Seismic Design of Pile Foundation for Oil Tank by Using PLAXIS3D

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Abstract

Analysis and design of pile foundations in soft soil strata to support any geotechnical structures especially oil tanks are very important for geotechnical practitioners and more so in earthquake prone areas. In this paper, a complete design of pile foundation for oil tank in Iraq is mentioned by providing the details of soil strata at the site of oil tank construction which is in seismically active region. A finite element analysis by using PLAXIS3D for the design of pile foundation for oil tank in Iraq is carried out for both static and seismic loading conditions. In-situ soil at the site varies from loose fill material followed by soft to stiff clay layers and then by dense sand layer. Firstly, the basic static design of suitable pile foundation which is based on field observed ground details have been carried out in PLAXIS3D. A group of 89 piles of 26m length with 400mm radius each is proposed for the oil tank of height 15m and 23.5m diameter to withstand a maximum credible earthquake (MCE) of 0.15g. Results for pile foundations in terms of settlements, differential settlements between piles, bending moments are obtained by using finite element numerical modeling using PLAXIS3D, which are proposed as final design of the foundation system for oil tank at the specific soft soil site in Iraq.

Keywords: Pile, PLAXIS3D, Oil Tank, settlement, bending moment, earthquake.

1. Introduction

Pile foundation is mainly used to transfer the vertical and lateral loads coming from superstructure to the deeper strata bypassing loose or soft shallow strata. Their performance under seismic loading is of great concern to geotechnical practitioners. In-situ soil existing at particular site plays an important role in amplifying ground motion which influences the decision of particular type of foundation system for any superstructure. The study of Probabilistic Seismic Hazard Analysis (PSHA) and Deterministic seismic Hazard Analysis (DSHA) is very important to obtained Uniform Hazard Response spectra (UHRS) at the bed rock level which can be used to predict the response of overlying soil under seismic excitation as per (Masake and Choudhury[30], Shukla and Choudhury[37, 38, 39], Choudhury and Shukla[8], Naik and Choudhury[31, 33], Desai et al. [15, 16, 17, 18]). The UHRS can then be used to develop seismic ground motion for the concerned site from chosen seed accelerogram which further can be used for ground response analysis and liquefaction potential evaluation by using various computer tool like SHAKE 2000, DEEPSOIL and also Finite element and Finite difference program like PLAXIS, ABAQUS and FLAC etc.. Ground motions, free field site response have significant impact on behavior of pile in potentially liquefiable areas (Phanikanth et al.[35], Naik and Choudhury[32], Desai and Choudhury[19]). Similar types of preliminary studies are required for various geotechnical structures like retaining wall, tailing dam, shallow footing to predict the response of soil (Choudhury and ShubhaRao[5, 6], Mashake and Choudhury[29, 30], Choudhury and Masake[7], Ghosh and Choudhury[21], Chakraborty and Choudhury[10], Katdare and Choudhury[27], Chatterjee and Choudhury[12], , Kumar et al.[28]).

Various researchers [Hamada[22], Hamada et al.[23], Ishihara[24], Abdoun and Dobry[1], Abdoun et al.[2] Phanikanth et al.[36], Choudhury et al.[9], Chatterjee et al.[13]] stated that liquefaction of soil subjected to earthquake loading is key factor affecting pile foundation performance in seismically active areas where soil may experience liquefaction or cyclic mobility. Pile foundation may fail through the buckling instability when it is subjected to combined vertical and lateral load at the top [Bhattacharya[4] and Dash et al.[14]]. Japanese Highway bridge specification (JRA, 1972-1996)[25, 26], U.S. code (NEHRP, 2000)[34] and Eurocode8 (1998)[20] provides current design methodology for the design of pile under seismic conditions.

The analysis and design of oil tank foundation storing highly inflammable gases and liquids are critical for geotechnical practitioners because they vulnerable to strong seismic motions and are assets of national importance. The failure of such tanks in past earthquakes in Japan, US and Turkey caused extensive damage to life and heavy loss of property which forced geotechnical practitioners to incorporate earthquake event in the analysis and design of liquid storage tank. In the present study, complete static and seismic design for oil tank foundation in Iraq is carried out by using PLAXIS3D which is based on regional tectonics and geotechnical properties of in-situ soil.

2. Regional tectonics, local site condition and geotechnical properties of the site

Iraq is divided into five structural regions viz. Jeria, Zagros Mountains, Foothills, western and southern deserts and Mesopotamian plane. The site is located within Arabian tectonic plate and the earth crust thickness is about 45km in the region as per Agard et al.[3].

In-situ soil at site consist of 2.5m of granular engineering fill material followed by soft to stiff clay layer up to 24m depth then followed by dense sand layer. The SPT-N value along the depth of soil layer is shown in Figure 1 (a). The estimation of the undrained shear strength of soft clay layer from 2.5m to 20 m depth is carried out considering the given field tests i.e. SPT N-values, various laboratory tests i.e. TUU (Undrained Unconsolidated Triaxial test) and SDSS (Static Direct Simple Shear tests; after application of cyclic loading). Based on the observations, the design cohesive strength (in form of undrained cohesion – Cu) is also marked on the Figure. In order to capture the moisture content of clay profile with its Liquid Limits and Plastic Limits, a graph is prepared to represent the laboratory observations. Figure 1 (b) represents the observed variation of undrained cohesion (Cu), LL, PL and moisture contents observed during laboratory testing.

3. Loading details on Oil Tank Foundation

The oil tank of height 15m and diameter 23.5m is proposed. The empty weight of the oil tank is 1400kN and the weight of tank under full operating conditions is 62000kN. The tank carries maximum shear and moment due to wind as 160kN and 1200kN.m, respectively. The characteristics strength of concrete used is 35 N/mm^2.

4. Numerical modelling

A finite element based geotechnical computer program is used to simulate the in-situ condition for the foundation of oil tank. Soil is modelled as Mohr-Coulomb failure criteria. A soil model of size 100m x 100m x 70m (L x B x H) is created with finer mesh near foundation foot print area and relatively coarser mesh away from foundation foot print. The details of different soil type and layer thicknesses as modelled in PLAXIS3D are shown in Figure 4 (a). The soil model is fixed at its base in all the directions and top surface of the model is as kept free. The sides of the model are laterally restrained against movement. Piles are modelled as 10-noded tetrahedral embedded pile element to obtain bending moment induced in piles under the application of load as shown in Figure 4(b). Very fine mesh is generated with 190708 numbers of soil elements and 27443 numbers of nodes having average element size of 1.92m. Table 1 shows the geotechnical properties of different layers of soil taken in PLAXIS3D. Piles are modelled as end bearing pile. The end bearing resistance is provided as per the static design of pile. Pile cap is modelled as 6-noded plate element.

5. Validation of the model and static analysis results

Figure 2 shows the pile load test set up of oil tank site in Iraq. Loading test is simulated in PLAXIS3D and maximum settlement of 16.37mm is observed which is in well agreement with field measured value of 15.79mm as shown in Figure 3. The obtained and measured results of pile load test are comparable and can be considered as a good validation of present model with field test result. Hence the same model can be adopted for further analysis.

The plan and sectional view showing arrangement of piles in a group consisting of 89 piles having 400mm radius and length of 26m is shown in the Figure 4 (b). Piles are arranged in 5 rings. Pile group foundation system is modelled in PLAXIS3D to analyze the foundation system under both static and seismic loading condition.

Three-dimensional view of the z-displacement contour of the soil model under static loading condition in PLAXIS3D is shows in Figure 5. Maximum vertical settlement of 37mm is observed at the center of the foundation with 34mm of settlement observed around periphery of the foundation which results 3 mm of differential settlement (settlement at the center in excess of settlement at the periphery of the foundation). Figure 6 shows the vertical displacement vector diagram obtained in PLAXIS3D for static loading condition which shows the movement pattern of soil and pile elements. The axial load carried by pile varies from 510kN for center pile to 697kN for outer periphery pile.

6. Seismic analysis of pile foundation

PLAXIS3D provides option for dynamic analysis of foundation system which can be done through ground shaking. The prescribed displacement has to be defined for seismic excitation and then seismic input motion in form of acceleration, displacement or velocity time history is applied at the base of the soil model. The response of foundation in terms of settlement, differential settlement and bending moment are obtained and reported.

7. Input acceleration time history and mesh size

Probabilistic seismic Hazard Analysis is carried out for the site considering the influence of 300 km around the site that combines earthquake source zoning, reoccurrence and annual frequency of exceedance. Based on the results of Probabilistic Seismic hazard Analysis, target response spectra of Maximum Credible Earthquake (MCE) having return period of 2475 years at the bedrock level and chosen Seed accelerogram, used to develop seismic input motion using RSP Match that is further used as an input in PLAXIS3D. The input acceleration-time history is shown in Figure 7 which has Peak Ground Acceleration (PGA) of 0.15g.

For accurate representation of wave transmission through the model, mesh size (ΔL) must be smaller than approximately one tenth of wave length associated with the highest frequency component of Input wave. The mesh size of 1.95m is adopted for present model considering the above criteria.

8. Boundary conditions and material damping for dynamic analysis

Geotechnical problems can be modelled by assuming regions far away from area of interest. Seismic wave travels infinitely in all directions. To model infinite boundary, numerical model is reduced to acceptable size by using artificial boundaries. PLAXIS3D provides viscous boundary conditions that contain dampers which can absorb reflected wave so that foundation will not experience multiple wave transmission. The viscous boundaries is applied for x and y planes.

Material damping in soil is governed by its viscous, friction properties and development of plasticity. The role of damping in PLAXIS3D model is provided by Rayleigh damping. 5% damping is used in the present model which is typical value for the geological material.

9. Results of dynamic analysis

Figure 8 illustrates z-displacement contour of soil model with maximum displacement of 39 mm at the center of foundation. The z-displacement around the periphery of foundation is obtained as 35 mm which gives the total differential settlement of 4 mm. The acceleration response at the top of the pile cap is shown in Figure 9 which shows amplification in the acceleration. The amplified acceleration has value of 0.2g. Figure 10 shows displacement response observed at pile cap under dynamic input motion. The maximum displacement of 13.63 mm at 19.35 sec is observed at pile cap but at the end of seismic excitation the residual displacement is negligible. The maximum bending moment at the point of maximum displacement is obtained as 107kN.m in the outer periphery pile and 85kN.m in the central pile. Hence, in the design of pile group foundation it has to be ensured that pile is safe at the point of maximum displacement which is critical for the design. The maximum axial load of 1284kN is obtained at the outer periphery pile which gradually reduces to 772kN at the central pile.

10. Discussion and conclusions

In the present study, 3D non-linear analysis of pile group foundation is carried out for oil tank by using finite element program PLAXIS3D. The present numerical model is first validated with available field pile load test results which are found to be in well agreement. The PLAXIS3D pile group model is then analyzed under static as well as seismic loading conditions. The pile group is subjected to maximum vertical displacement of 37mm and 39mm under static and seismic loading condition, respectively. Pile group is subjected to maximum differential settlement of 4mm under the static loading condition as well as seismic loading condition. The axial load is piles vary from 697kN to 510kN and 1284kN to 772kN i.e. outer periphery to center pile for static and seismic condition, respectively. Under seismic excitation, pile cap undergoes maximum displacement of 13.63mm and corresponding induced bending moment varies from 107kN.m to 85kN.m from outer periphery to central pile. These values are critical for design consideration.

The present study states that numerical modelling of pile group foundation efficiently models the state of static as well as seismic loading conditions and can be used not only for the validation of the statically designed model but also can be used to obtain the responses of the foundation system under various seismic loading conditions.

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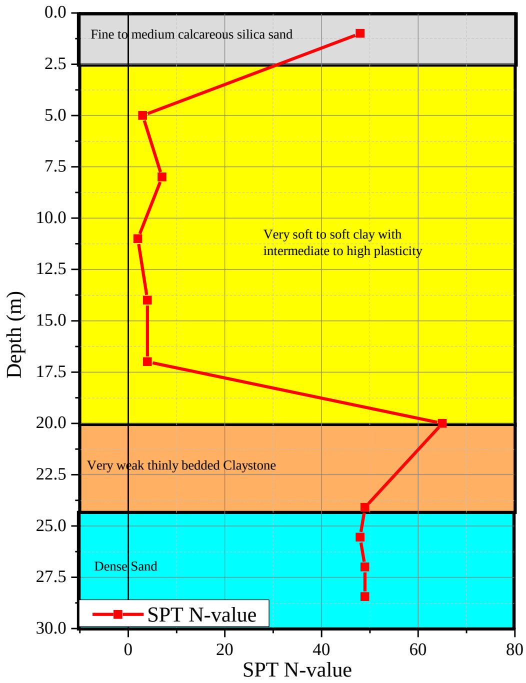

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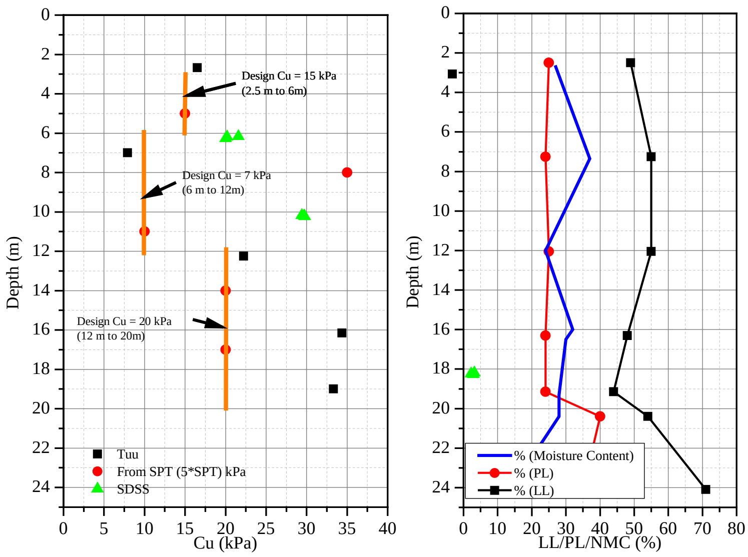


(b)

Figure 1: Geotechnical properties of soil along the soil depth (a) SPT N-Value (b) C_u and Atterberg's limits

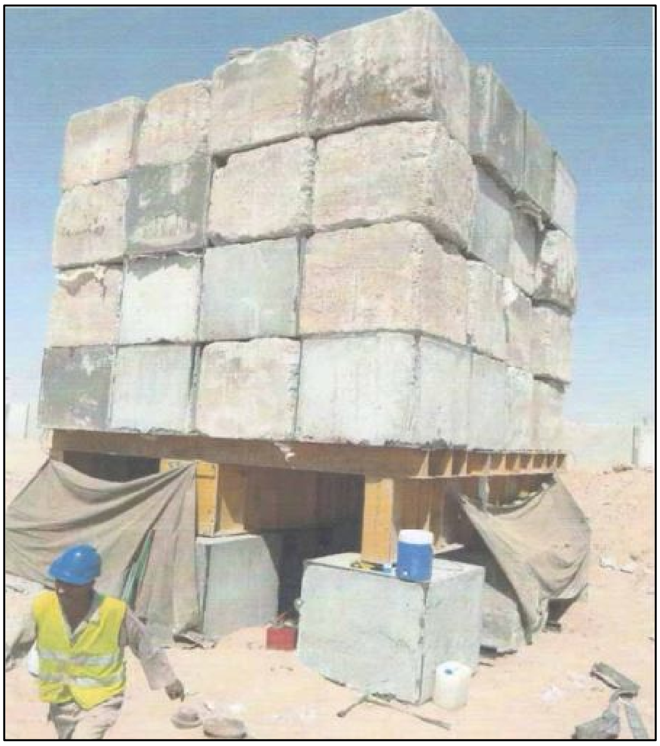
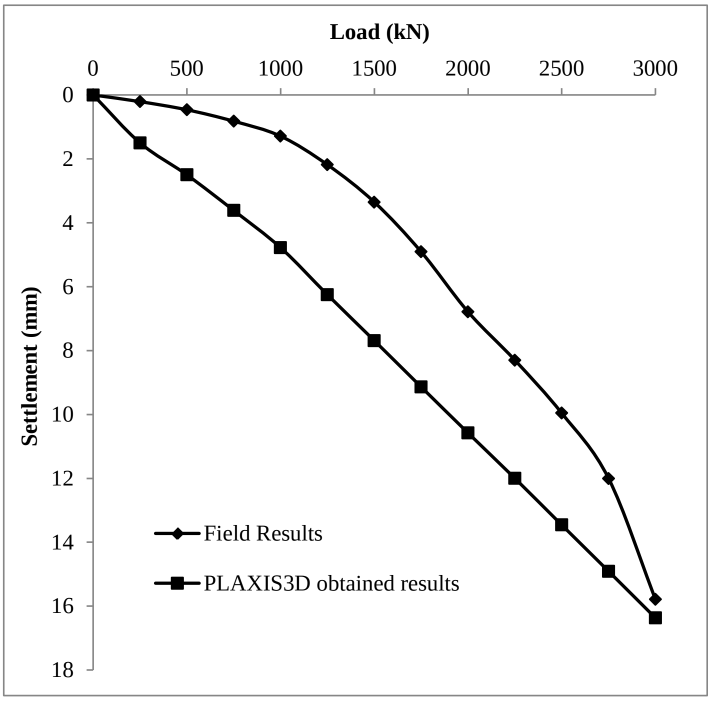


Figure 2: Setup for Pile load test in Iraq



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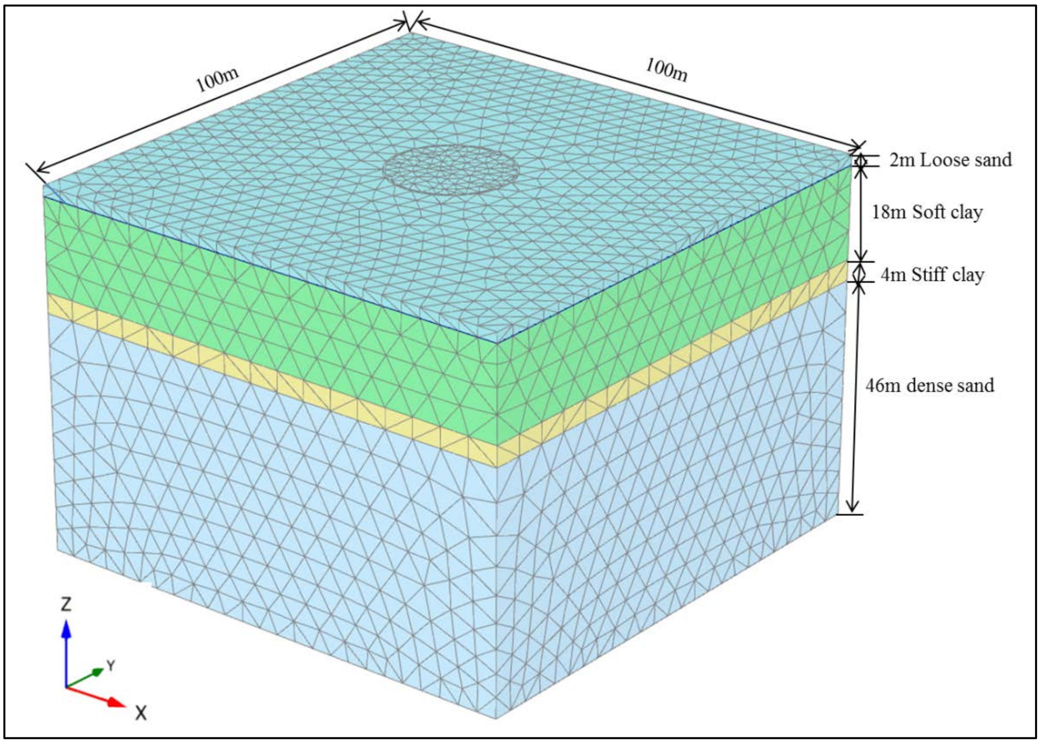

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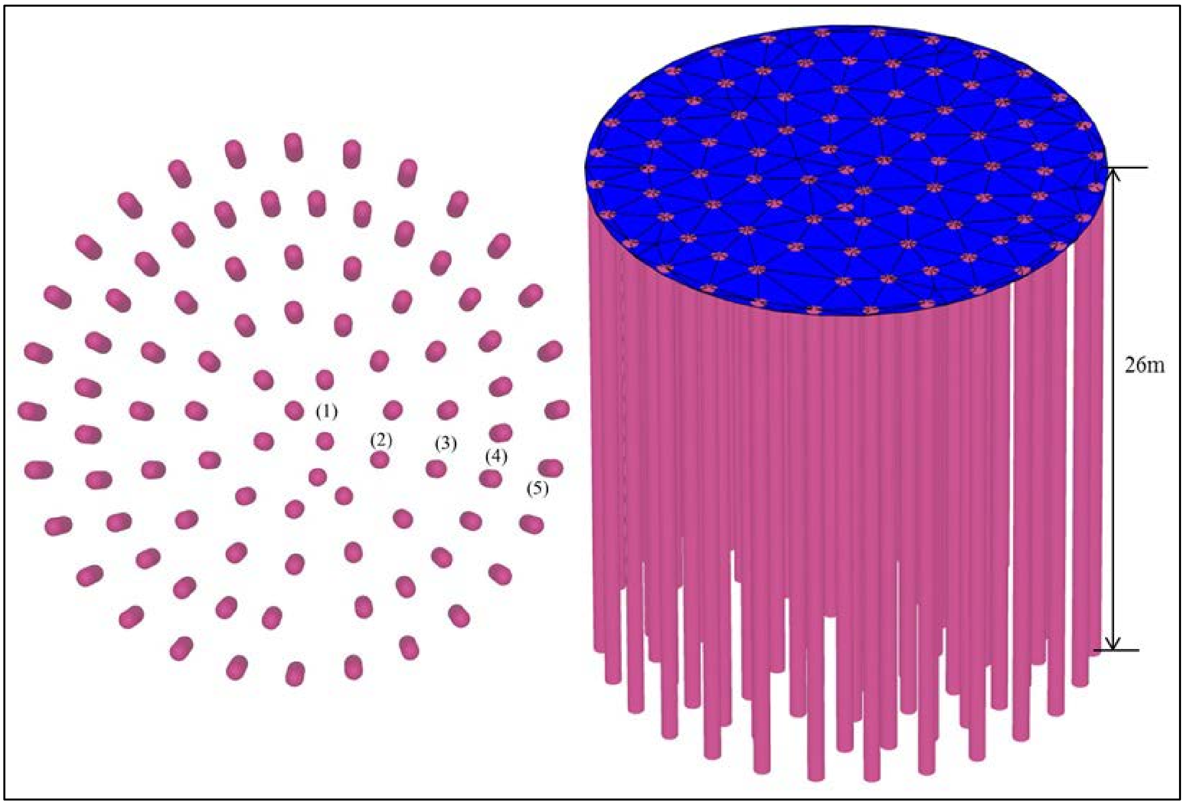

(b)

Figure 4: 3D view of (a) Different layers of soil model (b) pile group model showing paln and sectional view of pile arrangement in PLAXIS3D

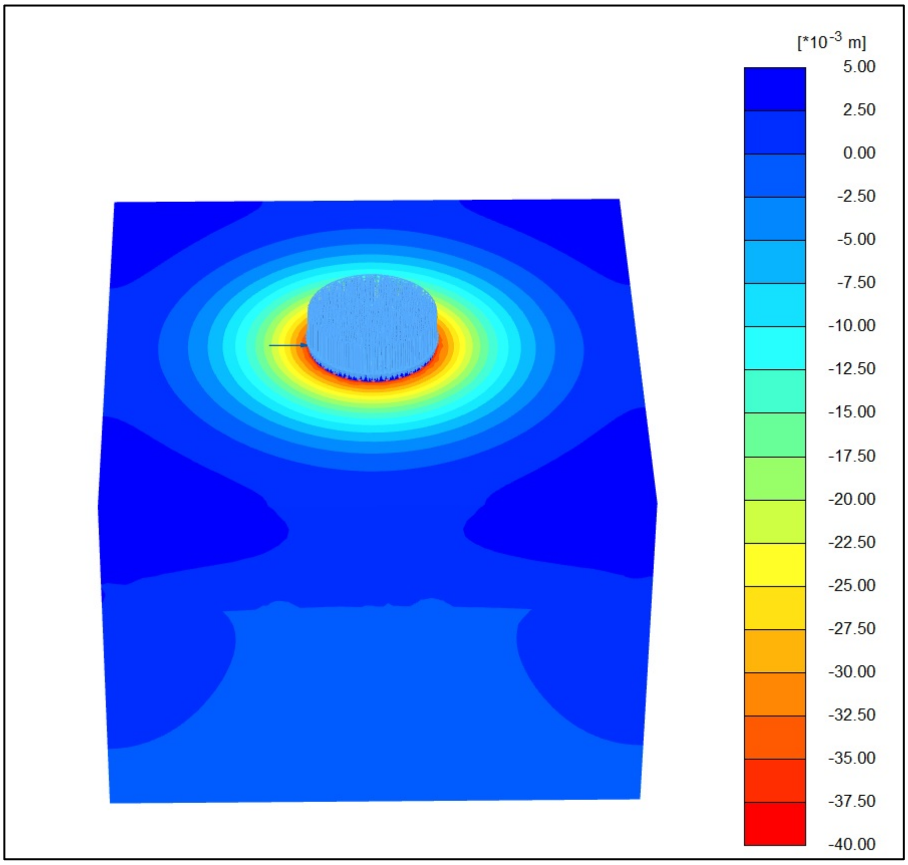

Figure 5: Z-displacement contour (in m) obtained for static case in PLAXIS3D

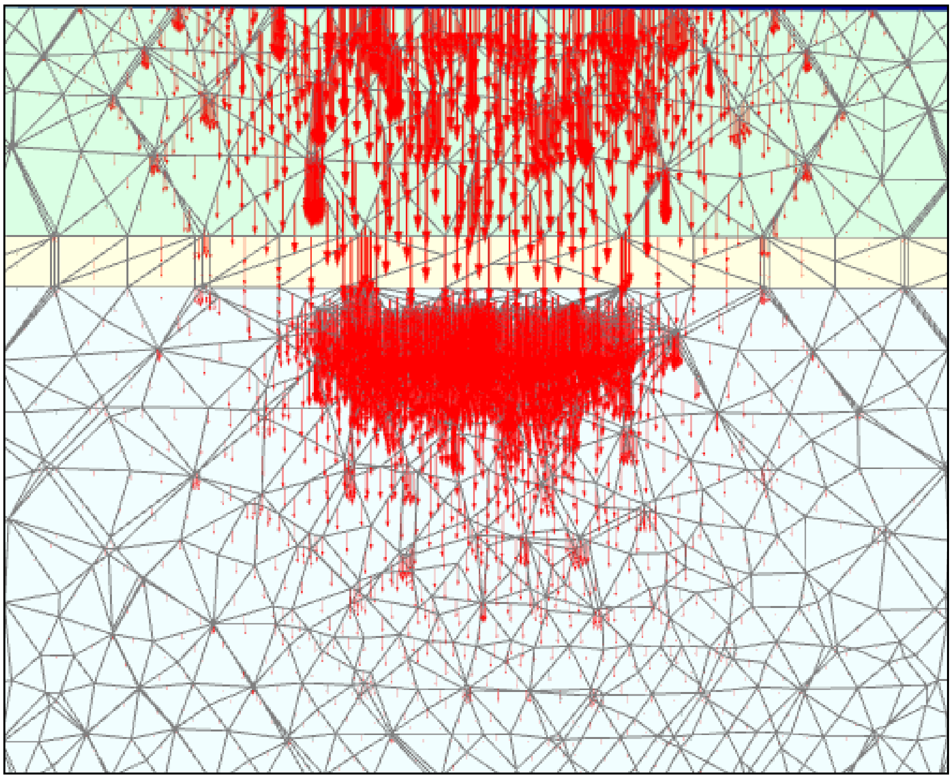

Figure 6: Displacement vector diagram obtained for static case in PLAXIS3D

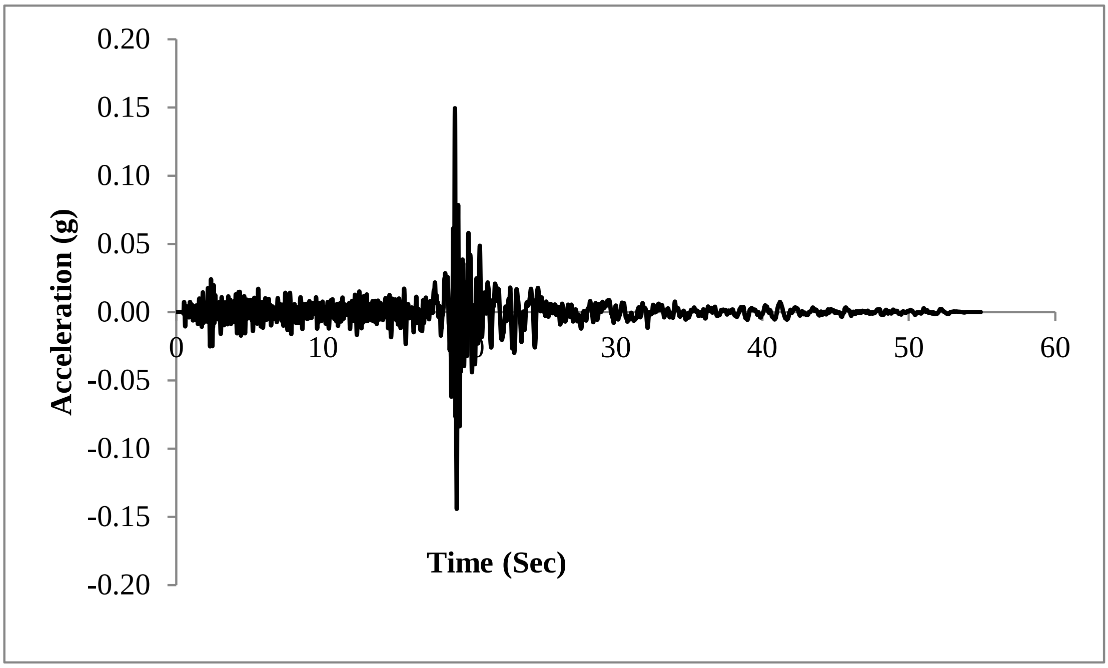

Figure 7: Acceleration-time history used an Input in PLAXIS3D

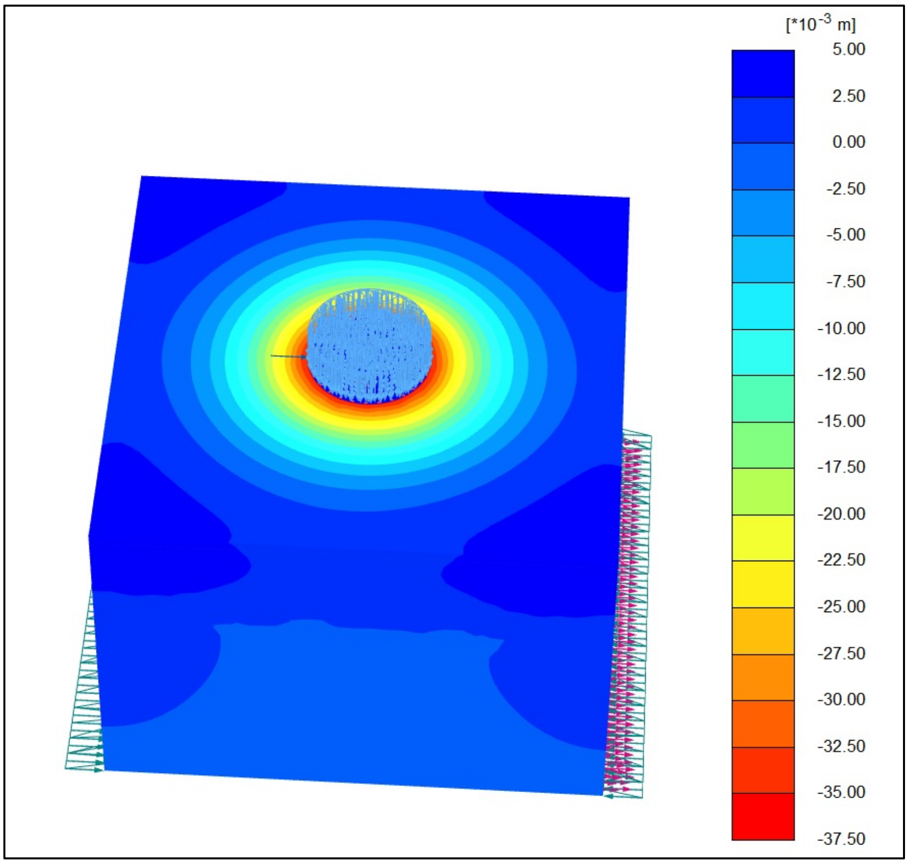

Figure 8: Z-displacement contour (in m) obtained for seismic case in PLAXIS3D

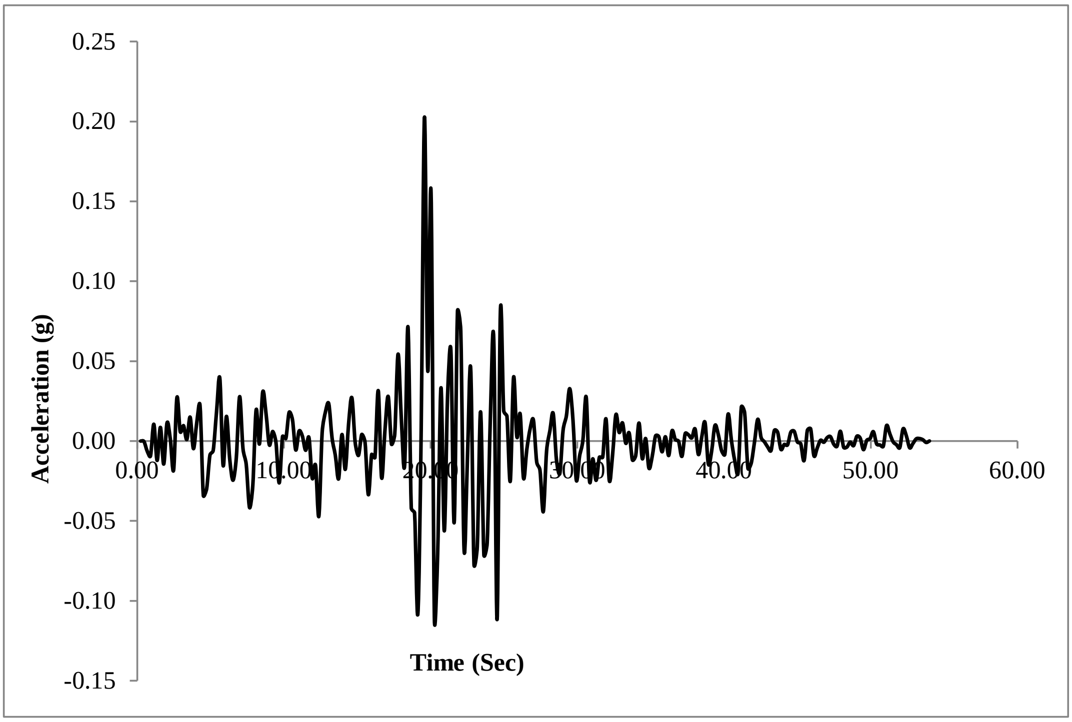

Figure 9: Acceleration response obtained at the top of pile cap in PLAXIS3D

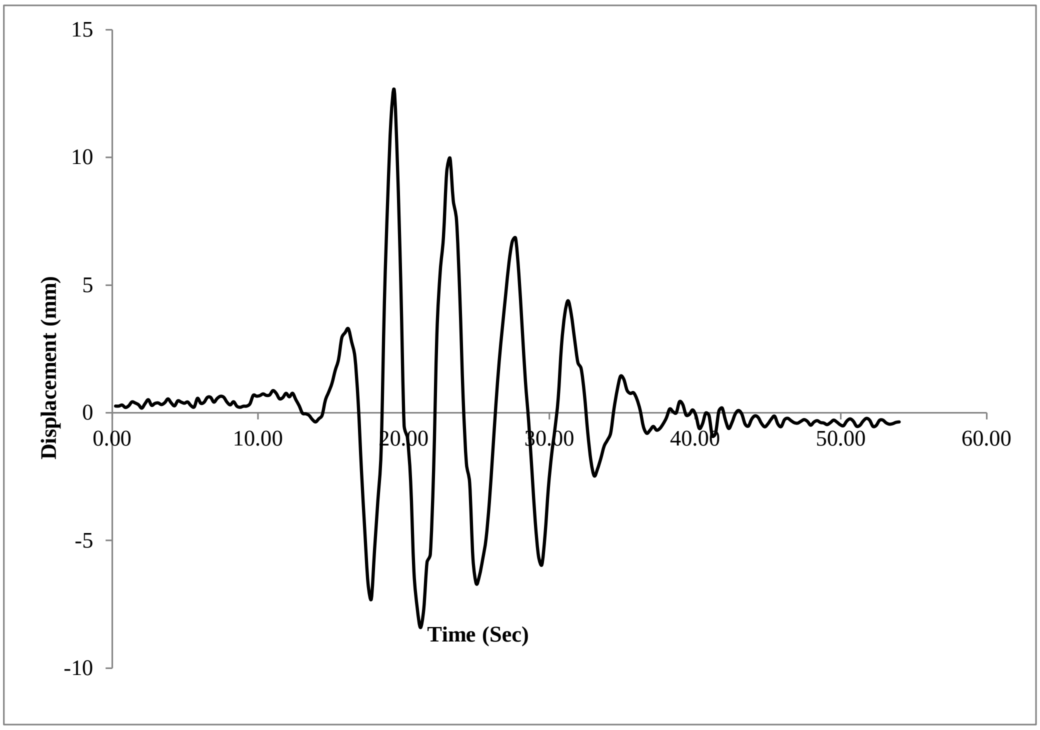

Figure 10: Displacement response at the top of pile cap in PLAXIS3D

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Table 1 Geotechnical properties of soil model used in PLAXIS3D

Layer No.	Depth (m)	Soil type	Effective Unit wt. (kN/m^3)	Cohesion C_u (kPa)	Angle of friction (φ)
1	0- 2.5	Loose sand (Engineering fill material)	18	-	30
2	2.5 - 20	Soft Clay	7	15	-
3	20 - 24	Stiff Clay	9	250	-
4	24- 70	Very Dense sand	9	-	35