Seismic Design of Pile Foundations for Different Ground Conditions

A. Murali Krishna, A. Phani Teja
Department of Civil Engineering, Indian Institute of Technology Guwahti, Guwahati-781039, Assam, India. Email: amurali@iitg.ernet.in, a.teja@iitg.ernet.in

S. Bhattacharya
Department of Civil Engineering, University of Bristol, Bristol, Bristol – BS8 1TR, United Kingdom. Email: S.Bhattacharya@bristol.ac.uk

Barnali Ghosh
Geotechnical Seismic group, ARUP, 13 Fitzroy Street, London W1T 4BQ, United Kingdom, Email: barnali.ghosh@arup.com

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SUMMARY:
Pile foundations are commonly adopted for various types of multi storied and industrial structures, bridges and offshore structures. Their seismic design is very important to ensure efficient functioning of various structures even under severe seismic loading conditions. In the design process, ground conditions (soil type) play an important role in terms of seismic loads transferred to foundation and foundation capacity. This paper presents seismic design of pile foundations for different ground conditions. Estimation of seismic loads, for a typical multi-storeyed building considered being located in different seismic zones, for different ground conditions according to Indian and European standard are presented. Design considerations based on various theories evolved on pile foundation performance concepts under seismic conditions are discussed. Two different ground conditions (C and D type) are selected as exemplary cases in demonstrating the evaluation of seismic loads and seismic design of pile foundations as per codes of practice.

Keywords: Seismic Design, Pile Foundations, Ground Conditions.

1. INTRODUCTION

Piles are the most commonly adopted deep foundations to support massive superstructures like multi-storeyed buildings, bridges, towers, dams, etc., when the founding soil is weak and result bearing capacity and settlement problems. In addition to carrying the vertical compressive loads, piles must also resist the uplift loads (loads due to wind or hydrostatic pressure) and the dynamic lateral loads which are common in the offshore structures, retaining walls and the structures in the earthquake prone regions. With increasing infrastructure growth and seismic activities, and the devastation witnessed, designing pile foundations for seismic conditions is of considerable importance. Several studies were conducted by various researchers on the seismic analysis and the design of pile foundations and evolved different theories on the same. Codes of practice available in different countries suggest some procedures for seismic design of pile foundations. In the design process, ground condition plays an important role in selecting the design parameters and also to consider various failure mechanisms. The estimation of the loads that act on a structure during an earthquake depends on the seismicity of its location (zone) and the subsurface conditions of the site. Different codes of practice around the world have suggested different methods to estimate the seismic action on a structure. Indian standard (IS 1893: Criteria for Earthquake Resistant Design of Structures (2002)) and Eurocode (EN 1998: Design of Structures for Earthquake Resistance (2004)) recommend different ground conditions based on the nature of the engineering hard stratum in selecting design acceleration level.

Ground condition (soil type) also governs the different failure mechanisms that are needed to be adopted in the design process. Different researchers suggested different failure mechanisms for the piles in liquefiable and non-liquefiable soils: For example, Finn and Fujita 2002; Liyanapathirana and

Polos 2005; Bhattacharya and Madabhushi 2008 on piles in liquefiable soil and Gazetas 1984; Mylonakis 2001 and Haldar and Babu 2009 on piles in non-liquefiable soil. Bhattacharya and Madabhushi (2008) presented a review of the research work on mechanism of pile failures. Major failure mechanisms/modes can be outlined as: Bending mechanism due to permanent lateral deformations or lateral spreading, buckling instability, settlement failure and dynamic failure.

This paper presents a short discussion on the methods proposed in the Indian code (IS 1893) and the Euro code (EN8) to estimate the seismic loads. As a case study, a model of a typical multi storied residential building is considered and the seismic action on it is determined for the different seismic zones in India and the different ground types. The two procedures, as per IS 1893 and EN8 are followed to estimate the seismic loads on the structure, and compared. The structure is then analyzed with the structural and seismic loads using the computer program SAP2000 (CSI, 2004) to determining the loads that are transferred to the foundations. Among different foundation loads the maximum loaded foundation was considered for the foundation design. Before proceeding to the design of the foundation, the susceptibility of the underlying soil to liquefaction is evaluated. For this case study, the borehole data from the subsurface investigation carried out in the three locations in the Guwahati region is taken and the liquefaction potential of the underlying layers is evaluated using the simplified cyclic stress based approach (Idriss and Boulanger 2004). The pile foundation is then designed for the estimated design loads using the Characteristic Load Method (Evans and Duncan 1982).

2. ESTIMATION OF SEISMIC LOADS ON THE STRUCTURE

For an efficient seismic design of the foundation, it is important to estimate the loads that are being transferred to the foundation during an earthquake. These loads depend on the seismic loads that act on the super structure during an earthquake. Different codes around the world propose different methods of estimation of these seismic loads on the super structure. The methods proposed by the Indian standard (IS 1893) and the Eurocode (EN 1998) are reviewed and used to estimate the seismic loads. A case study of a typical multi storied structure is considered as a model super structure for the purpose.

2.1 Model of the Building and Various Parameters Considered

As a case study, to estimate the seismic loads that act on a structure during an earthquake, a typical multi storied building frame model is considered. The building frame is a moment resisting frame with reinforced concrete members. The plan and elevation of the concrete building frame considered are shown in Fig. 1. The parameters used for the modelling of the building were based on the values used in general practice during the construction of a residential complex. Suitable cross-sectional dimensions of beams and columns, as well as the thickness of slabs and unreinforced brick masonry infill walls were assumed (all in accordance with the Indian standards). The assumed values are shown in Table 1. The grade of concrete and the grade of steel were considered to be M30 and Fe415 respectively. Also a uniform imposed load intensity of 3.0 kPa and 1.5 kPa were assumed to be present on all the floors and roof slab respectively. The modelling of the building without the staircase was done in the computer program SAP2000 with the assumed geometry and material properties.

Table 1 Dimensions of the members of the RC Building Frame

Members	**Dimensions**
Beams	230 mm x 450 mm
Columns	450 mm x 450 mm
Slab Thickness	150 mm
Masonry Wall Thickness	230 mm

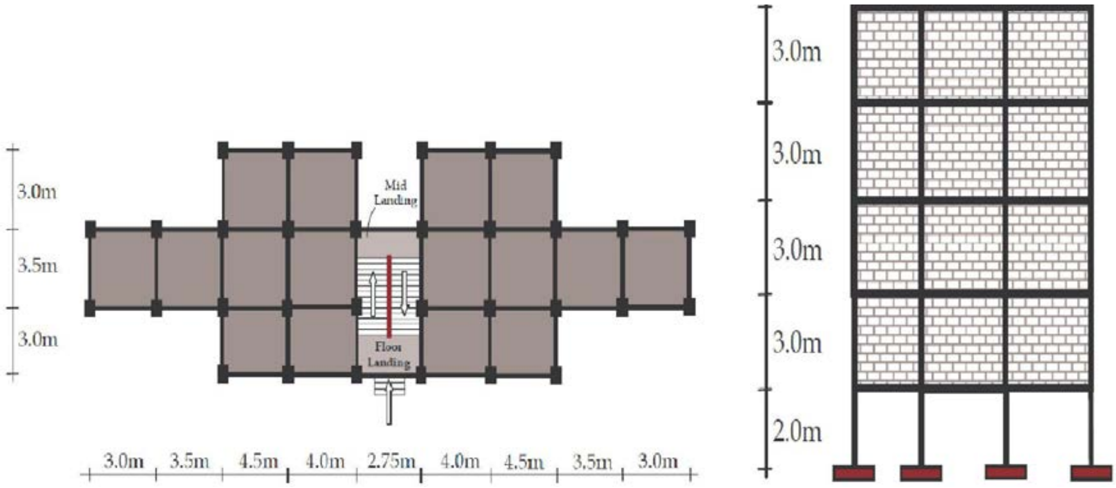

Figure 1. The Plan (left) and the Elevation (right) of the Building Considered.

The seismic weight of the building (W_s) is calculated as the total dead load plus one-fourth of the imposed load. The seismic weight of each floor of the structure is calculated to be 1908.52kN and that of the roof to be 1551.64kN. Then the seismic weight of the entire structure is four times the seismic weight of each floor plus the seismic weight of the roof. Thus, the seismic weight (W_s) of the considered structure is 9185.72 kN.

2.2. Seismic Loads as per IS 1893

The Indian Standard (IS 1893) identifies three types of soils as foundation soil, based on N values obtained from the standard penetration test (SPT). Type I, Type II and Type III being the rock or hard soils, medium soils and soft soils respectively. In the present discussion, the seismic loads on the structure are evaluated for the Type II and Type III soils which are equivalent to the ground types C and D of the Euro code (EN8). Also, different cases are considered for the location of the building being in different seismic zones: Zone V, Zone IV and Zone III of India.

2.2.1. Calculating the Base Shear

The total lateral force that acts at the base of the structure during an earthquake is called the design seismic base shear (V_B). As per IS 1893, base shear is calculated using the Eqn. 1.

$$V_B = A_h \, . W_s \tag{1}$$

The seismic weight of the structure (W_s) is as calculated above. The design horizontal seismic coefficient (A_h) is a function of the soil type (its stiffness and damping), the time period of the structure and the zone. Equation 2 is being used to calculate the design horizontal seismic coefficient.

$$A_h = \frac{\mathrm{Z\,.I\,.Sa}}{2\,.R.g} \tag{2}$$

The Zone factor 'Z' which is indicative of the effective peak ground acceleration of a particular zone is given in Table 2 of IS-1893. The values for the Importance factor '*I*', which depends on the functional use of the structure, are given in Table 6 of IS-1893. Considering the present structure as an important service and community building, the value of '*I*' adopted is I = 1.5. The Response Reduction factor '*R*', depends on the perceived seismic damage performance of the structure, characterized by brittle or ductile deformations. From Table 7 of the code, the value of R for a special moment resisting frame is taken as R = 5. The value of the average spectral acceleration coefficient 'S_a/g' depends on the soil type, the time period (T) of the structure and the damping ratio. The acceleration response spectra for the different soil types and five percent damping are shown in Fig. 2. The time period of the structure is calculated for a RC frame building using the Eqn. 3 as per IS code.

$$T = 0.075 \, . \, h^{0.75} \tag{3}$$

The time period of the building frame considered with a height of 14 m is calculated to be T = 0.543s. From Fig. 2, the values of the spectral acceleration coefficients for Type II and Type III soils are same and equal to 2.5. Assuming the damping to be five percent, the base shear acting on the structure in different zones and different soil types is calculated and the values are tabulated in Table 2.

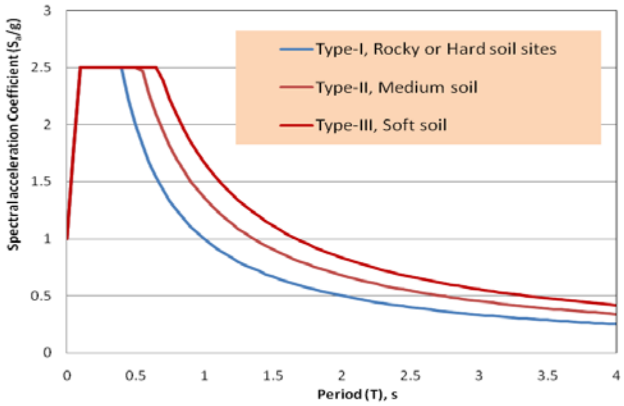

Figure 2. Response Spectra for Rock and Soil sites as per IS 1893 for five percent Damping

Table 2. Base Shear calculated for different cases as per IS 1893

Seismic Zone	Ground Type	*Z*	S_a/g	A_h	V_B (kN)
Zone V	Type II	0.36	2.5	0.135	1240
	Type III	0.36	2.5	0.135	1240
Zone IV	Type II	0.24	2.5	0.09	827
	Type III	0.24	2.5	0.09	827
Zone III	Type II	0.16	2.5	0.06	551
	Type III	0.16	2.5	0.06	551

2.2.2 Distribution of Base Shear

The base shear calculated was the total lateral force that acts at the base of the structure during an earthquake. This base shear force is to be distributed to the entire structure assuming that the mass of the structure is concentrated at different floor levels. As per IS 1893, the base shear is distributed at the floor levels as given in Eqn. 4.

$$Q_i = V_B \frac{Wi \, .hi^2}{\sum_{j=1}^{n} Wj \, .hj^2} \tag{4}$$

Where, ‘Q_i’ is the design lateral force at floor *i*, ‘W_i’ is the seismic weight of the floor *i*, ‘h_i’ is the height of the floor ‘*i*’ from the base and ‘*n*’ is the number of stories in the building.

2.2.3 Foundation loads

The earthquake loads calculated from the aforementioned equations are applied to the structure in addition to the normal loads for structural analysis using a computer program SAP2000. The analysis is performed for the dead, live and the earthquake loads for various load combinations prescribed in the code. The results of the analysis consisted of the forces, displacements and reactions of all the members of the structure. The results are sorted to find the maximum loads that are transferred to the foundation of the system. Table 3 shows the maximum (design) loads transferred to the foundation in each case. Where ‘*P*’ is the axial load, ‘*V*’ is the lateral force and ‘*M*’ is the moment.

Table 3. Design Loads transferred to the pile as per IS 1893

Seismic Zone	Ground Type	Max. *P* (kN)	Max. *V* (kN)	Max. *M* (kN-m)
Zone V	Type II	980	175	170
	Type III	980	175	170
Zone IV	Type II	898	132	128
	Type III	898	132	128
Zone III	Type II	898	103	101
	Type IIII	898	103	101

2.3. Seismic Loads as per EN 1998

The Eurocode (EN8) specifies five different ground types (A, B, C, D & E) and two special ground types (S1 & S2) according to the average shear wave velocity, V_{s30}. If the shear wave velocity data is not available the SPT N-values can be used to classify the ground type. Two ground types: C and D are considered for the estimation of seismic loads on the super structure.

2.3.1. Calculating the Base Shear

As per the Eurocode, the base shear force F_b, for each horizontal direction in which the building is analyzed is determined using Eqn. 5.

$$F_b = S_d(T_1)\,.\,m\,.\,\lambda \qquad (5)$$

Where, the seismic mass (*m*) of the structure is the calculated seismic weight divided by the acceleration due to gravity '*g*',. The seismic mass of the modeled structure is calculated to be m = 936.36 x 10^3 kg. The term $S_d(T_1)$ is the ordinate of the Design Spectrum corresponding to the fundamental period of the building (T_1). The period T_1 of the building is calculated by the same formula used as in Eqn. 3. The Design Spectrum values $S_d(T)$ are determined using the equations suggested by the code for different cases. The elastic response spectra (Type I) of the different Ground Types at 5% damping as per the Eurocode is shown in Fig. 3.

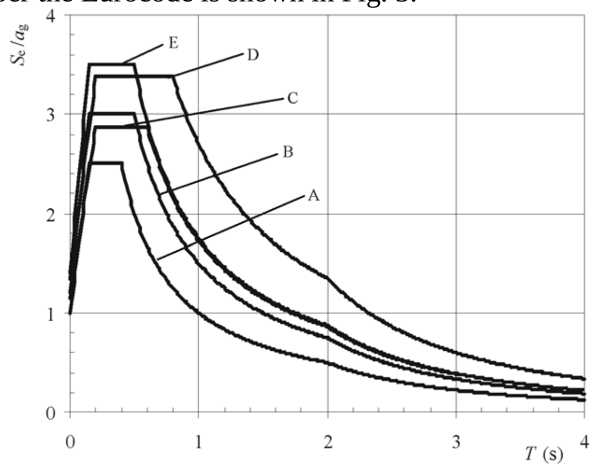

Figure 3. Elastic Response Spectra (Type I) for Ground Types A to E for five percent Damping (EN 1998).

λ in Eqn. 5 is the correction factor, the value of which is equal to: λ = 0.85 if $T_1 < 2\ T_C$ and the building has more than two stories, or λ = 1.0 otherwise. Using the design spectral values calculated from equations suggested by the code, the seismic mass of the structure and the correction factor the base shear force F_b is calculated for each case and the results are as shown in Table 4.

2.3.2. Distribution of Base Shear

For the distribution of the base shear force along the height of the building at various floor levels, the Eurocode suggests the equation as shown in Eqn. 6.

$$F_i = F_b \cdot \frac{z_i \cdot m_i}{\sum z_j \cdot m_j} \tag{6}$$

Where F_i is the lateral force acting on the floor i, m_i is the seismic mass of the floor i and z_i is the height of the floor level 'i' above the level of application of the seismic action F_b.

Table 4. Base Shear calculated for different cases as per EN 1998

Seismic Zone	Ground Type	S_d (T)	F_b (kN)
Zone V	C	2.27	1805
	D	3.55	2825
Zone IV	C	1.51	1203
	D	2.37	1883
Zone III	C	1.01	802
	D	1.58	1256

2.3.3 Foundation loads

Results of structural analysis in SAP2000 including various load combinations with the above evaluated seismic loads are shown the Table 5. The table presents the maximum loads at the foundation level according to Eurocode (EN1998): '*P*', the axial load; '*V*', the lateral load and '*M*', the moment. Out of the all these cases, the most severe one which is Zone V, Type D is selected for the liquefaction evaluation case study and the pile design.

Table 5. Design Loads transferred to the pile as per EN 1998

Seismic Zone	Ground Type	Max. P (kN)	Max. V (kN)	Max. M (kN-m)
Zone V	C	1158	233	225
	D	1580	338	328
Zone IV	C	909	70	166
	D	1191	240	234
Zone III	C	898	128	126
	D	931	175	171

2.4. Observations

The column which bears the maximum loads transferred to foundation has been noted and it has the location as shown in Fig. 4. This ground floor column is observed to bear the deign loads in all the cases analyzed for the loads according to IS 1893 and EN 1998.

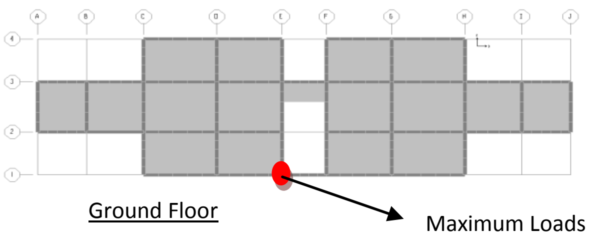

Figure 4. Plan of the Building showing the Column bearing the maximum Loads.

The variations in the values of the seismic loads calculated for the same structure in the above sections show that the two codes differ in their considerations.

- The first and the major difference one can spot is the identification of the soil types. The Indian Standard IS1893 considers only three types of soils for determining the design accelerations from the response spectrum, while the Eurocode identifies five types.
- The other difference that is observed is the difference in distribution of the estimated base shear force in the two codes (Fig. 5). The Indian code distributes the base shear force to the floor levels by the proportions of the weighted average of the square of the height of the floor while the Eurocode distributes it by the proportion of the weighted average of just the heights of the floor level. This causes the lower stories to carry much less lateral load as compared to the top floors as per the Indian Standard whereas as per the Eurocode the distribution much more even, in the proportion of their heights.
- The considerations and the narrow classification of soil types and spectral acceleration values recommended by IS 1893 cause the estimated seismic loads to be same for the two cases of ground types (Type II and Type III soils).
- Also the values of calculated design loads show that the Indian code is more lenient in estimating the loads while the Eurocode estimates more sterner (and thus more safer) values.

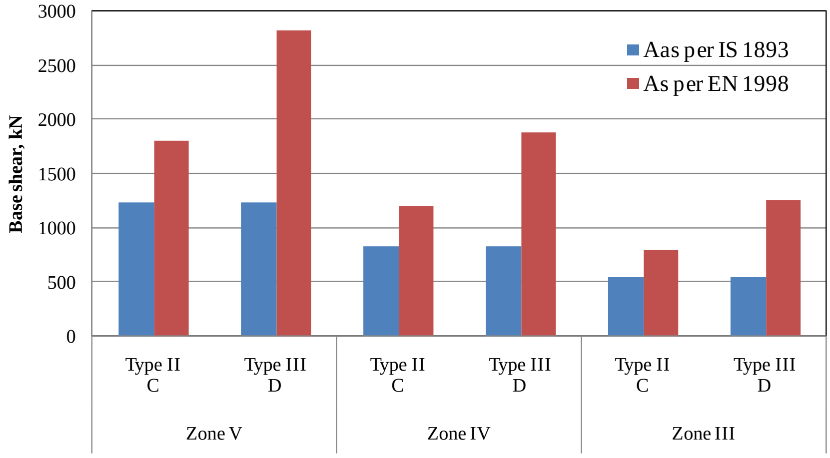

Figure 5. A bar chart comparing the base shear forces as per the two codes

3. LIQUEFACTION EVALUATION

The major problem concerning the seismic resistant design of pile foundations is the presence of liquefiable soils in the foundation region. Liquefiable soil layers alter the pile capacity and also can cause large lateral loads on pile foundations. Piles driven through a weak, potentially liquefiable, soil layer to a stronger layer not only have to carry vertical loads from the superstructure, but must also be able to resist horizontal loads and bending moments induced by lateral movements if the weak layer liquefies. Thus, it is very essential to investigate the liquefaction susceptibility of sub surface soil layers before proceed for the seismic design. Semi empirical method recommended by Idriss and Boulanger (2004) is being followed to evaluating the liquefaction potential.

As a case study, borehole data of three different sites (Dibrugarh, Tezpur and Dhirenpara) near the Guwahati region of India have been acquired. The liquefaction potential of the cohesionless layers under the water table from these data have been evaluated using the simplified procedure (Idriss and Boulanger 2004). The liquefaction evaluation has been done for each of the sites in two cases, one with the structure and the other without the structure. The values of the various parameters considered in the evaluation are: the value of (a_{max}/g) for the sites is taken as 0.18 after considering various site factors (the peak ground acceleration of Guwahati region is 0.36g). For the total and the effective vertical stresses in the cases with the structure, the axial pressure transferred from the column is added (considering the results of the case of Zone V and Ground Type C from Table 5). The load (Cyclic Stress Ratio) and the resistance (Cyclic Resistance Ratio) of the soil to liquefaction have been calculated and the factor of safety is estimated as proposed by Idriss and Boulanger (2004).

The results of the liquefaction evaluation carried out for the three soil profiles show that the saturated cohesion less soil layers in the sites at Dhirenpara and Tezpur have the liquefaction factor of safety, FS above 1, even with or without the super structure and thus can be considered as ‘Non-Liquefiable’. The results for soil profile at Dibrugrh show that the cohesion less soil layer between 5 m and 8 m has the liquefaction factor of safety less than 1 and thus it is susceptible to liquefaction (Fig. 6). Therefore, anticipating the worst case scenario, the pile must be designed neglecting the frictional resistance offered by this layer of the soil and. Also, it is observed that the factor of safety of the soil layer decreases with the presence of the super structure. Thus, it can also be inferred that the risk of liquefaction of saturated cohesion less soils increases with the presence of a super structure over them.

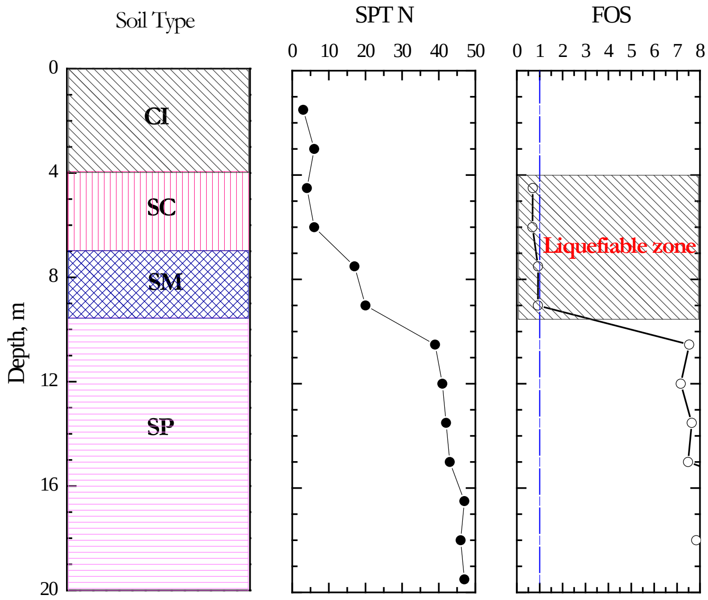

Figure. 6 Typical soil profile data considered and its liquefaction susceptibility

4. PILE DESIGN

Considering the subsurface conditions of the soil profile at Dibrugarh, the pile is designed for the design loads calculated for the case of Zone V and Ground Type C in Table 5. From the borehole data of the soil profile, it can be identified as the ground type C of the Eurocode (from the average N-values). As per the Indian standard code for design and construction of pile foundations IS 2911 (1979), the pile is designed for the static (structural) loads and it is calculated that a driven cast in-situ pile of length 18 m and 0.9 m would be safe to bear the structural loads with a factor of safety of 3.5. But, the pile must also be able to resist the lateral loads and the moments caused during the earthquakes. One of the methods commonly used for the design of the piles for lateral loads is the Characteristic Load Method (Brettmann and Duncan 1996)

4.1. Design for Seismic Loads

The Characteristic Load Method developed by Brettmann and Duncan (1996) is used to design the pile for the estimated lateral load and moment in this study (Sadek and Freiha, 2004). This method is based on the pseudo-static’ approach and the formulation is based on non-dimensional relationships related to load and moment. For the given subsurface conditions, the dimensions of the pile and the applied lateral load and moment, the ground line deflection of the pile and the maximum moment in the pile can be determined. In the present case study, for the soil profile at Dibrugarh and the seismic loads estimated, the dimensions of the pile designed for the structural loads. Length of pile is considered as minimum of 18 m to have enough embedment in the bottom stiff soil below the liquefiable layer. Thus a single 18 m length and 0.9 m diameter, is found to be acceptable (Fig. 7) for a factor of safety of 3.5. Since the 3 m thick cohesionless soil layer in the soil profile has been evaluated to be liquefiable, the following conditions must be considered:

(i) The frictional resistance offered by the soil in the liquefiable layer must be neglected. This leads to increase in the pile length for the same factor of safety.
(ii) Due to change in fixity point after liquefaction and loss of lateral confinement to the pile in the liquefied layer, the pile is essentially designed as a column against buckling. Bhattacharya and Bolton (2004) suggested the minimum pile diameters needed to be adopted based on thickness of the liquefiable layer.
(iii) The natural period of the system will change due to liquefaction because of the reduction in strength of the soil and the change in fixity point.
(iv) When the layer is liquefied, the soil layers above the liquefied zone move according to the liquefied zone movement, resulting in passive pressures on the pile. These additional passive pressures rise the moments at the fixity point and thus the moment capacity of pile has to be increased. This can be achieved by the increasing the reinforcement in the originally adopted section or by increasing the pile section to meet the requirement.

Considering the above points, the design of the pile for the estimated seismic loads is again done assuming the cohesionless soil layer in the soil profile is liquefiable. Variations of the pile capacity versus and the resulting Factor of safety values with the pile diameter and the cases with and without liquefaction are as shown in Fig. 7. The results show that a driven cast in-situ, free headed pile of length 18 m and diameter 0.95 m must be adopted for the liquefiable case to get the factor of safety of 3.5.

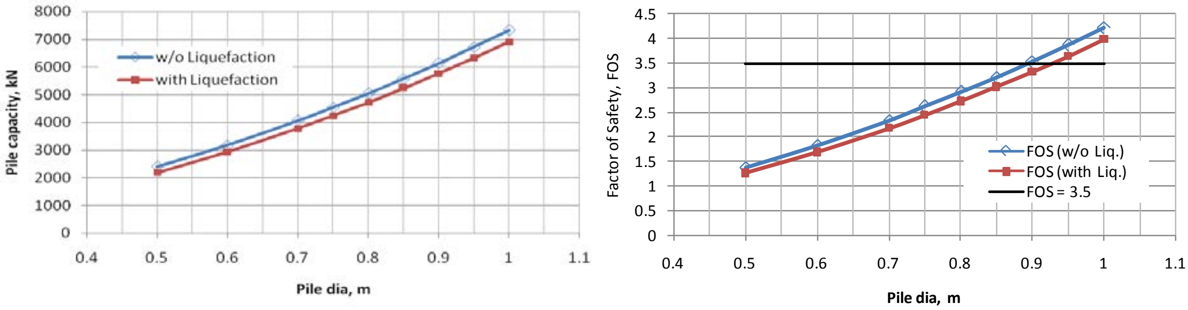

Figure 7. Variation of Pile Capacity (kN) and Factor of safety with the Pile diameter (m) with and without Liquefaction

5. SUMMARY AND CONLUSIONS

With the increasing seismic activities in the recent times an efficient design of the pile foundations to resist the estimated earthquake loads is a major concerned issue. In this interest, this study deals with the estimation of the seismic loads on a super structure as per the two international codes selected, IS 1893 and EN 1998. Different cases are considered assuming the location of the structure to be in different seismic zones of India and on different ground types (Type C and Type D). The estimated seismic loads are applied to the SAP2000 model of the structure and analyzed to find the maximum (design) foundation loads. Liquefaction potential was evaluated, before proceeding to the pile design, for the selected soil profiles in the Guwahati region. Then the pile is designed for a selected case of seismic zone V and the ground type C. The pile is first designed for using the Indian Standard IS 2911. Then the design was checked against lateral deflection and limiting moment capacity of pile for the estimated lateral loads and moments under seismic condition using commonly used method called the Characteristic Load Method. Further the seismic design is revised for both the cases considering the soil profile to be liquefiable. It is to conclude that ground conditions should be considered much prior in the analysis of any structure to evaluate the seismic loads acting on the structure which will further influence the foundation design loads and foundation capacity.

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