Engineering and Technology Journal 39 (12) (2021) 1748-1752

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Effect of Dynamic Earth Vibration on the Behavior of Laterally Loaded Single Pile Embedded within Unsaturated Soil

Maha H. Abood[*], **Mahmood R. Mahmood, Nahla M. Salim**

Civil Engineering Department,University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.

*Corresponding author Email: civil_eng001@yahoo.com

HIGHLIGHTS

- A single pile embedded in the unsaturated soil and subjected to lateral shaking load (earthquake)
- The bending moment and deflection will decrease with increasing of the matric suction.
- Bending moment in unsaturated condition reduced 57% with matric suction (10kPa).
- Bending moment in dry condition reduces about 28% than those of the saturated condition.
- In saturated soil, liquefaction occur after about (12sec) of shaking time for 0.32 g acceleration.

ARTICLE INFO

Handling editor: Wasan I. Khalil

Keywords:
Unsaturated soil
Laterally Dynamic loading
Bending moment
Deflection
Soil resistance

ABSTRACT

Most of the studies of laterally loaded piles focused on the behavior for piles subjected to static or cyclic lateral loading embedded within dry or saturated soils, few studies investigate the behavior of piles embedded within partially saturated soils and subjected to dynamic loads. In this research, an experimental study presents an aluminum pile model embedded within dry, fully saturated and partially saturated soils, subjected to dynamic load with the El Centro 1940 NS acceleration data (0.05g, 0.15g, and 0.32g) accelerations. Three different lowering levels of the water table for fully saturated soils model is achieved to get partially saturated soils of three different values of matrix suction. During an earthquake model, a liquefaction phenomenon is observed by boiling of sand and completed collapse in the soil as shown in the results. It is concluded that the resisting to the bending moment reduced by 22%, 50%, and 57% after 1st, 2nd and 3rd lowering of water level respectively, than that of the saturated condition. This reduction approaches to 28% for completely dry soil. It is worth to mention, that, the deflection of the pile reduced as the lowering of water level increased. The soil resistance increases with the increasing of dynamic load acceleration. The soil resistance increases about 35% when the acceleration increase from 0.05g to 0.15g and an increase of about 22% when the acceleration increases from 0.15g to 0.32g.

1. Introduction

In seismic activity regions, the analysis and design of pile that supported structures require an accurate prediction of the pile response and the load resistance to lateral shaking caused by earthquake ground motions. The results of a lateral load test (moments, shear and deflections) can be used directly to design pile foundations. At total test load, dynamic load test anticipated settlement is less than that of static load settlement measured [1]. Also the maximum displacement happened at the head of the pile and decreasing with the depth and the lower loading [2].

The earthquake force, in essence, is dynamic in nature based on the potential occurrence of earthquakes in a particular zone, soil condition, the type of foundation and code recommends a certain percentage of weight of the structure which it is expected to resist lateral force.

The major effect on the soil affected by an earthquake can be classified as follows:

1-Liquefaction of soil
2-Settlement of foundation due to deep-seated liquefaction failure
3-Reduction of bearing capacity and,
4-Ground Subsidence

http://doi.org/10.30684/etj.v39i12.508
Received 02 August 2019; Accepted 10 May 2021; Available online 25 December 2021

The liquefaction (from all the above phenomena) is probably the most important factor that has caused major damage in many earthquakes [3]. Also the increase of load amplitude show increase in the Liquefaction zones [4]. Dynamic loading usually obtained from machines, traffic, ocean waves, and earthquakes. For static loadings soil resistance can be related to the stress-strain characteristics of the soil; however, with dynamic loading, an inertia effect must be considered [5].

The dynamic properties of soils including shear wave velocity, shear modulus, damping ratio and the seismic response of soil layers are affected by the different unsaturated soils state of stress. The coupled seismic soil pile-structure response, particularly in the shallow soil layers may also affected by these differences in dynamic material characteristics and seismic response in unsaturated soil [6, 7].

The pile shows higher acceleration amplification and lower lateral deformation when the soil is unsaturated than the dry soil, and also made an inverse simple pseudo-static to back-calculate soil modulus values and found that the soil modulus is higher for the unsaturated sand and show increase in soil stiffness by the effect of the metrics suction.

In this research prediction of the pile response under lateral load to lateral shaking caused by an earthquake ground motions model of partially saturated soils will be investigated [8].

2. Methodology

2.1 Testing Program

The soil used in this study is fine sandy soil and its particle size distribution curve shown in Figure 1. The unit weight of the soil, γ=15.5 kN/m3 for medium relative density and the angle of internal friction was, Ø = 34°. Aluminum single pile model of (16mm) outer diameter and (600mm) length were used to conduct all the tests. Steel container of (600mm) diameter and (600mm) depth with four valves fixed at different levels to achieve partially saturation of the soil was used, the pile model embedded to a depth of (500mm) within the soil.

The unsaturated condition in this study was obtained by supplying water to the soil in the container from the lower valve as shown in Figure 2 and left for 24 hours until the soil is fully saturated, the other valves were used for lowering water table to a specific level, to obtain unsaturated conditions with different matric suction values. Five pairs of strain gages of (9mm) size fixed at an equal spacing of (10cm) on both sides of pile model to measure the compression and tension along the pile length as shown in Figure 2. The lateral shaking caused by earthquake ground motions that applied to the soil and pile model under lateral loading in the present study is an El Centro seismic data which is well-recorded earthquake data and also contains a wide range of frequencies. Ground Motion for El Centro 1940 NS Accelerogram Component was applied at different amplitudes to evaluate the soil and model pile performance under seismic excitation and lateral loading at the same time.

The used record was time-compressed to satisfy the similitude requirements. The active seismic excitation time was about 16.3 seconds as shown in Figure 3. The simulation of lateral shaking caused by earthquake ground motions carried out by the use of the shaking table system as shown in Plate 1. Three accelerations mode of (0.05g, 0.15g, and 0.32g) were used to investigate the real behavior of laterally loaded pile against earthquakes.

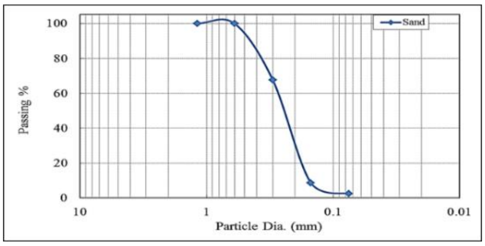


Figure 1: Particle size distribution of the soil used in this paper

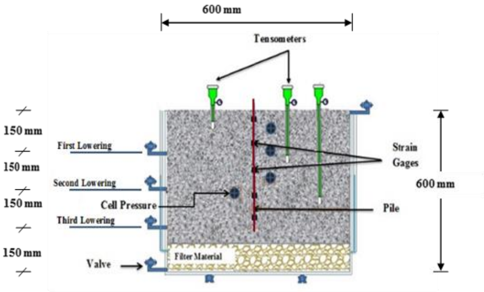


Figure 2: Sketch shows the model test

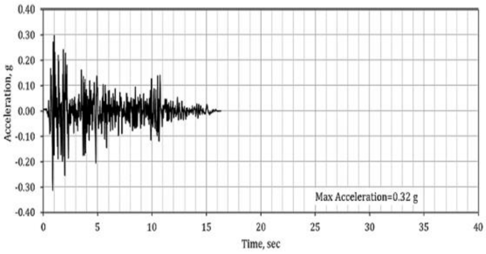


Figure 3: Ground Motion for El Centro 1940 NS Accelerogram Component

Plate 1: Shaking table system

2.2 Soil–Water Characteristic Curve (SWCC) of Partially Saturated Soil

To understand the behavior and estimation properties of the unsaturated soils, measurement of the soil-water characteristic curve (SWCC) for the soil has been established according to Fredlund and Xing, and Fredlund, et. al. [9, 10]. It describes the corresponding constitutive relationship between soil suction and soil-water content and depends on the stress state and initial water content which should be considered corresponding to field situations as they have the greatest influence [11].

The two critical variables were obtained from the soil–water characteristic curve (SWCC) is the air-entry value and residual state suction which is fundamental for the prediction of unsaturated soil properties [12]. Soil-water characteristic curve is evaluated at the laboratory which measured directly by three L.T. Tensiometers (Low Tension) suction device that used for sandy soil as shown in Plate 2. The Soil-Water Characteristic Curve illustrated in Figure 4 represents the suction of the soil used in this research which measured, against the gravitational water content, after 1st, 2nd and 3rd lowering of water level the matric suction is (5,7 and 10 kPa) respectively.

3. Results

3.1 Bending Moments

The pile model embedded in dry, saturated and unsaturated cohesionless soil conditions and then subjected to the lateral shaking load (earthquake) present with El Centro data (0.05g, 0.15g, and 0.32g) accelerations. Different values of bending moment obtained for each soil condition and lateral shaking load (earthquake) acceleration. Figure 5 shows the effect of soil saturation on the maximum bending moment for a single pile model under lateral shaking load (earthquake) with (0.05g, 0.15g, and 0.32g) acceleration and embedded in (Dry, Saturated and Unsaturated) cohesionless soil. The maximum bending moment occurs when the soil is saturated and minimum bending moment occurs when the soil is at the (3rd lowering of water level) of unsaturated soil. Plate 3 shows the test model of a single pile embedded in unsaturated soil under a lateral shaking loading (earthquake). The results of applying (0.05g, 0.15g and 0.32g) acceleration on the bending moment of single pile model embedded in saturated cohesionless soil show that the 0.05g effect is not recognizable as the effect of 0.15g and 0.32g at which the Plate 3 shows the test model of a single pile embedded in unsaturated soil under a lateral shaking loading (earthquake). The results of applying (0.05g, 0.15g and 0.32g) acceleration on the bending moment of single pile model embedded in saturated cohesionless soil show that the 0.05g effect is not recognizable as the effect of 0.15g and 0.32g at which the liquefaction phenomena occur after 12 seconds of applying 0.15g acceleration to the model test, while occur after 7 seconds with the applying of 0.32g acceleration. Plate 4 shows the liquefaction phenomena that occurred during the test. The liquefaction also occurs when the soil is unsaturated after the first lowering of water level and subjected to (0.32g) acceleration of dynamic load.

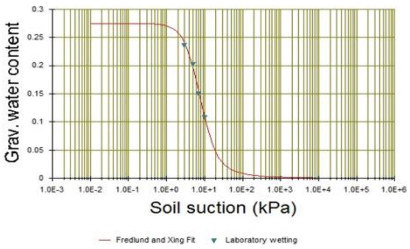


Figure 4: Gravitational water content and the matric suction relationship for utilized soil established by Soil Vision program (Fredlund and Xing equation).

Plate 2: Soil suction test by LT Tensiometer

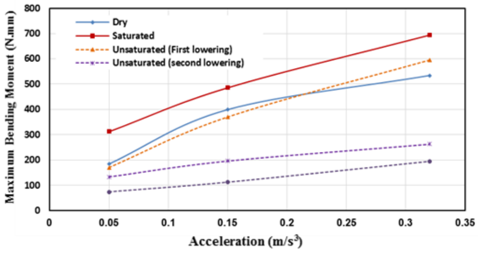


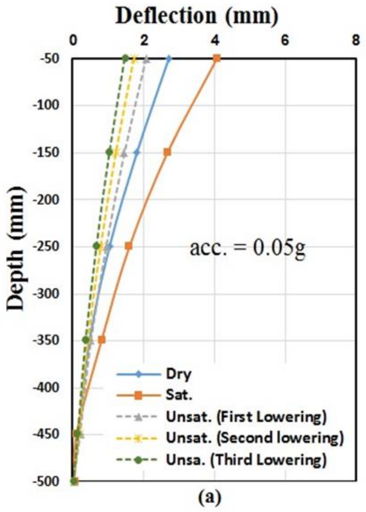
Figure 5: Maximum bending moment with the acceleration of single pile under lateral shaking load (earthquake) (0.05g, 0.15g, 0.32g) acceleration and embedded in (dry, saturated and unsaturated) cohessionless soil.

Plate 3: Single pile embedded in unsaturated soil subjected to lateral shaking load (earthquake). Single phenomena occurred after applying 0.32g acceleration

3.2 Deflection Due to lateral shaking Loads (earthquake)

Figure 6 shows the deflection results of a single pile model embedded in (dry, saturated and unsaturated) cohesionless soil and subjected to (0.05g, 0.15g, and 0.32g) acceleration of lateral shaking load (earthquake). It is demonstrated that the deflection increases with increasing acceleration of lateral shaking load (earthquake) and decreases with decreasing soil saturation. The deflection of the pile model embedded in dry soil is less than that when the pile model embedded in saturated soil due to the decrement in soil strength.

Plate 4: liquefaction phenomena occurred after applying 0.32g acceleration



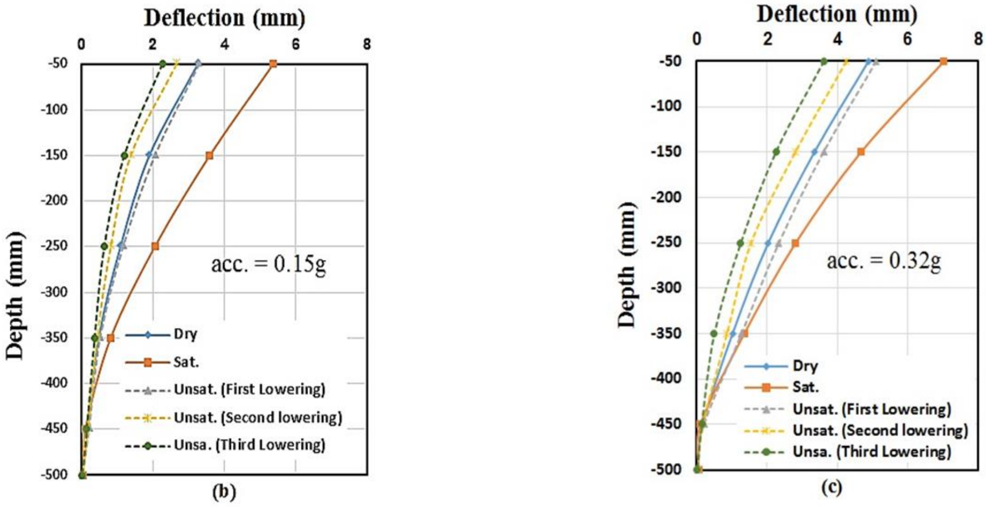


Figure 6: Deflection of single pile model under acceleration of lateral shaking load (earthquake) of (a) 0.05g, (b) 0.15g, (c) 0.32g and embedded in cohsionless soil of different saturation condition

4. Conclusions

1) For a single pile embedded in dry soil and subjected to lateral shaking load (earthquake), the bending moment will decrease with time because of the soil densification by the effect of lateral shaking load (earthquake).
2) When the pile embedded in saturated soil, liquefaction will occur at (0.15g acceleration) applied to the model after about (12) seconds of the shaking time. While for 0.32 g acceleration, the liquefaction will occur after about (7) second of the shaking time.
3) For a single pile embedded in the unsaturated soil, the bending moment and deflection will decrease with increasing of the matric suction.
4) When a lateral shaking load (earthquake) is applied to a single pile embedded in the unsaturated soil (after first lowering of water level), a liquefaction will occur when 0.32g acceleration is applied while not occur with the application of 0.05g and 0.15g acceleration.
5) The 0.05g acceleration has a very small effect on the single pile bending moment and deflection than the effect of 0.15g and 0.32g acceleration.

6) The bending moment increases with the increasing of loading and reduces with the increasing of matric suction. Bending moment in dry condition reduces about 28% than those of the saturated condition while for unsaturated condition reduced about 22%, 50% and 57% after 1st, 2nd and 3rd lowering of water level of the matric suction (5,7 and 10kPa) respectively, than that of the saturated condition.
7) The soil resistance increases with the increasing of lateral shaking load (earthquake) acceleration. The soil resistance increases about 35% when the acceleration increase from 0.05g to 0.15g and an increase of about 22% when the acceleration increase from 0.15g to 0.32g.

Author contribution

All authors contributed equally to this work.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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