Seismic Analysis of Soil-pile Interaction under Various Soil Conditions

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Abstract

Study of Soil-Pile interaction is an important consideration in evaluating the seismic performance of pile-group supported structures, particularly in soft clay or liquefiable soils. Additionally, dynamic deformations can also get induced within the structure due to the underneath soft soils. An understanding from historical catastrophic earthquakes evidently demonstrated that the ground motions were responsible for the failure of foundations, which in turn have caused damage to the structures, leading to the majority of property loss and casualties. In view of the necessity to precisely predict the response of a pile in a soil-structure interaction problem during an earthquake, in this paper, numerical analysis of a single pile subjected to the 1940 El Centro earthquake (Mw 6.9) ground motion was carried out to understand the soil-pile interaction for different soil conditions, namely, C-soil, Ø-soil, and C-Ø soil. The axi-symmetric numerical model was developed by using Finite Element Program “OpenSeesPL”, to understand the soil pile interaction for the dynamic earthquake loading condition. Response profiles, displacements response time history at the base and at the crest, and stress contours are studied to understand the behavior of short and long piles in various soil conditions.

Keywords: Soil-pile interaction, rigid and flexible piles, Open-sees PL, C, Ø, and C-Ø soils.

INTRODUCTION

Piles are generally used in soft, liquefiable soils and often in very soft rocks which have spread to the substantial depth. The geological map of India (Fig.1.) shows the formation of recent sedimentary and Pleistocene alluvial soils spread over the plains of north India. These soils since formed from the river deposits are new and are susceptible for liquefaction during earthquakes. Shallow foundations in such soils are not cost-effective and they in turn perform poor for the dynamic load cases and fail under bearing capacity of the boundary domain i.e. soil. Coincidentally, these north Indian plains experience earthquakes of moderate to high intensity (Fig.2.). Additionally, these soils because of their rich mineral sources are inhabited more. Fig.3. shows the density of housing in these districts. Combined with the seismicity in the area and construction practices, the housing risk factor faced by the residents in these areas is high and is presented in Fig.4.

Structures supported by piles or pile-groups can be an imperative solution, predominantly for soft clay and liquefiable soils. The phenomenon could be understood by assessing from the seismic performance analysis of pile, pile-group and pile-group supported with structures. However, it is essential to precisely predict the structures response considering the soil-structure interaction. Soil-pile interaction during an earthquake is a complex study and thus is not always taken into analysis for the seismic design of structures.

Based on the information from Fig.1 to 4 and Table 1, it is understood that the north Indian plains need piles to support the structures safe from earthquakes and earthquake triggered liquefaction.

In this paper, the response of a short and long pile for the 1940 El Centro earthquake (Mw 6.9) ground motion has been presented. For the analysis, OpenSeesPL finite element software has been employed. A short and a long pile are modeled in three soil types, namely, C-soil, Ø-soil, and C-Ø soil, for which the time-history analysis has been performed. In the numerical analysis, the soil-pile interaction is achieved by representing boundary conditions of a pile with discrete non-linear springs with the stiffness equal to the equivalent soil subgrade reaction.
Numerical Modeling of Soil-Pile interaction

The numerical analysis is performed by using OpenSeesPL. Developed by the Regents of the University of California (2000), is a graphical user interface (GUI) for three-dimensional (3D) soil-pile interaction responses. The base shaking simulation is performed with a control boundary conditions and zero inclination mode. The pile is modelled with linear beam element and soil with nonlinear beam element. The interface between pile and soil is simulated with zero-length elements. These elements connect the fixed node of pile with slave spring nodes of soil.

Soil Properties

The different types of soils considered for the analysis are homogeneous, namely, purely cohesive (C-soil), purely non-cohesive (Ø-soil) and combination of both (C-Ø soil).
explains the different soil parameters of the soils considered for the analysis.

Table 2: Soil types and their parameters

<table>
<thead>
<tr>
<th>Soil Parameters</th>
<th>C-Soil</th>
<th>Ω-Soil</th>
<th>C-Ω Soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Modulus, G (kPa)</td>
<td>6x10^4</td>
<td>13x10^4</td>
<td>10x10^4</td>
</tr>
<tr>
<td>Bulk Modulus, K (kN/m^2)</td>
<td>3x10^5</td>
<td>39x10^4</td>
<td>2.3x10^4</td>
</tr>
<tr>
<td>Cohesion, C (kN/m^2)</td>
<td>37</td>
<td>0.3</td>
<td>25</td>
</tr>
<tr>
<td>Coeff. of Permeability, (m/s)</td>
<td>1x10^-9</td>
<td>1x10^-7</td>
<td>1x10^-4</td>
</tr>
<tr>
<td>Mass density (Mg/m^3)</td>
<td>1.5</td>
<td>2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>Friction Angle (Degrees)</td>
<td>0°</td>
<td>40°</td>
<td>33.5°</td>
</tr>
</tbody>
</table>

Pile Properties

Numerical analysis is carried out for circular rigid short and flexible long concrete piles. The lengths of 4.5 m and 18 m respectively are modeled with a diameter 0.5 m. The pile is fixed at the bottom and pinned at the top to find its response against the given dynamic load. The short and long piles are modeled with a semi-infinite soil medium of size 25m x 25m x 9m, and 40m x 40m x 36m, to simulate the soil structure interaction phenomenon. Fig.5. shows half-mesh Soil-Pile interactive model considered for the dynamic analysis.

Dynamic analysis of the soil pile interaction model

A dynamic load in the form of El Centro ground motion (M_w 6.9) with peak ground acceleration of 0.348g is applied at the base of the soil model, to perform the analysis. The acceleration time history of the ground motion used for the study is shown in Fig.6. Fig.7. shows the Fourier Amplitude Spectra of El Centro ground motion. Fig.8. shows the IS 1893 design response spectra and El Centro ground motion response spectra.

RESULTS

For the given ground motion, response profiles for short and long piles are observed in the direction of the lateral load applied and are shown in Fig.9&10. The displacement response time histories at the base and top of the short and
long piles for different soil types are presented in Fig.11&12. Amplification of displacement response is observed at the top of the pile. Fig.13&14 shows the stress contours for short and long piles modeled in different soil strata. It is observed that the displacements and stresses high for C-Ø soil.

**Figure 9:** Short pile response profile for different soil types

**Figure 10:** Long pile response profile for different soil types

**Figure 11:** Displacement response time history of short pile at the base and at the crest for a) Ø-Cohesionless soil b) C-Cohesive soil c) C-Ø soil

**Figure 12:** Displacement response time history of long pile at the base and at the crest for a) Ø-Cohesionless soil b) C-Cohesive soil c) C-Ø soil

**Figure 13:** Longitudinal stress [kPa] profiles observed in the soil and short pile subjected to El Centro earthquake ground motion for a) Ø-Cohesionless soil b) C-Cohesive soil c) C-Ø soil
SUMMARY AND CONCLUSIONS

To carry comparative study on soil pile interaction for long and short pile for different soil types like C-soil, Ø-soil and C-Ø soil, time history analysis has been carried out on the finite element models.

Subsequent are some interpretations drawn from the existent study:

1. For short rigid short pile and flexible long pile, the peak displacements at the top of the pile are found to be less for C-Ø soil as compared to C-soil and Ø-soil.

2. The values of peak displacements are more for long pile than the short pile; hence length of the pile is one of the important parameter for displacement controls.

3. The grade of the concrete is not influencing the displacement characteristics of the pile. Change in displacements is negligible for the parametric grades considered for the present study.

4. The type of surrounding soil of the pile plays an important role in the displacements at the top of the pile.

The finite element tool is found to be easy to understand and operate for the interaction problem.

NOTATIONS

Ø-Cohesionless soil
C-Cohesive soil
C-Ø combination soil having both the cohesive and cohesionless material
γ and β Newmark’s integration coefficients

REFERENCES


