Comparison of DMT, CPT, SPT, and V_S based Liquefaction Assessment on Treasure Island during the Loma Prieta Earthquake

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ABSTRACT: Investigations at Treasure Island involving CPT, DMT, SPT and V_s measurements provide a relatively rare opportunity to compare these methods in predicting liquefaction. All the in-situ techniques were relatively consistent in predicting liquefaction within a depth range of 3 to 7.5 m below the ground surface. The factors of safety predicted by the CPT and DMT were quite consistent except at shallow depths where the DMT gave higher values owing to the higher K_o in this zone. Analysis of the CSR and K_D data points within the depth range from 3 to 7.5 m suggests that the liquefaction boundary curve is reasonable for sand but may be somewhat unconservative for silty sands. The factor of safety predicted by the V_s correlation was consistently lower than other methods owing to insensitivity to higher K_o values and higher silt content.

1 INTRODUCTION

Procedures for assessing the liquefaction potential of sands and silty sands have been developed for a number of in-situ tests including: the Standard Penetration (SPT) test (Youd et al. 2001), the Cone Penetration (CPT) test (Robertson & Wride 1998), and the shear wave velocity (V_S) test (Andrus & Stokoe 2000).

More recently, Monaco et al. (2005), proposed a method for predicting liquefaction using the K_D value obtained from Flat Dilatometer (DMT) testing. Research has shown that K_D is more sensitive than V_S to factors such as stress history, aging, cementation, and structure, which greatly increase the liquefaction resistance for a given relative density (Maugeri & Monaco 2006). Unfortunately, the database for assessing liquefaction from DMT testing is relatively small and additional results from field test sites are necessary to improve the reliability of the procedure. This is particularly important for profiles containing silty sand in addition to clean sand.

As noted by several researchers, it is often useful to evaluate liquefaction using more than one in-situ test to confirm the potential for liquefaction (Rollins et al. 1998, Robertson & Wride 1998, and Idriss & Boulanger 2004). However, it is sometimes difficult to determine which method to rely upon when there are conflicts between competing methods as has been noted by Rollins et al. (1998) as well as Liu & Mitchell (2006).

This paper provides additional field performance data than can be added to the database for liquefaction assessment with the DMT for both clean and silty sands. In addition, the results from the DMT based approach are compared with results from SPT, CPT and V_S methods at the same site. The test results were obtained from a site on Treasure Island, a man-made island in San Francisco Bay where liquefaction was pervasive during the M6.7 Loma Prieta Earthquake in 1989.

2 SITE CHARACTERIZATION AT TREASURE ISLAND LIQUEFACTION TEST (TILT)

Treasure Island was constructed by building a rock-fill berm on native shoal sands around the perimeter of the island and placing dredged sand within the berm using hydraulic filling techniques. The test site described in this investigation was located near the interior of the island. This site was thoroughly investigated in connection with a series of lateral pile load tests conducted after inducing liquefaction using small explosive charges. This test program, known as the Treasure Island Liquefaction Test (TILT), has been described in a number of papers (Ashford & Rollins 2001, Ashford et al. 2004, Rollins et al. 2005, Weaver et al. 2005). Prior to lateral pile load testing, about 0.9 m of the hydraulic fill was excavated to bring the ground surface closer to the water table. Test results are referenced relative to this excavated ground surface although corrections required by the various methods are based on the ground surface elevation at the time of testing.

2.1 *Cone Penetrometer (CPT) Testing*

A cone penetration sounding was performed using the Univ. of Michigan truck mounted CPT rig which could be anchored to the ground for increased reactive force. Readings were taken at 0.05 m intervals. The soil profile interpreted from the cone penetration testing along with profiles of cone tip resistance (q_c), sleeve friction (F_s), friction ratio (R_f), and soil behavior type index (I_c) are provided in Fig. 1. The I_c value provides a detailed indication of the variation of soil types with depth. There is a decrease in cone tip resistance from the ground surface consistent with overconsolidation, then the value oscillates between 3 and 7 MPa within the interbedded sand and silty sand layers typical of hydraulic fill. The friction ratio from 0 to 7 m is generally about 0.5%. The cone tip resistance decreases to around 1 MPa in the clayey silt/silty clay layer while the friction ratio ranges from 0 to 3%. The I_c in the clayey silt layer is typically 2.6 or greater indicating that this layer is not liquefiable; however there are some thin interbedded layers with I_c below 2.6.

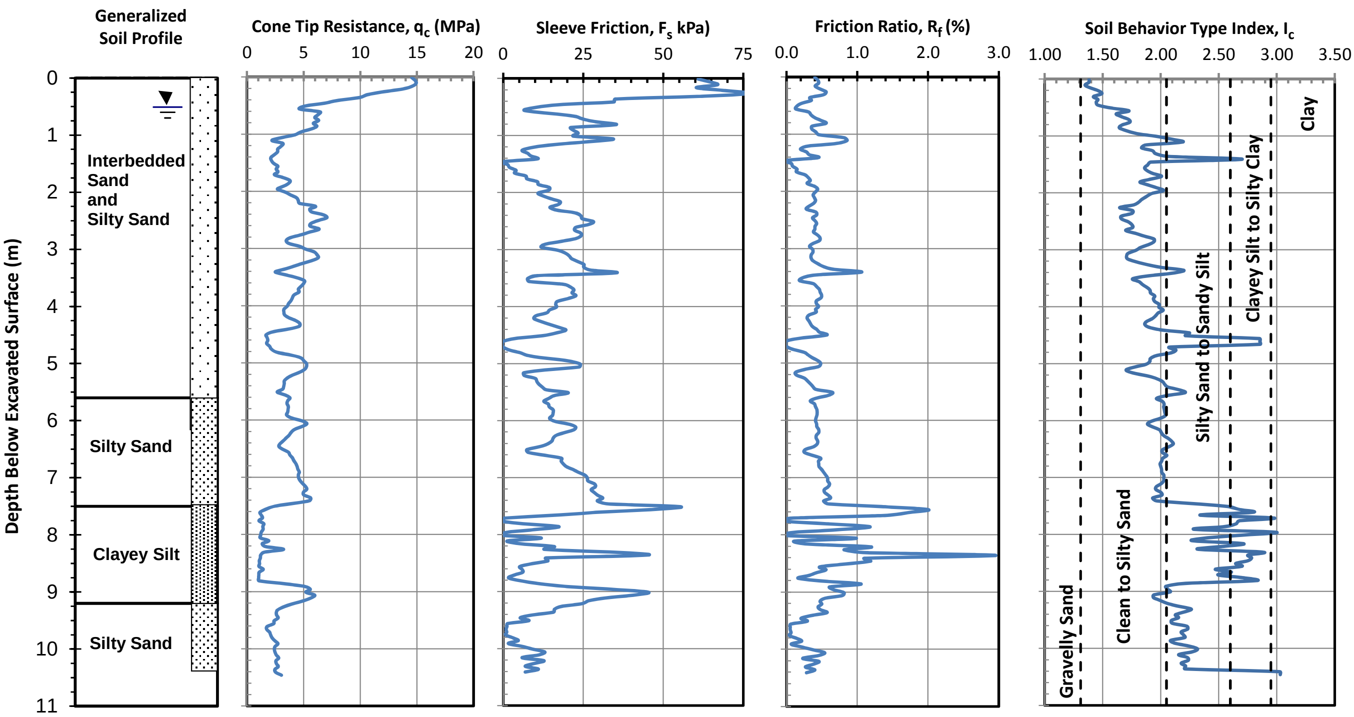

Fig. 1. Soil profile interpreted from Cone Penetration (CPT) testing along with profiles of cone tip resistance (q_c), sleeve friction (F_s), friction ratio (R_f) and soil behavior type index (I_c).

2.2 *Flat Dilatometer (DMT) Testing*

The flat dilatometer testing was performed with the Univ. of Michigan rig immediately adjacent to the CPT test sounding described previously. Readings were taken at 0.1 m intervals. The soil profile interpreted from the DMT test results is shown in Fig. 2 along with profiles of the dilatometer modulus (E_D), the material index (I_D), and the horizontal stress index (K_D), according to the common DMT interpretation formulae (Marchetti 1980, Marchetti et al. 2001). The interpreted soil profile is generally consistent with that obtained from the CPT. The soil profile from 0 to 5.6 m generally consists of thinly interbedded layers of silty sand and sand, typical of hydraulic fill, which are well resolved relative to other in-situ tests. Below this layer the profile becomes somewhat more uniform with thicker layers of silty sand (5.6 to 7.5 m), silty clay (7.5 to 9.2 m), and silty sand (9.2 to 10 m). The high horizontal stress index above a depth of 3 m suggests overconsolidation near the surface. The coefficient of earth pressure at rest (K_o) has been interpreted using the K_D value from the DMT and the q_c value from the CPT according to the following equations proposed by Baldi et al. (1986):

$$K_0 = 0.376 + 0.095\, K_D - 0.005\, q_c / \sigma'_{v0} \qquad (1)$$

valid for "seasoned" sand and

$$K_0 = 0.376 + 0.095\, K_D - 0.002\, q_c / \sigma'_{v0} \qquad (2)$$

valid for "freshly deposited" sand

Eq. 1 was used for the hydraulic fill to a depth of about 5.5 m and Eq. 2 was used for the deeper sand deposits and the results are plotted in Fig. 2. The K_o value from 3 to 7.5 m is typically between 0.4 and 0.5 indicating a normally consolidated sand; however, above 3 m, higher K_o values are indicating overconsolidated sands, presumably owing to desiccation.

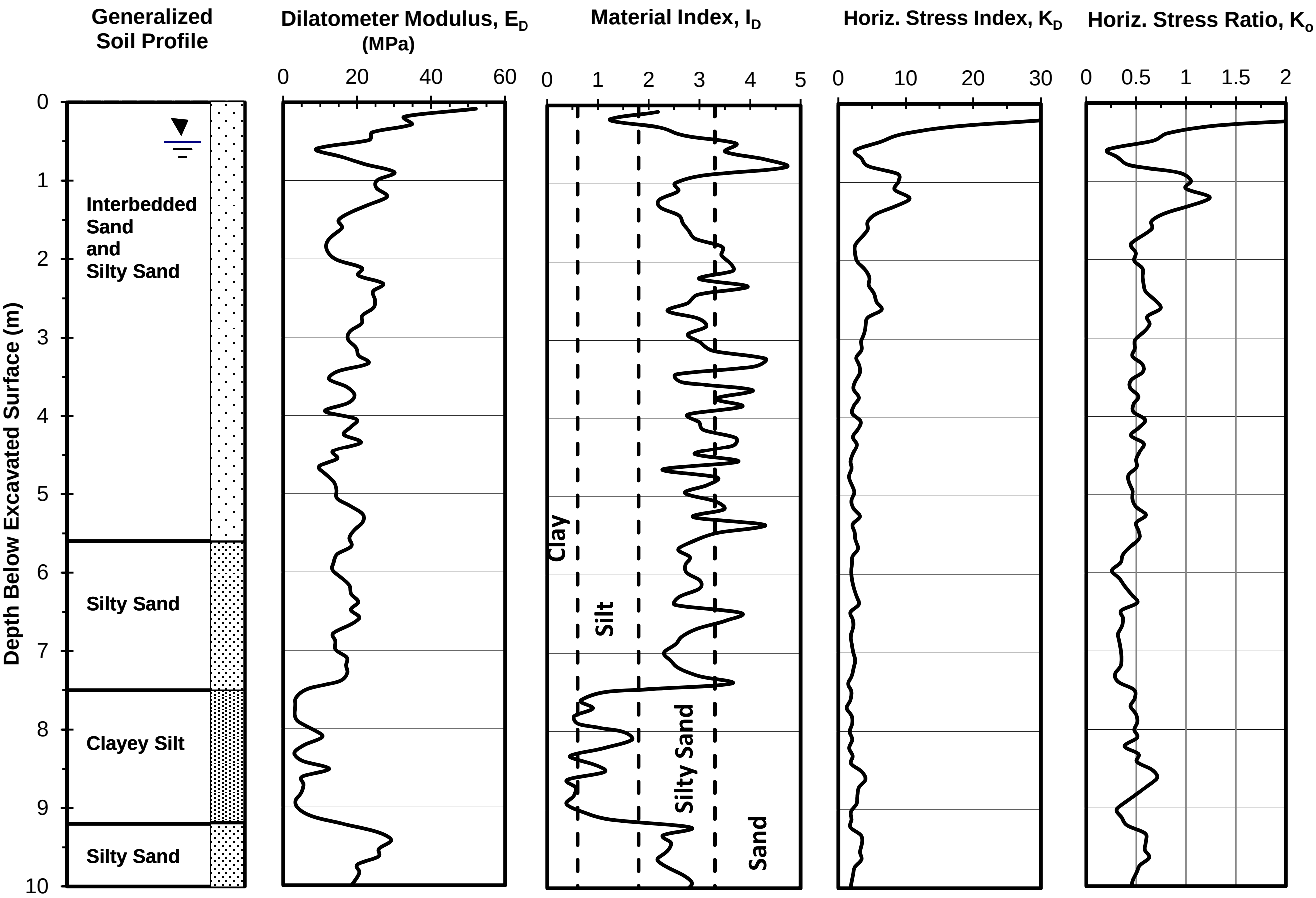

Fig. 2. Soil profile interpreted from flat dilatometer (DMT) testing along with profiles of dilatometer modulus, material index, horizontal stress index, and earth pressure ratio.

2.3 *Shear Wave Velocity (V_S) Testing*

Shear wave velocity measurements were made at the single pile test site located approximately 15 m north of the CPT/DMT soundings. In two cases the wave velocity was measured at 1 m intervals using a downhole seismic cone penetrometer approach. In the third case, the velocity was measured using downhole techniques with the receiver inside a steel test pile. The overburden corrected shear wave velocity (V_{S1}) profiles obtained from the three tests are plotted in Fig. 3 along with the soil profile at the test location. V_{s1} was obtained using the equation:

$$V_{S1} = V_S\, (\sigma'_{vo}/P_a)^{0.25} \qquad (3)$$

where P_a = atmospheric pressure approximated by 100 kPa and σ'_{vo}= initial effective vertical stress in the same units as P_a (Youd et al. 2001).

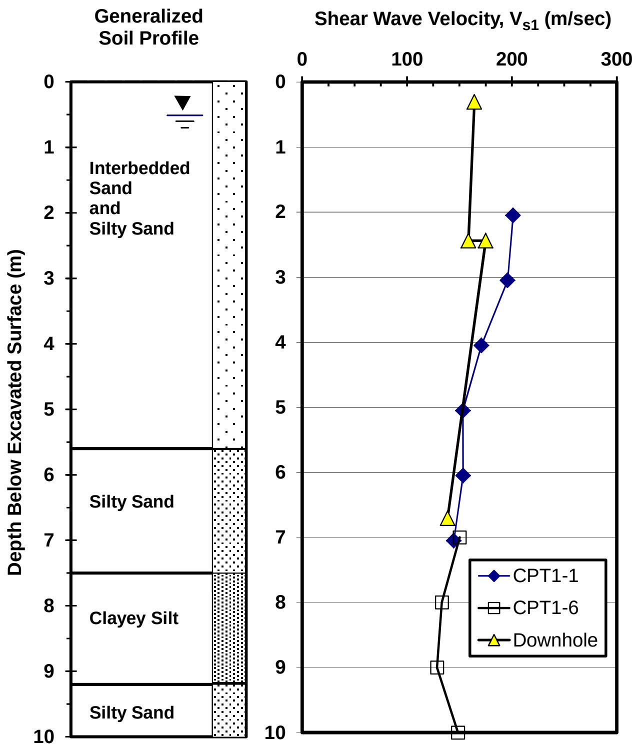

Fig. 3. Overburden corrected shear wave velocity profiles at a site about 15 m from the CPT/DMT soundings.

In general, the agreement between the three tests is very good. On average the velocity within the interbedded sand and silty sand layer is about 155 m/s. Based on the correlation between liquefaction resistance and V_{s1} developed by Andrus & Stokoe (2000), all of the sand layers would be considered susceptible to liquefaction as the measured V_{s1} is less than 210 m/s.

2.4 *Standard Penetration (SPT) Testing*

Standard penetration (SPT) tests were performed in bore holes at the single pile and four pile test sites located about 15 m north and south, respectively of the DMT/CPT soundings. Test borings were performed with drilling mud to stabilize the hole. A safety hammer, lifted with a rope and cathead system, was used to perform the tests. Energy measurements indicated that the hammer was providing 57% of the theoretical free-fall energy on average. The normalized penetration resistance $(N_1)_{60}$ was computed using the equation:

$$(N_1)_{60} = C_N C_E N \tag{4}$$

where $C_N = (\sigma'_{vo}/P_a)^{0.50}$, $C_E = ER/60$, and ER is the ratio of free-fall energy (57%) supplied by the hammer.

Plots of the $(N_1)_{60}$ values and fines contents from the two holes are provided in Fig. 4. The penetration resistance decreases from about 15 at 1 m to about 4 at a depth of 5.5 m. In contrast, the fines content increases with depth and may explain part of the decrease in $(N_1)_{60}$ with depth.

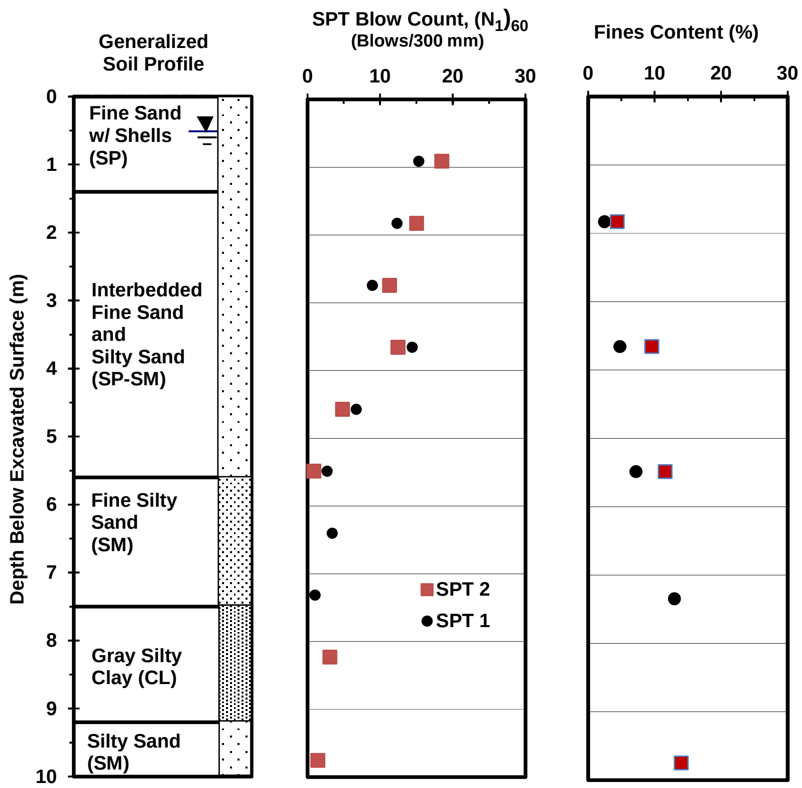

Fig. 4. Soil profile from SPT borings along with profiles of $(N_1)_{60}$ and fines content.

3 LIQUEFACTION ASSESSMENT

According to the simplified procedure developed by Seed & Idriss (1971), the factor of safety (FS) against liquefaction is given by the equation

$$FS = (CRR_{7.5}/CSR)\ MSF \tag{5}$$

where *CSR* = calculated cyclic stress ratio generated by the earthquake shaking; and $CRR_{7.5}$ = cyclic resistance ratio for magnitude 7.5 earthquakes, and *MSF* = magnitude scale factor = $10^{2.24}/M_w^{2.56}$, and M_w is the magnitude of the earthquake under consideration (Youd et al. 2001). For this study, which considers performance during the 1989 M6.7 Loma Prieta earthquake, the magnitude scaling factor is 1.33.

Seed & Idriss (1971) also developed the equation for the cyclic stress ratio (*CSR*) as follows

$$CSR = (\tau_{av}/\sigma'_{vo}) = 0.65(a_{max}/g)(\sigma_{vo}/\sigma'_{vo})r_d \tag{6}$$

where a_{max} = peak horizontal acceleration at the ground surface generated by the earthquake; g = acceleration of gravity; σ_{vo} and σ'_{vo} are total and effective vertical overburden stresses, respectively; and r_d = stress reduction coefficient = 1.0 - 0.00765z for $z < 9.15$ m. Ground motion recordings on Treasure Island and ground response analyses conducted at a number of sites around Treasure Island indicate that a_{max} in the vicinity of the test site was approximately 0.16g (Rollins et al. 1994)

For simplicity, the cyclic resistance ratio (*CRR*) was generally computed based on recommendations by Youd et al. (2001) where the resistance ratio from CPT results is determined using techniques formulated by Robertson & Wride (1998) and the resistance ratio based on V_S is based on charts developed by Andrus & Stokoe (2000). With respect to DMT results, the *CRR* was determined using the equation:

$$CRR=0.0107K_D^3–0.0741K_D^2+0.2169K_D–0.1306 \tag{7}$$

proposed by Monaco et al. (2005) where K_D is the horizontal stress index obtained from the DMT.

A comparison of the factor of safety against liquefaction computed using the CPT, DMT, SPT and V_S approaches for determining *CRR* is provided in Fig. 5. Although there are some notable differences, the agreement between the various methods is generally quite good. For example all methods predict liquefaction ($FS < 1.0$) from a depth of about 3 m to 7.5 m below the ground surface. This result provides a high degree of confidence that this layer actually liquefied during the Loma Prieta earthquake.

Despite the fact that the DMT based approach was primarily developed for clean sand, the computed factor of safety tracks the factor of safety obtained with the CPT quite well in the depth range from 3 m to 7.5 m where a number of silty sand layers are encountered. In contrast, the factor of safety from the DMT is considerably higher near the ground surface than predicted by the CPT or SPT methods. The high DMT-based factors of safety appear to be associated with higher K_o values within this depth range (see Fig. 2). Although the CPT based factor of safety also increases in this range, presumably owing to the higher K_o values, they are still lower than predicted by the DMT approach. The increased factor of safety predicted by the DMT is likely a result of the increased sensitivity of the DMT to K_o effects relative to the CPT (Maugeri and Monaco 2006). Because the database of field performance data relative to the DMT approach is so limited, it is not possible to determine if the increased factor of safety is justified at the present time.

As noted by a number of researchers (e.g. Ishihara et al. 1977, Seed 1979), the liquefaction resistance of sand clearly increases as the K_o value increases. However, the correlations between *CRR* and in-situ test parameters [i.e. q_c, $(N_1)_{60}$, V_s, K_D] have generally been assumed to be independent of K_o because an increase in K_o is expected to produce a comparable increase in the in-situ test parameter as suggested by Seed (1979).

Salgado et al. (1997) examined the effect of K_o on both liquefaction resistance and cone penetration resistance separately and concluded that the *CRR* vs q_{c1} relationship was relatively unaffected by K_o for q_{c1} values less than 12 MPa and slightly unconservative for higher q_{c1} values. In contrast, Harada et al. (2008) also investigated the influence of K_o on both liquefaction resistance and on SPT and CPT resistance and found that both the *CRR* vs q_{c1} and *CRR* vs $(N_1)_{60}$ curves were conservative without consideration of K_o effects. Harada et al. (2008) recommend a suite of *CRR* vs q_{c1} curves to properly account for K_o effects. Therefore, there is some controversy in the literature regarding the effect of K_o on liquefaction correlations based on in-situ tests which is deserving of additional research. This issue is particularly important in evaluating liquefaction resistance after ground improvement because ground improvement typically increases both the soil density and K_o.

The liquefaction factor of safety predicted by the V_s correlation is significantly less than that predicted by the other methods throughout the depth investigated. At shallow depths where K_o is high, the lower factor of safety may be attributed to V_s being less sensitive to K_o than the CPT q_c or DMT K_D as noted by Maugeri & Monaco (2006). At greater depths, the discrepancy is likely associated with the presence of non-plastic silt. Liu & Mitchell (2006) noted that *CRR* vs V_s correlations for silty sands are often overly conservative for these materials and predict liquefaction when it does not occur in the field. Liu & Mitchell (2006) recommend curves which plot to the left of the Andrus & Stokoe (2000) curve for silty sands. These curves would lead to higher factors of safety for the silty sand layers and better agreement with the other methods.

Typically, the boundary between liquefaction and no liquefaction for a given in-situ test parameter [q_c, $(N_1)_{60}$, V_s, K_D] is evaluated by plotting the *CSR* for a given event versus the in-situ parameter for the loosest layer in the profile which is assumed to be the liquefiable layer. When this procedure is employed for the Treasure Island sites using DMT results both the loosest silty sand and sand layers plot considerably above the *CRR*-K_D curve. Although this result is consistent with field performance, it is not particularly helpful in defining the location of the boundary curve.

In lieu of waiting for additional field performance data, the CSR and K_D data pairs within the depth range from 3.0 m to 7.5 m have been plotted against the *CRR* vs K_D curve in Figs. 6 and 7 for clean sand and silty sands, respectively. As noted previously, all of the in-situ tests generally predicted liquefaction within this zone. For the points identified as sand based on the DMT I_D, the data points in Fig. 6 plot right up to the boundary curve but do not cross over, suggesting that the curve is appropriately positioned for this *CSR* value. For the data points identified as silty sand based on the DMT I_D, the data points in Fig. 7 typically plot to the left of the curve but some points cross over the curve indicating that the curve may be somewhat unconservative for silty sands at this *CSR* value.

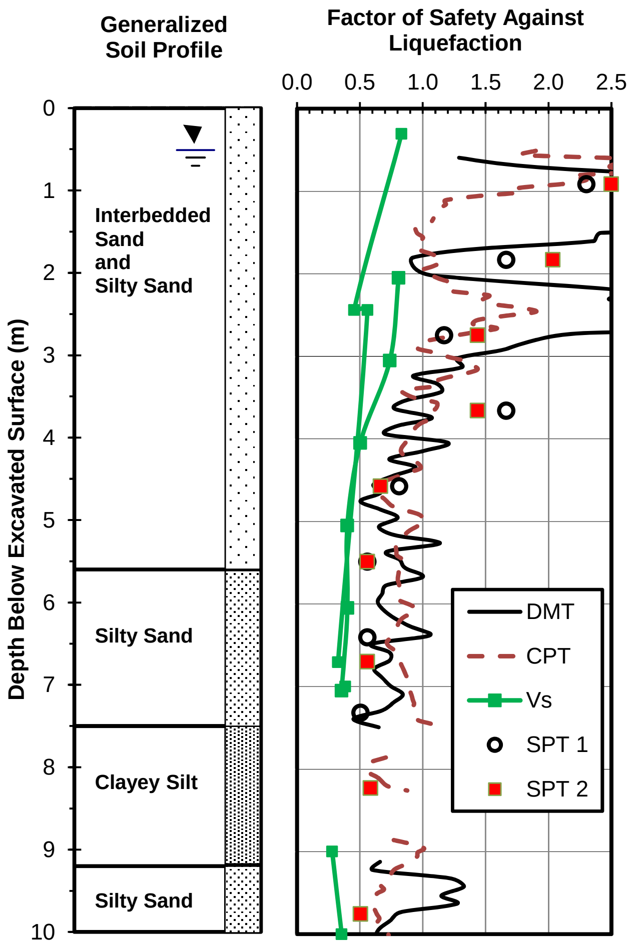

Fig. 5. Comparison of factor of safety against liquefaction computed using CRR obtained from CPT, DMT, SPT and V_S test results.

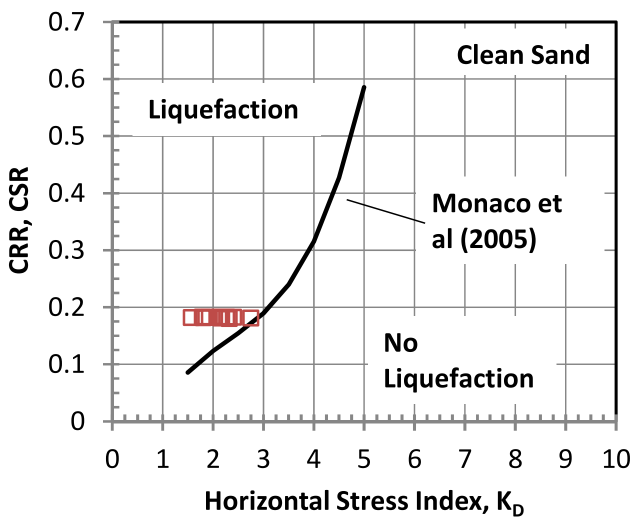

Fig. 6. Comparison of *CSR* vs K_D values for clean sand predicted to liquefy between 3.0 and 7.5 m depth in comparison with the *CRR* vs K_D curve for clean sand proposed by Monaco et al. (2005).

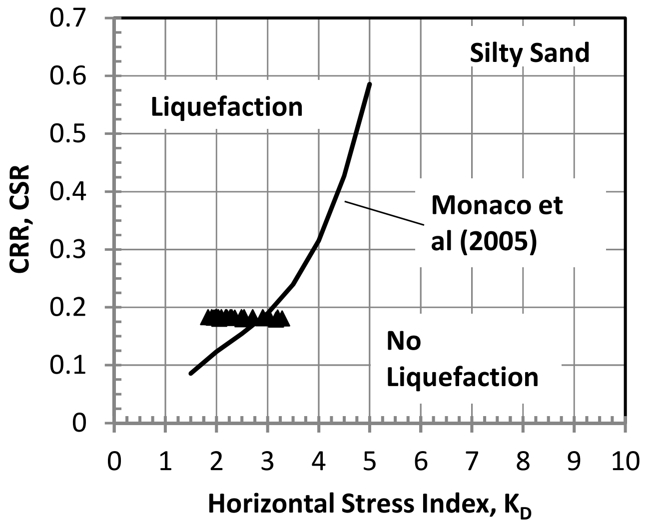

Fig. 7. Comparison of *CSR* vs K_D values for silty sand predicted to liquefy between 3.0 and 7.5 m depth in comparison with the *CRR* vs K_D curve for clean sand proposed by Monaco et al. (2005).

4 CONCLUSIONS

Investigations at Treasure Island involving CPT, DMT, SPT and V_s measurements provide a relatively rare opportunity to compare and contrast the performance of these methods in predicting liquefaction. Based on the results of the field testing and analysis described previously the follow conclusions are presented:

1. All the in-situ techniques were relatively consistent in predicting liquefaction within a depth range of 3 m to 7.5 m below the ground surface. This result highlights the value of obtaining consistent results from multiple methods in assessing liquefaction hazards.

2. The liquefaction factor of safety predicted by the CPT and DMT approaches was quite consistent in the depth range from 3 m to 7.5 m despite the higher fines content in this zone for which the DMT correlation is not well calibrated.

3. At depths less than 3 m with relatively clean sand, the DMT predicted higher factors of safety than the CPT, although the CPT also showed increased resistance in this zone. The higher factors of safety from the DMT are likely a result of the increased sensitivity of the DMT to the higher K_o values in this zone relative to the CPT.

4. Analysis of the *CSR* and K_D data points within the depth range from 3 m to 7.5 m, where all methods predict liquefaction, suggests that the liquefaction boundary curve by Monaco et al. (2005) is reasonable for clean sand but may be somewhat unconservative for sitly sands.

5. The liquefaction factor of safety from the Andrus & Stokoe (2000) *CRR* vs V_{s1} correlation was consistently lower than predicted by other in-situ techniques. At shallow depths this appears to be due to the insensitivity of V_{s1} to increases in K_o relative to other in-situ tests. At greater depths this is likely due to the higher silt content which has led to over-conservatism in V_{s1} based assessments of liquefaction in silty sands at other sites (Liu & Mitchell 2006).

6. There is a significant need for increased research to understand better the influence of K_o on liquefaction resistance curves from in-situ tests. This is particularly important in assessing liquefaction resistance after ground improvement which often increases both sand density and the horizontal earth pressure.

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