Comparative study of sub-soil profiles obtained by SDMT and SPT tests and subsequent determination of settlement of post earthquake condition

K. Bandyopadhyay[i)] and S. Bhattacharjee[ii)]

i) Professor, Department of Construction Engineering, Jadavpur University, Salt Lake Campus, Kolkata700-098, India
ii) Deputy Project Manager, Mackintosh Burn Ltd., Salt Lake, Kolkata700-064, India

ABSTRACT

Seismic dilatometer test (SDMT) was conducted in the Salt Lake campus of Jadavpur University, Kolkata using Marchetti's SDMT equipment. Another location in Kolkata was chosen where alluvial deposits were encountered for performing liquefaction analysis by SPT method only. Using the usual correlations as mentioned in the report of the ISSMGE TC 16 on ground property characterization from in-situ testing (2001), oedometer modulus, undrained shear strength, friction angle and shear wave velocity profile were found out. In the same location, standard penetration test (SPT) was also carried out. Based on the field SPT values and visual soil classification, a sub-soil profile was delineated. Engineering properties of the various layers were determined from standard correlations available in the literature. It was observed that both the sub-soil profiles obtained from these two tests were more or less similar. In the present investigation, an attempt has been made to compare the results of these two methods viz., seismic dilatometer test (SDMT) and standard penetration test (SPT). Based on the small strain shear modulus from DMT as well as shear wave velocity profile from SDMT tests, an effort has also been made to determine the liquefaction potential and settlement of post earthquake condition of the sand layers using standard charts given by Ishihara and Yoshimine (1992). Besides, using the correlation between $(N_1)_{60}$ and volumetric strain (ε_v) as reported by Tokimatsu and Seed (1987), the same were obtained for SPT tests. Subsequently, comparison is made between results of these two methods. Finally, recommendations are made regarding the suitability of these two methods with particular reference to liquefaction potential and post earthquake settlements.

Keywords: SDMT, SPT, Earthquake, Liquefaction, Volumetric strain

1 INTRODUCTION

Flat dilatometer test (DMT) was developed in Italy by Prof. Silvano Marchetti being initially introduced in North America and Europe during 1980s. Subsequently, in recent years many other countries have started using it. It is basically a push-in type in-situ test. It is relatively quick, simple, economical and highly reproducible. It is executable with a variety of field equipment. It provides estimates of various important design parameters/ information. One of the most important one is the investigation of the in-situ soil compressibility for settlement prediction. Seismic dilatometer test (SDMT) is a DMT with an add-on seismic module for measuring the shear wave velocity, V_s also. Procedures for assessing the liquefaction potential of sands and silty sands have been reported by many researchers. Amongst these, the Standard Penetration Test (SPT) by Youd et al (2001), the Cone Penetration test (CPT) by Roberstson & Wride (1998) and the shear wave velocity (V_s) test by Andrews & Stokoe (2000) deserve special mention. More recently, Monaco et al (2005) proposed a method for predicting the liquefaction using K_d value obtained from Flat Dilatometer (DMT) testing. They have observed that K_d is more sensitive to factors such as stress history, ageing, cementation and structure than V_s and that it greatly increases the liquefaction resistance for a given relative density (Maugeri & Monaco, 2006).

Seismic dilatometer test (SDMT) was conducted in the Salt Lake campus of Jadavpur University, Kolkata using Marchetti's SDMT equipment. In this case, a clear sub-soil profile was obtained. It was revealed that sub-soil consisted of a fill layer of silty sand of about 2.5m thickness from the existing ground level. This layer was followed by a very soft to soft silty clay layer of 4.5m depth underlain by a stiff clay layer up to great depth. Using the usual correlations as mentioned in the report of the ISSMGE TC 16 on ground property characterization from in-situ testing (2001), oedometer modulus, undrained shear strength, friction angle and shear wave velocity profile were found out. In the same location, standard penetration test (SPT) was also carried out. Based on the field SPT values and visual soil classification, a sub-soil profile was delineated. Engineering properties of the various layers were determined from standard correlations available in the literature. It was observed that both the sub-soil profiles obtained from these two tests were more or less similar and reveals a typical normal Calcutta deposit for this place.

SPT method was adopted for another site in Kolkata which consisted predominantly of alluvial deposit. Liquefaction analysis was done and post-earthquake settlement was also calculated based on which extent of damage due to earthquake is predicted.

The recent spate of geological activity in the region around Kolkata reveals that it has become vulnerable to earthquakes. Besides, the subsoil profile at some locations reveals an alluvial deposit of the Gangetic basin. This is why it is strongly felt that a study of the liquefaction potential of this region will be relevant in this context. Based on the small strain shear modulus and shear wave velocity profile from SDMT tests, an effort has also been made to determine the liquefaction potential and settlement of post earthquake condition of the topmost soil layer by various methods. Besides, using the correlation between $(N_1)_{60}$ and volumetric strain (ε_v) as reported by Tokimatsu and Seed (1987), the same parameters were obtained for SPT tests. For SPT tests, post-earthquake settlement is calculated using both the methods of Tokimatsu and Seed (1987) as well as of Ishihara and Yoshimine (1992). Subsequently, comparison is made between results of these three methods. Finally, recommendations will be made regarding the suitability of these methods with particular reference to liquefaction potential and post earthquake settlements.

2 GEOLOGICAL CONTEXT

The extensive Indo-Gangetic alluvial plains of Bengal, Bihar, Uttar Pradesh and the Punjab lie in between the Peninsula and the Extra-Peninsula as per the different stratigraphic groups of the vast Indian subcontinent. This Indo-Gangetic alluvial plain has been formed during the Quaternary era. They are basically made up of sand, clay and peat beds. Extensive stretches of low land with a very small gradient towards the sea are found in these regions. The Indo-Gangetic alluvial plains are made up of undisturbed layers of geologically recent sediments. They have been deposited gradually in a very large depression, lying in between the Peninsula and the Extra-Peninsula. The thickness of this structurally simple sedimentary column is of the order of about 1.5 to 6 kilometers. The precise geology of the basement on which the Indo-Gangetic alluvium lies has not been known as yet.

Numerous borings have been carried out in and around Kolkata long since the various developmental activities had been gathering momentum. The subsoil profiles obtained from these exploratory programs reveal that there are two distinct categories of sub-soil, viz., one which is called the Normal Calcutta deposit and the other the newer alluvial deposit. In some places, superposition of these two deposits is also encountered. It is the latter deposit which is of concern owing to its susceptibility to liquefaction. The recent geological activities in the region show various small to medium range earthquakes. This is why it is strongly felt that it will be worthwhile to undertake some liquefaction analysis of this region and the present paper focuses on some of these aspects.

In the present study, liquefaction analysis was carried out for two sites in Kolkata comprising the two types of deposits as mentioned earlier. One of the sites was inside the Salt Lake Campus of Jadavpur University (Site A) and another was near Tollygunge Metro station beside the Tolly's nallah (Site B).

3 LIQUEFACTION ANALYSIS

The liquefaction analysis is carried out according to the "simplified procedure" introduced by Seed and Idriss (1971) and values of the liquefaction safety factor, FS_L are calculated for both the sites. For site A, the liquefaction safety factor, FS_L is determined by DMT analysis as well as by the method of Tokimatsu and Seed (1987). For site B, this is calculated by the procedure proposed by Ishihara and Yoshimine (1992). Besides, the post-earthquake settlement is also evaluated.

3.1 Analysis by DMT method

Flat dilatometer (DMT) test was carried out in Salt Lake Campus of Jadavpur University (Site A) only. The sub-soil profile reveals silty sand/sandy silt upto a depth of 2.2m below the existing ground level. Below this depth clay is observed upto great depth. This is why DMT results upto the depth of 2.2m is presented here for liquefaction analysis. Standard DMT curves for various parameters for different depths are presented in Fig.1.

Cyclic Resistance Ratio (CRR) was calculated from horizontal stress index (K_d) values using the equation proposed by Monaco et al (2005)-

$$CRR = 0.0107K_d^3 - 0.0741K_d^2 + 0.2169K_d - 0.1306 \quad (1)$$

CRR was also calculated from corrected shear wave velocity (V_{s1}) as given by Andrus and Stokoe (2000). The plot of CRR vs. K_d is shown in Fig. 2.

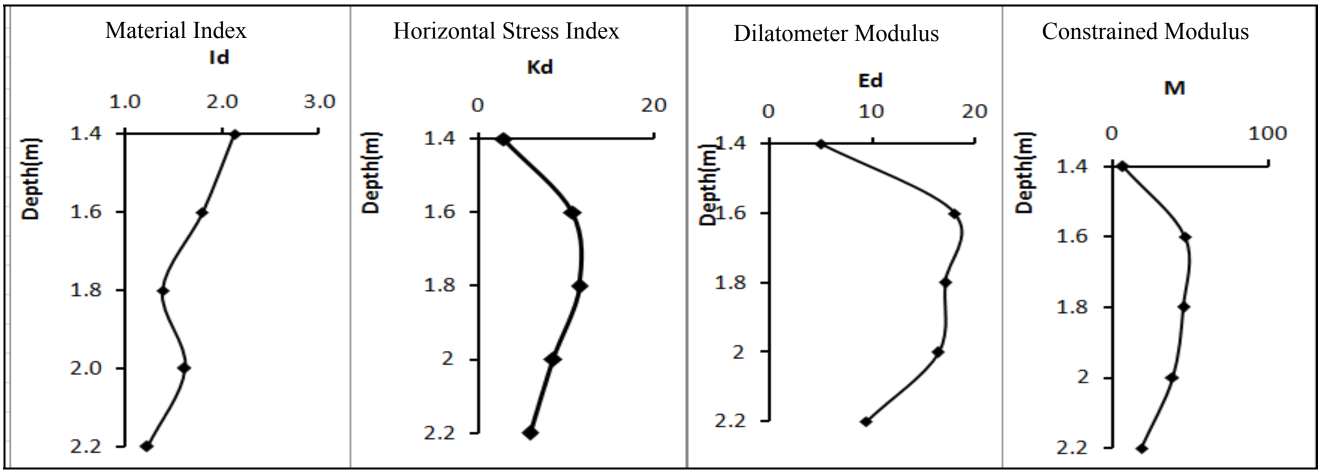

Fig. 1. Standard DMT curves for various parameters for different depths

Besides, the factor of safety against liquefaction (FS_L) is also calculated by these two methods. As the CRR values are too high for both the methods, the FS_L values are also very high. Similar trend is also noticed when FS_L values are obtained from Vs_1 as some of the values are more than 200m/s giving FS_L values out of range of curve. CRR obtained from these two methods are more or less at par with each other.

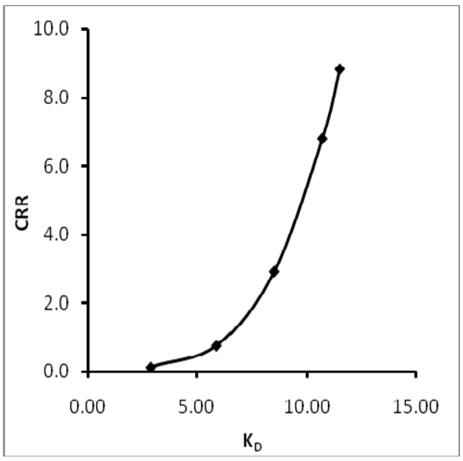

Fig. 2. Plot of CRR vs. K_d

Subsequently, these points are plotted in Monaco's standard plot of CRR/CSR vs. K_d and is shown in Fig. 3.

It is observed that all the points fall to the right side of Monaco's line indicating no liquefaction. Besides, G_0/E_d vs. K_d and G_0/M_{DMT} vs. K_d are also plotted and shown in Figs.4 & 5.

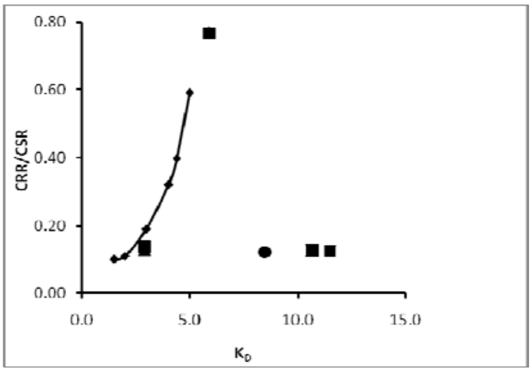

Fig. 3. Plot of CRR,CSR vs. K_d and comparison with Monaco's curve

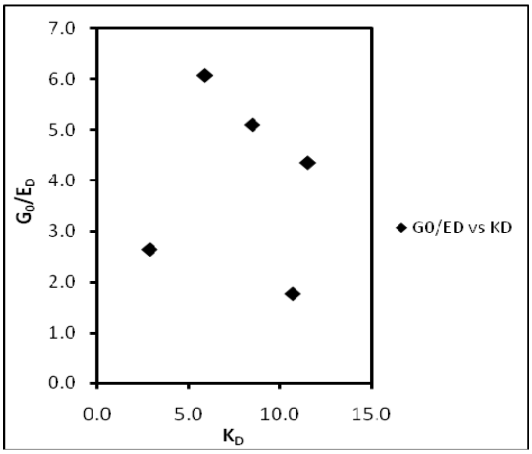

Fig. 4. Figure showing variation of G_0/E_D vs. K_D

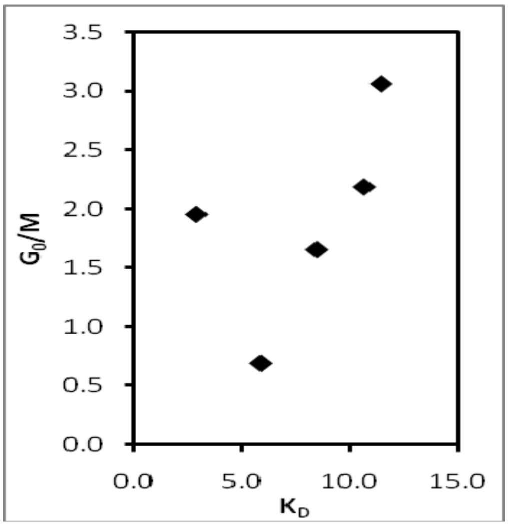

Fig. 5. Figure showing variation of G_0/M vs. K_D

Shear wave velocity, Vs vs depth curve is presented in Fig. 6.

Vs_1 values are superposed in the standard plot of Andrus and Stokoe (2000). As expected all the values fall in the region of no liquefaction as shown in Fig.7.

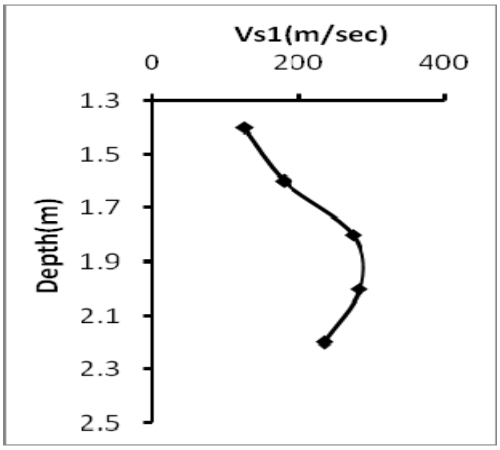

Fig. 6. Plot of shear wave velocity vs. depth

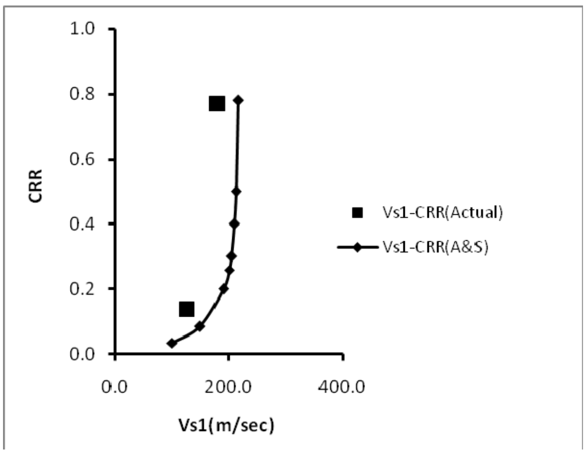

Fig. 7. Figure showing variation of CRR vs. V_{s1} and comparison with Andrus & Stokoe

3.1.1 Development of the field G- γ curve

In this present study an effort is also made to develop the field G/G_0 vs. γ curve from the results of DMT test. The working strain shear modulus, G is calculated from the relationship given by Monaco et al (2009) as: $G = M_{dmt}/2.67$.

The values of small strain modulus, G_0 are obtained from its relationship with K_d. Finally, by trial and error, a curve is drawn manually for the range of values of G/G_0 as obtained from this site and using Ishihara's (2001) intermediate working strain limit of 1 to 0.01%. This curve is presented in the Fig. 8. This plot shows close proximity with that of Athanasopoulos (1995) as mentioned in Monaco *et al* (2009).

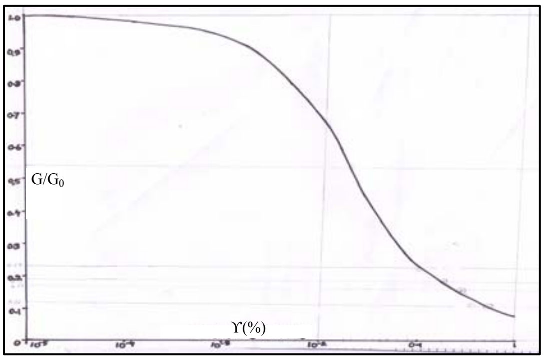

Fig. 8. Development of field G-Υ curve by DMT test

3.1.2 Calculation of settlement

At first, the value of the expression, $\gamma_{eff}(G_{eff}/ G_{max})$ is determined from the eqn.(1) as:

$$\gamma_{eff}(G_{eff}/ G_{max}) = 0.65\ (a_{max}/g)\ \sigma_{v0} r_d / G_{max} \qquad (2)$$

For each depth, the values of the working strain (γ_{eff}) is obtained from each of the values of 0.65 (a_{max}/g) $\gamma_{v0} r_d/ G_{max}$ from the plot of Tokimatsu & Seed (1987). Subsequently, the small strain shear modulus (G_{max}) is calculated from the Dilatometer modulus (E_d) using the equation developed by Bellotti et al (1986) i.e., $G_{max}/ E_d = 2.9$.Then, the values of G_{eff} are calculated from the above eqn.(2) by substituting the values of γ_{eff} as obtained earlier and the new G_{max}. Also, G_0 is determined from the usual correlations with M_{dmt} and K_d as formulated by Marchetti et al (2008) and Monaco et al (2009). Finally, the values of G_{eff}/ G_0 are plotted in the G-γ curve of Fig. 8 to obtain the values of effective shear strains (γ) to take into consideration the dynamic effect due to the earthquake. Corresponding to the values of γ, the values of the volumetric strains (ϵ_v) are obtained from the chart of Tokimatsu and Seed (1987) to calculate the settlement of different layers. Here, values of peak ground acceleration, a_{max} is assumed to be 0.2g with 10% probability of exceedence in 50 years. The depth reduction factor, r_d is calculated according to the values proposed by Liao & Whitman (1986) given by the equations, (3A & 3B):

$$r_d = 1-0.00765z, \text{ for } z<9.15\text{m} \quad (3A)$$
$$r_d = 1.174-0.0267z, \text{ for } 9.15\text{m}<z<23\text{mm} \quad (3B)$$

σ_{v0} is the total vertical stress at the bottom of soil column. At this site (A), the water table was at a depth of 3.0 m below the existing ground level and as such the sand layer which lies much above this depth was assumed dry. This is why the settlement analysis is done by the method of Tokimatsu & Seed (1987).

3. 2 Analysis by SPT method

Both the locations (Site A and B) were analyzed for liquefaction by this method.

3.2.1 Analysis of Site A

The sub-soil profile of this site has been presented in Fig. 9. Here CRR values have been determined against $(N_1)_{60}$ values from the plot of Seed & Idris (1983). As most of the $(N_1)_{60}$ values are more than 35 indicating dense to very dense condition of the layers, values of CRR cannot be obtained from this chart. Factors of safety against liquefaction are also found to be much higher than unity for all the depth ranges considered.

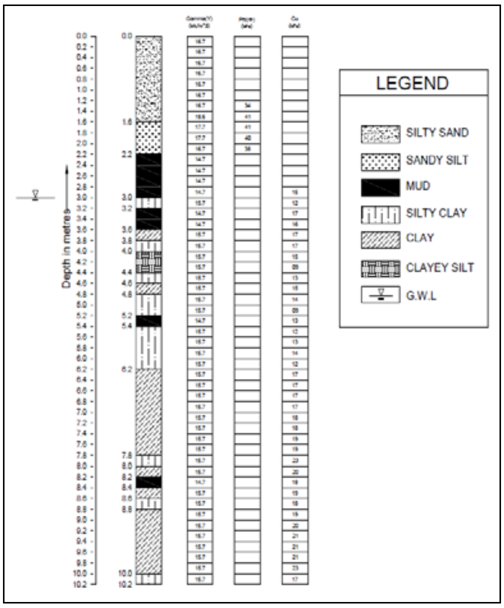

Fig. 9. Sub-soil profile at JU site (A)

Subsequently, the settlement of each of the layers and the total settlement upto the depth of 2.2m were calculated applying the method of Tokimatsu & Seed (1987). The results of depth vs. settlement of this study are presented in Fig.10. In the same figure, comparison with the settlements obtained from DMT method is also shown.

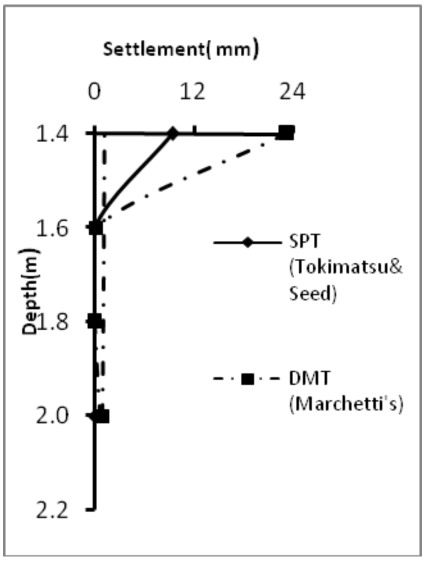

Fig. 10. Plot of depth vs. settlement for site A

3.2.2 Analysis of site B

The sub-soil profile of this site is presented in the Fig.11. The sub-oil profile reveals that there is a top soil of 2.5m depth consisting of soft/medium stiff grey silty clay/clayey silt underlain by layers of fine to coarse sand of varying relative density from very loose to dense state. The water table was located at a depth of 3.5m below the existing ground level.

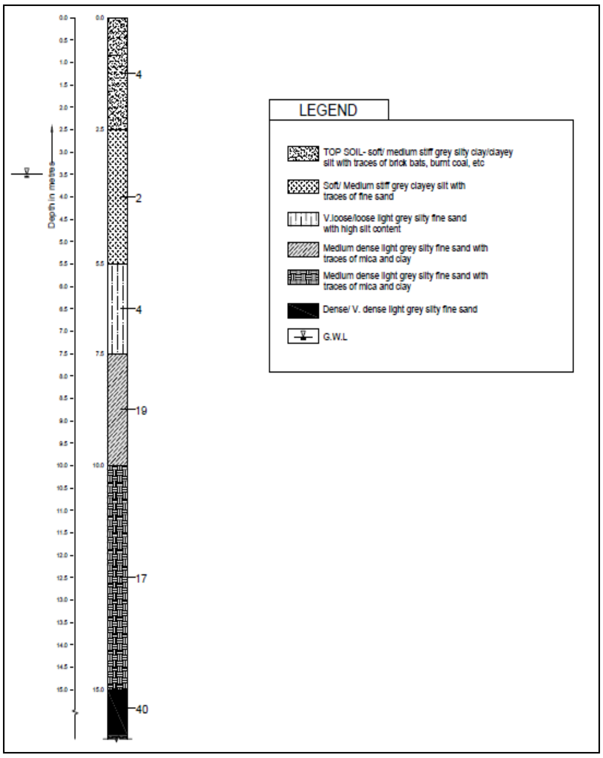

Fig. 11. Sub-soil profile at site (B)

The liquefaction analysis was carried out for the sand layers from the depth of 3.5m upto 20m assuming the soil to be fully saturated. Here, the liquefaction analysis is carried out using the “simplified procedure” introduced by Seed and Idriss (1971).

The results of factor of safety vs. depth are plotted in Fig.12.

It is observed from this figure that for all the depths considered, the factors of safety are less than unity indicating liquefaction. The post-earthquake volumetric strains were obtained from charts developed by Ishihara & Yoshimine (1992) and also from Tokimatsu & Seed (1984).

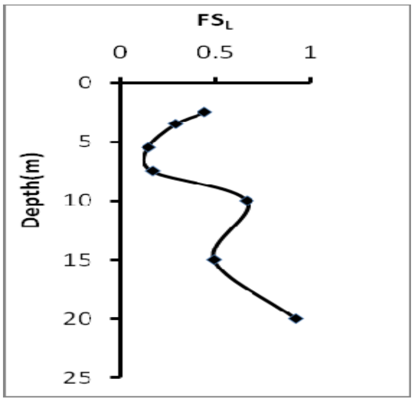

Fig. 12. Variation of factor safety vs. depth for site B

Finally, the settlements were calculated. The depth vs. settlement plots are presented in Fig. 13.

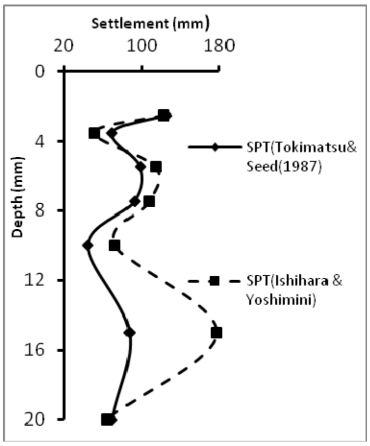

Fig. 13. Comparison of settlement vs. depth at site B

4 COMPARATIVE STUDY OF VARIOUS METHODS

Factor of safety vs. depth for both DMT and that of by Tokimatsu & Seed (1984) for site A are presented in Fig. 14.

The depth vs. settlement for these two methods is plotted in Fig. 10 earlier.

Besides, an attempt is also made to show the inter-relationship of K_d with $(N_1)_{60}$. This distribution is presented in Fig.15 below and the corresponding equation of the best fit line is found to be:

$$(N_1)_{60} = 18.32 \times \exp(0.074K_D) \quad (4)$$

Similar work is being carried out for different locations in order to collect sufficient data to comment on any conclusive relationship in this aspect.

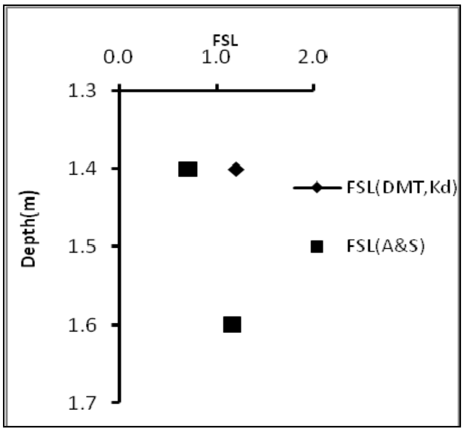

Fig. 14. Variation of factor of safety vs. depth

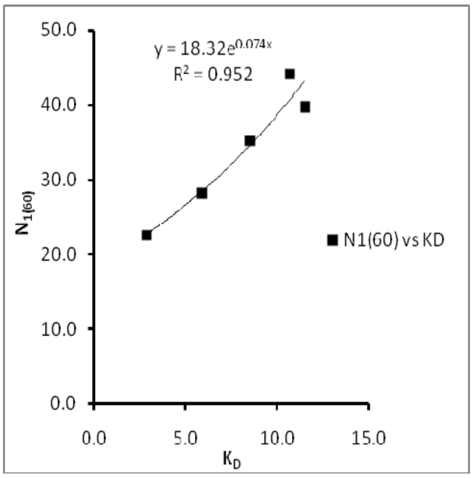

Fig. 15. Comparison of K_d vs. $(N_1)_{60}$

5 RANGE OF SETTLEMENTS AND FORECASTING EXTENT OF DAMAGE

The range of settlement was from 0.03 mm to 23.3 mm in all the layers and the total settlement upto 2.2 m depth was 26.14 mm as per DMT method. The corresponding values were 0.017 mm to 9.52 mm respectively and the total settlement was 9.74 mm by Tokimatsu & Seed (1984). As the total depth of the sand layers is not significant, the settlements in both the cases are very small. The settlement of the top layer from DMT method was more than double than that of the latter and the reason may be attributed to the fact that the effective shear strain corresponding to this layer was out of bound of the field G-γ curve and the maximum value was considered.

In the second site (B), the range of settlement in the sand layers was from 57.7 mm to 177 mm and the total settlement upto 20m depth was 536.6 mm as per

Ishihara & Yoshimine (1992) and that from 45 mm to125 mm and the total settlement was 392.5 mm as per Tokimatsu & Seed (1984) respectively. Both these values are more or less comparable and they lie within 300 to 700 mm range. As per Ishihara & Yoshimine (1992) if the settlement values lie in this region, extensive damage is predicted with consequent occurrence of large cracks, sprouting of sands and lateral movement of the ground surface.

But, here at this site, there is a cushion of soft clay layer at the top upto a depth of about 5.0 m. This cushion is expected to arrest the settlements to a greater extent and might bring down the severity of damage within the medium range (100 to 300 mm).

6 CONCLUSION

The outcome of this present investigation reveals that the development of the field G-γ decay curve from SDMT tests gives important information on the effective shear strains. Once this is developed, the effective shear strains corresponding to a given earthquake loading may be obtained using the standard correlations of other researchers. It is also observed that the settlements calculated from this method are comparable with those of other methods. Further research may be carried out to establish any definite relationship of SPT with K_d.

It is also observed from this study that if there is a moderate to high intensity earthquake, settlement of soil and consequent damage to structures may be significant in this region where alluvial deposit is encountered.

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