Dynamic Analysis and Design of Foundations for Liquid Storage Tanks

Madan Kumar Annam and P. R. Sastry

Abstract Dealing with soft and loose soils is always a challenge to the practicing Civil Engineers. Foundations to support heavy loads on weak deposits in high seismic zones attracts more attention in design of foundations of structures. Seismic wave propagation and its impact on foundation elements induces additional bending moments and shear forces. This paper deals with analysis and design of foundations adopted for a 41 m diameter storage tank executed in the East Coast of India. The efficacy of lateral pile capacity has been assessed using PLAXIS 3D dynamic module. The performance of foundation system under earthquake loading was extensively studied and covered in this paper. A full geotechnical seismic site response analysis was conducted with a full mesh of soil layers and piles. Appropriate site-specific seismic acceleration history with time was imposed on the bedrock. Sloshing forces for both full and empty tank conditions were considered in the analysis. The 3D FEM seismic analysis of the pile movement and forces during and after earthquake were checked for structural adequacy of the piles against the M–N envelope.

Keywords Bored piles · Seismic loads · Storage tanks · Dynamic analysis · 3D FEM & PLAXIS 3D

1 Introduction

Storage tanks resting on pile foundations installed through soft soils and socketed into weathered rock and its performance under seismic conditions is great concern. The presence of soft soils plays important role in amplifying the ground motion, especially under seismic activity. Liquefaction of weak soils subjected to earthquake loading is key factor affecting the performance of pile foundation in seismically active zones where soil may experience liquefaction or cyclic mobility [1]. This paper presents

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aspects of 3D FEM analysis applied to an oil storage tank founded on a group of piles installed through soft soils and all piles got socketed into rock. Numerical modelling was carried out using PLAXIS 3D dynamic module to assess adequacy of lateral pile capacity and efficacy of reinforcement in the event of earthquake [2]. The use of 3D Finite Element analysis for modelling of foundations in seismic conditions is often challenge to design engineers in understanding its behavior.

2 Project Background

An oil storage tank of 41 m diameter resting on 800 mm diameter bored cast in-situ (BCIS) piles along with reinforced concrete tank pad and associated civil works were executed in one of the oil tank farms. A full geotechnical seismic site response analysis was conducted with a full mesh of soil layers in order to evaluate seismic dynamic pile-soil interaction. Piles with an appropriate site-specific seismic acceleration history with time (accelerogram) was imposed on the underlying bedrock and propagates upward to the ground surface.

One of the requirements of design aspects in this project was to assess the concern of seismic impact on the pile foundation due to dynamic pile-soil interaction. This check was necessitated as the seismic wave propagates from the underlying bedrock upward to the ground surface [3]. A geotechnical 3D FEM seismic analysis was thus resorted as the present case is highly three dimensional in nature as seismic forces induce additional pile movements as well as additional bending moment & shear force along the pile shaft. The plan view and cross section of the proposed foundation system of storage tank is shown in Fig. 1 and 2 respectively.

3 Geological Conditions

The subsurface soil profile revealed by the relevant boreholes around the proposed tank is quite consistent with the SPT N with depth. Design soil parameters are presented in Table 1 and the ground conditions are uniform across the project site.

4 Load Combinations and Seismic Analysis

The site-specific seismic action characterized by the generated seismic response spectrum according to Clause 3.5 IS-1893 (Part 4): 2015 [4] was considered for a return period of 475 years. The site-specific seismic response spectrum is shown in Fig. 3. The seismic response spectrum matches reasonably with the target site specific seismic response spectrum.

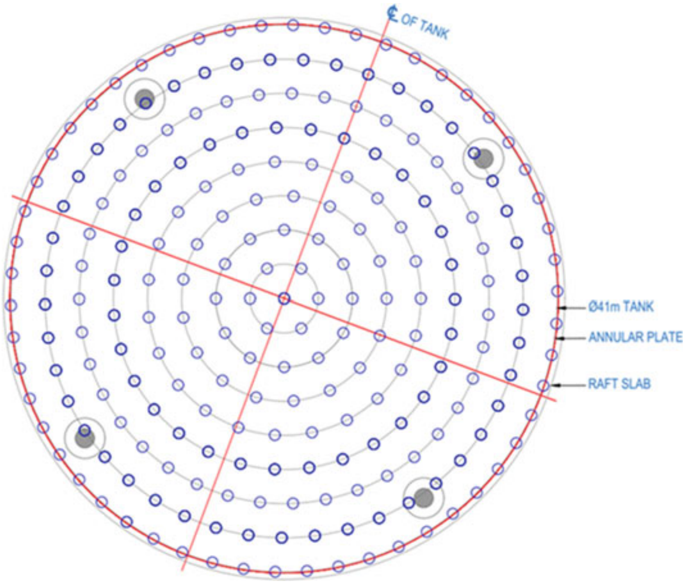

Fig. 1 Plan of the proposed tank foundation

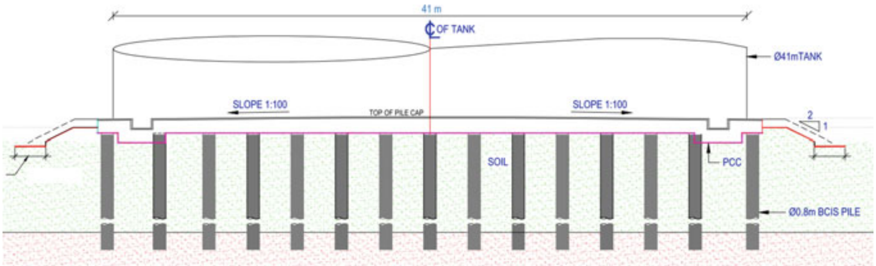

Fig. 2 Typical cross section of the foundation

Table 1 Soil parameters for the various soil types

S. No	RL (m)		Soil description	SPT N values	Unit weight	Cu	φ
	From	To			(kN/m^3)	(kPa)	(deg)
1	4	0	Filled up soil	8	17.0	–	29
2	0	−8	Clay (CH)	3	14.5	10	–
3	−8	−12	Clay (CI-CH)	6	16.0	20	–
4	−12	−17	Clayey silty sand	36	18.5	180	–
5	−17	−19	Highly weathered rock	>60	20.0	300	–
6	−19		Weathered rock	>100	20.0	600	–

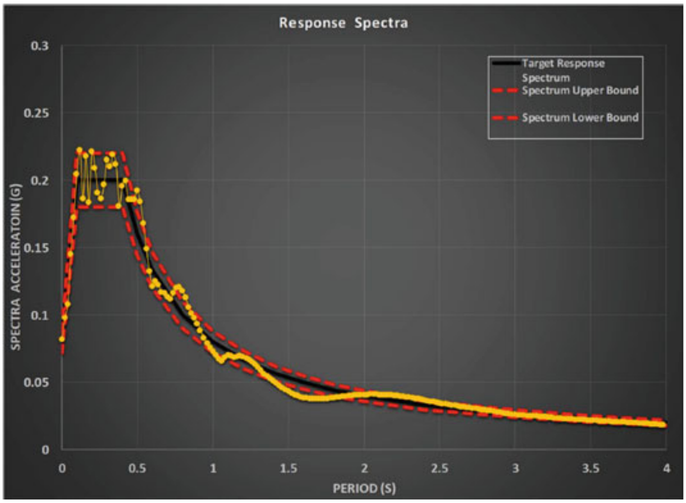

Fig. 3 The seismic response spectrum

The methodology adopted for Geotechnical 3D seismic analysis was based on the guidelines stipulated in IS-1893 Part 1 CL.6.3.4 [4] viz. (a) unfactored seismic signal as per DBE and (b) load combinations covering tank full and empty conditions with appropriate load factors, were checked along the full pile length.

5 Geotechnical 3D FEM Seismic Analysis

Latest version of Geotechnical 3D FEM (Plaxis 3D) dynamic module was used as it is highly three-dimensional in nature. The model was made initially with in-situ soil conditions followed by construction of piles and pile cap. The steel tank with base thickness of 10 mm and shell thickness of 25 mm at bottom to 8 mm at top was then erected as illustrated in Fig. 4. The load intensity of about 150 kPa was considered as content load acting on the foundation raft (reinforced concrete tank pad, resting on pile foundations).

Illustration of forces applied in Plaxis 3D model for seismic analysis is presented in Fig. 5.

The accelerogram was then applied to the base of underlying bedrock and propagate waves upwards. The accelerogram time history was sub-divided into 25 ms sub-steps for dynamic time-stepping analysis. Snapshots of intermediate moments of the tank movements during the earthquake is illustrated Fig. 6.

Based on the PLAXIS 3D study, it is assessed that for the full tank case, the calculated post-earthquake pile movement and forces are much smaller after the earthquake. Figure 7 presents the induced bending moment profiles of the piles during the earthquake with a maximum value of about 375 kNm.

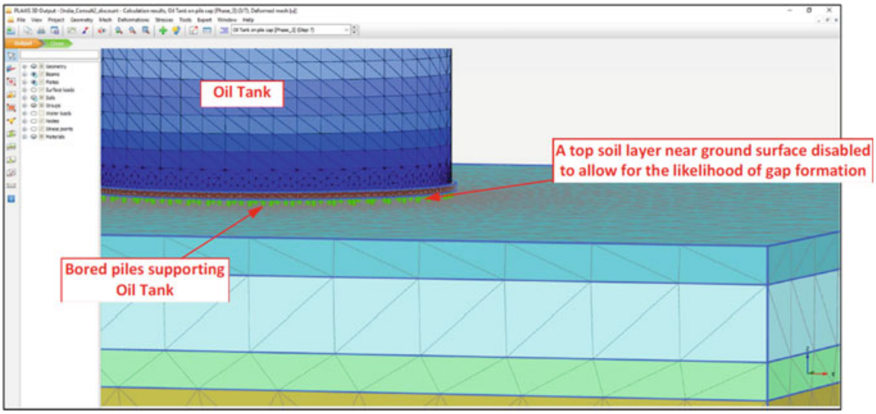

Fig. 4 Geotechnical 3D FEM model

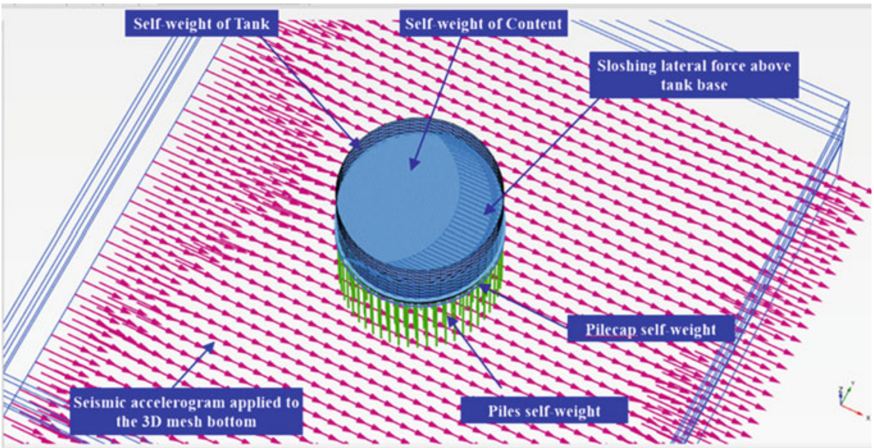

Fig. 5 Forces applied in Plaxis 3D model for seismic analysis

The induced pile forces are much smaller for the empty tank case due to much less inertial effect during earthquake. Load combinations for empty tank case and tank full conditions were complying with the IS1893 CL.6.3.4 [4] consistently.

6 Structural Analysis of the Foundation

Structural analysis of the foundation system was carried out using 'STAAD PRO'. Base raft was modeled as a circular reinforced concrete slab of 42.0 m diameter using plate elements resting on piles. Analysis and design of tank structure is not covered

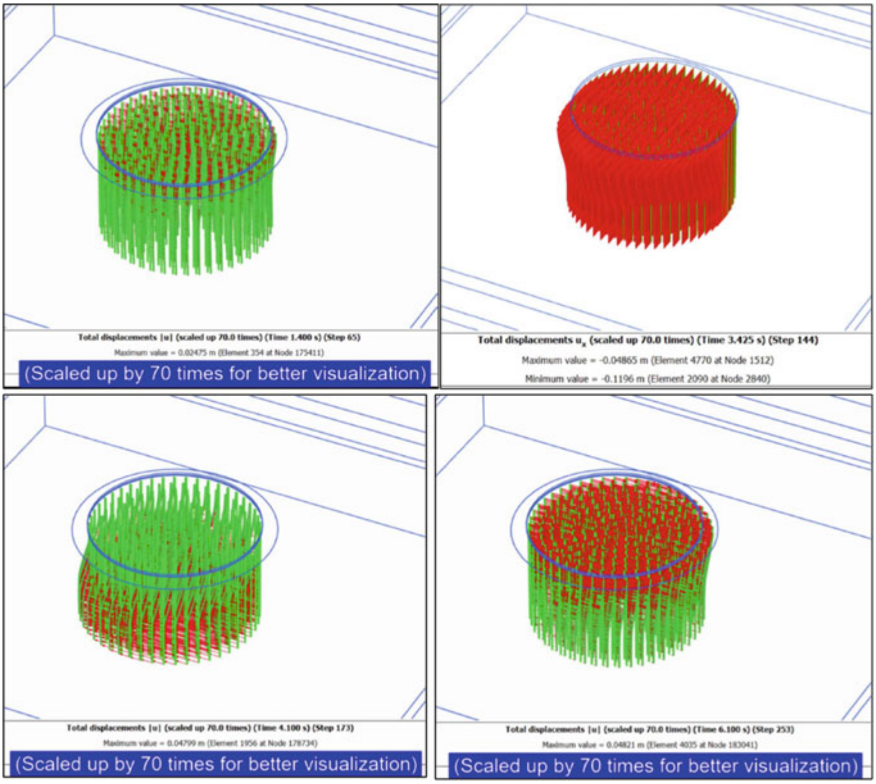

Fig. 6 Illustration of pile deflection during the earthquake (scaled up by 70 times)

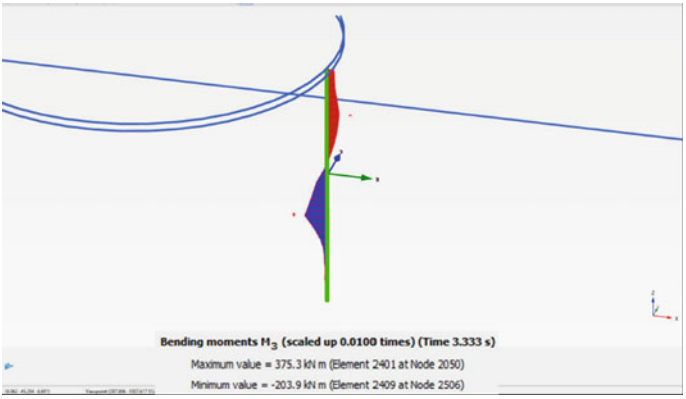

Fig. 7 The BM profile of the most critical pile during earthquake

in this paper. Foundation analysis was performed according to the forces supplied by client are applied in the structural model. Plate elements were modelled as annular grids and piles are considered as spring supports. Stiffness values of piles derived from its capacity and settlement. A concealed ring beam with nominal properties was placed at the edge of tank raft on which loads can be applied on the tank walls. The analysis was made for three scenarios namely empty condition, test load (with water) and service conditions. Loads due to empty tank and contents weight along with external loads viz. wind load and earthquake loads on the tank structure were applied on the model appropriately including the sloshing effects during operation stage.

The analyses revealed that for the tanks supported on piles, the number of piles solely based on geotechnical capacity for static loads and Design Basis Earthquake (DBE) conditions. The number of piles were selected to meet structural capacity requirements. The results of the structural analyses found that in most instances, the design of the tanks and the foundations are governed by the DBE. Bending moment and shear stress at critical locations for factored load combinations were obtained. Figure 8 illustrates the induced maximum M–N forces in the pile M–N envelope for both during & post-earthquake conditions.

It can be seen from the geotechnical 3D FEM seismic and structural analysis that the proposed number of bored piles are sufficient to resist the earthquake impact and hence foundation system is adequate.

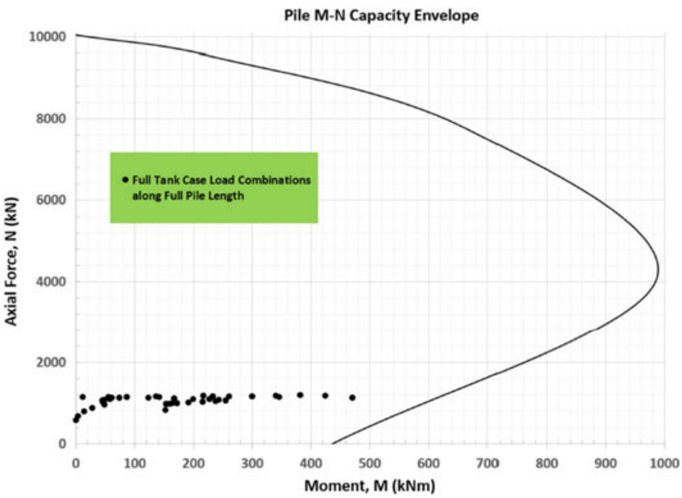

Fig. 8 Load combination along the full pile length on pile M–N capacity envelope

7 Results and Discussions

A full geotechnical 3D seismic analysis with a full mesh of soil layers was conducted for the storage tank foundation resting on piles. Dynamic pile-soil interaction with appropriate site-specific seismic accelerogram was imposed on the underlying bedrock. Seismic wave to propagate upward direction from the bed rock to ground surface was considered to evaluate the soil-structure interaction. The lateral loads arrived from geotechnical 3D FEM seismic analysis confirms structural integrity through M–N envelope that the re-bar provided is enough. On the other hand, the calculated post-earthquake pile movement and forces are much smaller after the earthquake, and a structural integrity check based on M–N envelope show the re-bar provided is more than sufficient for the post-earthquake forces.

Seismic analysis of the pile movement and forces during and after earthquake are checked for structural adequacy against the pile M–N structural capacity envelope and found satisfactory.

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