Evaluation of Liquefaction Potential of Coastal Alluvium Using SPT Data - A Comparative Case Study

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Abstract. Earthquake induced soil liquefaction causes large scale damage to the infrastructures, lifeline systems and harbor facilities. Evaluation of the liquefaction potential of a soil subjected to seismic loading is one of the most important steps towards mitigation of liquefaction-induced damages. Nowadays, evaluation of liquefaction potential in case of susceptible soils is considered as a routine practice. The proposed coastal National Highway (NH) connecting Digha of West Bengal to Gopalpur of Odisha under Bharatmala Pariyojana is a major NH project undertaken by the National Highway Authority of India (NHAI). The district Kendrapara lies in 20° 20’ N to 20° 37’ N Latitude and 86° 14˚ E to 87° 01˚ E Longitude and situated in central coastal plain on the Bay of Bengal and comes under the seismic zone III as per the seismic zoning map of Bureau of Indian Standards (IS 1893 (Part 1): 2016). As the coastal alluvium is susceptible to liquefaction, some of the SPT bore log data collected from the two coastal locations of Kendrapara district of Odisha under the above project is used for evaluation of liquefaction potential of soil following available statistical method, artificial neural network (ANN) based method and multi-gene genetic programming (MGGP) based method. It is observed that some layers of the above soil are liquefiable considering a future seismic event of moment magnitude (Mw), 7. All the above three methods are predicting well the liquefaction and non-liquefaction cases.

1. Introduction

Earthquake induced liquefaction of soil causes huge loss of life and damage to infrastructures and lifeline systems. Some microzonation work has been done for Delhi, Kolkata and Bangalore in India but no study has so far been undertaken to establish liquefaction possibilities at local levels in the state of Odisha. In Odisha, the district Kendrapara lies in 20° 20’ N to 20° 37’ N Latitude and 86° 14˚ E to 87° 01˚ E Longitude and situated in central coastal plain on the Bay of Bengal and adjacent to Port City Paradeep. This district has huge potential of growth by way of industrialization in near future. The proposed construction of 2/4 laning with paved shoulder coastal national highway connecting Digha of West Bengal to Gopalpur of Odisha under Bharatmala Pariyojana of Government of India is of 415km. It connects major places of coastal districts of Odisha: Gopalpur – Satpada – Konark – Astarang – Naugaon - Paradip port – Ratnapur – Satabhaya – Dhamra – Basudevpur – Talapada – Chandipur - Chandeswar to the most sought after tourist place, Digha. The main objective of the above project is to reduce the distance and travel time and to give connectivity to remote area. The project lays emphasis
on development of these areas and makes them available with the resources [1-20]. The proposed highway would act as the primary arterial route for the socio-economic growth of this region. In this investigation, evaluation of liquefaction potential of soil at two places i.e. Ratnapur and Satabhaya of the district, Kendrapara nearer to Paradip under the above coastal NH project for an assumed future seismic event using available deterministic methods as per IS: 1893 (Part 1): 2016 [12], Juang et al. [4]; Muduli and Das [10] on the basis of collected SPT data.

2. Methodology
In the present study, the Statistical method, ANN based method and MGGP based method as per IS 1893 (Part1):2016 [12], Juang et al. [4]; Muduli and Das [10] respectively based on deterministic approach are followed for prediction of liquefaction potential of costal alluvial soil of the two places, Ratnapur and Satabhaya of district Kendrapara of the state Odisha. Above methods are discussed in brief for completeness and are as follows.

![Figure 1. Deterministic approach in liquefaction potential evaluation](image)

2.1. Statistical Method
CSR is employed as an earthquake loading constraint while CRR is signified by in-situ test constraints which reveal the density and pore pressure producing assets of top soil [13]. The utmost frequently used deterministic technique to evaluate the liquefaction probable of a site is “simplified procedure” initially established by Seed and Idriss [1]. Factor of safety \( F_s \) in contradiction of the incidence of liquefaction for any earthquake established on SPT data as prearranged by Youd et al. [2] is adopted by the Bureau of Indian Standards in IS: 1893 (Part 1): 2016.

\[
\begin{align*}
F_s &= \frac{CRR}{CSR} \\
\text{Margin of safety} &= \text{CRR-CSR}
\end{align*}
\]

2.2. ANN based Method
In ANN-based liquefaction method [4], wherein CSR is attuned to the point of reference earthquake, \( M_w \) of 7.5 using MSF and is as follows.

\[
CSR_{7.5} = 0.65 \left( \frac{\sigma'_v}{\sigma'_{vy}} \right) \left( \frac{d_{\max}}{g} \right) \left( r_d \right) / \text{MSF}
\]

Where, MSF is as defined earlier.

\[
CRR_{7.5} = -0.485 + 0.289 \left[ \left( \frac{N_1}{35} \right)_{60cse} \right] + \frac{0.739}{\left( 35 - \left( \frac{N_1}{35} \right)_{60cse} \right)^{0.1}}
\]

Above Equation is valid for \( (N_1)_{60cse} < 35 \) and for \( (N_1)_{60cse} \geq 35 \), there will be no liquefaction (NL) in the soil.
$$F_s = \frac{CRR_{7.5}}{CSR_{7.5}}$$  \hspace{1cm} (3)\\

2.3. MGGP based Method

Here in MGGP based method as per Muduli and Das [10], CSR is modified from Youd et al. [2] and is as given below.

$$CSR_{7.5} = 0.65 \left( \frac{\sigma_v}{\sigma_v'} \right) \left( \frac{a_{\text{max}}}{g} \right) (r_d) / MSF / K_\sigma$$  \hspace{1cm} (4)

where, MSF and $K_\sigma$ are as defined in earlier section

$$CRR = 0.008N_{1,60} - 0.613\cos[0.043N_{1,60}] + 0.077\cos[0.194N_{1,60}] + \frac{0.043}{N_{1,60}} + 0.609$$  \hspace{1cm} (5)

$$F_s = \frac{CRR}{CSR_{7.5}}$$  \hspace{1cm} (6)

3. Case Study

**Figure 2.** Alignment of proposed coastal NH passing through the state Odisha

3.1 Database Used

In the present study, two coastal areas of Kendrapara district (i) Ratnapur (ii) Satabhaya, through which proposed coastal NH project of NHAI “Gopalpur – Satpada – Konark – Astarang – Nausang – Paradip port - Ratnapur – Satabhaya – Dhamra – Basudevpur – Talapada – Chandipur – Chandeswar - Digha for up-gradation to two/four lane with paved shoulder and National Highway configuration under Bharatmala Pariyojana” as per the alignment shown in the Figure 2 passes, are selected for assessment of liquefaction probable of soil using the discussed SPT based methods in the earlier sections. These areas are coming under seismic zone-III as per Bureau of Indian Standards code of practice on “Criteria for Earthquake Resistance Design of Structures”, IS 1893 (Part 1): 2016. The bore log data pertaining to the geotechnical investigation for construction of some minor and major bridges in the above NH project close to the coast are obtained from the NHAI. Out of 10 collected SPT bore log 06 are selected and the bore log data are processed for analysis range from 3.5m to 23m depth below ground surface with measured $N$ values ranging from 01 to 49. Depth of water table is in the range of 0.8m to 2m below ground level for the above two locations. The $\sigma_v$ and $\sigma_v'$ values are in the range of 30.02-445.92kPa and...
15.31-225.19 kPa respectively. Also the $a_{\text{max}}$ value is assumed to be 0.16 g, which corresponds to the seismic zone-III in accordance to IS 1893 (Part 1): 2016. Further, the future seismic event of $M_L=7$ (i.e. Equivalent Richter’s Scale Magnitude, $M_L=6.4$) is considered in the present case for the liquefaction potential evaluation.

4. Results and Discussion

Out of the 06 bore log data 03 (BH1, BH2, BH3) are from Ratnapur and other 03 (BH4, BH5, BH6) are from Satabhaya of Kendrapara district. The bore log data of BH1, BH2, BH3, BH4, BH5 and BH6 are processed to obtain various parameters, which are to be used in liquefaction potential evaluation models and the analysis is made by using all the three SPT-based methods: Statistical Method (as per IS: 1893 (Part1):2016), ANN-based Method (as per Juang et al. [4]) and MGGP-based Method (as per Muduli and Das [10]) and the results are shown in the Table 1. From the BH1 data analysis it is found that at the depth 3 m, 6.5 m and 18.5 m below ground level the $F_s$ are 0.55, 0.46, 0.84; 0.64, 0.54, 0.98; 0.68, 0.60, 0.69; by using the above three methods respectively. This indicates the soil in each of the above layers is liquefiable (L) as $F_s \leq 1$ in a future seismic event. All above three methods are at par in predicting the liquefiable (L) soils. It can be noted here that in these layers the soil type is very soft silty clay with liquid limit (LL): 40-53%, plasticity index (PI): 15 to 17%, fines content (FC): 45%-60% and natural water content ($w_\text{n}$): 49-62%. These soil properties of the above liquefiable layers are matching with the criteria for liquefaction susceptibility as mentioned in Bray and Sancio [16]. At the depth 9.5 m and 21.5 m below ground level the soil layers are found to be non-liquefiable (NL) as the $F_s$ are 5.15 and 7.31 respectively, which are greater than 1 in accordance to MGGP-based method. For the above two layers ($N_{\text{l}}$) are 51.83 and 44.23 respectively. As per the Statistical Method the soil in the above two layers are non-liquefiable as ($N_{\text{l}}$) are >30. Similarly, as per ANN-based method the soil in the above two layers are also non-liquefiable as ($N_{\text{l}}$) are >35.

Similar study is made for the bore log data BH2 the results are shown in Table 1. In this case, it is observed that soil layers below 3.5 m and 5 m, from ground level are liquefiable in the assumed future seismic event as the calculated $F_s$ are 0.72, 0.65; 0.84, 0.76; 0.71, 0.68 by the Statistical method, ANN-based Method and MGGP based Method respectively. Bray and Sancio [16] observed similar results for the type of soil observed for the above bore log data. At the depth 12.5 m below the ground level the $F_s$ of the soil layer is found out to be 2.34, 2.28 and 4.15 by Statistical method, ANN-based Method and MGGP based Method respectively. This indicates that the above layer is non-liquefiable (NL). It is also found that ($N_{\text{l}}$) value of the soil layer at 23 m below ground level is 36.67 which indicates that soil is NL as per both Statistical method and ANN-based Method. Similar result is also found by the MGGP-based Method for the above layer as the $F_s$ is 7.35. All these three methods predict equally well the non-liquefiable (NL) soil layers.

The bore log data, BH3 are analyzed and it is observed that at the depth 9.5 m below the ground level soil is liquefiable under the assumed seismic conditions in future as per the results provided in Table 1 in accordance to the three methods. The soil type in this zone is very soft silty clay with LL: 44%, PI: 17%, FC: 90% and $w_\text{n}$: 47%. At the depth 15.5 m and 18.5 m below ground level the $F_s$ of the two layers are found to be 1.53, 1.79; 1.72, 1.99; 1.04, 1.38 by Statistical method, ANN-based Method and MGGP based Method respectively, which confirms that the above soil layers are NL as $F_s > 1$. The soil type in these zones is medium dense silty sand with LL: 39-48%, PI: 22-29%, FC: 68-73% and $w_\text{n}$: 24-30%.

The bore log data of BH4 are analyzed and it is observed from the Table 1 that there is only one liquefiable (L) layer at the depth of 3.5 m below ground level as the evaluated $F_s$ is 0.76, 0.90 and 0.77 by Statistical method, ANN-based Method and MGGP-based Method respectively. Soil type in this zone is very soft silty clay with LL: 43%, PI: 18%, FC: 90% and $w_\text{n}$: 35%. Further, based on plasticity criteria in accordance to Bray and Sancio [16] the above layer of soil is susceptible to liquefaction.

Similar analysis is made for the bore log data of BH5 and the results are shown in Table 1. It is found that only one layer, 9.5 m below ground level is on the verge of margin of liquefaction as the evaluated $F_s$ is found out to be 0.99 by both Statistical Method and MGGP-based Method though the $F_s$ is evaluated
to be 1.16 by ANN-based Method, which is close to 1. The two soil layers 15.5m and 21.5m below ground level are found to be NL as per the evaluated $F_s$ (7.63, 15.07) by MGGP-based Method and $(N_1)_{60cr}$ values (52.54, 74.41) as shown in the Table 1.

| Depth (m) | SPT $(N_1)_{60}$ value | SPT $(N_1)_{60cr}$ value | Statistical Method (IS 1893 (Part1): 2016) $F_s$ | ANN based Method [4] $F_s$ | MGGP based Method [10] $F_s$ | Remark |
|----------|------------------------|--------------------------|-----------------------------------------------|--------------------------|-----------------------------|--------|
| BH1      |                        |                          |                                               |                          |                             |        |
| 3.0      | 1.69                   | 7.04                     | 0.55                                          | 0.64                     | 0.68                        | L      |
| 6.5      | 1.49                   | 6.79                     | 0.46                                          | 0.54                     | 0.60                        | L      |
| 9.5      | 39.02                  | 51.83                    | $(N_1)_{60cr}>30$                             | $(N_1)_{60cr}>35$        | 5.15                        | NL     |
| 18.5     | 5.17                   | 11.20                    | 0.84                                          | 0.98                     | 0.69                        | L      |
| 21.5     | 38.03                  | 44.23                    | $(N_1)_{60cr}>30$                             | $(N_1)_{60cr}>35$        | 7.31                        | NL     |
| BH2      |                        |                          |                                               |                          |                             |        |
| 3.5      | 3.27                   | 8.93                     | 0.72                                          | 0.84                     | 0.71                        | L      |
| 5        | 2.83                   | 8.39                     | 0.65                                          | 0.76                     | 0.68                        | L      |
| 12.5     | 27.36                  | 27.71                    | 2.34                                          | 2.28                     | 4.15                        | NL     |
| 23       | 35.92                  | 36.67                    | $(N_1)_{60cr}>30$                             | $(N_1)_{60cr}>35$        | 7.37                        | NL     |
| BH3      |                        |                          |                                               |                          |                             |        |
| 9.5      | 2.21                   | 7.66                     | 0.58                                          | 0.68                     | 0.66                        | L      |
| 15.5     | 12.74                  | 20.29                    | 1.53                                          | 1.72                     | 1.04                        | NL     |
| 18.5     | 14.12                  | 21.95                    | 1.79                                          | 1.99                     | 1.38                        | NL     |
| BH4      |                        |                          |                                               |                          |                             |        |
| 3.5      | 3.15                   | 8.78                     | 0.76                                          | 0.90                     | 0.77                        | L      |
| 14.5     | 18.21                  | 26.85                    | 2.56                                          | 2.58                     | 1.93                        | NL     |
| 18       | 13.70                  | 21.43                    | 2.72                                          | 4.46                     | 2.45                        | NL     |
| BH5      |                        |                          |                                               |                          |                             |        |
| 9.5      | 14.54                  | 14.78                    | 0.99                                          | 1.16                     | 0.99                        | L      |
| 15.5     | 39.61                  | 52.54                    | $(N_1)_{60cr}>30$                             | $(N_1)_{60cr}>35$        | 7.63                        | NL     |
| 21.5     | 57.84                  | 74.41                    | $(N_1)_{60cr}>30$                             | $(N_1)_{60cr}>35$        | 15.07                       | NL     |
| BH6      |                        |                          |                                               |                          |                             |        |
| 9.5      | 32.89                  | 44.46                    | $(N_1)_{60cr}>30$                             | $(N_1)_{60cr}>35$        | 6.15                        | NL     |
| 15.5     | 55.44                  | 71.53                    | $(N_1)_{60cr}>30$                             | $(N_1)_{60cr}>35$        | 12.52                       | NL     |
| 18.5     | 83.38                  | 105.06                   | $(N_1)_{60cr}>30$                             | $(N_1)_{60cr}>35$        | 16.05                       | NL     |
| 21.5     | 108.70                 | 135.44                   | $(N_1)_{60cr}>30$                             | $(N_1)_{60cr}>35$        | 14.95                       | NL     |

Bore log data pertaining to BH6 are analysed and liquefaction potential of soil layers at 9.5m, 15.5m, 18.5m and 21.5m below the ground surface are evaluated using all the above methods. It is observed that the $F_s$ at the above depths as evaluated by MGPP-based Method are 6.15, 12.52, 16.05 and 14.95 respectively, which indicates that the soil layers are NL. $(N_1)_{60cr}$ values of the above layers are found out to be 44.46, 71.53, 105.06 and 135.44 respectively. The Statistical Method as well as ANN-based Method confirms that these layers are NL as $(N_1)_{60cr} > 30$.

From the above findings, it is pertinent to mention here that even though MGGP-based CRR model does not include fines content (FC) parameter, it predicts well all the NL soil layers having $(N_1)_{60cr}>30$, which
are considered to be too clay rich to liquefy. This shows the compactness as well as effectiveness of MGGP-based CRR model over the lengthy CRR models of the Statistical and ANN–based methods. In case of important projects, it is always necessary to verify the result obtained by one method with that of the other available methods to get confirmation and take proper design decisions. All the three deterministic methods: Statistical Method, ANN-based Method and MGGP-based Method are equally efficient in predicting liquefaction potential of soil for a future seismic event.

5. Conclusion
Ratanpur and Satabhaya of Kendrapara district is under seismic zone-III as per the seismic zoning map of Bureau of Indian Standards (IS 1893(Part 1): 2016). Based on composition of soil the liquefaction susceptibility in these areas is high. It is observed that certain layers of soil are liquefiable in five cases except one as studied by the three different deterministic methods. All the three deterministic methods: Statistical Method, ANN-based Method and MGGP-based Method are equally efficient in predicting liquefaction potential of soil for a future seismic event. The coastal alluvial soil is susceptible to liquefaction, which is clear from the present findings. Hence, the National Highway Authority of India (NHAI) has to pay special attention while undertaking the proposed coastal NH project in Odisha under Bharatmala Pariyojana.

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