SOIL STRUCTURE INTERACTION OF HIGH RISE STRUCTURE SUPPORTED BY PILE FOUNDATION

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ABSTRACT: In this paper, a detailed dynamic analysis of a high rise structure supported by pile foundation is done with and without considering the soil stiffness. Firstly, the response of the soil embedded with piles is calculated using VERSAT-P3D [1]. A high rise structure is modeled using SAP2000 [2] and analyzed using the El-Centro earthquake data. Secondly, the effect of soil-structure interaction on high rise structure resting on pile foundation is analyzed by finite element discretization. The piles are modeled by beam-column element supported by laterally distributed springs. The stiffness of the foundation quantifies the effect of soil-structure interaction on the response of the superstructure.

INTRODUCTION
Seismic soil-structure interaction analysis of a high rise structure substantiated by pile foundations is one of the most complex problems in earthquake engineering. Soil-structure interaction is a collection of phenomena in the response of structures caused by the flexibility of the foundation soils, as well as the response of soils caused by the presence of structures. The combined behavior of the soil and structure can be known from detailed Soil-structure interaction (SSI) analysis. To adequately account for the soil nonlinearity, dynamic analysis should be performed in the time domain. Dynamic response of high rise structures to strong ground motion has to be understood for the development and enforcement of techniques to minimize severe consequences of earthquakes. This paper involves detailed analysis of a high rise structure of 12 stories (40m) residential building supported by pile foundation using VERSAT-P3D [1] and SAP2000 [2]. Initially response of the substrata embedded by piles is found out using VERSAT-P3D [1]. For this, a soil profile of depth 10m without considering the stiffness of the soil is adopted and acceleration time history is generated. A high rise structure is modeled and dynamically analyzed using SAP2000 [2]. Later soil structure interaction analysis of high rise structure of 15 stories (45m) substantiated by group of piles is done using finite element model. The piles are modeled by beam-column element supported by laterally compression-only distributed springs. Equivalent soil springs are considered for the flexibility at base of the structure due to presence of soil. Time history response results of both the models are presented in this paper. The effect of considering the soil stiffness and the interaction effect can be clearly understood.

METHODOLOGY
Ground response analysis is an important criteria that is to be considered for structural seismic hazard evaluation. The response of the soil in which piles are embedded is calculated using VERSAT-P3D [1]. In the current study, an earthquake of moment magnitude 6 which has peak ground acceleration of 0.521m/sec² was considered for the analysis with 5% damping. A soil profile with 10 layers is considered. No external mass is applied at the pile cap. Under the Shaking mode, earthquake motions are applied in the horizontal direction. The pile cap is set at the highest Z-coordinate of soil surface. A pile group of 5 piles embedded in the soil are shown in Fig. 1.

Fig. 1 Piles embedded in soil strata

The length of the pile is the same as the depth of the soil profile. Pile foundation configurations affect the seismic response of soil-pile-structure systems. The model of the pile group computed in VERSAT-P3D [1] can be viewed in Fig. 2.
Details of soil profile considered in the present analysis are shown in Table 1. The soil properties affect pile head acceleration, pile head displacement, and seismic interaction of the soil-pile system greatly. Details of pile properties considered in the present analysis are shown in Table 2.

**Table 1** Details of soil properties

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>IS Classification</th>
<th>Unit weight (kN/m³)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>MI-CI</td>
<td>0.25</td>
<td>0.16</td>
</tr>
<tr>
<td>0.95</td>
<td>MI-CI/SM</td>
<td>0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>2.5</td>
<td>SM-SP</td>
<td>0.35</td>
<td>0.16</td>
</tr>
<tr>
<td>4.95</td>
<td>SP</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>5.5</td>
<td>SC</td>
<td>0.28</td>
<td>0.20</td>
</tr>
<tr>
<td>7</td>
<td>SP</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>7.5</td>
<td>SC</td>
<td>0.28</td>
<td>0.20</td>
</tr>
<tr>
<td>8</td>
<td>MI-CI</td>
<td>0.25</td>
<td>0.16</td>
</tr>
<tr>
<td>9</td>
<td>SP</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>10</td>
<td>SM-SP</td>
<td>0.25</td>
<td>0.16</td>
</tr>
</tbody>
</table>

**Table 2** Details of pile properties

<table>
<thead>
<tr>
<th>Young's modulus (kN/m²)</th>
<th>Unit weight (kN/m³)</th>
<th>Damping ratio (%)</th>
<th>Moment of inertia (mm⁴)</th>
<th>Reduction factor</th>
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</thead>
<tbody>
<tr>
<td>100</td>
<td>25</td>
<td>4</td>
<td>0.05</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Structural Idealization**
A three-dimensional model of the structure was modeled in computer program SAP2000 [2] and dynamic analysis was performed on the structure to evaluate the structural response. Damping ratio is taken as 5%.

**ANALYSIS**
The earthquake ground motion data which is obtained from VERSAT-P3D [1] is given as seismic input for the high rise building and analysis has been carried out. Fixed-base analyses of the high rise building were performed using SAP 2000 [2]. The displacement time history graph and the response spectrum curves are as shown in Fig. 3-6.

**Fig. 2** Soil-pile view in VERSAT-P3D

**Fig. 3** Displacement time history of joint at first floor

**Fig. 4** Response spectrum of joint at first floor

**Fig. 5** Displacement time history of joint at top floor
SEISMIC ANALYSIS USING FINITE ELEMENT MODELLING

A detailed study has been carried out assuming the behavior of both soil and structure to be linearly elastic. Flexibility of soil is taken into account. Problems involving three dimensional axisymmetric solids subjected to axisymmetric loading reduce to simple two dimensional problems because of the total symmetry about the z-axis, with all deformations and stresses independent of the rotational angle θ [3]. Thus the problem needs to be looked at as a two dimensional problem in rz. The dynamic equilibrium equations in the finite element formulation are shown in Eq. 1.

\[ M\ddot{u} + C\dot{u} + Ku = f(t) \]  

(1)

where M, K and C are harmonic dependent mass, stiffness and damping matrices, respectively, f(t) is the external force vectors, and \( \ddot{u}, \dot{u} \) are second and first derivatives of displacements. Using the three shape functions N1, N2 and N3, displacement is defined as shown in Eq. 2.

\[ U = Nq \]  

(2)

The element stiffness matrix is given as below in Eq. 3.

\[ K_e = \int \sigma^{T}DB \]  

(3)

A high rise building supported by pile foundation has been idealized by finite elements, consisting of three noded isoparametric elements. The dynamic response to ground motion is obtained by time wise mode superposition method. The time history analysis is carried out using Newmark’s method [4] where \( \beta = \frac{1}{4} \) and \( \gamma = \frac{1}{2} \) (the average acceleration method). The soil boundary is taken as viscous media. A simplified and easy approach to model the dynamic interaction effects is by associating linear springs and dashpots to the degrees of freedom of the foundation. The springs account for the change in the stiffness and consequently the changes in the natural frequencies whereas the dashpots contribute for the dissipation of the building vibrational energy. The pile group interaction factor has significant effect on the dynamic response on the system.

The boundary of the soil is extended to substantial distance away both at the sides and from the pile tip in vertical direction enabling the model to predict the exact response of the system [5]. Foundation raft is assumed to be supported on number of springs distributed over the total plan area of the foundation raft and connected to the different nodes of raft elements. The piles are modeled as frequency independent equivalent springs in horizontal and vertical direction having six degrees of freedom at each node [6]. The finite element model is shown in Fig. 7.

The equivalent spring stiffness and the equivalent damping for the pile group is defined as shown in Eq. 4-5.

\[ k_e = \frac{\sum L N_k aL}{\sum L N_k oL} \]  

(4)

\[ c_e = \frac{\sum L N_k aL}{\sum L N_k oL} \]  

(5)

where, \( N = \) number of piles in a group; \( a_A = \) displacement interaction factor (axial).

The expressions for calculating the stiffness and the damping constant for an embedded cap are shown in Eq. 6-7.

\[ k_e = G_e N S_{u1} \]  

(6)

\[ c_e = \frac{G_e f}{\sqrt{\phi f_{u1}}} \]  

(7)
Fig. 9 Displacement time history of pile cap.

where $G_d$ = dynamic shear modulus; $e$ = embedded depth; $r_e$ = equivalent radius of pile; $g$ = acceleration due to gravity; $\gamma$ = average weight density of soil; $S_{ul}$ and $S_{uw}$ are the factors depending on Poisson’s ratio.

The material properties are presented in Table 3.

Table 3 Details of Material properties

<table>
<thead>
<tr>
<th>Description of the structure</th>
<th>Poisson’s Ratio</th>
<th>Modulus of elasticity (kN/m²)</th>
<th>Density (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>0.40</td>
<td>25x10⁶</td>
<td>18</td>
</tr>
<tr>
<td>Pile</td>
<td>0.25</td>
<td>25x10⁶</td>
<td>25</td>
</tr>
<tr>
<td>Pile cap</td>
<td>0.20</td>
<td>25x10⁶</td>
<td>25</td>
</tr>
<tr>
<td>Superstructure</td>
<td>0.20</td>
<td>3x10⁷</td>
<td>25</td>
</tr>
</tbody>
</table>

The displacement time history results for the nodes existing at the pile, pile cap and high rise building is shown in Fig. 8-10.

CONCLUSIONS

A detailed estimation of Seismic soil-structure interaction (SSI) analysis of a high rise structure resting on pile foundation is presented in this paper. Dynamic analysis of high rise structure of 12 stories modeled in SAP2000 [2] has been performed using the data obtained from VERSAT-P3D [1]. The maximum displacements for the top and first floors of structure are $1.174x10^{-2}$ m and $1.080x10^{-2}$ m respectively. A high rise building of 15 stories supported by pile foundation has been idealized by finite elements and analyzed using the El-Centro earthquake data. The displacement time history results for the nodes existing at the pile, pile cap and at the top floor of the high rise building are $0.0031$m, $0.185$m, $0.3135$m respectively. Total displacements of the structure are larger in flexibly based structure. Modeling the structure along with soil supported by piles gives more pragmatic outputs. Therefore, the soil-structure interaction analysis of high rise buildings is of prior importance in design considerations for seismic conditions.

REFERENCES