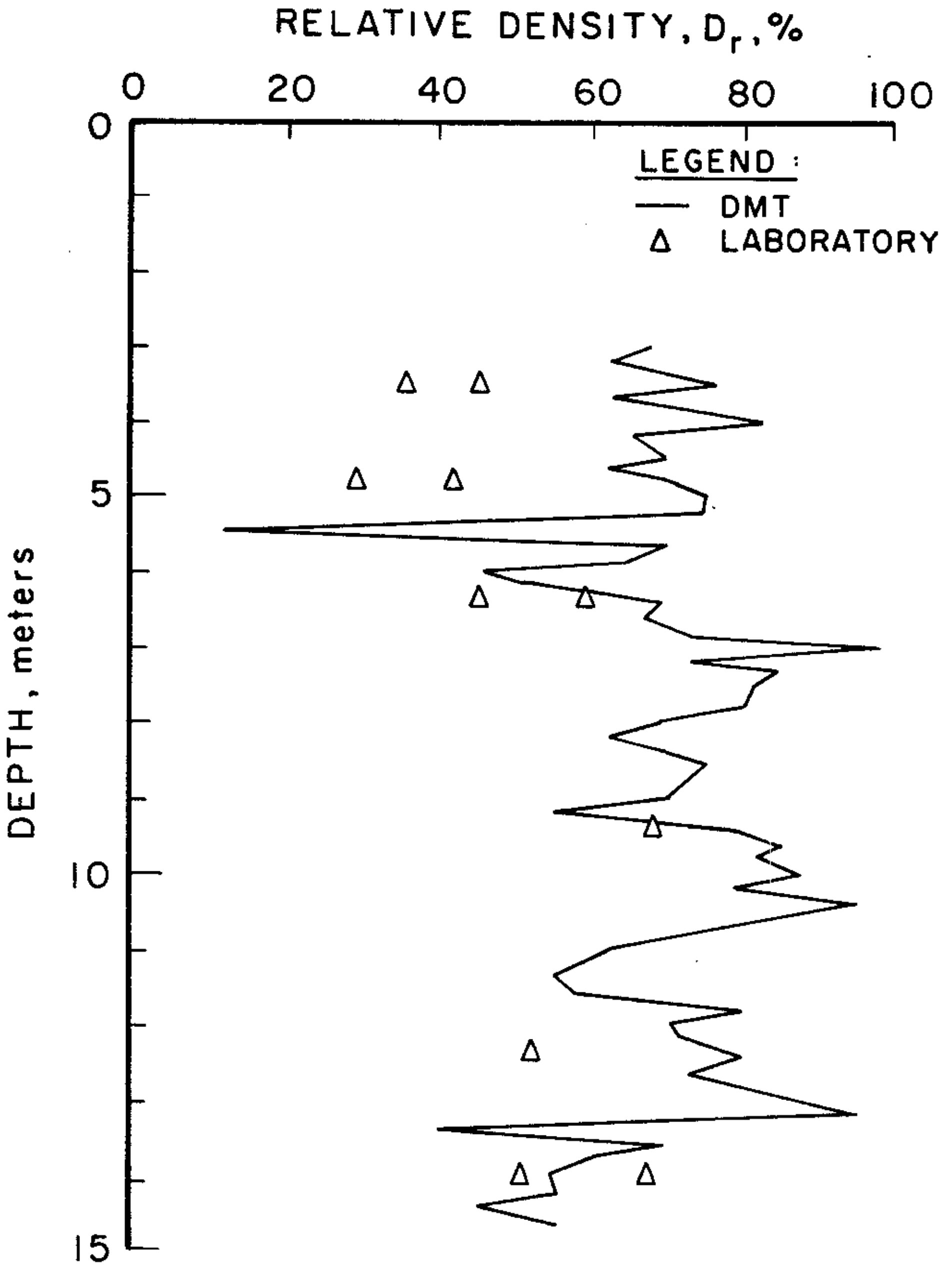

Figure 5. Comparison of Predicted Relative Density and Measured Laboratory Relative Density at McDonald's Farm Site, B.C.

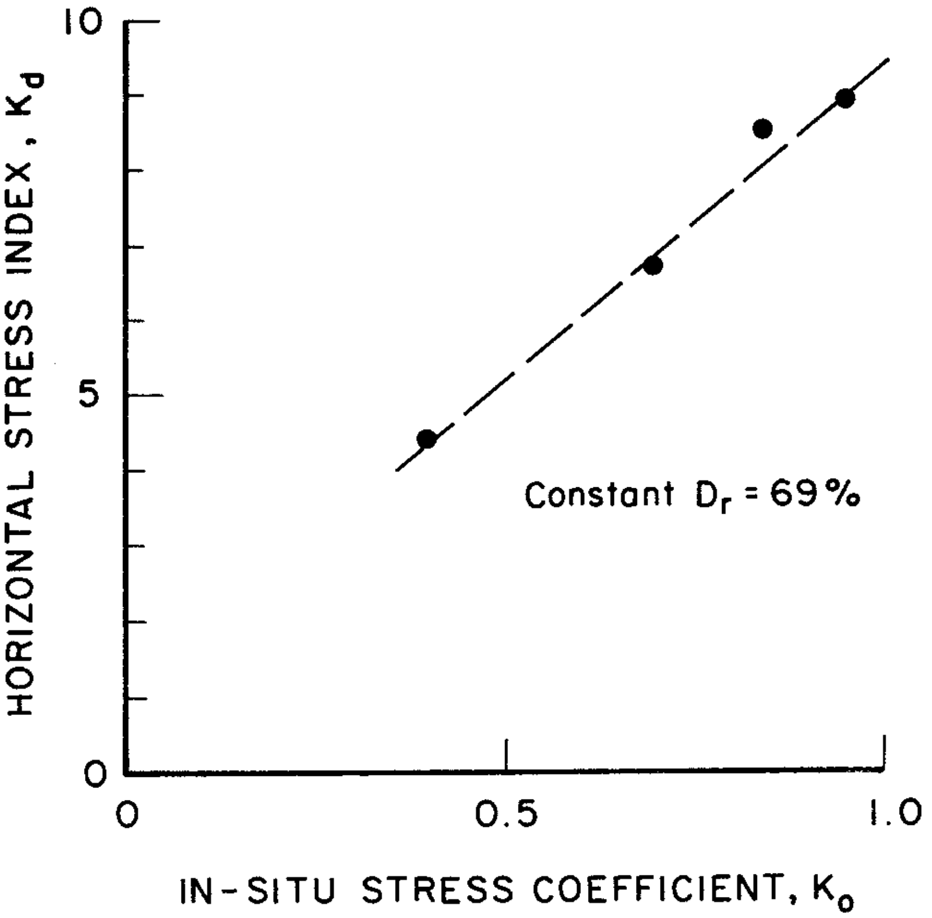

Figure 6. Correlation between In-situ Stress Coefficient, $K_o$, and Dilatometer Horizontal Stress Index for Ticino Sand at a Relative Density of 69% (Data from Bellotti et al., 1979)

considered not unreasonable for the sand deposit at McDonald's Farm.

The liquefaction resistance of the sand was assessed using the proposed correlation shown in Fig. 3. A comparison between the cyclic stress ratios to cause liquefaction predicted from the proposed DMT, and the SPT and CPT based methods (Seed et al., 1983 and Robertson and Campanella, 1984) and laboratory derived cyclic stress ratios are compared in Fig. 7. Good agreement is aparent between the DMT and laboratory, SPT and CPT derived liquefaction resistance. At first this seems a little surprising, since the DMT correlation is based on a relative density correlation (Fig. 2) and the DMT $K_d$ appeared to overpredict the relative density (see Fig. 5) at McDonald's Farm. However, increases in $K_o$ causes an increase in both $K_d$ and the liquefaction resistance of a sand at constant relative density.

The proposed correlation in Fig. 3 had no data beyond $K_d = 4.5$. However, the results shown in Fig. 7 indicate the proposed extrapolation beyond $K_d = 4.5$ appears reasonable.

If the liquefaction resistance were predicted from the DMT data using the approach suggested by Marchetti (1982) (Eq. 1), the cyclic stress ratio to cause liquefaction would have been very much overpredicted, with an average value of about 0.4.

Penetration of the CPT in the sand deposit at McDonald's Farm occurred under drained conditions (see Fig. 4). Recent testing with a research dilatometer which incorporates a piezometer element on the diaphragm confirms that both penetration and membrane expansion occur under drained conditions. Results from another site (New Westminster) show that DMT testing in silts can generate significant pore pressures which influence the measured $K_d$ value and thus the resulting liquefaction assessment.

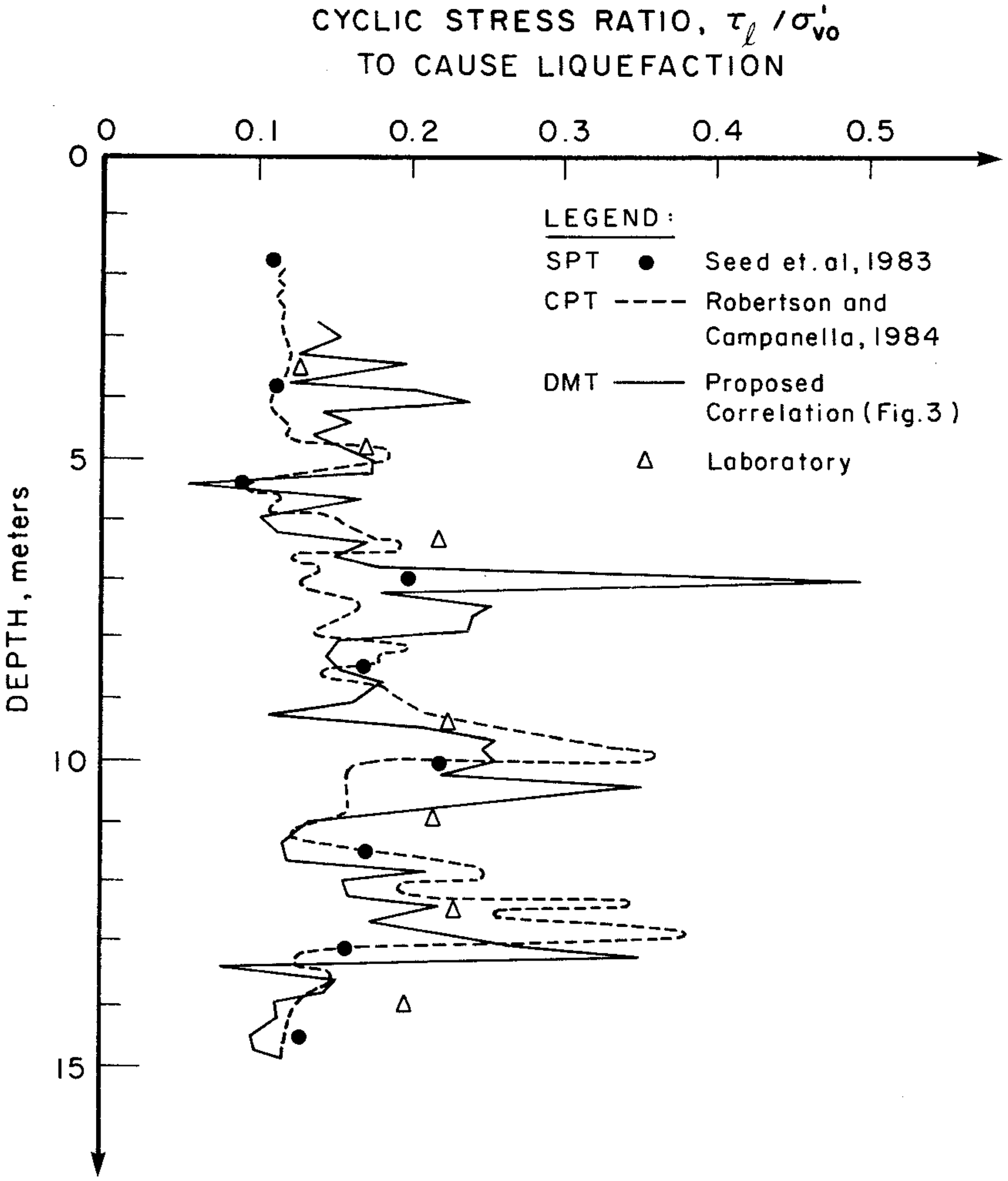

Figure 7. Comparison of Predicted Cyclic Stress Ratio to Cause Liquefaction from DMT, SPT, CPT and Laboratory Testing at McDonald's Farm Site, B.C.

New Westminster Site - Another research site for in-situ testing is located on a former dock area in New Westminster, B.C. The site is located on the north bank of the main channel of the Fraser River just at the entrance to the North Arm. The entire site was gradually reclaimed between the early 1900's and 1945 for dock facilities. The reclamation was carried out in several stages. The river adjacent to the dock was dredged and the sand and silt spoil was used to fill the site behind timber bulkheads.

The upper 12 m consists of a loose hydraulically placed sandy and silty soil. The sandy soil exists to a depth of about 5 m and a low plastic silt layer lies between 5 and 8 m depth. The silt layer varies in thickness and elevation across the area due to depositional history. The silt has a plasticity index (PI) of about 8% and a liquidity index of about 1.0. The site is approximately level at elevation +3.65 m. Groundwater fluctuates with tidal movements and varies from about 1 m to 4 m below ground surface.

The site is the proposed location of a major condominium structure. The geotechnical consultants were concerned about the stability of the site under earthquake loading. Two soil stabilization methods were studied by the consultants, Vibro-compaction and Dynamic Compaction. A test program was undertaken by the consultants to evaluate the effectiveness of each method. Access to the site was made available to the authors before and after stabilization treatment.

Fig. 8 shows a summary of the piezometer cone data from the test section before and after treatment by dynamic compaction. It is interesting to note that before treatment, the silt layer generated very high excess pore pressures during penetration as indicated by the large differential pore pressure ratio values. However, after treatment, there

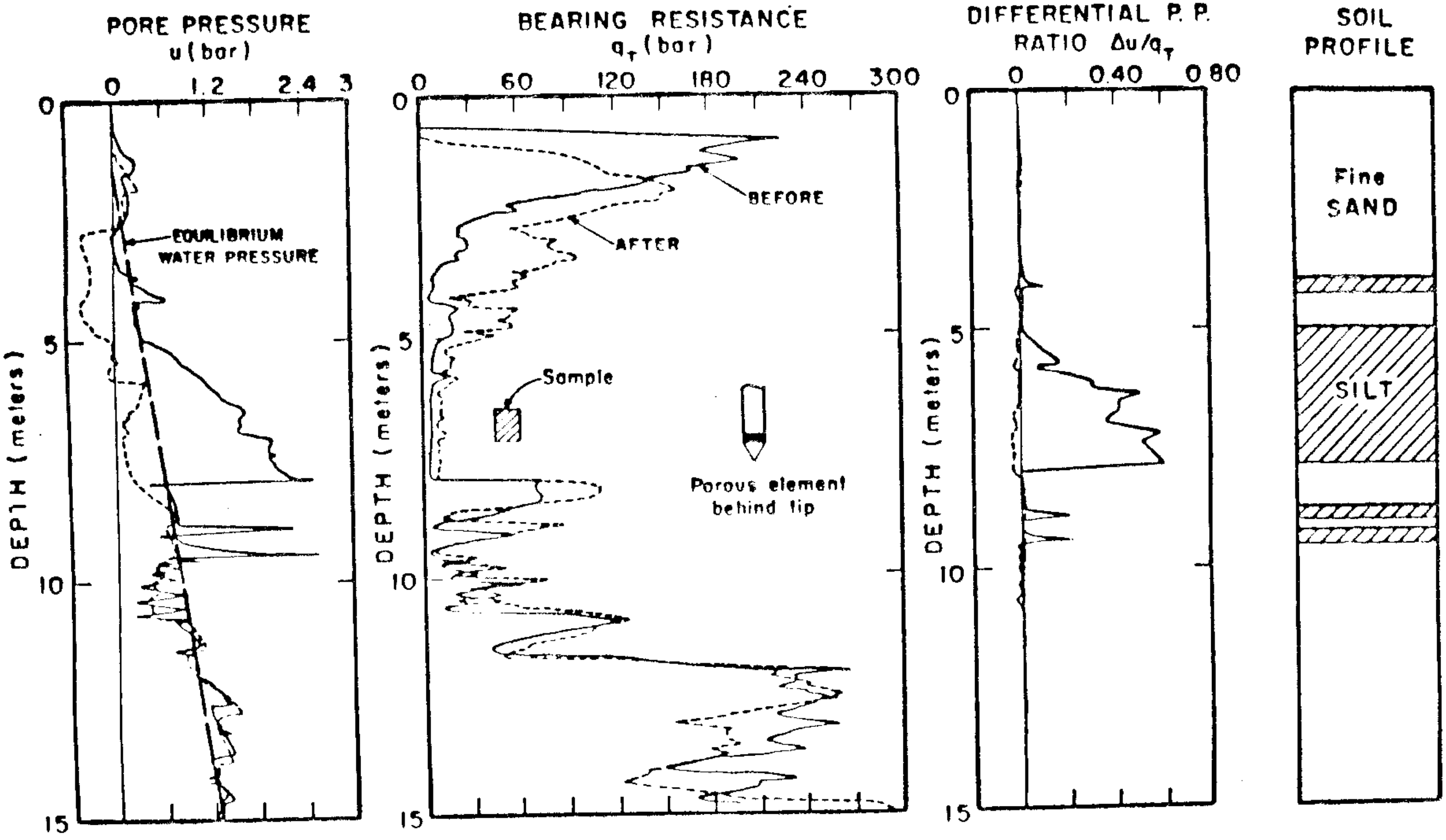

Fig. 8. PIEZOMETER CONE LOGGING BEFORE AND AFTER DYNAMIC COMPACTION (NEW WESTMINSTER, B.C.)

was a remarkable change in the pore pressure behaviour with significant pore pressures less than hydrostatic. Similar pore pressure behaviour was observed during cone penetration for the test section where treatment was by vibro-compaction. The very different pore pressure behaviour suggests that volume change characteristics of the silty layer have been altered dramatically. From the standpoint of liquefaction resistance, volume change characteristics are very important.

A summary of the field and laboratory results for the silt layer before and after compaction is shown in Table 1. The laboratory testing clearly showed that the silt was soft and contractive before treatment but dilative after treatment.

Figure 9 shows a summary of the DMT results from the control area where no treatment was carried out. The material index, $I_d$, has clearly identified the silt layer from 7 to 9.5 m and the horizontal index, $K_d$, is constant at about 1.8. Figure 10 shows a summary of the DMT results after dynamic compaction. The silt layer exists from a depth of about 5 to 7 m and can be identified from the basic DMT data ($P_0$ and $P_1$). However, the $I_d$ is barely able to identify the silt. The $K_d$ within the silt has now dropped to about 1.2. In the overlying sand the $K_d$ has increased due to the increase in density and horizontal stresses. However, in the silt the $K_d$ has decreased. This decrease is more marked in the DMT results after vibrocompaction (Figure 11). In the vibrocompaction area the silt exists from about 7 to 8.5 m and can again be identified from the basic DMT data ($P_0$ and $P_1$). However, the silt layer is not identified from the material index, $I_d$. The $K_d$ has now decreased in the silt to about 0.6. However, in

## Table 1

## Comparison of Silt Parameters Before and After Compaction, New Westminster Site

| | Control Area (No Compaction) | Dynamic Compaction Area (After Compaction) |
|---|---|---|
| SPT N-value, blows/ft. | 5 | 7 |
| CPT cone bearing, $q_T$, kPa | 450 | 1000 |
| Undrained shear strength, $c_u$ | 14 kPa | 82 kPa |
| Cyclic stress ratio, $\tau/\sigma'$ to cause liquefaction in 10 cycles | 0.10 | $> 0.20$ |
| <u>Dilatometer</u> | | |
| Horizontal Stress Index, $K_D$ | 1.8 | 1.2 |

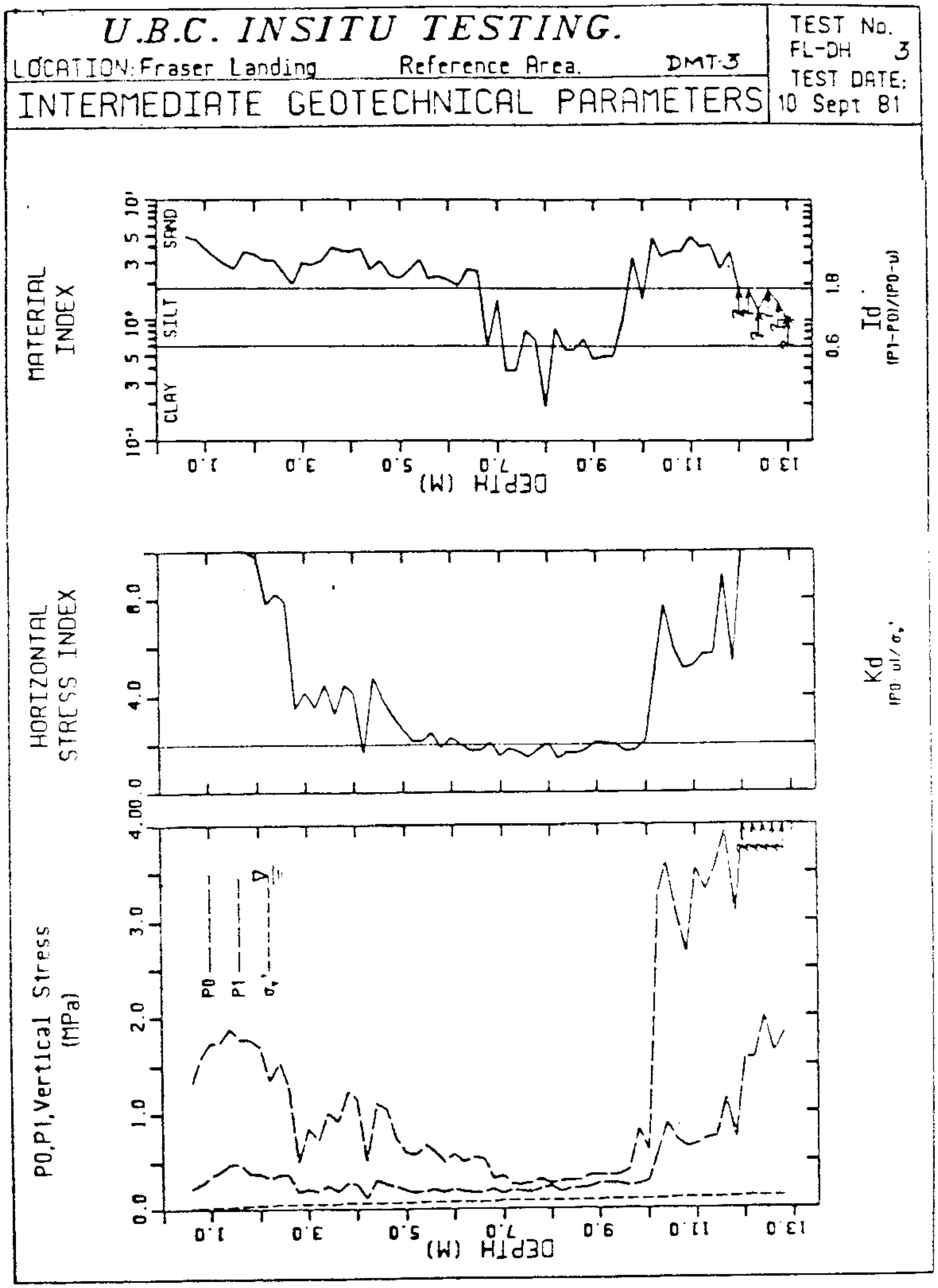

Fig. 9. Intermediate Geotechnical Parameters from DMT in Control Area, New Westminster Site.

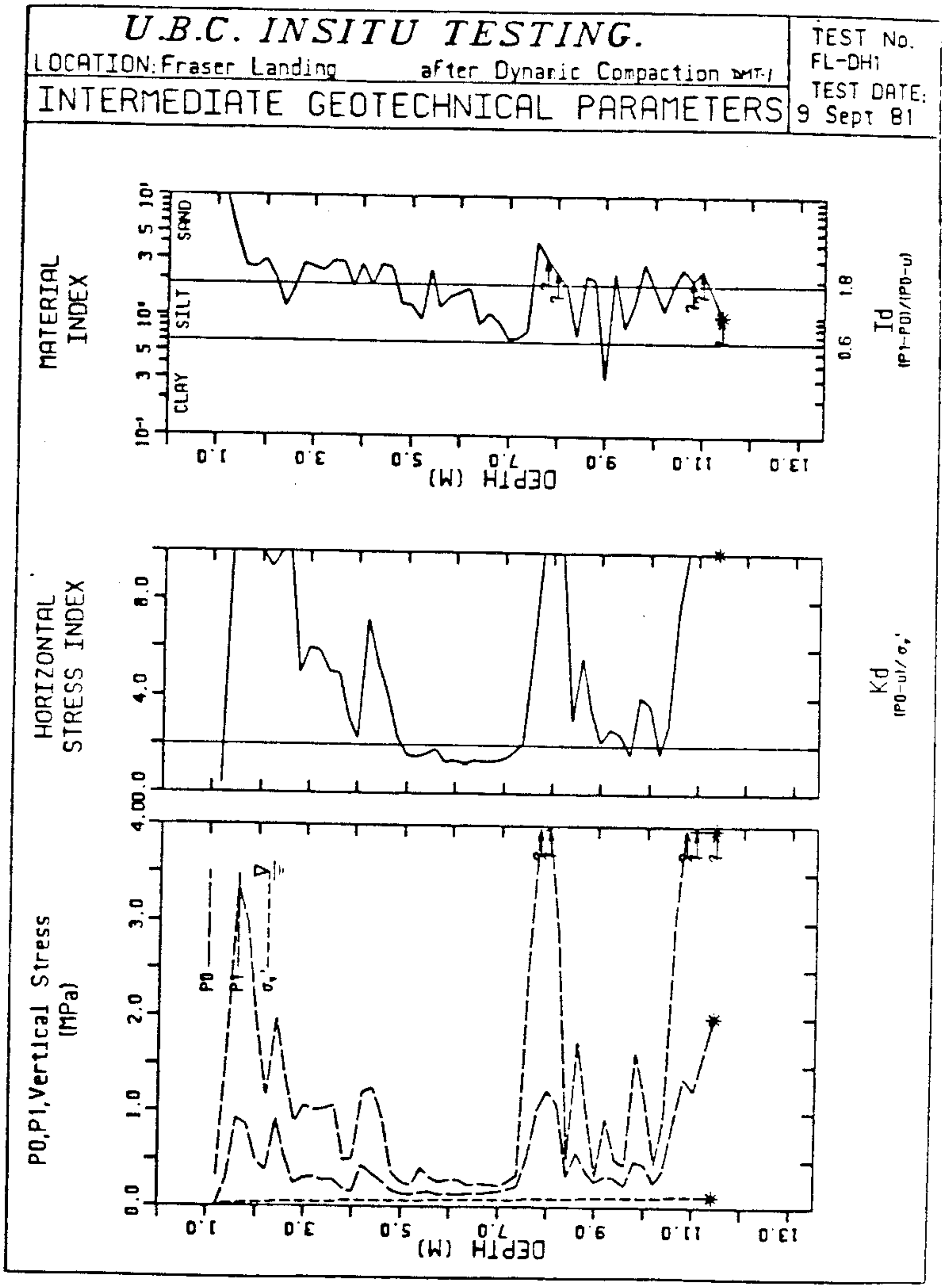

Fig. 10. Intermediate Geotechnical Parameters from DMT after Dynamic Compaction, New Westminster Site.

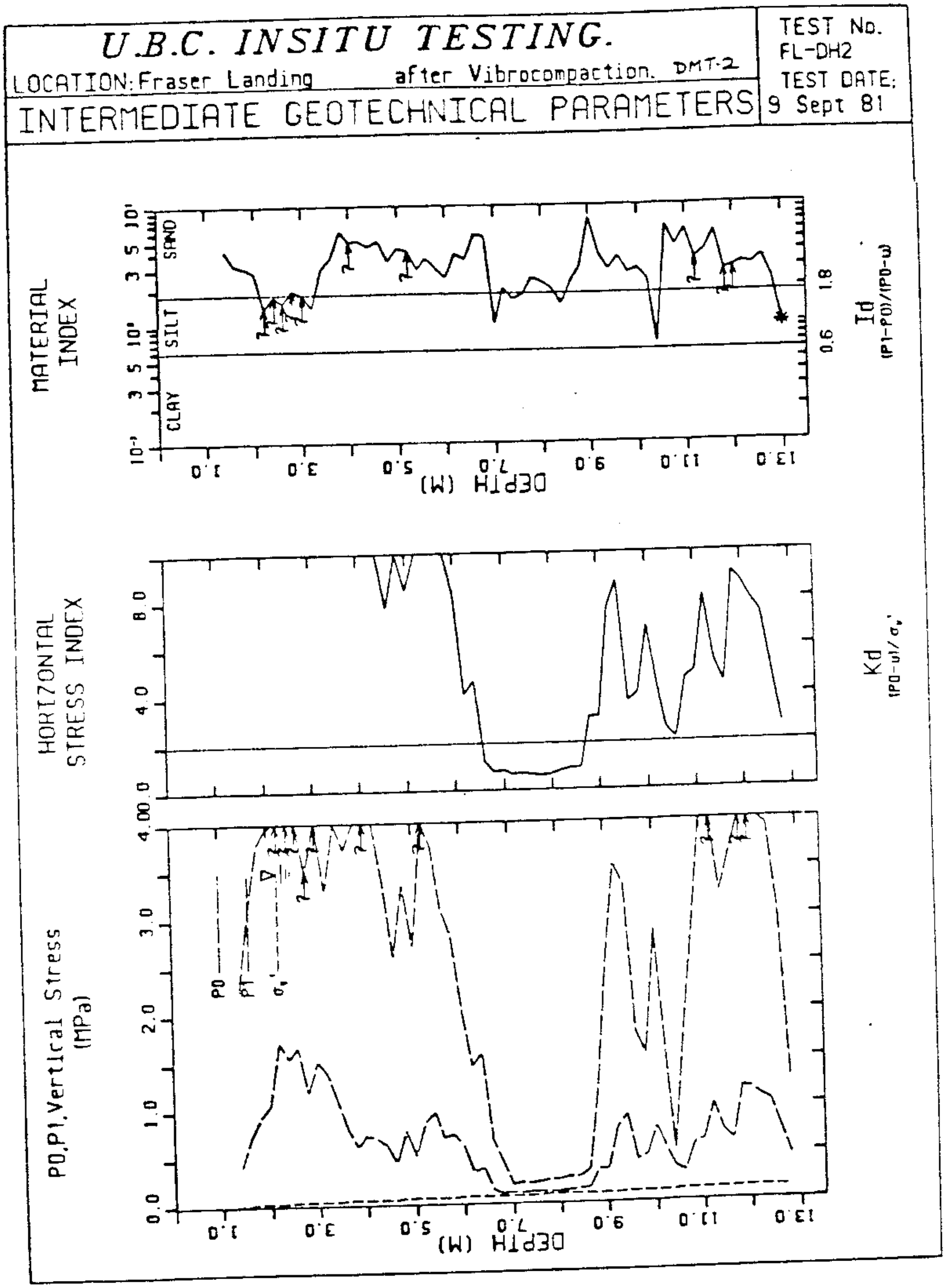

Fig. 11. Intermediate Geotechnical Parameters from DMT after Vibrocompaction, New Westminster Site.

the overlying sand the $K_d$ has increased significantly due to the large increase in horizontal stresses caused by the vibrocompaction treatment.

Table 1 summarizes the average measured $K_d$ values in the silt before and after compaction. The decrease in $K_d$ after compaction would indicate a decrease in the liquefaction resistance if the correlation in Fig. 3 were applied. However, the cylcic laboratory tests clearly show that the silt showed a marked increase in liquefaction resistance after treatment. Thus, for some reason, the DMT results predict compeltely the wrong behaviour of the silt after treatment. The reason for this response probably results from the pore pressure behaviour of the silt during penetration. Before treatment, very large pore pressures exist around the dilatometer during testing. However, after treatment, the piezometer cone data incidates that very small pore pressures exist aound the dilatometer during testing. Since the dilatometer records total stresses, it is very sensitive to the pore pressures around the instrument during the test. Thus, a decrease in the pore pressures around the instrument reduce the total stress to lift the membrane and therefore reduce the horizontal stress index, $K_d$.

## Conclusion

A correlation between cyclic stress ratio to cause liquefaction and horizontal stress index, $K_d$, from the DMT has been proposed for sands. The correlation is based on empirical relationships and requires considerable field verification. However, the proposed correlation provides a basis from which to evaluate the use of DMT data for assessment of field liquefaction. The proposed DMT based method should be used in a similar manner to the SPT based method proposed by Seed et al. (1983), although no correction is required for overburden pressure. For any given site with level ground conditions and a given value of maximum ground acceleration, the possibility of liquefaction can be evaluated on an empirical basis with the aid of Fig. 3.

The proposed DMT correlation was evaluated using field and laboratory data in sand from the UBC research site (McDonald's Farm). DMT testing in fine grained soils such as silt may take place under undrained or partially drained conditions and dyanamic pore pressures generated during penetration can significantly effect the DMT data. The proposed correlation (Fig. 3) is not recommended for DMT results in silts.

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