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The behavior of Pile Group Constructed on Clayey Soil under El-Centro Seismic Using Finite Element Analysis

Afnan H. Ali[1], Hassan O. Abbas[1*], Safa H. Abd[1] and Muftah Mohamed Sreh[2]

[1]Department of Civil Engineering, University of Diyala, 32001 Diyala, Iraq
[2]Departement of Civil Engineering ,University of Elmergib, Al-Khoms, Libya

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ABSTRACT

Over the past decades, pile foundations used to support buildings through a transfer of superstructure loads into more stable soil strata than surface soil layers. Buildings are exposed to seismic force, pile undergoes more stress through the significant vibration of the surrounding soil in addition to the static stresses of buildings. The investigation of the behavior of pile foundations under the influence of earthquakes is still limited or not well described. Further, this paper presents a theoretical study to evaluate the vertical settlement and horizontal displacement of piles embedded in clay and silty soil of Baqubah soil under the effect of the acceleration time history of the 1940 El-Centro earthquake. The study was carried out by using the commercial finite element software PLAXIS 3D. A three-dimensional analysis of the soil-pile foundation for four multi-story buildings is performed with different diameters (0.5, 0.7, and 1) m for the corner, exterior, and interior pile, respectively. The linear elastic model for pile foundation and the Mohr-Coulomb model for soil layers were used in this numerical analysis. The research showed that vertical settlement and horizontal displacement increase as the duration of the earthquake increases, and horizontal displacement with values smaller than vertical displacement. Also, the results showed the vertical settlement is similar for different diameters, in contrast to the horizontal displacement, which was of different values with a range between (3% to 22%) when the diameter increased from 0.5m, 0.7m, and 1m. Also, it can be observed that values increased with the direction of the earthquake from the right to the left side of the pile-soil system with a range of (12% to 32%).

1. Introduction

Constructions and buildings are subjected to lateral loads as water waves, wind forces, earthquake vibrations, and static loads are supported with raft structures in general. If shallow cases of the subsoil (soft soil, liquefiable soil, compressible conditions), pile foundations are used to transfer these loads of superstructure to deep and more stable soil strata.

Pile foundations are subject to more horizontal stress in addition to the vertical load by constructions, that are subjected to high wind or earthquake forces. As the phenomenon of earthquakes is considered one of the most dangerous natural disasters that occur without warning and causes damage to any building or structure through settlement, and ground cracking, As an important reason for studying their impact on the foundation systems for those buildings [1]. In comparison to the static case, seismic foundation design necessitates special considerations, one of the most difficult challenges in civil engineering is seismic risk

* Corresponding author.
E-mail address: temimi71@yahoo.com
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mitigation, and geotechnical earthquake engineering can make an important contribution to this challenge [2].

As a result, to achieve cost-effective and safe designs, foundation engineers must keep abreast of technological advancements in these domains or be well informed in these fields. Much work remains to be done in developing methodologies for evaluating seismic bearing capacity and earthquake-induced permanent displacements in shallow and deep foundations [3]. In softer or more compressible soil, pile foundations are usually required to increase bearing capacity and decrease differential settlement. The forces on the pile foundation change during an earthquake due to ground deformation caused by the lateral seismic load. Because most pile foundation failures in recent years have been caused by soil liquefaction, studies on damage in non-liquefiable soil are extremely rare [4].

For several decades, earthquake and geotechnical engineers have been fascinated by pile foundations. The devastation caused by major earthquakes around the world may be reason enough to research the seismic behavior of piles, and lateral vibration is the most dangerous in the analysis and design of these foundations. To date, several numerical models and approaches have been proposed to predict pile response in such situations. Beam on Nonlinear Winkler Foundation (BNWF) models, Finite Element models, and so on are examples [5, 6, 7].

Structures resting on pile foundations continue to collapse after strong earthquakes that are founded on or through liquefaction soil. It has been discovered that the assumed some of the observed seismic pile failures cannot be explained by the failure mechanism underlying current design methods; the superstructure remained undamaged, but the structure as a whole tilted or moved laterally. The piles beneath the foundation most likely failed structurally due to the formation of plastic hinges [8].

[9] Studied the dynamic response of piles in a composite homogeneous soil layer, with a numerical solution to the plane-strain issue of a pile slice subjected to vertical vibration. The stiffness and damping of a pile are presented using the finite element method, The findings showed the soil-pile system is under repeated and severe excitation and exhibits nonlinear properties. The pile stiffness and damping were lowered as the excitation intensities increased.

Also, a study by [10] found excitation frequency increases, stiffness (Ks) is increased, while damping (Cs) for the pile decreased and, dynamic pile-soil interaction depends on the excitation frequency. Increasing the pile slenderness decrease the peak displacement, As a result of increasing the group size (ng = 9 instead of 4) the group stiffness/damping efficiency may drop or rise, according to numerical analysis with a 3D finite element model.

A study by [11] investigated the response and performance of piers of "Sheikh Sa'ad Bridge" and the soil surrounding under actual seismic loads recorded in the middle and south of Iraq over the last few years using the (ANSYS 14.5) finite element program to see if these typical piers and surrounding soils can withstand the stresses induced by earthquake loads. It was discovered that typical piers used in Iraqi bridges can withstand earthquakes up to M_L(local magnitude on Richter scale) = 6.8 maximum magnitude. Also, the highest displacements in piles cap (at the sites where the earthquake impacts were applied).

Most of the problems that grow from excessive ground movements greatly affect the performance of the structures that are supported by piles. Deep foundation design for dynamic load resistance is primarily based on limiting deflection criteria that take into account the safe operation of the superstructure, [12]. As a result, a careful engineering analysis of the behavior of pile foundations under anticipated static and dynamic working loads becomes a critical step in the satisfactory performance of pile foundations. Also, through the experimental studies of the dynamic behavior of pile foundations embedded in both soft clay and loose soil to medium soil, it was observed that all of the bending moment, settlement, and amplitudes of the accelerations increased as the frequency of the ground motions increased [12,8].

As Diyala governorate (Baquba city) is considered an affected area by seismic activity, and this is due to geology characterization, which is situated along the earthquake line that runs between the Arab and Iranian plates, making it sensitive to accurately forecast the ground motion distribution from an urban point of view. Which is the main reason for conducting this study. It also has a diverse terrain, comprising mountains, plateaus, and plains, as well as a range of soil types, including rocky, sandy, and clay soil types [13].

Therefore, the present paper aims to investigate the effect of the seismic load on the lateral displacement and vertical settlement of the pile group embedded in clayey soil (Baquba city).

2. Numerical modeling

Finite element analyses were applied for problems with three-dimensional analysis code. The finite element analysis is an excellent technique for getting approximate solutions for boundary value problems, by dividing the objects into small elements (volumes), each element contains several nodes with many degrees of freedom that correspond to the discrete values of the boundary value problem's unknowns, and making the solution easier, [14]. Numerous computer program packages have effectively implemented the finite element approach, which supports the analysis and design of engineering structures.

2.1 Plaxis 3-D program

Plaxis 3D program is a finite element designed for geotechnical problems in which soil models were used to illustrate soil behavior and developed to assess structure constructions, including foundations and superstructures. The soil characteristics in the site, as well as the construction method, are used, and determine settlements.

With PLAXIS 3D, two main modes can be defined: the geometry of the soil and the geometry of the structures. The intersection and mesh generation processes can generate 3D solid models.

Furthermore, by activating and deactivating clusters of soil volume and structural masses, load application, water table change, and so on, the staged construction mode aids in simulating the construction and excavation processes. The output results include a full visualization suite of tools for inspecting the inner 3D soil-structural model [15].

2.2 Formulation problem of study in Plaxis-3D 2020 program

Pile foundations are principally used to transfer the vertical loads from superstructures, through weak strata or water onto more compact and stiff depth soil to resist horizontal loads, according to this investigation the behavior of piles under these loads must be taken into account especially when embedded in clayey soil in the present multi-story table with 1.5m from the ground surface.

The case study of the soil–pile system of four-multi story building were formulated with Plaxis. The boundary condition for the finite element method for piles into soil media (40x40x30) m according to [16], the dimensions of the soil body surface of a cube shape (10D) from the center of the pile diameter, and (5D) below the pile base as illustrated in Figure 1.

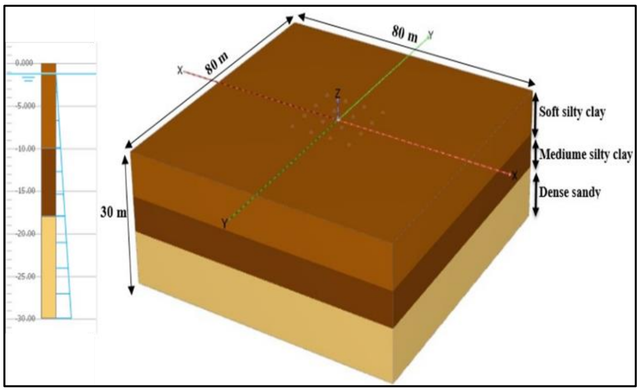

Figure 1. The geometry of soil layers

The group piles length was taken equal to 19 m embedded in an 18 m clay soil layer resting on 12 m dense sandy soil, and the diameter of the interior pile was 1m with 2,600 kN axial load, exterior and corner piles with (0.7m, 1,300 kN) and (0.5m, 700 kN) diameter and load respectively, are used for the FEM analysis in the present study. Figure 2 demonstrated the details of the pile group foundations of this study.

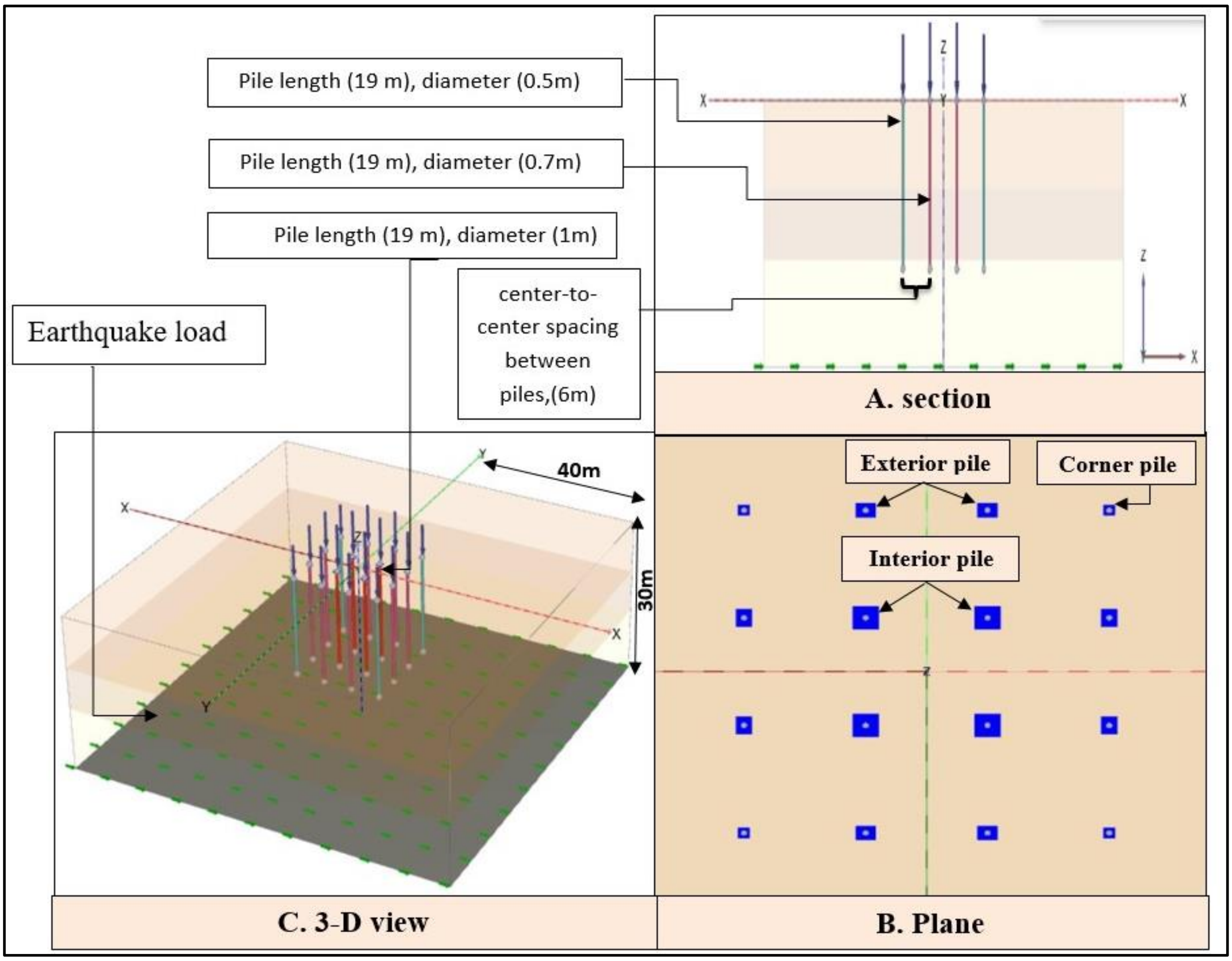

Figure 2. Geometric model of the group pile

2.2.1 Constitutive model

Plaxis software applies a set of general boundary conditions to the actual geometry model automatically. It also includes the creation of the Geometry model creation, material properties, mesh generation, calculation, and result evaluation.

The formation of a geometry model is the first step in the generation of a finite element model. Geometry models are made up of points, lines, and clusters. By entering the coordinates in the command line, points and lines are created in the drawing area. Each cluster provides properties that can be used to simulate the behavior of soil and structure objectives and was modeled employing 10 nodes of tetrahedral elements with rigid interface strength of the soil–pile system.

This study's model consists of two parts: material soil simulate with elastic perfectly plastic with three square layers (Mohr-Coulomb model). While two-part (pile foundation) with linear elastic. The failure envelope of the Mohr-coulomb criteria shows the stress points under the line represent elastic behavior, and when the stress circles come into contact with the failure line, soil behavior changes from elastic to plastic. This means that the material behavior is ideal elastic until shear strength is mobilized, at which time load increments cause plastic strains.

In Figure 3, the Elasto-plastic basic principle states that strain rates and strains are split into plastic and an elastic component. Mohr-Coulomb is more commonly used than other models for mostly geotechnical problems because it is simple, easy to use, and computations are relatively quick [17,18] from consists of two main parameters, namely the cohesion intercept c, and the friction angle ϕ, in addition to another three parameters namely: Young's modulus E, Poisson's ratio ν, and. Dilatancy angle ψ.

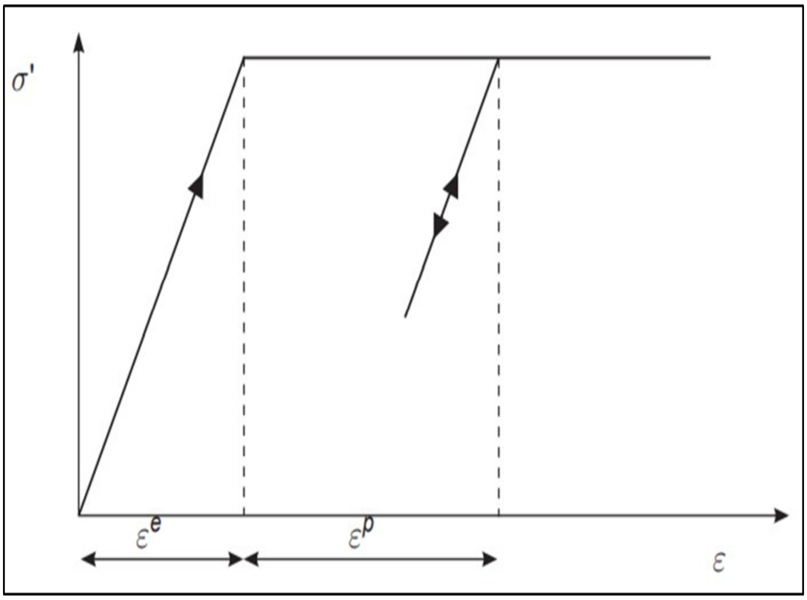

Figure 3. The basic idea of the elastic perfectly plastic model (Scientific Manual - Plaxis)

Another component of the model with linear elastic is the pile foundation, which is based on isotropic elasticity and is molded into an embedded beam for the body pile, and a plate of cap pile.

The soil undrained response in short term without considering pore pressure development, as the change of stress (the loading and unloading), excess pore water pressure will generate as a combination with time. As the water level is 1.5m below the ground surface, Plaxis software can represent clay soil with short-term behavior (undrained A), with ineffective properties. The sand soil with drained or long-term behavior material with high permeability.

After completion, the geometry component, and the pile parameters are assigned to the corresponding geometry component the mesh generation is generated. The values of the pile parameter and soils used in this study are listed in Tables 1 and 2.

2.2.2 Earthquake loading and boundary condition

At the bedrock level of the model, the input motion used in this study is defined as dynamic surface load (load multipliers). The acceleration time history for the earthquake selected in this search is EL-Centro, which is applied along the X-direction at the bottom boundary of the 3-D model in m/s^2 and s respectively,[15] as illustrated in Figure 4.

In reality, seismic waves propagate indefinitely through the soil. Based on this fact, and to avoid the sudden reflection of these waves on the model boundaries inside the soil body, absorbent boundaries are generated [15]. by selecting the standard absorbent boundaries (viscous boundary) in the Plaxis program. The absorbent boundaries are applied at the lateral sides and the bottom boundary in this model. The characters of the earthquake used in this study are demonstrated in Table 3.

Table 1: Properties of embedded pile and cap pile

Property	**Unit**	**Value**
Pile Material	-	concrete
Elastic Modulus (E)	kN/m^2	$3x10^7$
Poisson's Ratio(υ)	-	0.15
Unit Weight (γ)	kN/m^3	24

Table 2: Properties of soil layers for the numerical analysis

Property	**Soft Silty Clay**	**Medium Silty Clay**	**Dense sandy**
Elastic Modulus, E (MPa)	10	50	90
Poisson's Ratio, υ	0.4	0.4	0.3
Unsaturated Unit Weight, γ_{unsat} (kN/m^3)	15	16	17
Saturated Unit Weight, γ_{sat} (kN/m^3)	19.39	19.62	20
Cohesion, c (kPa)	40	82	-
Friction Angle,(φ)	-	-	35
Interface Strength (R_{inter})	Rigid	Rigid	Rigid
Damping Ratio, ξ	0.01	0.01	0.005

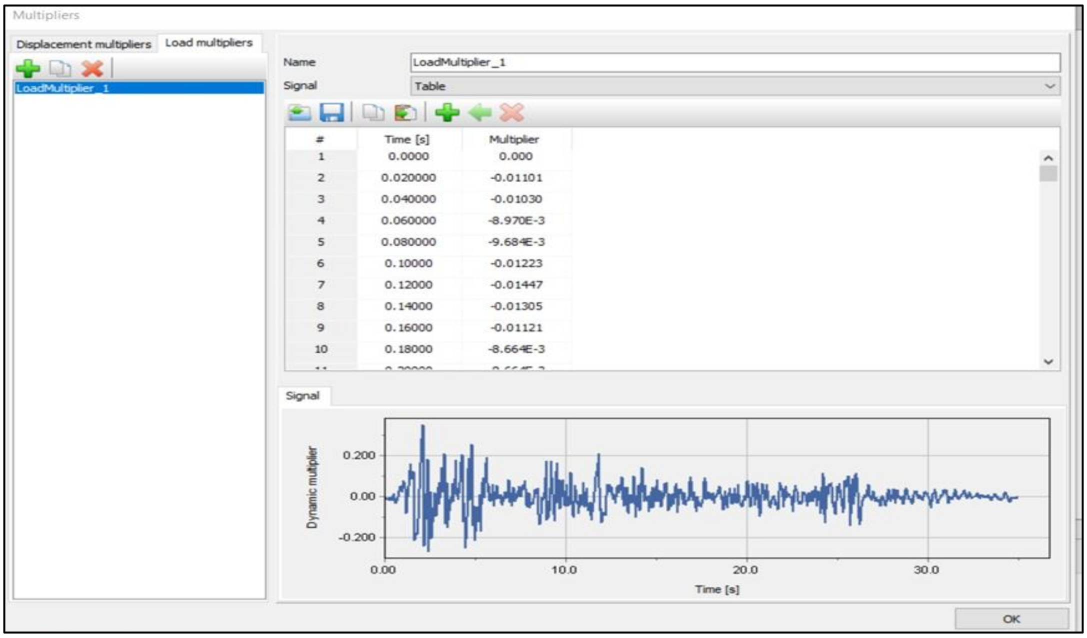

Figure 4. Acceleration time-history of the El-Centro earthquake

Table 3: The data of the earthquake used in this study

Earthquake	El-Centro
Region	Southern California
Data (UTC*)	19/5/1940 04:36:41
Magnitude,(M_w)	6.9M_w
Mercalli Intensity, (MMI)	X-Extreme
Epicenter depth,(km)	16
Shake Duration,(sec)	34.98
Station distance to the epicenter, (km)	250
Sampling Frequency,(Hz)	3.57
Acceleration direction	N-W
Maximum acceleration,(g)	0.35
Station code	MGA
Reference	Seismicity of the united states By Stover and Coffman*

*[19]

2.2.3 Mesh generation and calculations

The PLAXIS application makes use of an unstructured mesh that is generated automatically using global settings to divide the geometry of the soil - pile into elements for performing finite element calculations.

The mesh element distribution has five options: very coarse, coarse, medium, fine, and very fine mesh, and In some areas where substantial stress is expected, the mesh can be refined to improve the accuracy of the results.

In this investigation, a medium-mesh was chosen to avoid lengthy calculations of time with fine or very fine-mesh as demonstrated in figure 5. After completing the generation of the finite element mesh, the proper finite element calculations are carried out. The calculation process is divided into multi phases.

In the initial phase (Initial Stress Generation) the initial stress of the soil body can be determined based on the weight of the material and its history of formation depending on the Ko procedure.

Second phase pile stresses will be calculated using the plastic calculation method, according to the theory of deformation.

Finally, the phase for the dynamic calculations is a dynamic analysis following a series of plastic calculations on the structural model, as well as a dynamic selection calculation after creating dynamic load multipliers to calculate the earthquake stresses with a dynamic time interval equal to 35 (s).

After the analysis carried out for the soil pile system, the variations of the settlement and maximum displacement of the pile group are observed.

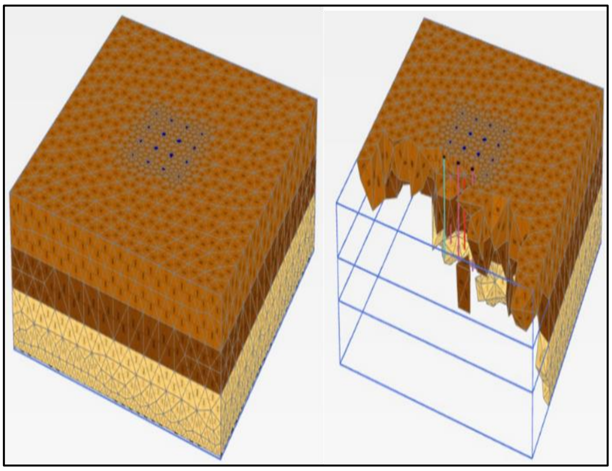

Figure 5. Finite element mesh for pile foundation

3. Analysis results

The finite element analyses of the pile groups' behavior under the lateral earthquake load are studied by using time-deflection curves. The curves are drawn for vertical and horizontal displacement for given dynamic loads. The PlAXIS model is formulated according to the case study presented in the previous section.

Based on the model of group pile is symmetrical, and the direction of the input motion in the x-direction, the results of the numerical analysis after completing all stages of construction of calculations, including initial stress, pile construction, static and earthquake loads of this study are presented for the selected pile's A, B, C, and D as shown in Figure 6.

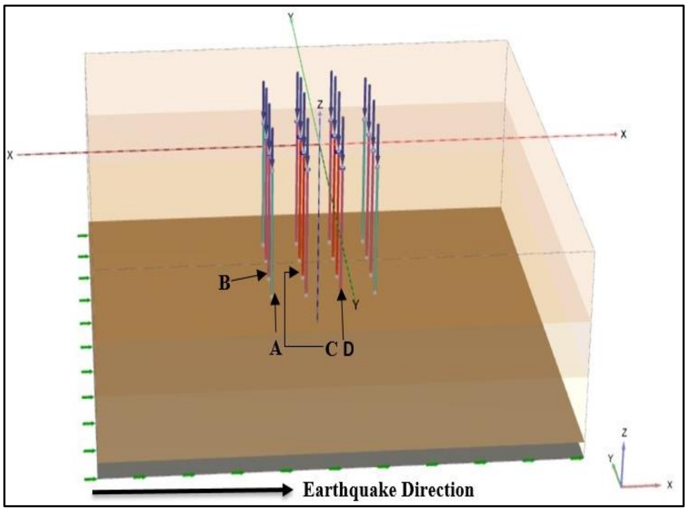

Figure 6. Selected piles A, B, C, and D from the group of piles model

Figure 7 shows the relationship between the vertical settlement of the pile group over time in the clay soils under the influence of the El-Centro earthquake, this settlement increases with the increase in time of the wave. This increases with low values and continues to the end time of seismic force in a steady manner and this response is clear for all the piles selected in the graph and agrees with experimental studies [8,12] settlement of clay soil with sand increases as the frequency increase.

This behavior is attributed to the occurrence of distortions in the surface of the ground as a result of the earth’s vibration and when the earth or the layers of soil surrounding the foundation shake, generating horizontal and vertical displacements. This leads to the layers of soil vibrating violently according to the earthquake’s intensity until it resists the movement that occurs between its particles. As a result, a decrease in both the elasticity and hardness modulus of soil to inability the to mitigate or resist the accelerating effect that the soil particles are exposed to. In addition, the shear waves in the soil saturated with water lead to the dislocation of soil particles and increase the water pressure.

Thus, this behavior is reflected in the foundations that are in direct contact with the soil, as they work as a single unit. Also, this could refer to the displacement caused by the seismic waves' duration and magnitude [20], as well as the earthquake's peak ground acceleration.

Figure 8, for the same case study, illustrated the relationship between the dynamic time of the earthquake and horizontal displacement for A, B, C, and D piles, which explains the displacement increase as the time of earthquake increases, with high oscillation at the beginning of earthquake time up to eight seconds, and after that counties to increase in a steady pattern until the end of time with the maximum settlement at the piles head this agree the highest displacements in piles cap by [11].

As the depth of the soil profile increases the velocity of the propagating waves increases [21], Unlike through travel the waves to the surface ground level, gains more damping of the intensity. So the values can be considered small in comparison to the vertical displacement. Also, the values of the selected piles are different as appearing for vertical displacement, with a range for pile C (19.7%-22%) more than piles B and A.Whlie Pile B more than A is about 3%, and increase in the right direction with a range (12% to32%).

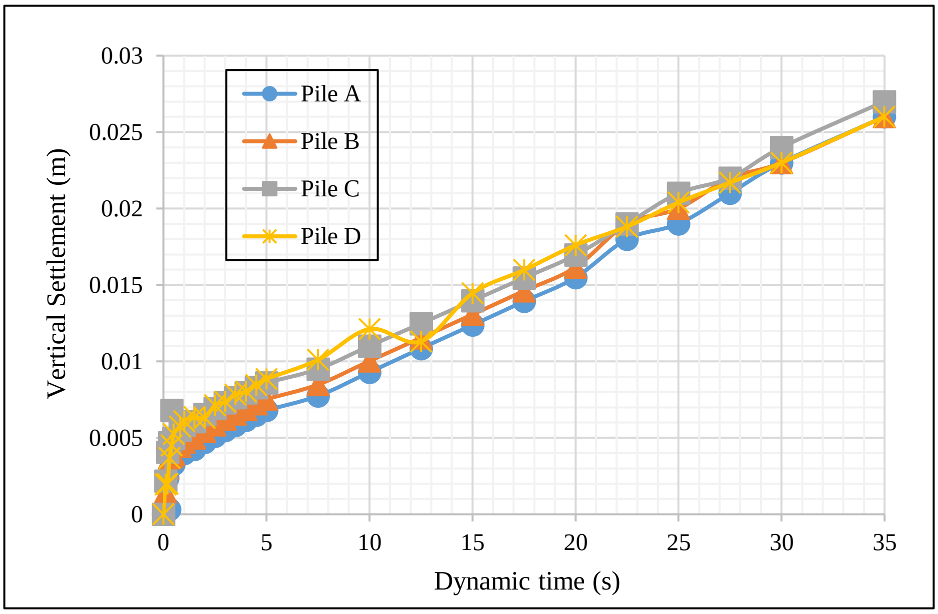

Figure 7. Vertical settlement versus dynamic time for group pile embedded in soil layers under El-Centro earthquake

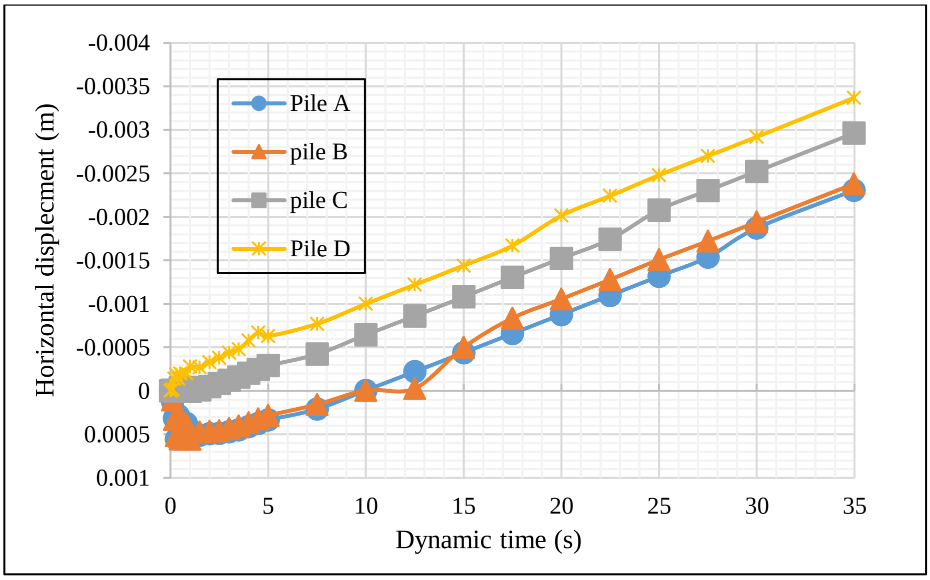

Figure 8. Horizontal displacement versus dynamic time for group pile embedded in soil layers under El-Centro earthquake

4. Conclusions

This paper evaluated the effect of the 1940 El-Centro earthquake ML=6.9 on the vertical and horizontal displacement of piles embedded in clayey soil over layered dense sand. The conclusions from this study can be drawn as the following:

1. The vertical settlement increase when the duration of the earthquake increases even after the peak ground acceleration of the wave as the settlement function to the loads.
2. The vertical settlement was similar to or closer to the edge pile with a 0.5m

diameter, exterior pile with 0.7m diameter, and interior pile with 1m diameter which means the diameter of the pile did not affect the vertical settlement**.**

3. The horizontal displacement increases when the duration of the earthquake increases even after the peak ground acceleration of the wave, with values smaller than vertical displacement**.**
4. The values of the horizontal displacement are different for the pile's groups, where values are high as the diameter increases from 0.5m, 0.7m, and 1m with a range between (3% to 22%), also increasing with the direction of the earthquake from the right to the left side of the pile-soil system with range (12% to 32%). While decreasing towards the base of the pile**.**
5. Most studies indicate the geophysical and natural geological characteristics and the groundwater content of the soil that is subjected to earthquakes play an important role in the values of both vertical and lateral displacement for resisting these forces, and this is consistent with the diversity of the profile soil, which consists of different layers of soil.

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