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Observation on Soil Liquefaction Analysis at Uttara Depot of Dhaka MRT Line 6

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Abstract

The Dhaka Metro Rail Line 6, also known as DMRT Line 6, is the first metro rail megaproject in Bangladesh which is undertaken by the government owned autonomous institution named Dhaka Mass Transit Company Limited (DMTCL). The Dhaka MRT Line-6 project consists of eight packages in total from CP (Contract Package)-01 to CP-08. The CP-01 package covers the construction of a depot at Diabari in Uttara, Dhaka. This package includes the soil improvement and land development for the construction of embankment at depot area. As CP-01 is a land development project, this project is sensitive to various geotechnical challenges, so it is obvious to identify and mitigate the geotechnical concerns associated with the project. This research analyses the potential of soil liquefaction which is a prime geotechnical challenge for this project at different boreholes of the depot. The required data is taken from the soil test report of three major boreholes (NDP-02, NDP-08 and NDP-11) at depot area and the analysis is then done according to the Seed and Idriss formula. Finally, the Factor of Safety (FL) at different depths of the soil is represented graphically to understand the overall potentiality of liquefaction with subsoil condition of the depot area.

Keywords

Soil liquefaction, liquefaction potential, seed and idriss formula, uttara depot, Dhaka MRT Line-6

INTRODUCTION

The Dhaka Metro Rail mega-project (Dhaka MRT Line 6) is the first metro project of Bangladesh. This line is currently under construction and starts in Uttara III and continues via Pallabi, Mirpur 10, Khamarbari, Farmgate, Shahbagh, TSC, Doel Chattar, Press Club, and ends at the Bangladesh Bank (Motijheel). This 20.1km urban railway line consists of an elevated section, 16 stations and a depot in Uttara (See Figure 1).

Figure 1 Route Map of Dhaka MRT Line 6 [1]

The depot is located on the ground at risk for consolidation and liquefaction. Figure 2 shows the typical soil profile of the depot area, i.e., Diabari (Uttara).

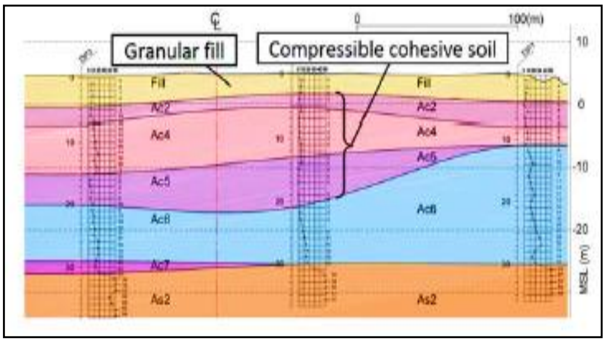

Figure 2 Typical Soil Profile of Uttara Depot [1]

Diabari was low-lying and filled with dredged sand. General soil profile shows that from the existing ground level (EGL) up to the first 3.0m depth, a loosely dense dredged sand layer exists, followed by an organic clayey silt layer of thickness of 1 to 5m [1]. With an SPT N-value of around 5 and located below the ground surface to a depth of approximately 5m, the granular fill layer is at danger of liquefaction. Consolidation settling is a possibility in certain of the cohesive soil layers that are present at a depth of around 5-15 meters and have an SPT N-value of less

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than 8. As a result of the filling embankment and the liquefaction of the granular soil layer due to seismic activity, the depot at Uttara is situated on terrain subject to geotechnical risk [1]. This project will significantly impact the economy of Bangladesh, making it evident that the geotechnical risks related with it should be identified and addressed effectively.

RESEARCH SIGNIFICANCE

This study seeks to analyze the liquefaction probabilities at the soil layers of different zones on depot area. The methodology will be approached for the analysis of liquefaction will be Seed and Idriss formula (1971). It will be analyzed whether below the ground surface to a depth of approximately 5m (with SPT N value 5), the granular fill layer of clayey silt is at danger of liquefaction or not. The soil data of three different boreholes at various locations will be considered for this study and the liquefaction potential will also be assessed at different depth of the soil of these boreholes.

METHODOLOGY

Empirical methods that utilize field exploration data are straightforward, efficient, and less time-consuming for quantitatively evaluating the liquefaction potential of soil deposits. These methods typically rely on field penetration tests, which can be correlated to the cyclic shear resistance of the in-situ soil. In-situ penetration tests are favored because field measurements provide a cost-effective indication of deposit variability [2]. For this reason, empirical methods based on in-situ penetration tests are preferred for assessing liquefaction potential. Several empirical relationships have been developed by different researchers based on in-situ test data. Among these, the empirical relationship recommended by Youd et al. (2001) [3] is considered one of the most reliable for assessing liquefaction potential. This recommendation was the result of a comprehensive review and consensus among 20 liquefaction experts during workshops held in 1996 and 1998, sponsored by the National Center for Earthquake Engineering Research (NCEER). The workshops reviewed and developed empirical relationships based on four key factors: (1) Standard Penetration Test (SPT) blow count, (2) Cone Penetration Test (CPT) tip resistance, (3) in-situ shear wave velocity, and (4) Becker Penetration Test (BPT) blow count. Additionally, the workshops addressed magnitude scaling factors, correction factors for overburden pressures and sloping ground, and input values for earthquake magnitude and peak acceleration. In this study, the empirical relationship based on SPT blow count recommended by Youd et al. (2001) [3] will be used to calculate the factor of safety (FL) against liquefaction for different soil layers at a specific site location.

A. QUANTATITIVE ANALYSIS BASED ON SPT BLOW COUNT

Following the devastating 1964 earthquakes in Alaska and Niigata, Seed and Idriss (1971) made a major breakthrough by developing an empirical methodology based on copious field data known as the "simplified procedure" for evaluating the liquefaction resistance of soils. This innovative approach has become the most popular method for liquefaction potential analysis worldwide. Numerous academics have improved and honed it over time, highlighting its usefulness and importance. Notably, the National Center for Earthquake Engineering Research (NCEER) convened significant workshops with 20 top liquefaction specialists in 1996 and 1998 to come to an agreement on essential revisions and extensions to the long-standing protocols that had evolved over thirty years. All participants were acknowledged as co-authors of the thorough summary report that was published in 2001 as a result of the cooperative efforts of these workshops, with Youd and Idriss serving as the primary writers. Important suggestions for empirical analysis of Standard Penetration Test (SPT) data are presented in this crucial publication. Using SPT data for computations, the quantitative analysis in this study makes use of the empirical relationships put forward by Youd et al. (2001) [3]. Researchers can efficiently move through four essential steps by using the revised, simplified process suggested by Youd et al. (2001) [3], which gives them the ability to make well-informed conclusions about soil liquefaction resistance.

B. GROUND WATER TABLE

The soil layer above the ground water table does not need to include in the liquefaction potential analysis. Similarly, Soil layer which has an SPT N value greater than 30 normally do not liquefy during earthquake. These are the basis to identify the potential liquefiable layers to be analyzed.

C. CYCLIC STRESS RATIO (CSR) INDUCED BY EARTHQUAKE

Cyclic Stress Ratio (CSR) was calculated using the relation formulated by Seed and Idriss (1971) and suggested by Youd et al. (2001)

$$\mathbf{CSR = 0.65 \times a_{max} \times r_d \times \frac{\delta v}{\delta v'}}$$

where δv = Total vertical stress at a particular depth
$\delta v'$ = Effective vertical stress at a particular depth
a_{max} = maximum horizontal acceleration at ground surface that is induced by the earthquake (See Figure-3),
r_d = depth reduction factor

As reported by Youd et al. (2001) [3], Liao and Whiteman (1986) [4] developed a new relationship to calculate the reduction factor rd
r_d=1.0-0.00765*z per z≤9.15m
r_d=1.174-0.0267*z per 9.15m<z≤23m
Where z is the depth below ground surface in meters.

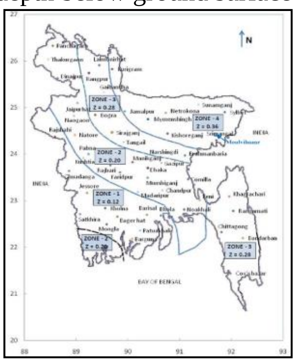

Figure 3 Seismic Zone of Bangladesh [5]

D. CALCULATION OF SOIL LAYER CAPACITY EXPRESSED AS CRR (CYCLIC RESISTANCE RATIO)

Based on the characteristics of the potentially liquefiable soil layer (eg. density, fine contents, measured SPT N value), the cyclic resistance ratio (CRR) can be determined by using the empirical relation developed by different researchers and recommended by Youd et al. (2001) [3].

$$(N1)_{60} = Nm\, C_N\, C_E\, C_B\, C_R\, C_s$$

The measured SPT N value of the field test was corrected by the following equation which was modified from Skempton (1986) [6] and as listed by Robertson and wide (1998) [7] and recommended by Youd et al. (2001).Where (N1)60 = Corrected or normalized SPT N value, Nm = measured SPT N value, C_N = Correction factor for overburden stress, C_E = Correction for hammer energy ratio (ER), C_B = Correction factor for borehole diameter, C_R = Correction factor for rod length and C_S = correction for samplers with or without liners. SPT N- values increase with increasing effective overburden stress, an overburden stress correction factor was estimated by the equation modified from Skempton (1986) [6] listed by Robertson and Wride (1998) [8] and recommended by Youd et al (2001) [3].

$$C_N = \left(\frac{P_a}{\delta v'}\right)^{0.5}$$

Where Pa is atmospheric pressure equals to approximately 100 kPa (1 atm) and the value of C_N is not exceeded and limited to 1.7. Values of other correction factors included in Eq. (4) such as C_E = Energy ratio for safety hammer is 0.7-1.2, Correction factor for energy ratio is taken as 1, C_B = 1 for bore hole diameter 100 mm, C_R = 0.85 for rod length 4 m to 6 m and C_S = 1 for sampler without liners listed in Robertson and Wride (1998) were used in this study. Cyclic resistance ratio (CRR) is influenced by fine contents in the soil layer. As noted by Seed et al. (1985) [9] CRR increases with the increase of fine contents in the soil layer. The equation developed by Idriss with the assistance of Seed (Youd and Idriss, 1997) [10] for correction of $(N1)_{60}$ to an equivalent clean sand value considering the fine contents as cited by Youd et al. (2001) [3] was used in the analysis.

$$(N1)_{60cs} = \alpha + \beta\, (N1)_{60}$$

Where α and β =coefficients determined from the following relationship

$$\alpha = 0 \text{ for } FC \leq \%5$$

$$\alpha = \exp\left[1.76 - \left(\frac{190}{FC^2}\right)\right] \text{ for } 5\% < FC < 35\%$$

$$\alpha = 5 \text{ for } FC \geq 35\%$$

$$\beta = 1 \text{ for } FC \leq \%5$$

$$\beta = \left[0.99 + \frac{FC^{1.5}}{1000}\right] \text{ for } 5\% < FC < 35\%$$

$$\beta = 1.2 \text{ for } FC \geq 35\%$$

Cyclic Resistance Ratio (CRR) for clean sand derived for 7.5 magnitude earthquakes was calculated by the following equation (Rauch, 1998) [11].

$$CRR_{7.5} = \frac{1}{34 - (N_1)_{60cs}} + \frac{(N_1)_{60cs}}{135} + \frac{50}{[10(N_1)_{60cs} + 45]^2} - \frac{1}{200}$$

The equation is valid for $(N_1)_{60cs}<30$. For $(N_1)_{60cs} \geq 30$, clean granular soils are too dense to liquefy and are classed as non-liquefiable (Youd et al. 2001) [3].

E. CALCULATION OF FACTOR OF SAFETY (F_L) AGAINST LIQUEFACTION

The clean sand-based equation only applies to magnitude 7.5 earthquakes. To apply this equation to magnitudes smaller or larger than 7.5, Seed (1983) [12] introduced correction factors termed "magnitude scaling factors (MSFs). Similarly, Youd et al. (2001) [3] recommended the equation to calculate the factor of safety (FL) against liquefaction including magnitude scaling factors and correction factors for larger overburden pressure with static shear stress conditions in sloping ground.

$$F_L = \frac{CRR_{7.5}}{CSR} \cdot MSF \cdot K_\alpha \cdot K_\sigma$$

Where MSF is the magnitude scaling factor. For earthquake magnitude others than 7.5 we need to modify factor of safety by multiplying MSF. The value of MSF for lower bound (M<7.5) and upper bound (M>7.5) as recommended by Youd et al. (2001) [3] was used in the analysis.

$$MSF = \frac{10^{2.24}}{M_w^{2.56}} \quad \text{for } M < 7.5$$

$$MSF = \left(\frac{M_w}{7.5}\right)^{-2.56} \text{for } M > 7.5$$

$K\sigma$ is the correction factor for large effective overburden and $K\alpha$ is correction factors for sloping ground.

As mentioned by Youd et al. (2001) [3] the application of and in a simplified procedure beyond routine practice and require specialized expertise therefore these two factors are not considered in this study.

$F_L \leq 1$: Liquefaction will occur
F_L = 1-1.2: Marginal Liquefaction
$F_L > 1$: No Liquefaction

F. SITE INFORMATION AND DATA COLLECTION

In Figure 4 it is shown the typical borehole layout plan at the depot area and considered 15 boreholes for the investigation of subsoil. From the usual soil profile of Uttara depot, it was seen that the granular fill layer which reaches below the ground surface for approximately 5m and has an SPT N-value of around 5, may be liquefiable. The co-ordinates of all 15 boreholes are shown in Table 1. From the 15 boreholes, in this study liquefaction analysis is done based on the data of three boreholes (NDP – 02; NDP – 08; NDP – 11). From Table 2 to Table 4, the analyzed bore log data are given below:

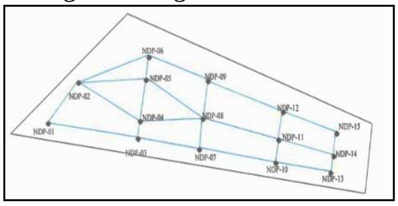

Figure 4 Soil Investigation Point Layout Plan (Source: Author, 2016)

Table 1 Co-ordinates of Soil Investigation Points or Boreholes

Borehole ID	Easting (m)	Northing (m)
NDP - 1	230743.79	2640917.9
NDP - 2	230849.75	2641039.1
NDP - 3	231053.28	2640867.7
NDP - 4	231062.21	2640921
NDP - 5	231083.1	2641045.8
NDP - 6	231094.74	2641115.3
NDP - 7	231264.41	2640833.7
NDP - 8	231278.07	2640927.2
NDP - 9	231297.06	2641040.7
NDP - 10	231527.32	2640790.7
NDP - 11	231538.79	2640859.1
NDP - 12	231553.36	2640946.2
NDP - 13	231716.12	2640760
NDP - 14	231724.59	2640810.6
NDP - 15	231736.02	2640878.9

RESULTS AND DISCUSSIONS

In total, 3 boreholes (NDP-02, NDP-08 & NDP-11) collected from 15 boreholes at depot area were considered for analysis. Factor of safety (FL) against liquefaction at different soil layer deposits was calculated and analyzed for each borehole. Factor of Safety was calculated for the soil layer deposit below the ground water table.

Factor of safety (FL) Vs depth, Fine content Vs depth and SPT N Vs depth relations are plotted and analyzed for 3 boreholes where liquefaction potential seen from the quantitative analysis. The all parameters are plotted and analyzed upto 24m depth because the formula of reduction factor rd proposed by Liao and Whtemen,1986 is only applicable upto the depth of 23 m.

In Table 5 the calculated Factor of Safety are shown in tabular format. From the above result and Figure 5, it is clearly noticed that liquefaction potentiality is non-linearly varied with increasing depth. This is because up to 14m depth, the SPT N value gradually increases (See Figure 6). But after that stated depth, the SPT N value suddenly falls and especially after 18m depth it significantly decreases, but the unit weight of soil increases. It is seen a liquefiable prone area at 5m depth and at 9m depth due to the relatively low SPT value. At 14m depth the SPT N value is quite high (SPT N value 26) and the fine content of the soil specimen in that depth is comparatively low (See Figure-7) rather than other depth. For this reason, in that depth the CRR7.5 value is more than 30 and it is observed a non-liquefiable area at 14m depth. But after 14m depth SPT N value suddenly decreases and at 21m and 24m depth it is seen a marginal liquefiable area from quantitative analysis.

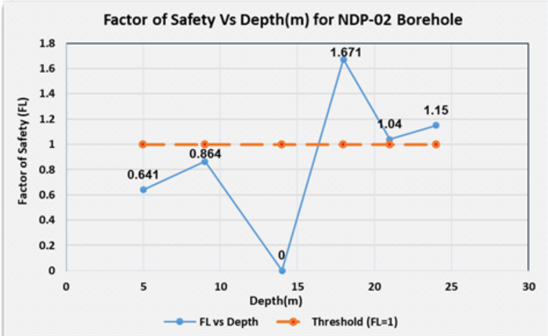

Figure 5 Crucial Zones of Liquefaction (marked in red circle) at NDP-02 Borehole

Table 2 Bore Log Data for NDP-02 (GWT=0.33m)

Depth (m)	SPT N	γ_{sat} (KN/m^3)	Fc (%)	D_{50}	Soil Type
4-5 (D-5) UD-01	6	16.73	99.5	0.0115	Grey To Black Clayey Silt
8-9 (D-9) UD-02	12	17.33	94.6	0.0240	Grey Clayey Silt with Few to Trace Sand
13-14 (D-14) UD-03	26	17.16	90.8	0.0266	Grey Clayey Silt with Few to Trace Sand
17-18 (D-18) UD-04	22	18.01	96.2	0.0158	Grey Clayey Silt with Few to Trace Sand
20-21 (D-21) UD-05	13	18.49	96.5	0.0215	Grey Clayey Silt with Few to Trace Sand
23-24 (D-24) UD-06	13	18.86	98.7	0.0144	Grey Clayey Silt
25-26 (D-26) UD-07	19	19.96	96.9	0.0126	Grey Silt with Trace Sand
27-28 (D-28) UD-08	38	19.69	100	0.0061	Grey Clayey Silt

Table 3 Bore Log Data for NDP-08 (GWT=0.25m)

Depth (m)	SPT N	γ_{sat} (KN/m^3)	Fc (%)	D_{50}	Soil Type
6-7 (D-7) UD-09	6	18.77	98.4	0.0078	Grey Clayey Silt
10-11 (D-11) UD-10	5	19.19	98.7	0.0115	Grey Silt with Trace Sand
16-17 (D-17) UD-11	8	19.20	97.5	0.0124	Grey Silt with Trace Sand
19-20 (D-20) UD-12	13	17.88	98.5	0.0056	Grey to Brown Clayey Silt
22-23 (D-23) UD-13	12	19.48	83.3	0.0048	Grey to Brown Clayey Silt
26-27 (D-27) UD-14	8	19.75	98.7	0.0074	Grey to Brown Clayey Silt with Trace Sand
29-30 (D-30) UD-15	50	20.33	96.9	0.0175	Grey to Brown Clayey Silt with Trace Sand

Table 4 Bore Log Data for NDP-11 (GWT=0.31m)

Depth (m)	SPT N	γ_{sat} (KN/m^3)	Fc (%)	D_{50}	Soil Type
8-9 (D-9) UD-16	3	10.1	98	0.0112	Grey to Black Clayey Silt with Organic Content
12-13 (D-13) UD-17	10	16.5	97.1	0.0106	Grey Clayey Silt with Trace Sand
14-15 (D-15) UD-18	12	18.9	92.3	0.0102	Grey Clayey Silt with Trace Sand
17-18 (D-18) UD-19	7	19.5	98.7	0.0106	Grey Clayey Silt
19-20 (D-20) UD-20	20	16.7	98	0.0079	Grey Clayey Silt
23-24 (D-24) UD-21	13	18.1	97.6	0.0096	Grey to Brown Clayey Silt with Trace Sand
27-28 (D-28) UD-22	50	20.4	80.8	0.0111	Grey to Brown Sandy Silt with Some Clay

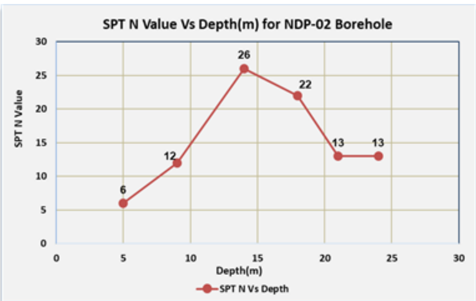

Figure 6 SPT N vs Depth(m) Graph of NDP – 02 Borehole

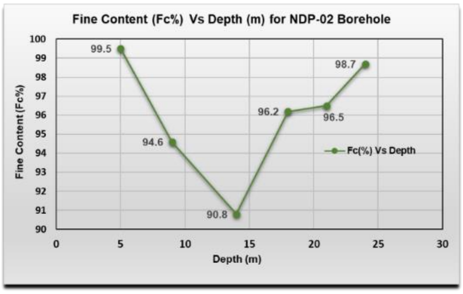

Figure 7 Fine Content (Fc %) vs Depth(m) Graph of NDP – 02 Borehole

Table 6 displays the determined Factor of Safety in tabular form upto the depth of 23m for the borehole no. NDP-08. It is clear from the above results and Figure 8 that liquefaction potential changes in a non-linear way with increasing depth due to the varying value of SPT N. The most crucial liquefiable area is at 11m depth due to the lowest SPT N value (SPT Value 5 & See Figure-9) and causes higher liquefaction potentiality. But at 20m and 23m depth we can see a marginal liquefiable area due to the relatively higher SPT N value rather than other depth with increased unit weight of soil and relatively lower fine content value at 23m depth (See Figure-10).

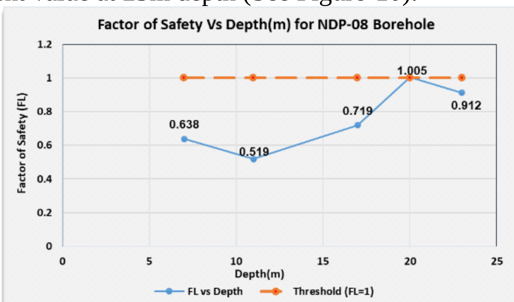

Figure 8 Crucial Zones of Liquefaction (marked in red circle) at NDP-08 Borehole

Table 5 Factor of Safety (FL) Result for Borehole NDP-02 (GWT=0.33m)

Depth(m)	SPT N Value	$(N_1)_{60cs}$	$CRR_{7.5}$	CSR	F_L	Comments
5	6	16.664	0.177	0.276	0.641	Liquefaction will Occur
9	12	20.093	0.229	0.265	0.864	Liquefaction will Occur
14	26	35.357	N/A	0.237	N/A	No Liquefaction
18	22	26.542	0.326	0.195	1.671	No Liquefaction
21	13	16.435	0.175	0.167	1.04	Marginal Liquefaction
24	13	15.530	0.165	0.143	1.15	Marginal Liquefaction

Table 6 Factor of Safety (FL) Result for Borehole NDP-08 (GWT=0.25m)

Depth(m)	SPT N Value	$(N1)_{60cs}$	$CRR_{7.5}$	CSR	F_L	Comments
7	6	7.920	0.159	0.249	0.638	Liquefaction will Occur
11	5	8.002	0.120	0.231	0.519	Liquefaction will Occur
17	8	12.546	0.136	0.189	0.719	Liquefaction will Occur
20	13	17.199	0.183	0.182	1.005	Marginal Liquefaction
23	12	12.105	0.132	0.144	0.912	Liquefaction will Occur

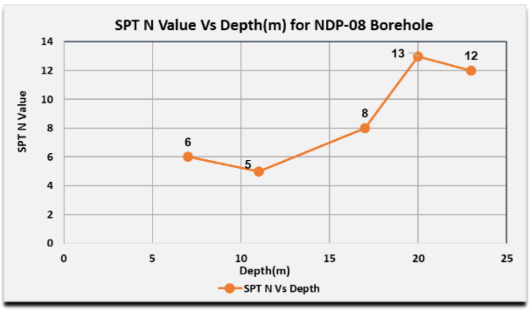

Figure 9 SPT N vs Depth(m) Graph of NDP – 08 Borehole

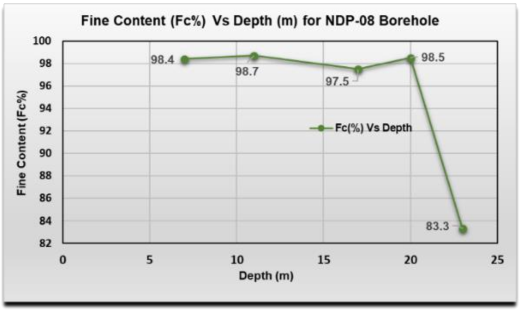

Figure 10 Fine Content (Fc %) vs Depth(m) Graph of NDP – 08 Borehole

The computed Factor of Safety upto 24m depth is presented in Table 7. Because of the initial finding, it is evident that liquefaction fluctuates non-linearly with increasing depth like NDP-02 and 08 (See Figure 11). The most complicated liquifiable area is at 9m depth because of the lowest SPT N value (SPT Value 3 & See Figure-12) but a challenging area to improve is at 18m because of the larger depth. Though having a higher Fine content value at 20m and 24m depth (See Figure-13) but due to having a higher SPT N value, it is observed no liquefaction prone zone at 20m depth but marginal liquefaction can occur at 24m depth.

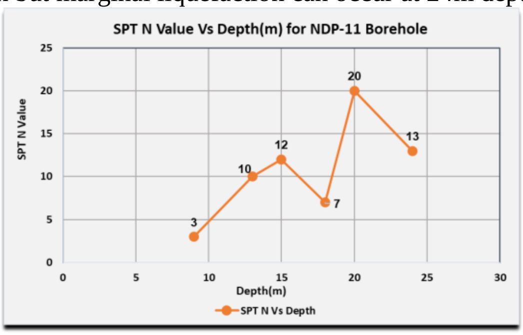

Figure 12 SPT N vs Depth(m) Graph of NDP – 11 Borehole

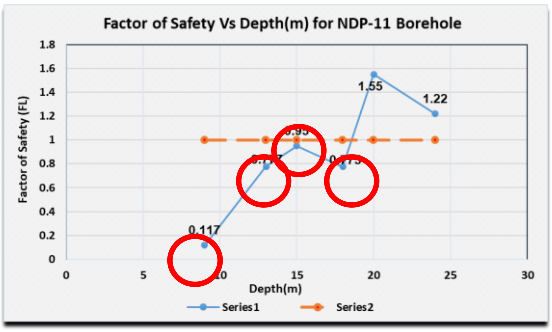

Figure 11 Crucial Zones of Liquefaction (marked in red circle) at NDP-11 Borehole

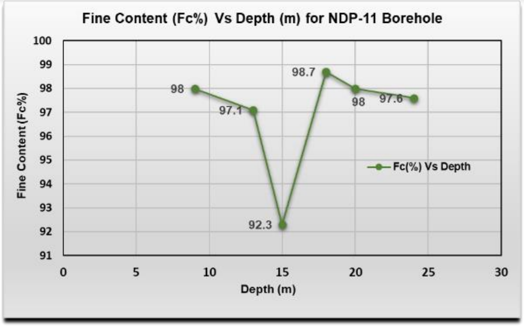

Figure 13 Fine Content (Fc %) vs Depth(m) Graph of NDP – 11 Borehole

CONCLUSIONS

1. So, it is true evident form the quantitative analysis that with an SPT N-value of around 5 and located below the ground surface to a depth of approximately 5m, the granular fill layer is at danger of liquefaction.
2. From the analysis and calculation, an overall decision can be made for the improvement of soil of the depot area. For the surrounding area of the NDP-02 borehole, the soil must be improved upto at least 14m depth.
3. From the perspective of NDP-08 borehole, the soil area around this borehole should be improved upto at least 17m. While for the NDP-11 borehole, the soil layer around this borehole can be improved upto at least 18m.
4. Different soil improvement techniques like Sand Compaction Pile (SCP), Prefabricated Vertical Drain (PVD) and Dynamic Compaction (DC) can be applied for the ground improvement of the depot area.
5. If the Sand Compaction Pile technique is being adopted, then the pile length should be rest upon the 18m depth of the soil layer. But this length can differ according to the soil conditions around the borehole like SPT N value, relative density, fine content and overall Ground Water Table (GWT) location etc.

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