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SYNOPSIS: The liquefaction potential of several sites in the Imperial Valley, South California, is evaluated on the basis of standard penetration, cone, and dilatometer test data. The performance of the soil deposits at these sites during past earthquakes has been documented in earlier studies. Since the dilatometer parameter K_d is expected to reflect factors (e.g. fabric, prestress, preshaking, aging) affecting liquefaction potential to a certain extent (Marchetti, 1982), this paper primarily focuses on this parameter as an index for evaluating liquefaction potential. A tentative boundary curve (in terms of stress ratio vs. K_d) for evaluating liquefaction potential that takes advantage of earlier boundaries is proposed. A promising index which combines dynamic and static dilatometer tests is also proposed.

INTRODUCTION

The performance of several sites located within the Imperial Valley, South California, during earthquakes such as the El Centro, 1940, Imperial Valley, 1979, and Westmorland, 1981, events has been well documented in the past (e.g. Bennett et al., 1981 and 1984). These earthquakes produced widespread liquefaction effects in some areas such as sand boils, ground cracks, and lateral spreads. Nearly all of these effects occurred in gravel-free sands and silts. Following the more recent events, a number of field expeditions were conducted by the U.S.G.S. and others to obtain in situ characteristics of the materials that liquefied. A large portion of this field work concentrated on standard and cone penetration testing.

More recently, additional series of field tests were conducted at three of these sites, known as the Heber Road, Kornbloom, and Wildlife sites (Reyna, 1990). The testing program included cone penetration (CPT), dilatometer (DMT), standard penetration (SPT), piezocone (CPTU), and screw plate tests. In addition to dilatometer and cone tests performed under normal conditions, "slow" tests were performed at a rate of advancement of 0.3 cm/sec, and "fast" tests at rate of 10 cm/sec. A number of cyclic and driven dilatometer tests were also conducted. Reyna and Chameau (1991) presented a subset of this data base, with emphasis on a comparison of the cone and dilatometer effectiveness and levels of variability. The study also involved an assessment of the difference in penetration resistance values obtained using the mechanical and electrical cones as well as the influence of the rate of penetration on the dilatometer values.

The main objective of this paper is to evaluate the use of the dilatometer parameter K_d as an index for evaluating liquefaction potential. Existing correlations (Marchetti, 1982, and Robertson and Campanella, 1986) are reviewed and applied to the Imperial Valley data. Comparison of results using K_d and other correlations based upon the SPT and CPT at the Heber Road site are presented. Finally, the possibility of creating an alternative index for evaluating liquefaction potential which takes advantage of driven and pushed dilatometer tests is discussed.

LOCATION OF THE SITES

The three sites, Heber Road, Kornbloom, and Wildlife, are located within the Imperial Valley in South California. Detailed descriptions of the sites and soil deposits and a summary of tests performed by the U.S.G.S were presented by Bennett et al. (1981 and 1984) and Youd et al. (1981). A summary of the field observations in recent earthquakes and material descriptions of the deposits is given in Table 1.

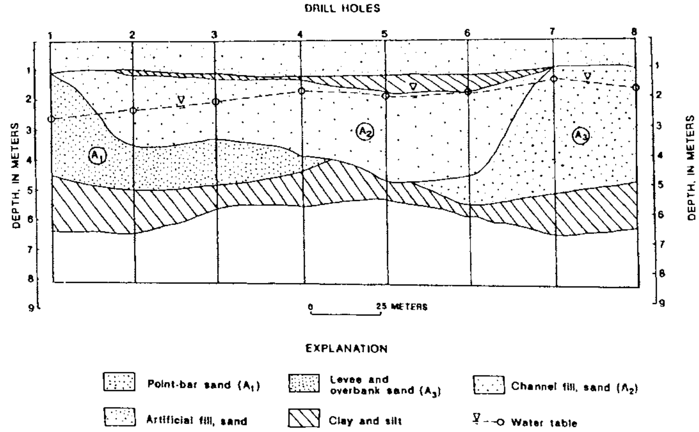

Figure 1: General cross section of Heber Road site based on dilatometer data

Stratigraphic Units	Material Description	Liquefied
Heber Road-A_1	Point bar Fine Silty sand top: medium dense bottom: dense	No
Heber Road-A_2	Channell fill Fine silty sand loose	Yes
Heber Road-A_3	Levee and overbank Fine silty sand medium dense	?
Heber Road-B	Silty clay stiff	No
Wildlife-B	Silty fine sand loose	Yes
Wildlife-C	Silty clay stiff	No
Kornbloom-B	Silt and sandy silt	Yes

Table 1: Summary of liquefaction behavior based upon USGS studies at the Heber Road, Wildlife and Kornbloom sites

The Imperial Valley lies within the central part of the Salton trough geomorphic province. During the late-Pleistocene the Imperial Valley became isolated from the southern part of the Salton trough as the Colorado River delta aggraded. As a result, the northern part of the valley now contains sediments deposited in fluvial and ephemeral lacustrine environments. Lake Cahuilla is the name given to the ancient lake which periodically filled the basin, now occupied by the Salton Sea. The Salton Sea was created between 1905 and 1907 when the entire flow of the Colorado River was accidentally diverted into the Imperial Valley. Between A.D. 700 and A.D. 1580, Lake Cahuilla filled the basin four times. The main depositional environments during the Holocene have been alluvial fans and braided streams that extend into the valley from the surrounding hills and, interbedded lacustrine, flood plain, and meandering channel environments in the central part of the valley.

Heber Road - The Heber Road site is located at the north end of Heber Dunes Co. Park, southeast of El Centro. Liquefaction effects produced by the 1979 earthquake included sand boils, ground cracks, and lateral spread. A generalized soil profile of the Heber Road site was prepared based upon dilatometer data (Figure 1). Of the three sand/silt layers found in the upper 5.0 to 6.0 m of the deposit, the fine silty sand A_2 was identified as the most likely cause of the effects observed in 1979 (Table 1), however the potential for liquefaction of the horizon A_3 also exists. Based on grain size distributions, the three stratigraphic units are susceptible to liquefaction according to the Tsuchida (1970) criteria (as illustrated in Figure 2 for the A_1 deposit).

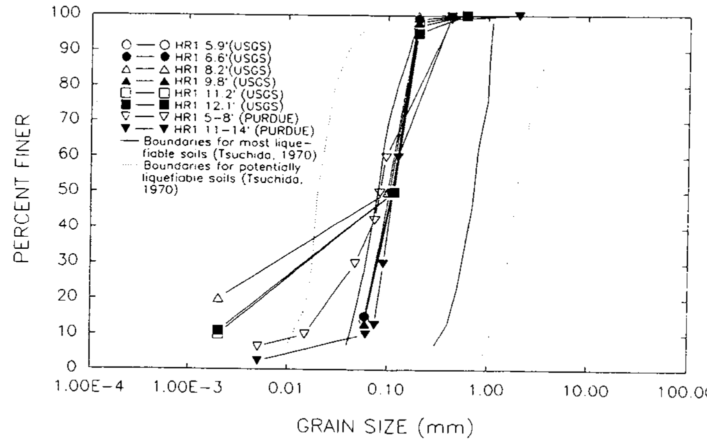

Figure 2: Grain size distribution curves for Deposit A1 at Heber Road

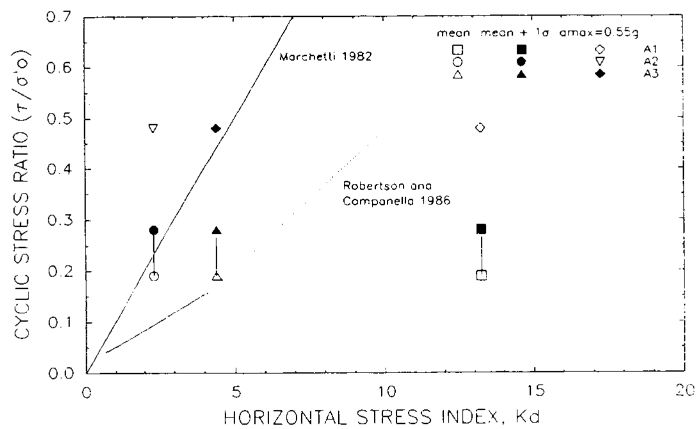

Figure 3: Liquefaction performance using the horizontal stress index K_d (average values) at the Heber Road site

Twenty DMT, 12 CPT, and two SPT tests were conducted at this site in addition to the CPT tests performed by the U.S.G.S.

Wildlife - The Wildlife site is located on the west side of the Alamo River within the Wildlife Management Areas. Sand boils developed in the flood plain during the 1981 earthquake (Ms = 6.0). The stratigraphy at this site in the upper 12.0 m consists of three horizontal layers of silt, sand and silty clay with approximately the same thickness. The water table is at a depth of about 1.0 m. The sand layer, known as the B unit, between depths of 3.0 and 7.0 m, was identified as the layer that liquefied and formed sand boils during the earthquake. This Wildlife B deposit is also susceptibly to liquefaction according to the Tsuchida (1970) criteria. Six CPT, nine DMT, and two SPT tests were conducted at this site.

Kornbloom - The Kornbloom Road site is in the northernmost part of the study area. This area was inundated by an enlarged Salton Sea during the flood of 1905-07, and sand boils were widespread after the 1981 earthquake. The stratigraphy consists of several horizontal layers of silt, sand, and silty clay. A layer of silt and silty sand between depths of 1.0 to 6.0 m, known as the Kornbloom B unit, is the probable source of the liquefaction based on the looseness of the material and the similarity in grain size to the sand boil sediments. This layer is located in between two layers of silty clay, and the water table is at approximately 2.0 m below the ground surface. Three dilatometer tests were conducted at this site.

K_d AS AN INDEX FOR LIQUEFACTION POTENTIAL

The dilatometer horizontal stress index is defined as:

$$K_d = (p_o - u_o)/\sigma'_o$$

where u_o and σ'_o are the pore water pressure and vertical effective stress, respectively, and p_o is the pressure required to just begin to move the dilatometer membrane.

Marchetti (1982) suggested that K_d be used to evaluate the liquefaction resistance of sands under level ground conditions. K_d reflects to a certain extent the following soil characteristics: relative density, in situ stresses, stress history, cementation, and aging. Nevertheless, it is not possible to identify the individual effect of each variable, and it is also recognized that the effect the fabric of the sand has on K_d (as on any other penetration test) is not well understood. An advantage of K_d is that it is fairly reproducible, and a statistical analysis of cone and dilatometer data (Reyna and Chameau, 1991) shows that the dilatometer parameters have less variability than the corresponding cone parameters for loose silty sands, however, the levels of variability are essentially the same for medium dense and dense sands.

Using data from Vaid et al. (1981), Marchetti (1982) suggested the following equation as a demarcation line for the occurrence of liquefaction in terms of stress ratio:

$$\tau/\sigma'_o = K_d/10$$

The ground motion intensity at the site is evaluated by the stress ratio τ_{av}/σ'_o (Seed, 1979):

$$\tau_{av}/\sigma'_o = 0.65\ a_{max}\sigma_o r_d/\sigma'_o\ g$$

where a_{max} is the peak ground acceleration (PGA) at the ground surface, σ'_o is the effective overburden stress at the depth of consideration, σ_o is the total overburden at the same depth, and r_d is a stress reduction factor that decreases from a value of 1 at the ground surface to a value of 0.90 at a depth of 35 ft.

Robertson and Campanella (1986) proposed another correlation to evaluate the susceptibility to liquefaction of normally consolidated, uncemented sands. This correlation also included the data obtained by Vaid et al (1981). The Robertson and Campanella correlation was developed for testing in sands where penetration and expansion occur under drained conditions. Testing in silty sands or silts may generate pore pressures which influence the measured K_d values. The two correlations are plotted in Figure 3. The correlation proposed by Robertson and Campanella predicts cyclic stress ratios significantly lower than those given by the Marchetti correlation.

LIQUEFACTION POTENTIAL AT HEBER ROAD USING K_d

Table 2 gives representative values of K_d for the A1, A2 and A3 deposits at the 8 Heber Road locations based upon 5 different criteria. Field observations (Bennett et al., 1981) show that the A2 deposit liquefied during the 1979 earthquake, and that liquefaction started at locations 4 to 6. The dilatometer data show that the weakest part of the A2 deposit is at locations 5 and 6.

Criteria	depth (m)	A1	A2	A3
Minimum K_d in the deposit		5.27	0.92	2.31
Average of the minimum K_d values of each boring		6.74	1.44	2.54
Average of the minimum K_d values at each depth	2	12.68	1.57	2.80
	3	16.78	1.67	3.31
	4	11.81	1.69	3.57
	5		1.92	3.02
Average of the K_d values at each depth (from several borings)	2	20.70	2.33	4.00
	3	19.60	2.31	5.43
	4	10.90	2.40	4.60
	5		1.74	3.88
Average of all K_d values	3.5	13.24	2.33	4.39

Table 2: K_d values for the different criteria (Heber Road - 1983 data)

The isolated data points given in Figure 3 were obtained with the following assumptions: (1) average value of K_D for each deposit; (2) a representative depth of 3.5 m to calculate stress ratios; (3) mass densities of the soil of 1.68 g/cm^3, as adopted by Youd and Bennett (1981), (4) peak ground acceleration of 0.55 g (value used by Seed and De Alba, 1986), and (5) an average water table depth of 1.90m (it ranged from 1.40 to 2.60m during the different series of measurements).

The assumption made for the PGA is critical to the evaluation of stress ratio when the actual acceleration was not measured at the site. The values connected by vertical bars in Figure 3 correspond to the median (50th percentile) and 84th percentile values of acceleration obtained with the Campbell (1981) attenuation equation:

$$PGA = 0.016\ \exp(0.87M)\ [R + 0.06\ \exp\ (0.70M)]^{-1.09}$$

The 84th percentile value of the PGA is obtained by multiplying the median value by a factor of 1.45 which represents an error of 0.372 on the natural logarithm of the PGA. For a magnitude of

6.6 and a distance to the fault of about 13 km, PGA's of 0.22 and 0.32 g were obtained for the 50th and 84th percentile, respectively. These values of acceleration (50th and 84th percentile) given by the Campbell (1981) equation are significantly less than the value of 0.55 g suggested earlier. The study made by Campbell was specifically performed for the near source attenuation of earthquakes of magnitude 5.0 to 7.7, including data from the 1979 Imperial Valley earthquake. Similar studies performed by Joyner and Boore (1981 and 1988) gave results very similar to that of Campbell, especially for distances of 8 to 30 kms. These relationships were developed for firm or rock sites, however Joyner and Boore noted that for small epicentral distances (near field) the ground motion is controlled mostly by the source parameters and less by the site conditions. Exceptions to this certainly exist for very soft sites. Making allowance for all the seismic and geotechnical uncertainties involved, it still appears that the value of 0.55 g may be conservative; it would correspond to a value even larger than the 99th percentile when using the Campbell equation. The high values of accelerations of 0.40 to 0.60 g that were measured during the Imperial Valley earthquakes were recorded at distances of 5 to 7 kms from the fault. These values are consistent with accelerations of the order of 0.20 to 0.35 g at a distance of 13 kms.

For an earthquake of magnitude 6.6, the data in Figure 3 show that both units A3 and unit A2 are susceptible to liquefaction and unit A1 resistant to liquefaction, according to both K_d based correlations if a value of 0.55g is assumed for the PGA. When the more likely ranges in acceleration are used, it appears that unit A3 would not have liquefied according to the Marchetti criteria, but would have according to the Robertson and Campanella one.

LIQUEFACTION POTENTIAL AT HEBER ROAD BASED ON SPT

The criteria used to summarize the SPT data were the same as that used for K_d. The results are summarized in Figure 4 for a PGA of 0.55, as well as for the acceleration values given by the Campbell equation. The SPT holes were pre-augered thus differing from the standard procedure and requiring adjustments. The number of blows (N) were corrected for the depth of overburden (N_1), and then multiplied by 2.5 to convert them to standard values (N'_1).

The data show that for an earthquake of magnitude 6.6 the channel fill (unit A2) is susceptible to liquefaction. The overbank deposit (unit A3) would not be susceptible to liquefaction for earthquakes of magnitude less than about 7.0 based upon the N'_1 values. However, points fall close to the demarcation lines for M = 6.6 and 7.50. The point bar deposit (unit A1) is resistant to liquefaction for all cases. Also given in Figure 4 are SPT data points obtained more recently (Reyna, 1990) with energy measurements. These N_{55} values (corrected to 55% of energy), are smaller than the N values obtained by the non-conventional method used by Bennett et al. (1981), however the A2 deposit is clearly susceptible to liquefaction according to both data sets.

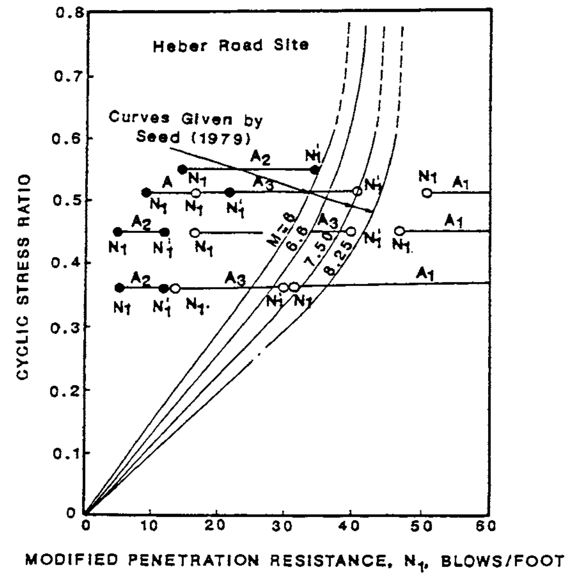

Figure 4: Cyclic stress ratio vs blow count values (average at each depth)

LIQUEFACTION POTENTIAL AT HEBER ROAD BASED ON CPT

The CPT provides a continuous record of penetration resistance and is a fairly sensitive device for locating pockets or thin strata of loose material within a generally denser but heterogeneous deposit. The measure of the pore water pressure during penetration can also contribute to the interpretation of the soil profile. The common procedure for applying cone data to liquefaction potential evaluation is to correlate cone resistance to blow count, and then enter a chart such as the one given in Figure 4. This procedure introduces additional uncertainty due to the correlation between cone resistance and blow count. The scatter around the average curve is very significant even for soils within a small range of grain size distribution (Chin et al., 1988).

Seed and De Alba (1986) used the cone data obtained from Bennett et al. (1981) at the Heber Road site to confirm their proposed CPT chart. Figure 5 shows the results of their evaluation. The stress ratios were calculated for a PGA of 0.55 g and divided by a factor of about 1.13 to be compatible with the chart for a magnitude of 7.5. The limiting curve separates the unit which liquefied from the one which did not. It shows that unit A_2 belongs clearly to the liquefaction group, and suggests that unit A3 is a borderline case. Data points obtained as part of the field work reported herein (Reyna, 1990) are incorporated to this figure and confirm the earlier studies.

COMPARISON OF LIQUEFACTION POTENTIAL ASSESSMENTS

According to the description given by Youd and Bennett (1981): "The field evidence indicates that the channel deposit did indeed liquefy generating sand boils, fissures, and a lateral spread. Other than a linear group of sand boils,

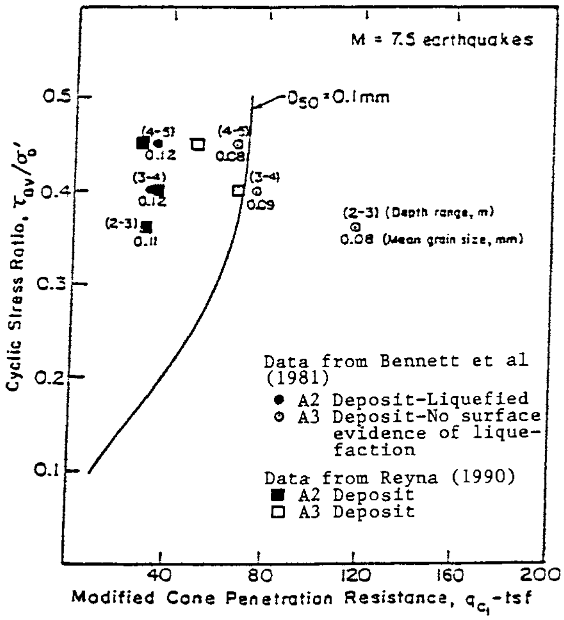

Figure 5: Cyclic stress ratio vs cone penetration resistance (average at each depth)

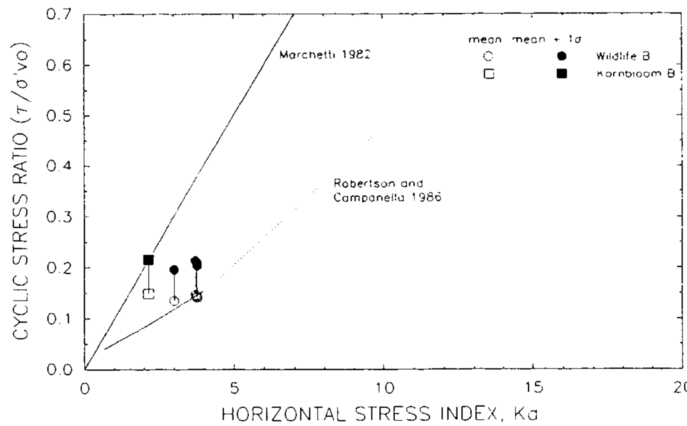

Figure 6: Liquefaction performance using the horizontal stress index at the Wildlife and Kornbloom sites

which apparently were caused by liquefaction of fill around a buried drain line, there was no surficial evidence of liquefaction in the flood-plain (A3) deposit. Nevertheless, pore pressures could have risen, and the unit might have transiently liquefied, without affecting the ground surface. There was no evidence of liquefaction in the point-bar deposit, although pore pressure may have increased".

The evaluations made with the CPT, DMT, and SPT all concur with respect to the A_2 and A_1 deposits, irrespective of the assumptions made for the peak acceleration actually experienced at the site. However, the assessment for the A_3 layer is very sensitive to the assumptions made. For the acceleration value used by previous investigators (0.55 g), the SPT, CPT, and DMT correlations suggest liquefaction, however it is a borderline case for the Marchetti DMT correlation. For accelerations calculated from attenuation curves, the A_3 deposit becomes a borderline material for CPT and SPT correlations, and falls in between the two DMT based correlations.

LIQUEFACTION POTENTIAL AT WILDLIFE USING K_d

Accelerations of 0.17 and 0.25 g were obtained for the 50th and 84th percentiles, respectively, based upon a magnitude of 5.6 and a distance of 8 km for the 1981 earthquake. Wang and Kavazanjian (1987), using a nonstationary random vibration deconvolution method, found that the first sublayer of silty sand sediment at a depth of 3 m was most vulnerable to liquefaction. Average values of K_D calculated at different depths confirmed their findings, and thus the data points for this site in Figure 6 were determined for average K_D values at 3 m (with a depth to water table of 1.40 m). The sublayer at a depth of 3 m in the B deposit is susceptible to liquefaction according to the Robertson and Campanella correlation, but it would not liquefy according to the Marchetti correlation, even if larger accelerations were used. Sand boils observed at the Wildlife site after the 1981 earthquake were attributed to that layer.

LIQUEFACTION POTENTIAL AT KORNBLOOM USING K_d

At the Kornbloom site, a magnitude of 5.6 and a distance of 5.8 km resulted in PGA's of 0.22 and 0.31 g for the 50th and 84th percentiles, respectively. Figure 6 shows that the B deposit at Kornbloom is susceptible to liquefaction based on the Robertson and Campanella correlation, but borderline for the Marchetti correlation. There are evidences that liquefaction occurred in that unit during the earthquake.

K_d BASED CORRELATIONS FOR LIQUEFACTION POTENTIAL

Figure 7 summarizes the cyclic stress ratio vs. horizontal stress index K_d for all the deposits analyzed. The ranges in data points in the figure attempt to represent the most likely physical conditions as well as to illustrate the uncertainties involved in the interpretation of the susceptibility to liquefaction of the deposits. The Wildlife deposit shows a weak sublayer at the depth of 3.0 m. Hence, an average K_d value at 3 m was used to evaluate the resistance of the deposit. The Kornbloom B deposit, the only one susceptible to liquefaction at that site, does not show a weak layer. Hence, average K_D values with a representative depth of 3.5 m were used at this site. In addition to the average K_d value, a range of plus and minus one standard deviation is given at each location. The A1 deposit is very erratic and exhibits large dispersions compared to the others. Cyclic stress ratios were computed for PGA values corresponding to 50th and 84th percentiles. For the Heber Road site, calculations were also made

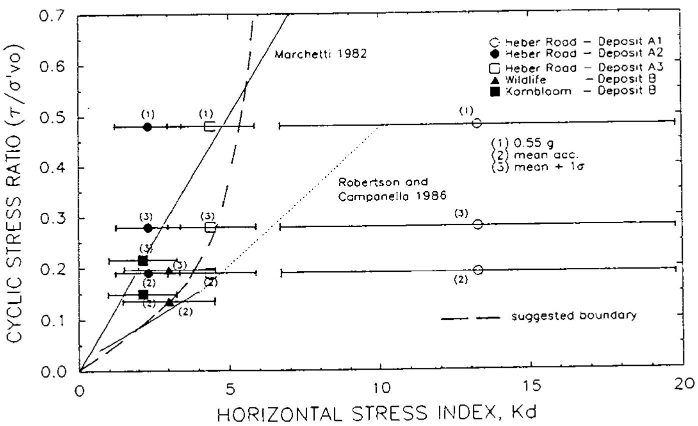

Figure 7: Marchetti (1982), Robertson and Campanella (1986), and suggested boundary curves using the horizontal stress index K_d

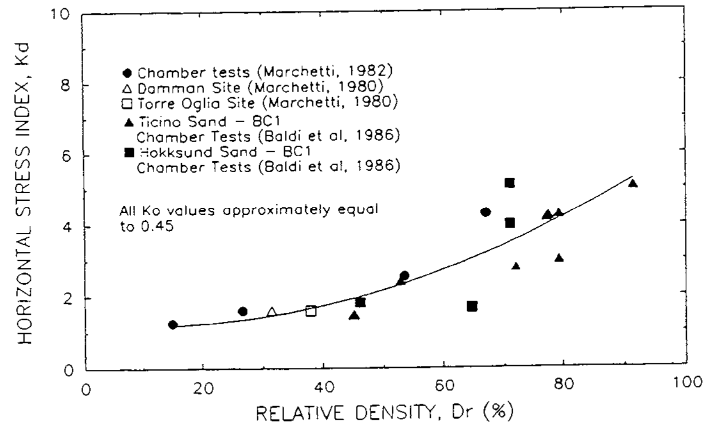

Figure 8: Correlation between horizontal stress index from DMT and relative density for normally consolidated, uncemented sand (modified from Robertson and Campanella, 1986)

for the value of 0.55 g used by previous investigators.

The data in Figure 7 and previous figures suggest that the Marchetti correlation is unconservative for small values of cyclic shear stress ratios. The A3 deposit at Heber Road can be considered to be a border line case according to the field observations. This indicates that the Robertson and Campanella correlation is too conservative for higher values of cyclic shear stress ratio. However, the Robertson and Campanella correlation seems to fit the field data fairly well for smaller cyclic shear stress ratios, less than about 0.15 to 0.20, and K_d values less than 3 to 4. Field data (e.g., Christian and Swiger, 1975) suggest that liquefaction of deposits with a relative density larger than 80% is unlikely. Nevertheless, for very high cyclic shear stress ratios, i.e. above 0.50, liquefaction could conceivably occur for higher relative densities. Figure 8 which combines the original data from Robertson and Campanella (1986) together with additional data from Baldi et al. (1986) indicates that a value of K_d of about 4.4 corresponds to a relative density of 80% or larger. Based upon these data and remarks, it is suggested that the Robertson and Campanella correlation is applicable for K_d values less than 3 to 4 and cyclic stress ratios less than 0.15, however, beyond this point, the demarcation line may depart sharply, moving closer to the Marchetti line. A tentative demarcation line is suggested in Figure 7. More field data is obviously needed to improve upon this chart, and possibly to define it using a statistical approach. In addition it is noted that the data available to date is limited to earthquakes of magnitude 5.5 to 6.5, and thus several demarcation lines may be required to reflect the size of the earthquake. Additional data is presently being gathered at several sites with known performance during the Loma Prieta earthquake.

One of the disadvantages of the dilatometer for evaluating liquefaction potential is that it is a quasi-static test. A combination of driven (or dynamic) and static dilatometer tests could

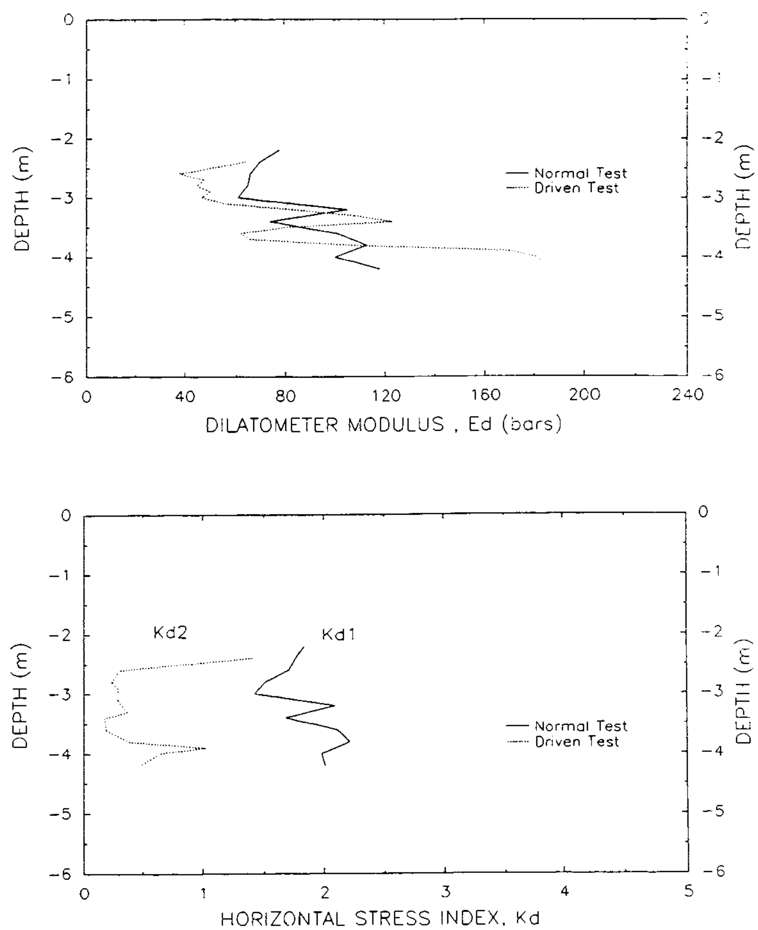

Figure 9: K_d and E_d values for driven and normal dilatometer tests in the A2 deposit at Heber Road

reflect not only the initial state of strength, aging, cementation, etc., but also the changes in pore water pressure and soil structure under dynamic conditions. Figure 9 shows the K_d and E_d values for driven and normal dilatometer tests in the A2 deposit at Heber Road. The effect of driving the blade on the modulus E_d is not significant. On the other hand, the K_d values from the driven test (K_{d2}) are much less than the normal values (K_{d1}). Schmertmann (1984) presented similar results for another very loose sand deposit. The difference in A readings for these tests is not as pronounced as for the Heber Road data because the deposit was extremely loose (relative density approximately equal to 15%). Schmertmann (1984) said that "...even hydraulic pushing may introduce enough vibrational disturbance (or possibly only diplacement disturbance in extremely loose sands) to exceed some "critical" level and compaction/collapse/ densify the sand structure to almost the same degree as the driving vibrations". The relative values of the two curves K_{D1} and K_{D2} will depend on changes in coefficient of lateral earth pressure (i.e. changes in soil structure) and pore water pressures during the different loading conditions. Thus, it may be possible to create an index for liquefaction potential that makes use of these two coefficients, possibly normalized with respect to one of them. However these observations are very qualitative and require further evaluation under field and laboratory conditions, as well as theoretical interpretation. It is noted that driven DMT tests also received attention for their use in stiff materials where the standard pushed tests can not be conducted (Davidson et al., 1988). Driven and pushed dilatometer data are also being gathered as part of studies related to the Loma Prieta event.

SUMMARY

The analysis of post-earthquake field data shows that the Robertson and Campanella dilatometer correlation fits well the field data for small cyclic shear stress ratios, less than 0.15; it appears very conservative for larger cyclic stress ratios. On the other hand, the Marchetti correlation may be unconservative for small stress ratios. It is recommended that a new demarcation line be developed (possibly as indicated in Figure 7) for evaluating liquefaction potential using the K_d parameter alone. An index combining the advantages of driven (or dynamic) and static test data is proposed for further study. Field and laboratory data are necessary to fully develop such an index, as well as to better define the demarcation line in Figure 7.

ACKNOWLEDGEMENTS

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