Siesmic Response of Single Pile Soil Structure Interaction
Effect of Cordera bridge foundation

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Abstract. The response of single pile foundations to the dynamic loads is considered in this paper. The behaviour of such foundation is important specifically in case of earthquake excitation through the supporting soil medium. An axisymmetric finite element model has been implemented to simulate the behaviour of pile in relatively clayey soil deposit using Abaqus software including the soil structure interaction effect soil system. Eight node axisymmetric quadrilateral element CAX8R used to simulate the soil continuum. Contact behaviour between the single pile part and the part of soil was simulated using the ‘surface to surface’ contact method with master-slave concept. Furthermore, the pile behaviour material has been simulated with a linear elastic model while, soil material has been simulated with an elasto-plastic model “Mohr-Coulomb failure criterion”. Two different excitation have been adopted during the analysis: El-Centro and Ali-Algharbi earthquakes in order to investigate the effect of various intensities. The results of the analysis demonstrate alteration in the relative displacement and stresses along the pile with different soil layer and different stiffness with both earthquake excitations.

1. Introduction
Generally, finite element method or ‘Numerical analysis’ shows a major role in case of investigating the behavior of many geotechnical structures. It can illustrate the effect of dynamic loading on such structures and also highlighting the aspects which are important in engineering practice, [1] In general, dynamic analysis, Soil structure or soil pile structure analysis is considered as very important aspect as it containing two components affecting the behaviour of the system, both components arisen during seismic events: kinematic interaction and inertial interaction. Where the kinematic soil-pile interaction refers to pile loading developed by the soil displacement from the seismic wave propagation, while the second component is reffered to as Inertial interaction which results from forces caused by superstructure actuations by the kinematic interaction[2]. Seismic soil-structure interaction analysis involving pile foundations is one of the more complex problems in geotechnical earthquake engineering. The analysis involves modeling soil-pile interaction, pile-to-pile interaction, inertial interaction and the nonlinear hysteretic behaviour of the soil. Most of the current methods for analyzing pile foundations can be categorized into two main groups. One is based on the elastic continuum models and the other on the Winkler springs model. The elastic continuum models are suitable for studying the response under low excitations only when the dynamic response is approximately elastic. They are not suitable for analyses under strong shaking. The reduction in soil stiffness and the increase in damping associated with strong shaking are sometimes modeled crudely in these elastic methods by making arbitrary reductions in shear moduli and arbitrary increases in viscous damping. Seismic soil-structure interaction analysis
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2. Material and overall Properties for the Simulated Model

Single pile selected from foundation of bridge site belongs to khanaqeen district within diyala governorate which lies northeast of Baghdad in Iraq adopted as a case study, details of the simulated model is described in the current next sections.

2.1 Case study

Cordera bridge Pile foundation located in 50 km North Ba'qubah region in Diyala Governorate, northeast of Baghdad in Iraq has been concerned in this study. The finite element modeling has been performed based on available design drawings for the pile and also the site survey and geotechnical reports (supplied from the consultant bureau-Diyala University).

2.2 Pile and soil model description

The geometric modeling consists of simulating the soil continuum and the pile foundation as separated parts then ABAQUS gathering the parts in the assemble module as an axisymmetric model. Pile foundation as a concrete structure with the circular section with diameter of pile is 1.5 m and depth of the pile is 30 m. The soil and pile assembly are shown in Figure 1. The simulation of the model was done in axisymmetric model. An axisymmetric modeling provides reasonable simplification for modeling piled-soil systems. The axisymmetric model has the advantage of simplifying the problem by reducing the size of the model. Subsequently, considerable saving in computational time can be achieved;
The element used to simulate the soil is an axisymmetric quadrilateral element named CAX8. Axisymmetric elements provide for the modeling of bodies of revolution under axially symmetric loading conditions, finite element mesh is as showed in Figure 2.

2.3 Constitutive Models

For most general 3D simulating models through the Abaqus program, soil mass consisting of three layers is typically modeled as an isotropic homogenous rectangular part, with approximately width and depth (10m x 30 m). The concrete pile body is modeled in term of linear elastic model. The soil constitutive model choosen to be as an elastic-perfect-plastic model by implementing the yielding criterion of Mohr-Coulomb. Indeed, large number of routine design calculations are still performed using Mohr-Coulomb (MC) criterion in geotechnical area. The following equations give the relations of this criterion (Abaqus Theory Manual, 2012); and as shown in Figure 3.

\[ \tau = c + \sigma \tan \phi \] (1)

Where \( \sigma \): normal stress; \( \tau \): shear stress, \( c \): cohesion of the soil, and \( \phi \): the angle of internal friction.

General properties for the system which contained in simulation and considering the model with negligible water level are showed in Table 1.

| Soil layers | Depth | Density \( \gamma \) | Elastic modulus \( E \) | Poisson’s ratio \( \nu \) | Cohesion \( c \) | Friction Angle \( \phi \) |
|-------------|-------|----------------------|------------------------|---------------------|----------------|-----------------------|
| Layer1      | 10    | 1911.5               | 3.62E+07               | 0.15                | 50000          | 5                     |
| Layer2      | 8     | 2008.7               | 3.22E+07               | 0.15                | 1000           | 36                    |
| Layer3      | 12    | 1782                 | 4.50E+07               | 0.15                | 1000           | 36.3                  |
| Concrete/pile | 25   | 2400                 | 2.40E+10               | 0.2                 |                |                       |

Figure 1. pile foundation system assembly

Figure 2. finite element mesh of the model.

Figure 3. (a) MC failure criterion (b) Elastic-perfectly plastic assumption of MC model (ABAQUS/CAE User’s Manual, (2012), Dassault Systemes Simulia Corp., Providence, RI, USA)
2.4 Contact Interactions

Most interesting numerical methods approved in contact problems include the laws, formulation, the geometries and also interfaces. Generally, many formulations have been established which can simulate problems of the interaction, especially for the soil-pile interaction systems. For modeling the contact behavior between the soil and pile material, friction coefficient which is mainly a function of the surface roughness, adhesion and porosity factors has been well-defined through two mechanisms: the normal and frictional mechanisms, thus, many formulations have been advanced for simulating interaction between soil and piles systems [6].

Current work adopt the master slave concept with method of the surface to surface contact is used which developed by Wirggers in 1995, which is broadly used due to its capability in representing large deformations within the area of contact.

3. Load Condition

In general most structures are subjected to static loads and also can exposed to dynamic loading event during their lifetime. Such as earthquakes as an instantaneous loading. Current study include two different shaking/earthquakes records, firstly, the earthquake of El-Centro (1940) of a magnitude (5.4) and peak ground acceleration PGA = 3.50 m/sec2. The second is Ali-Al Gharbi / south of Iraq (2012) with magnitude of (4.9) and PGA=1.04 m/sec2. In order to check the response of the system, these dynamic loading conditions as well as the gravity loads (static loads) was applied to the pile soil system. The time history records of both earthquakes are shown in the Figure 4 and 5 respectively.

![Figure 4. El-Centro (1940) EQ.](image1)

![Figure 5. Ali-Al Gharabi (2012) EQ.](image2)

4. Result and Discussion

Current work is curried out to make assessment and determination of the response of single pile system to earthquake loading in addition to static loading (dead and live loads) considering the site condition effect. The work is describing the relative displacements developed in the pile-soil interface (points in the top, mid, bottom of soil were considered).

The analysis steps were parted into two models (i.e. model 1 (M1) is under Ali-Algharbi EQ and model 2 (M2) is under El-Centro earthquake. In general, the deformed shape of the displacement under both loading cases is shown in Figure 6. It is found that the maximum relative displacement in the horizontal direction at the surface point is (0.00368 m) as shown in Figures 7 and 8 respectively. The stress response also conducted from the analysis with maximum value of (280.4 Pa) at the soil as shown in Figures 9 and 10. Additionally, the case M2 showed that the relative displacement results was closes in behaviour with M1 but with different magnitude of (-0.01161 m) at surfaced at the end of loading as shown in Figure 11 and 12. In the other hand, for case M1 as shown in Figure 13, the stresses change from maximum value of (330.2 Pa) at top region and decrease when measure at soil bottom with value of (142.3 Pa).
Generally, for the overall response of the system, under the consideration of properties of soil layers, the response of pile part which embedded in soft soil layer varied from the input motion and this variation reduced with increase in soil stiffness along the depth of pile. The response of the portion of soil near pile imbedded in the stiffer layer was almost the same as the input motion. Additionally, the maximum deflection along pile depth for the two earthquakes increased due to inertial soil structure interaction effect along the head part of the pile and its effect decrease with pile depth. It also can be seen that displacement for an input seismic case M2 increased somehow more than the case M1 peak groundacceleration increased.

Figure 6. horizontal displacement in soil.

Figure 7. relative horizontal displacement in soil under M1 case.

Figure 8. relative horizontal displacement along pile-depth in M1 case.

Figure 9. stresses response in soil under M1 case

Figure 10. stresses in soil under M1 case.

Figure 11. horizontal displacement in soil under M2 case.
5. Conclusions
The single pile-system foundation has been successfully modeled using Abaqus program, with actual data from the existing bridge site in Iraq, the following conclusion has been obtained.
1. The large influence of soil-pile system with different properties with different seismic loading.
2. The selection of governing model is directly influencing the performance of system as seems that variation of stresses in soil mass and also the deformation pattern become different and largely changed soil stiffness, and such step should be taken with cure into account at the beginning of analysis and design of and structural.
3. Important effect of the soil-pile-structure interaction (SPSI) has depicted in the dynamic analysis and seismic design of structures and foundations based the interactive response between soil and pile.
4. It can Obtaining better insight to the soil and pile performance expectation through this analysis as varying the peak ground acceleration.

References
[1] Maharaja D.K., (2003), “Load Settlement Behavior of Piled Raft Foundation by Three Dimensional Nonlinear Finite Element Analysis”, Electronic Journal of Geotechnical Engineering 2003.).
[2] Chenaf, N., & Chazelas, J. L. (2008, November). The Kinematic And Inertial Soil-Pile Interactions: Centrifuge Modelling.
[3] Thavaraj, T. and et. al. “Seismic Response Analysis Of Pile Foundation” Geotechnical and Geological Engineering 28(3):275-286 · May 2010
[4] Miyamoto Y., Sako Y., Miura K., Scott R. F. and Hushmand B., (1992): Dynamic behavior of pile group in liquefied sand deposits, Proc. of 10WCEE, 3, pp.1749-1754
[5] Miyamoto Y., Sako Y., Kitamura E. and Miura K., (1995): Earthquake response of pile foundation in nonlinear liquefiable soil deposit, J. Struct. Constr. Eng., AIJ, No.471, pp.41-50
[6] Miyamoto Y., Fukuoka A., Adachi N. and Koyamada K., (1997): Pile response induced by internal and kinematic interaction in liquefied soil deposit (Centrifuge model test for pile foundation in saturated sand layers and its analytical study, J. Struct. Constr. Eng., AIJ, No.494, pp.51-58
[7] Wriggers, P. “Finite Element Algorithms for Contact Problems”. Archives of Computational Methods in Engineering, Vol. 2, 4, 1-49, 2015.
[8] ABAQUS Lectures, (2003), “Analysis of Geotechnical Problems with ABAQUS”, ABAQUS, Inc., U.S.A.
[9] ABAQUS/CAE User’s Manual, (2012), Dassault Systemes Simulia Corp., Providence, RI, USA.