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Numerical Analysis of Bridge Foundation in Dry and Saturated Soils with Effect of Halabjah Earthquake (Case Study)

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ABSTRACT

The importance of this study comes from the expected risks as the bridge foundations is exposed and their effects on the lives of users. So, the aim of this study is to investigate the influence of earthquakes loading on the bridge foundation subjected to combined loading as a case study for Al-Shareef Bridge/ Diyala province in Iraq. The numerical analysis highlights the foundation settlement firstly, in flat ground and secondly, in slope ground with applied different value of axial loads starts from the zero-working load (no loading) to maximum working load. All cases were investigated in dry and saturated soil under effect of Halabjah earthquake. Plaxis 3D is one of the finite element programs that had been used to simulate the soil foundation interaction by Mohr-Coulomb failure criteria for the soil model and linear elastic for concrete materials. The conclusions of this study showed that the settlement of pile group is increased in saturated soil about 5% more than the dry soil under the effect of static loads for both groups, but, the settlement in group (2) is increased about 10% more than the group (1) in dry and saturated condition. The settlement in saturated soil is increased to 12% more than the dry soil when Halabjah earthquake loads is applied.

1. Introduction

In general, the bridge is usually a huge structure that connects gaps, obstacles, or rivers in cities and valleys to make paths through them. The foundation of bridge is the most important part because it must carry the entire weight of the bridge (dead loads), the traffic loads (live loads) and other sources of loading [1]. Piles are used to transfer the loads from the superstructure to deep and strong stratum. The load transfer mechanism is a very complex process for many reasons such as soil type, loads condition, design of foundations and many other factors. Loads transferred from foundations to strong soil layers must not cause soil shear failure or damaging settlement of the superstructure [2]. In general, the pile group should not be only design or analyze to support vertical loads or lateral loads separately but always a simultaneous combination of the vertical and lateral loads [3]. Earthquakes generate elastic waves when one of a large solid piece of hard material slides against another from earth layers. Seismic waves are transmitted through the body in all directions. Studying the behavior of foundations under earthquake excitation, especially in active seismic areas has attracted the attention of several researchers in the last years [4]. Generally, a slope is a ground surface that positions at an angle to a horizontal level. Slopes may be created from the nature or artificial (man-made). Due to the importance of

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slopes in civil engineering, the stability of structures on slip surface are usually one of the challenges to any researcher or engineer. An analytical study is required to predict the behavior of foundations in slopes. Many researchers studied the analysis of piles in sloping ground by finite element programs [5].

Many of recent researchers have been used finite elements analysis to simulate the settlements of pile group according to soil stiffness, pile length, pile spacing and super-structural loads. Some of them were studied in static case for example Xue et. al., 2011 studied the pile group settlement for bridge foundation in soft soils using plaxis 3D [6]. In addition, Yousif et al., 2011 also studied the analysis for the designed bridge firstly manual by using equations, secondly by using 3D Plaxis program of finite elements in static condition [7]. Others were studied the behaviour of foundations in dynamic conditions such as [8-16]. Diyala province is located within an active seismic zone and it is necessary to get an information about the expected dynamic response behavior of structures in this area. The main objective of this study is to investigate the difference between the vertical displacement in leveled and sloped ground for bridge foundation under the effect of static and dynamic loads in different condition of soil moisture. It is expected that the results of this study will have a positive influence in design of similar structures in the future, in addition to avoiding waste of money. Thus, this study included FE simulation using plaxis 3D for bridge foundation under earthquake loads.

2. Methodology

2.1 Description for case study

Al-shareef Bridge is a river bridge which is located in Diyala province–Iraq. This bridge has 6 spans of 24 m for each, with a total length of 144 m and is supported by reinforced concrete foundations.

The pile group for this case consists of 6 single piles with a diameter of 1.0m and a pile length of 20m with 2x3 pattern and the spacing between piles equal to 3m that is equivalent to 3D of the pile. The concrete pile cap is rectangular with length of 8m, width of 4.8 m and thickness is 1.4 m as shown in Figure 1.

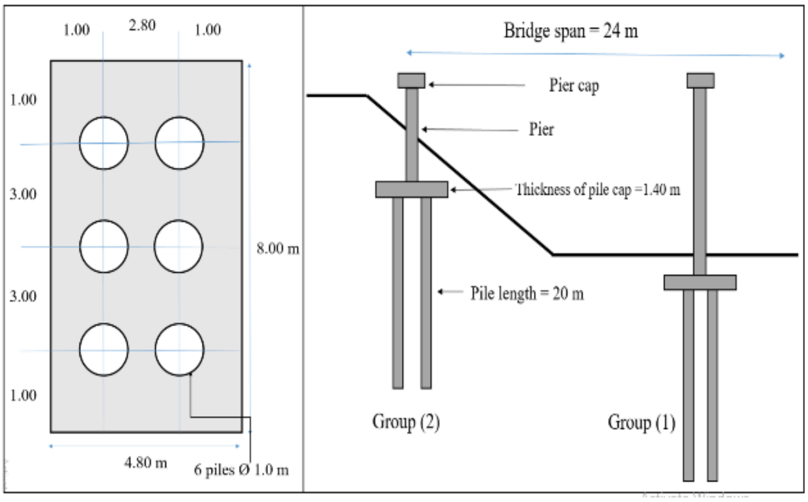


Figure 1. The geometrical model of bridge foundation and the section of piles distribution

Soil layers as stated in the soil investigation reports for the project, based on the geological investigations ASTM D5434 (Standard Guide for Field Explorations of Soil):

- The first soil layer is a Fill layer, which consists of (sand, gravel, silt and clay with brick fragments) this layer extends from ground surface down to (3) m depth.
- The second layer is a cohessionless soil, which consists of loose to medium gray sand with silt. This layer extends from the above layer down to 7.25m depth.

- The third soil layer is a cohesive soil, which consists of medium stiff to hard brown clay. This layer extends from the above layer down to 14.5m depth.
- The last soil layer is a cohessionless soil, which consists of medium to very dense gray sand. This layer extends from the above layer down to the end of boring (30) meter. The details of soil stratification are illustrated in Table 1 according to the boreholes reports.

Table 1: Geotechnical properties of soil layers

Soil parameter	**Layer 1 Fill**	**Layer 2 sand with silt**	**Layer 3 medium stiff to hard clay**	**Layer 4 sand**
Depth of layer (m)	3.0	7.2	14.5	30.0
γ (kN/m³)	16	18	17.5	17
γs (kN/m³)	18	20	21	18
E (kPa)	8.0 E3	9.0 E3	11.0 E3	30.0 E3
μ	0.33	0.3	0.3	0.2
c (kPa)	10	8	40	5
Φ (°)	30	35	5	38
ψ (°)	0	5	0	8

where: (μ) Poisson's ratio (from soil borehole report), (ψ) an angle of Dilatancy. When the angle of internal friction $\varphi>30°$ the value of dilation angle can be estimated as $\psi=\varphi-30$.

The tests and reports for piles from the project location were prepared according to ASTM D1143-07 (Piles under static compressive load). Deep foundation properties are illustrated in Table 2.

Table 2: Deep foundation properties for both groups.

Foundation parameter	**Pile cap**	**Piles**
ɣ conc. (kN/m³)	24	24
E (kn/m²)	30.0E6	24.0E6
μ	0.15	0.15
Area of pile cap	4.8*8 m²	----------
Thickness (d)	1.4 m	----------
Diameter of pile	--------	1m
Length of pile	---------	20.0m

2.2 Numerical Modelling

In geotechnical engineering the Finite Element Program Plaxis 3D is a very effective solution, it uses numerical methods to simulate the soil and foundations behavior. The analysis of the program depends on the soil parameters. The Mohr-Coulomb constitutive model was used to simulate the soil material and the linear elastic model was used for the concrete foundations. In addition, a thin layer interface element used to model the interface zone between the soil and the pile material.

To generate the finite element mesh, the geometry model has to be divided into (52730) elements with medium size. The basic soil elements of 3D FE mesh are the 10-noded tetrahedral elements. Choosing mesh’s size is one of the factors affecting on the results. As shown in Figure 2 the three dimension finite element mesh[17].

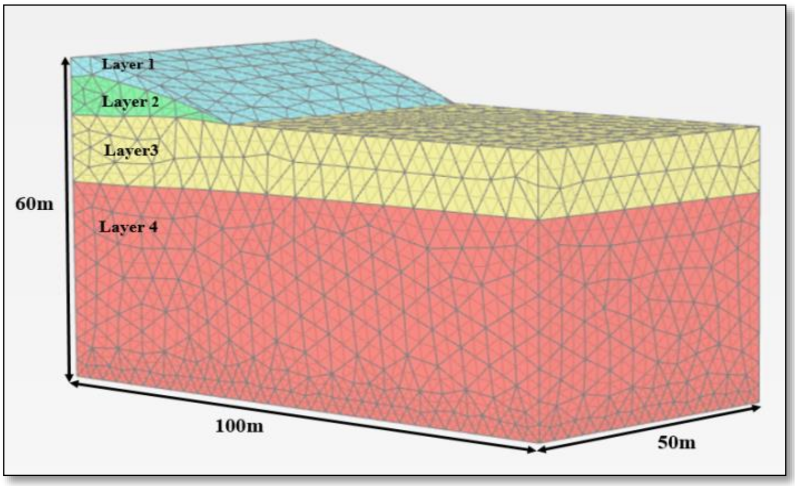
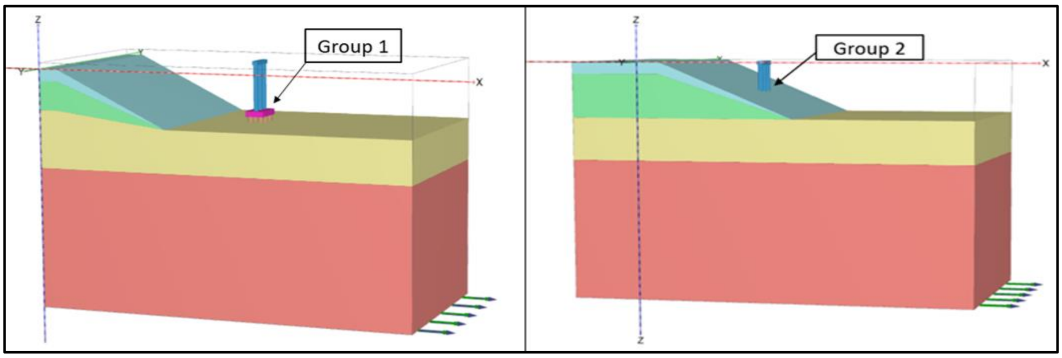


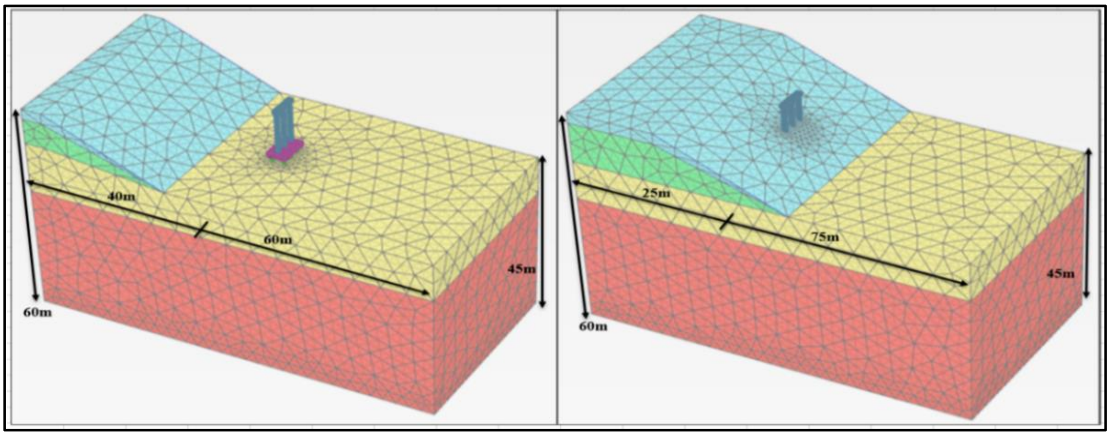
Figure 2. 3D- finite element mesh for soil mass

This study highlights the influence of earthquakes on bridge foundation with several variables such as:

- Location of pile group: The foundation position was taken as a variable where pile group in flat ground is called (group 1) and the group in slope ground is called (group 2) to comparison between the displacement of them. As shown in Figure 3(a, and b) which illustrated the 3D FE model and mesh for groups location.
- Vertical loads: Were taken different value of axial loads that applied as a surface load on the pile group started from zero (no vertical load) to 100% Vult which increased in five stages (V1= 0% Vult, V2= 25% Vult, V3= 50% Vult, V4= 75% Vult, and V5= 100% Vult). Where Vult for pile group equal to the value of working load for one pile (from project data) multiplier by numbers of piles divided on the area of pile cap As shown in Figure 4 is illustrated the loads which applied on the piles model.
- All modelling for groups were investigated in dry and saturated soil. In the dry state a proportion of the void spaces is filled with air. But in the saturated state all the void spaces between the particles are filled with water[18]. As shown in Figure 5 the model of pile group with changing the water level.
- Dynamic loads: By applied Halabjah seismic wave of 0.1g (PGA) were used in this study. The seismic motion used is defined as dynamic surface displacement (Displacement multipliers) which applied along X direction at the bottom level (Zmin) of the model as shown in Figure 6. The boundary conditions that used in analysis were performed by trial in soil mass to simulating deep foundation. A soil mass with depth of (60 m), and width (100 m), this dimensions ensure that the additional stresses applied are not influenced by the boundary conditions of the problem.



(a)



(b)

Figure 3. (a) 3D-FE model for pile groups' location where Group (1) is pile group in flat ground and Group (2) is pile group in slope ground, and **(b)** 3D-FE mesh for pile groups.

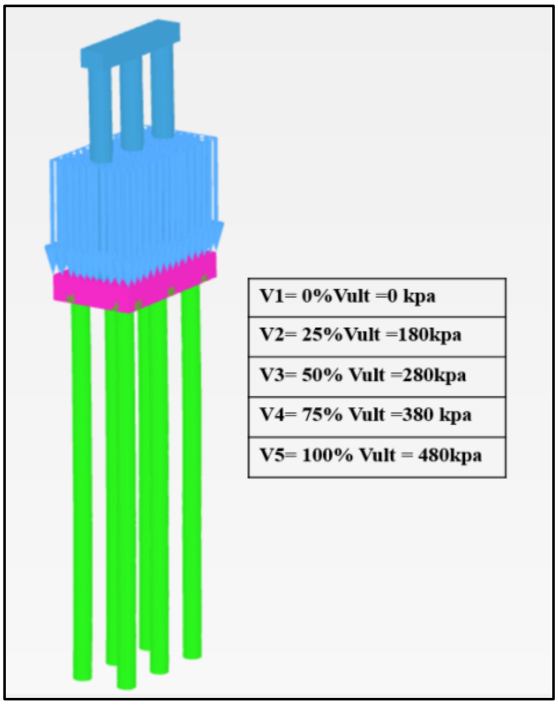


Figure 4. Structural member simulation and load intensities.

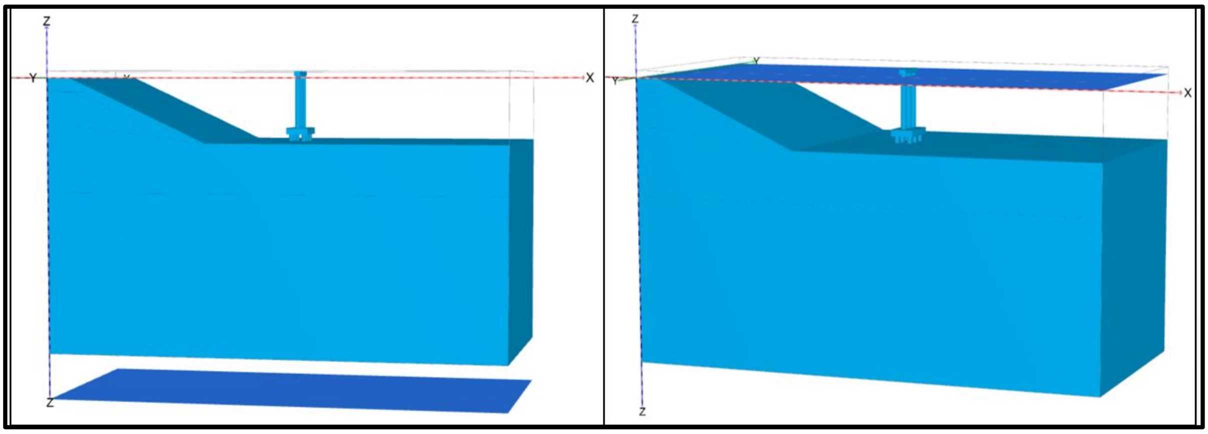


Figure 5. 3D-FE model for pile group with changing water level

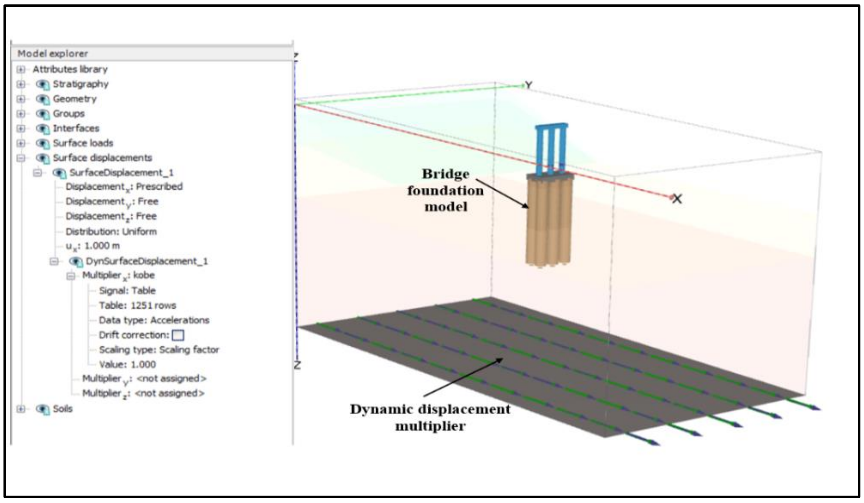


Figure 6. Analysis of bridge foundation with earthquake (Displacement multipliers) surface model

3. Results and discussion

This part includes the results of finite element simulation of bridge foundation. After completing all calculations of stages construction including piles and interfaces, piers of bridges, vertical load and earthquake load, the analysis was conducted to predict the different in vertical displacement for bridge foundation under different values of axial and lateral loads with effect of changing water level. The discussion of the results in the following sections:

3.1 Analysis of bridge foundation with effect of static loads in dry and saturated soil

This section of the study highlights on the results of influence the static loads on the pile group of bridge foundation. The load settlement analysis for pile groups is important to evaluate the performance of piles foundations. The settlement results of two pile groups were obtained by analysis the models under axial loads in flat ground for (group 1) and other in slope ground for (group 2) as follow, the first analysis was of a pile group (1) were obtained the results by analyzing ten models in flat ground, divided to five models in dry soil and other five in saturated soil.
The results presented in Figure 7 show that the load settlement curves for group (1) which are calculated under different stages of static working load (V1, V2, V3, V4, and V5) which are caused the vertical displacement (Uz) for pile group (1) in dry condition. As shown in Figure 8 the load-settlement curves for pile group (1) which are calculated in saturated soil under static load.

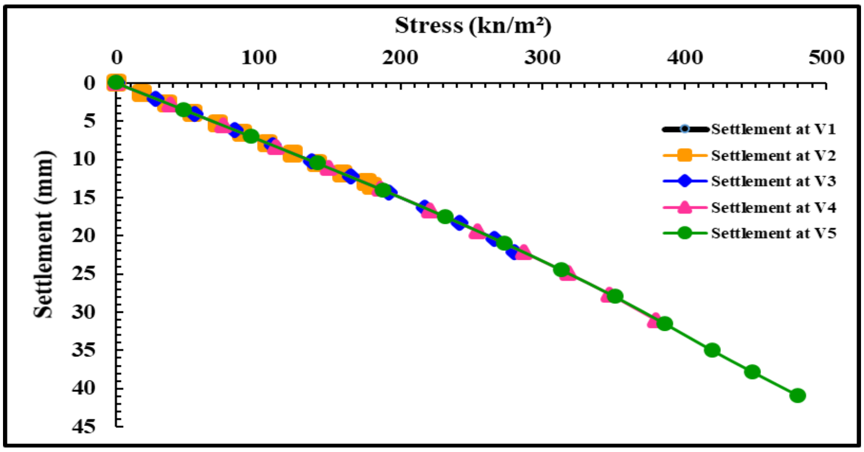


Figure 7. Load - settlement curves for pile group (1) in dry soil under static load

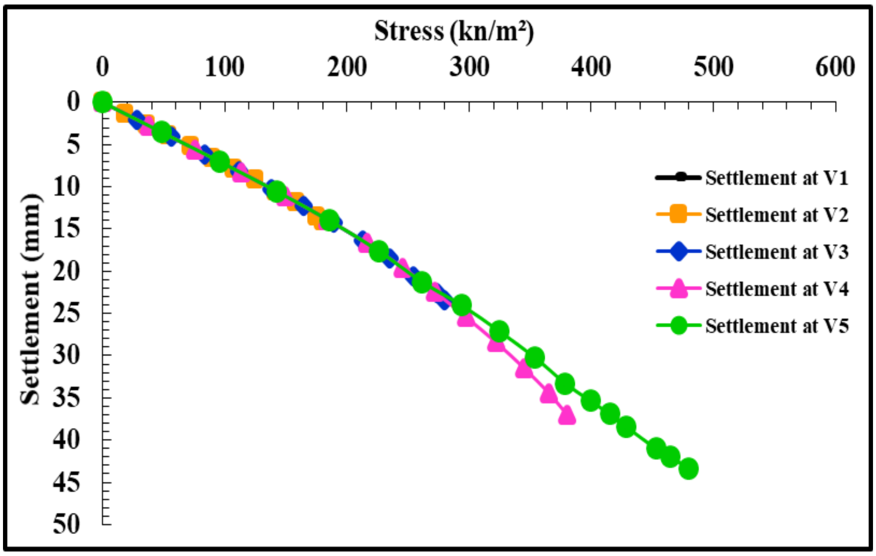


Figure 8. Load - settlement curves for pile group (1) in saturated soil under static load

From the settlement results of pile group (1) in two cases of dry and saturated state the group was settled from (0 mm) when the working load was zero (no loading) and reached to (41) mm and (43 mm) at maximum working load respectively. From the comparison between the settlements for pile group (1) under maximum axial load in dry and saturated soil, it can be concluded that the settlement in saturated soil is increased about (5%) more than the dry soil.

And the second results of a pile group (2) were obtained by analyzing ten models in sloped ground, divided to five models in dry soil and other five in saturated soil. As shown in Figure 9.

As shown in Figure 10 the load-settlement curves for pile group (2) which are calculated in saturated soil under static load.

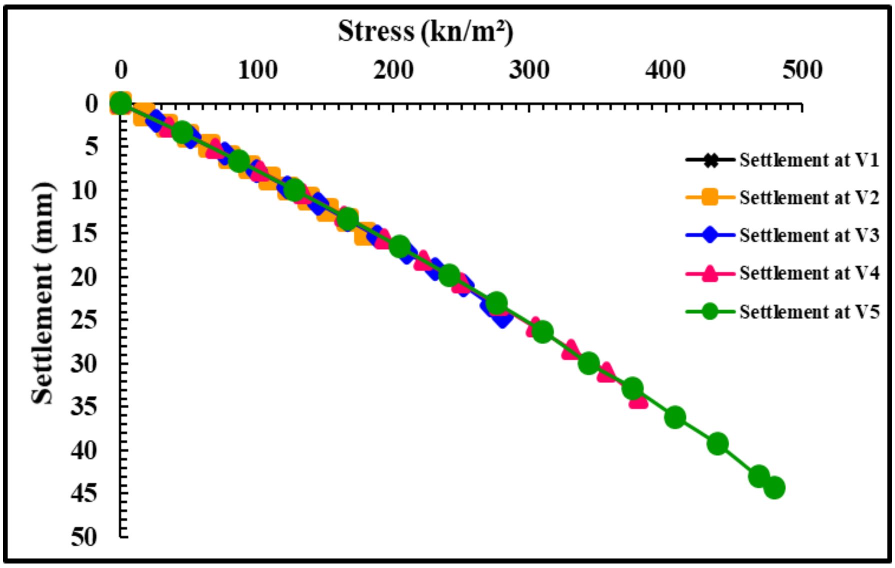


Figure 9. Load - settlement curves for pile group (2) in dry soil under static load

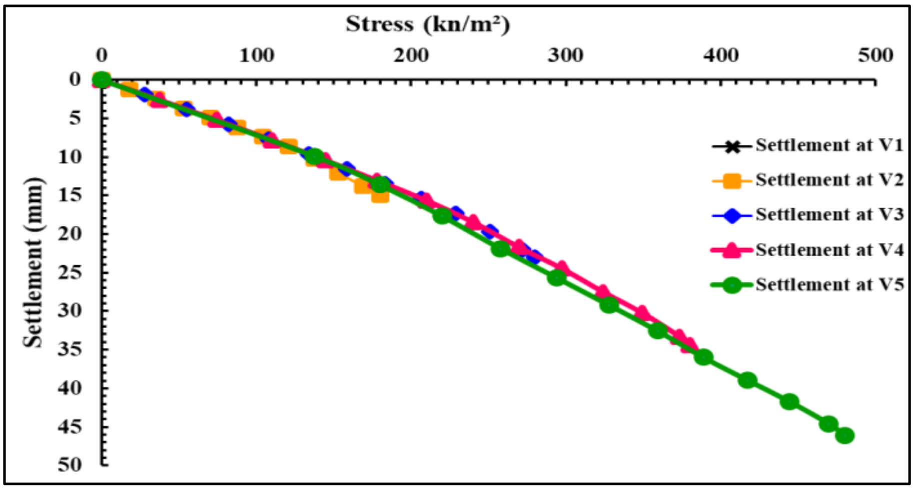


Figure 10. Load - settlement curves for pile group (2) in saturated soil under static load

From the comparison between the settlements for pile group (2) under maximum axial load in dry and saturated soil, the group was settled from (0 mm) when the working load was zero (no loading) and reached to (45) mm in dry state and (47 mm) in saturated state at maximum working load.

From the comparison between the settlements for pile group (2) under maximum axial load in dry and saturated soil, it can be concluded that the settlement in saturated soil is increased about (5%) more than the dry soil.

From the Figure 11, it can be shown that the results of settlement in both cases of dry and saturated conditions, for two groups the settlement increased linearly and convergent values. This is due to the consideration of different water levels in the field soil during the design of foundation, to reduce the large variation in settlement during the rise or fall of water level.

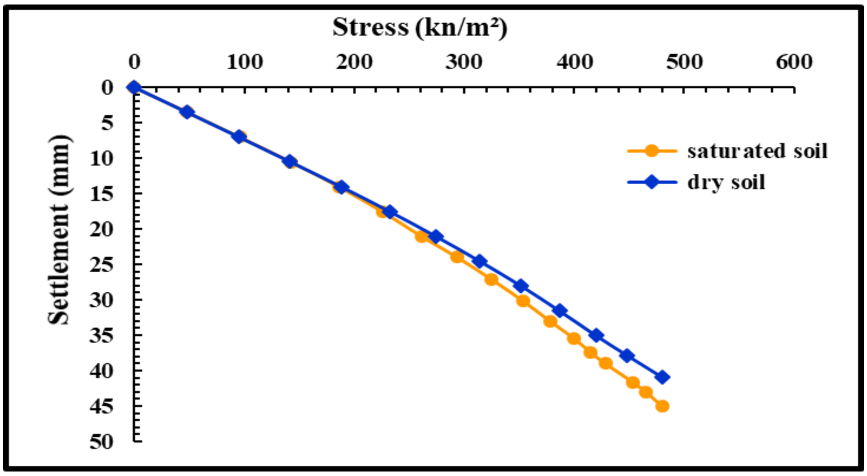


Figure 11: Comparison between the settlement in dry and saturated soil

One of the important factors effected on the foundations stability such as deep foundations is lateral earth pressure, is the pressure that soil exerts in the horizontal direction. The pile group (1) is in equilibrium condition when (Kactive = Kpassive) for the geostatic state of stress, so the settlement was occurred in a soil deposit with a horizontal surface and no shear stresses in lateral and vertical surfaces only from the external axial loads [19].

When a ground surface is not horizontal there is a components of soil gravity, weight of structure in addition to forces of water that tending to move the soil downward, which leads to increase the settlement of group (2) along the slip surface in saturated state. So, the settlement in group (2) is increased about (10%) more than in group (1), because the loose soil particles within the slope surface will collapse rapidly when the stress is increased. From the results of settlement of group (2) it can be concluded that the settlement in saturated soil is increased about (3%) more than in dry soil.

3.2 Analysis of Bridge Foundation with Effect of Halabjah earthquake in dry and saturated soil

The foundation behaviour under seismic loading is a complex phenomenon which effect on the structure's safety in earthquake-prone areas. Piles foundations may be damaged during or immediately after the occurrence of an earthquake. Damages and collapse of structures due to earthquakes depend on wave's intensity [20].

Halabjah seismic loading is adopted to the model in two case (group 1, and group 2) in both soil condition dry and saturated. Halabjah earthquake which occurred in Halabjah-Iraq with a peak ground acceleration (PGA) of intensity 0.1g. The time-acceleration history of Halabjah earthquake [4] as shown in Figure 12.

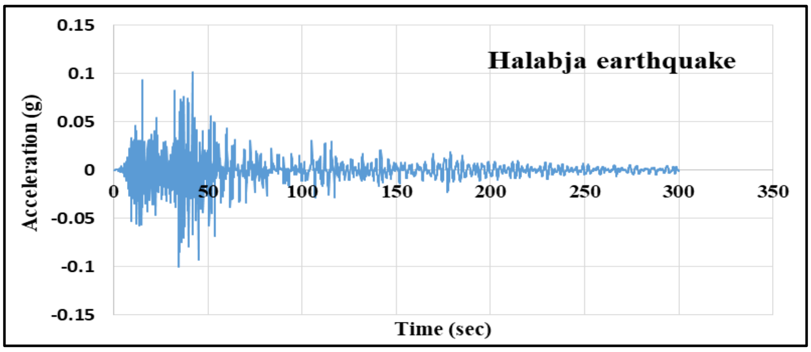


Figure 12. Time- acceleration history of Halabjah earthquake [4]

Acceleration-dynamic time analysis for pile groups is important to evaluate the performance of piles foundations under dynamic loads. From Halabjah seismic waves (was assume 25sec as a time of study) to simulate the response of bridge foundations under earthquakes [21].

This section of the study highlights on the influence of the Halabjah seismic wave on the pile groups of bridge foundation. The settlement results were obtained by analysis ten models for group (1) divided into five in dry state and other five in saturated state. As shown in Figure 13 the total settlement for pile group (1) under Halabjah earthquake in dry condition. And Figure 14 that presented the total settlement for pile group (1) under Halabjah earthquake in saturated condition.

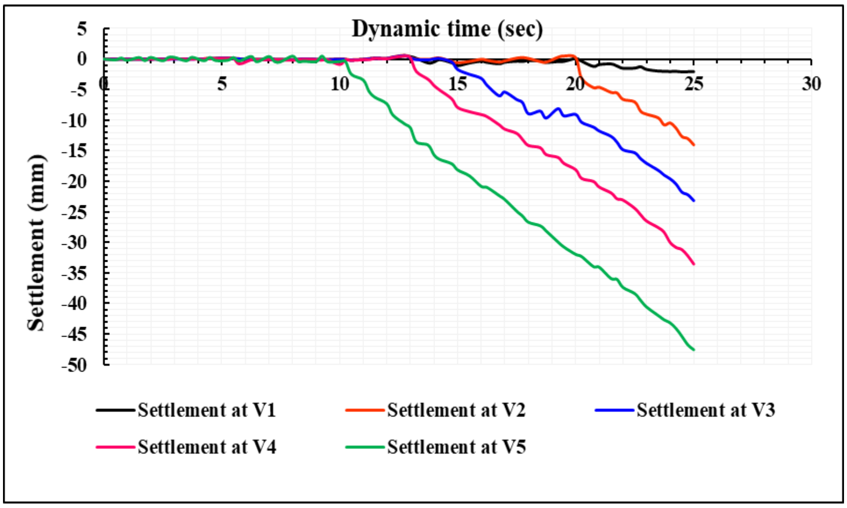


Figure 13. Total settlement for pile group (1) under Halabjah earthquake in dry condition

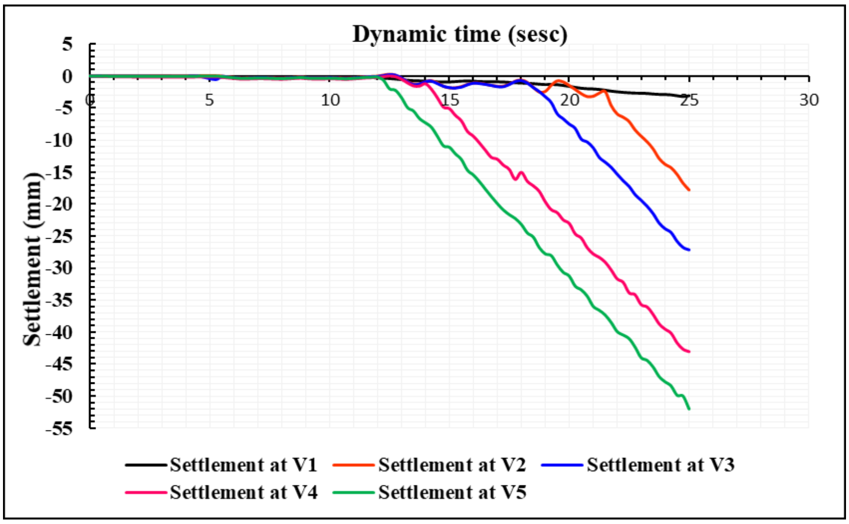


Figure 14. Total settlement for pile group (1) under Halabjah earthquake in saturated condition

During the earthquake occurs the soil particular will start moving and slide down one on another, and causes decreased in soil strength.

From the results presented in Figure 13 it can be seen that the maximum settlement reaches to (47 mm) at maximum stress in dry condition, and Figure 14 showed that the maximum settlement reaches to (53 mm). The settlement of group (1) in saturated soil increased about (12%) more than in saturated soil.

The settlement in group (1) still increased linearly and rapidly at 10 sec in dry condition, but at 12 sec in saturated depending on the time of exit water from soil particular under the impact of Halabjah earthquake.

The second case of settlement results were obtained by analysis ten models for group (2) divided into five in dry state and other five in saturated state. As shown in Figure 15 the total settlement for pile group (2) under Halabjah earthquake in dry condition.

And Figure 16 that presented the total settlement for pile group (2) under Halabjah earthquake in saturated condition.

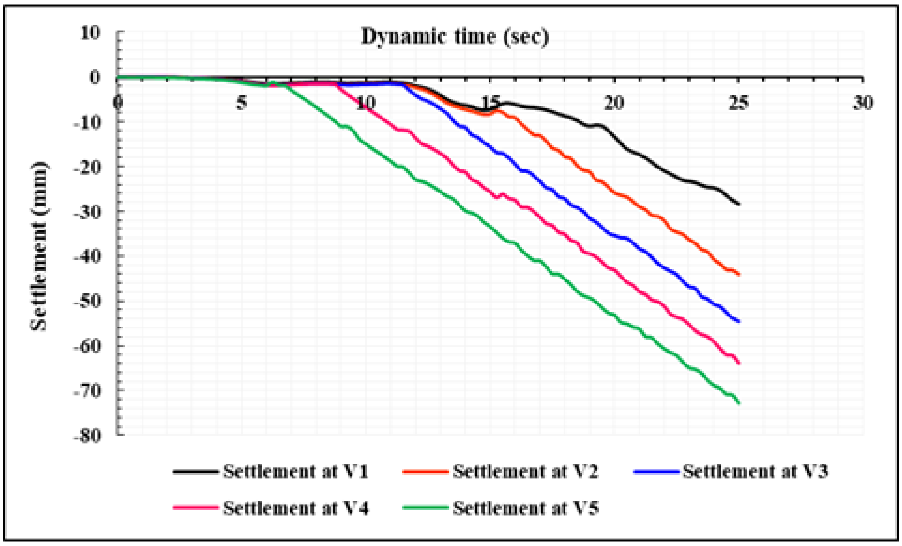


Figure 15. Total settlement for pile group (2) under Halabjah earthquake in dry condition

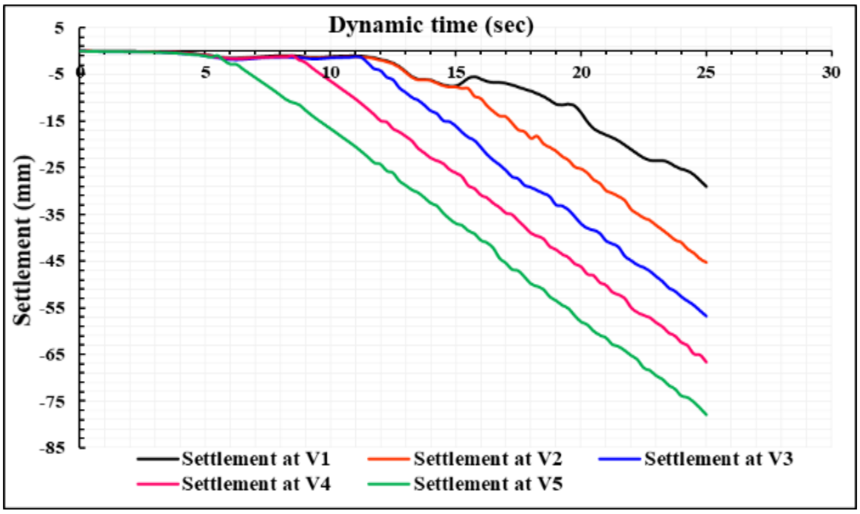


Figure 16. Total settlement for pile group (2) under Halabjah earthquake in saturated condition

From the results presented in Figure 15 it can be seen that the maximum settlement reaches to (72 mm) at maximum stress in dry condition, and Figure 16 showed that the maximum settlement reaches to (77 mm). The settlement of group (2) in saturated soil increased about (7%) more than in saturated soil.

The settlement in group (2) still increased linearly and rapidly at 7 sec in dry condition, but at 5 sec in saturated depending on the time of exit water from soil particular under the impact of Halabjah earthquake. The settlement in group (2) with effect of Halabjah earthquake increased about (35%) more than group (1).

4. Conclusions

In this study, a 3D-finite element analysis was used to assess the bridge foundation. The settlement calculations are an important part in the design of foundation resting on soil which have changing in water level under dynamic load. According to the results of numerical simulations using PLAXIS 3D, the following conclusions can be drawn:

- The results show relatively increase in settlement when the soil below the foundation gets saturated, in both static and dynamic load.
- The settlement of group (1) in saturated soil is more than the settlement in dry state about (5%) in static load, but the settlement in group (2) increased about (3%) in saturated soil is more than the dry state at maximum working loads.
- The settlement of foundations under effect of Halabjah earthquake of group (1) in saturated soil is more than the settlement in dry state about (12%), but the settlement in group (2) increased about (7%) in saturated soil is more than in dry state at maximum working loads.
- The increased in both cases is convergent due to the good design of foundations and taking into account the rise or fall water level during the seasonal fluctuations in the site soil
- The slip surface in slope ground contains many forces effected on its behavior such (soil weight and external loads for static case, in addition to the seismic forces of an earthquake, which increases the deformation in soil mass around the foundation.
- The settlement time in saturated soil increased more than in dry condition, depending on the time of exit water from soil particular under the impact of Halabjah earthquake.
- From the wave oscillation curves it can be seen that, the settlement at maximum loading in group (1) start from (10) sec. But, in group (2) increased rapidly at (5) sec along the analysis time.

- After comparing the results of settlement in two groups in static case it found that the settlement in group (2) is more than group (1) about 10%.
- The settlement in group (2) is more than in group (1) under effect of Halabjah earthquake about 35%.

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