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Numerical Analysis of the Stability of Bridge Foundation Pile under Earthquakes Effect

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ABSTRACT

This study was chosen because of the entry of our regions into the seismic zone recently, where Diyala governorate was hit by the Halabja earthquake in 2017 by 7.3Mw. Therefore, the impact of earthquakes will be studied on the AL-Mafraq bridge foundations piles located in Iraq- east of Baghdad in Diyala Governorate and the extent of its resistance to the Halabjah, EL-Centro, and Kobe earthquakes with acceleration 0.1g, 0.34 g, and 0.58 g, respectively. After modeling and performing the analysis by using Midas Gts-Nx software, the settlement (mm) results at nine nodes (four nodes for the pile cap and five nodes for the piles) were obtained for each of Halabjah, EL-Centro, and Kobe earthquakes to know the resistance of the bridge foundation and which intensity leads to the failure happen. After conducting the analysis, I found the maximum settlement is equal to 11.95 mm with a time of 443 sec at node 3 resulting from the Halabjah seismic, and 49.47 mm from the EL-Centro seismic with a time of 254 sec at node 3. They are within the allowable limits of settlements, but the maximum settlement resulting from the Kobe earthquake equals 359.9 mm with a time of 565 sec at node 3. So, the Kobe earthquake led to failure in the pile's foundation Halabjah earthquake and Centro did not affect the stability of the pile's foundation, Based on Terzaki's theory 1943.

Keywords: AL-Mafraq bridge foundation piles, Gts-Nx program, Halabja earthquake, EL-Centro earthquake, Kobe earthquake.

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التحليل العددي لثبات ركائز أساسات الجسور تحت تأثير الزلازل

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الخلاصة

اختيرت هذه الدراسة لدخول مناطقنا في الحدود الزلزالية في الفترة الأخيرة، حيث تعرضت محافظة ديالى لزلزال حلبجة عام 2017 بقوة 7.3 ميكاواط. تم دراسة تأثير الزلازل على ركائز اساسات جسر المفرق الواقع في العراق شرق بغداد في محافظة ديالى ومدى مقاومته لزلزال حلبجة والسنترو وكوبي بتعجيل 0.1، 0.34 و 0.58 على التوالي. بعد النمذجة وإجراء التحليل باستخدام برنامج Gts-Nx استحصلت نتائج الهبوط (ملم) للاساس في 9 عقد (4 عقد لغطاء الاعمده و 5 عقد للاعمده) لكل من زلزال حلبجة، زلزال سينترو و زلزال كوبي. لمعرفة مقاومة أساس الجسر وأي شدة تؤدي إلى حدوث الانهيار. بعد اجراء التحليل وجدَ ان الحد الأقصى للهبوط هو 11.95 ملم في الوقت 443 ثانية عند العقدة 3 الناتج عن الزلازل حلبجة و 49.47 ملم الناتج من زلازل سنترو في الوقت 254 ثانية عند العقدة 3 وهما ضمن الحدود المسموح بها لهبوط الركائز لكن الحد الأقصى للهبوط الناتج من زلزال كوبي يساوي 359.9 ملم في الوقت 565 ثانية عند العقدة 3. أدى زلزال كوبي إلى حدوث فشل في الركائز بينما لم يؤثر زلزال حلبجة وسنترو على استقرار الركائز اعتمادا" على نظرية ترزاكي لعام 1943.

الكلمات المفتاحية: ركائز أساس جسر المفرق، برنامج Gts-Nx، زلزال حلبجه، زلزال-سنترو، زلزال كوبي.

1. INTRODUCTION

An earthquake's load causes large strains and displacements in the soil and foundations. The soil's shear modulus decreases with increasing strain, but material stiffness increases **(Novak, 1974; Novak and Grigg, 1976).** Pile groupings behave differently with load applied than single piles because of the interaction of nearby piles. Piles are frequently used to decrease settlement by spreading loads across the layers through friction along the pile, by loads transfer from a soft to a stiff layer and increasing the capacity of the pile's load carrying and at higher depth, or by combining both **(Thavaraj, 2000; Reese et al., 2005).** Pile foundations transfer superstructure loads to deeper layers if the underlying soil is too weak **(Wong et al., 2000; Gaaver, 2013).**
Due to Iraq's position on the north-eastern edge of the Arab plates, which has been recognized as semi-continuous lines from the earthquake center, investigations have discovered a history of seismic in Iraq that more than 80 significant earthquakes happened to 1900 AD **(Abdulnaby et al., 2016; Mohammed and Sa'ur, 2016).**
Most earthquakes occur along the border of plate tectonics. The seismic activity in Iraq ranges from low in the southwest of Iraq to medium and strong quakes in the eastern and southeastern regions. The seismicity data are connected with tectonic components, and a significant correlation is discovered between them, particularly near the Iraq-Iran boundary **(Ghalib and Alsinawi, 1974; Talukdar, 2012; Al-Ridah et al., 2017).** Construction

response subjected to an earthquake depends on the highest intensity, frequency, maximum acceleration, and soil characteristics **(Bangash, 2011; Ajom and Bhattacharjee, 2017).**
The work deals with the behavior of the bridge piles of the AL-Mafraq overhead intersection in Diyala governorate, which has been subjected to earthquake activity in recent years — (Diyala is one of Iraq's earthquake hotspots. It is located on the border of Iraq–Iran in Iraq's north-eastern region). Nearly every year, many earthquakes happen in Diyala. Of them, six seismic waves are as follows: Jan.2005, Sept.2008, June 2009, Aug.2009, Nov.2013, and Aug.2014 **(Abdulnaby et al., 2016).**
Seismic loading must be evaluated before any building construction activity can occur. Significant steps have been achieved in plate tectonics through advances in geotechnical engineering **(Obaid, 2016).**
Iraq has recently had a seismic wave, particularly near the border with Iran, located near Diyala city east of Baghdad. Thus, it is necessary to study the earthquake activity in Iraq and reassess the earthquake hazard in this area after the magnitude 7.4 quake hit between Iran and Iraq **(Said, 2010; Al-Taie and Albusoda, 2019).** The failure of pile-supported bridge constructions is mainly caused by soil failures such as liquefaction, landslides, and severe lateral displacement **(Feng et al., 2019).** The foundations are located at a certain depth under the soil surface to transmit the structural loads to the soil. This procedure increases foundation stiffness **(Hanash et al., 2020).**
An earthquake is a natural event that happens suddenly because the rock's layers rupture, causing the earth's surface displacements and vibrations. And also happen A kind of natural event also causes earthquakes. Therefore, they are described as a sharp shock of the earth that results from the movement of the rocks under its surface and causes horizontal and/or vertical movements between the layers of the ground as a result of great pressures and rupture lines as a result of the seismic depending on earthquake size **(Abbas and Al-hadidi, 2021; Hussein et al., 2021)**. Structures in the crust of the earth may be harmed or destroyed by earthquakes. This work deals with one of the complex's significant problems, the effect of seismic waves on bridge foundation piles in a specific soil type and their effects on the total response of bridges, many bridges suffered extensive damage, and some failed due to the failure of the foundations. And the current design procedures to design the foundations and the bridge structures may be inadequate to resist new earthquakes **(Al-hadidi and Abbas, 2021).**
It is apparent from the movement and maximum bending of the pile under dynamic seismic stress that when the L/D ratio rises, the maximum displacement and bending moment decrease **(Deendayal and Nigitha, 2017).** More effect on the settlements is shown with variations in pile length than with pile diameter. Utilizing the piles minimizes the settlement of the structures by approximately 77%, 87%, and 93% when end-bearing and anchoring piles are used **(Mashallah et al., 2021).**
In this work, the Gts-Nx software was used to evaluate the stability of the AL-Mafraq bridge piles foundation and investigate the soil behavior under the impact of the earthquakes. One of its more popular uses is to simulate the conduct of constructions and soils under the effect of seismic.

2. SEISMIC ACTIVITY IN IRAQ

In a global context, tectonic earthquakes result from movement between numerous major plates composing the earth's crust **(Chen and Lui, 2005).** The magnitude and distribution of additional seismic lateral earth pressures are particularly questioned **(Ali and Mohammed, 2013)**.

The concourse of both the Eurasian and Arabian plates causes high seismic activity, which increases in the north, east, and northeast and decreases in the south, west, south-west, and north-west. This suggests that future earthquakes may occur in different areas of Iraq **(Kadhim and Dawood., 2020; Karkush and Naufel, 2022).**
Iraq constructed a Seismic Network (ISN) with five short-period sites at "Baghdad, Sulaymaniyah, Mosul, Basra, and Rutba" in 1976. The ISN built six broad-band three component sites in 2018: "Baghdad, Mosul, Kirkuk, Rutba, Badra, and Nasiriyah." both events had epicentral lengths of 127 km and 644 km, with Richter scale magnitudes of 3.5 to 6.6 **(Mohammed and Faraj, 2016; Onur et al., 2016).**

3. WAVES OF THE EARTHQUAKE

Earthquakes are generated by rapid changes in the size of the materials, which happen when one block of material moves against another and forms cracks. From the point of focus, earthquake waves travel in all ways through the body. Earthquakes generate waves with periods ranging from seconds to a few minutes. The ground motion after an earthquake or explosion is highly complicated**.** An earthquake may create many forms of waves in the soil. In this manner, two types of waves are produced **(Dhakal, 2004; Ali and Rahman, 2017).**

1. Body waves (Primary and Secondary Waves)
2. Surface waves (Love and Rayleigh waves)

4. DESCRIPTION OF THE STUDY AREA

The proposed bridge of the AL Mafraq intersection is situated in the middle area of Iraq- east of Baghdad in Diyala Governorate at Baquba city, as shown in **Fig. 1.** Where it connects with the old Baghdad Street and Al-Zaytouni Street in Baquba. The geotechnical engineers from the University of Diyala, Engineering Consultancy Bureau, in 5/2011, carried out the sub-soil investigation and structural designs. In addition, the bridge's total length is 312 m **(Engineering Consultancy Bureau 2011).**

Figure 1. The case study area of the AL-Mafraq bridge at Baquba–Almafraq region in Diyala Governorate.

5. THE METHODOLOGY

This work aims to study the effect of earthquakes on the piles of the AL-Mafraq Bridge. The amount of settlement that occurred was studied, considering that settlement is one of the most important factors determining failure. Through the maximum measured settlement, the highest intensity of an earthquake that can occur without causing failure is determined.

5.1 Description of the bridge foundation

The concrete foundation of the bridge consists of 26 pile caps, 247 piles, and 72 columns. The pile caps are called (F-1, F-2.... F-12) in the AutoCAD plans. The foundation F-1 (pile cap) was chosen for the analysis, whose dimensions were 35m length, 6m width, and 1.5m depth. Under the pile cap (F-1), 23 piles with a diameter of 1m and length of 6m. Above the pile cap are eight columns with a diameter of 1m, and the soil consists of three layers with a depth of 12m, 5m, and 5m, respectively, as shown in **Fig. 2** and given in **Table 1**.

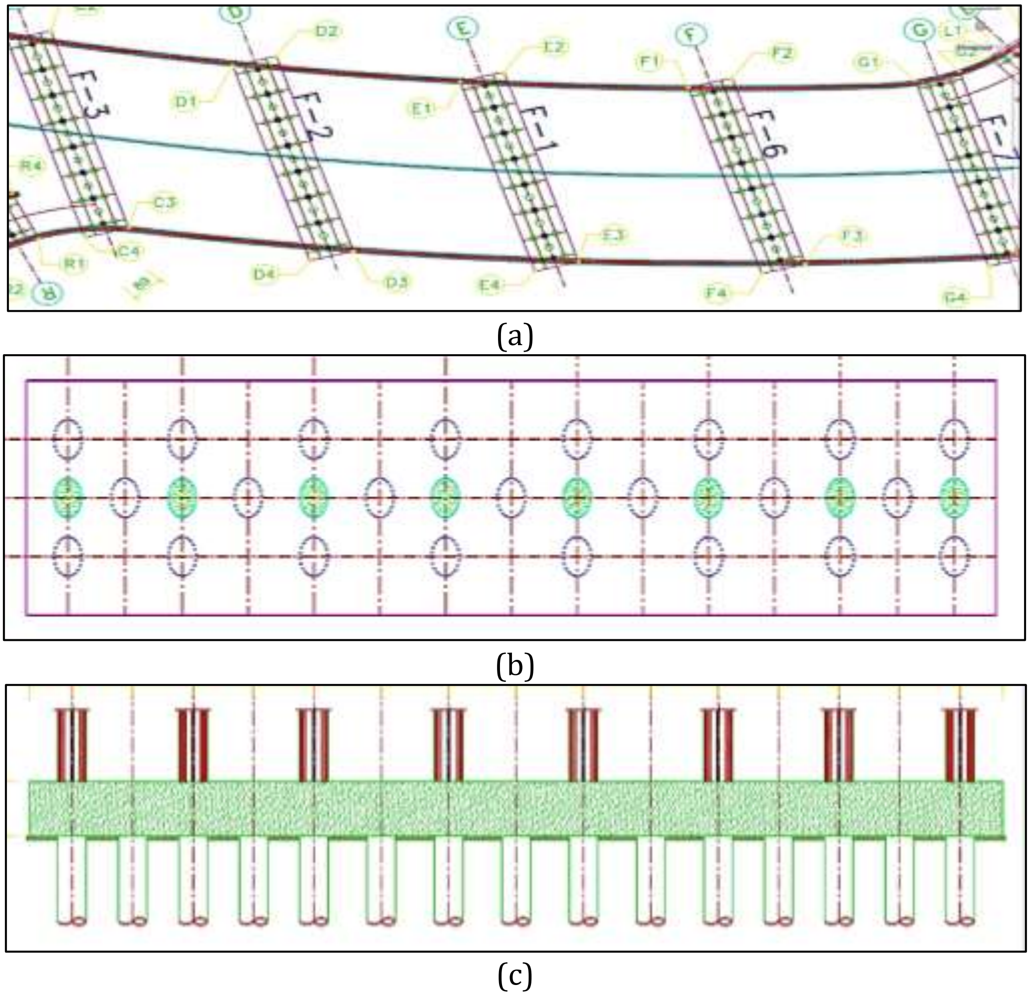


Figure 2. AutoCAD plan of Al-Mafraq bridge (a) Top view of the bridge, (b) Top view of the pile cap, (c) Piles, pile cap, and columns**. (Engineering Consultancy Bureau 2011).**

Table1. Description of the modeling parts of the bridge foundation.

Element Names	Shape	Diameter (D)	Depth (Z)	Width (X)	Length (Y)	Number of Elements
Columns	Cylinder	1	3	/	/	8
Pile caps F_1	Rectangle	/	1.5	6	35	1
Piles	Cylinder	1	6	/	/	23
soils	Rectangle	/	12	110	200	Layer 1
		/	5	110	200	Layer 2
		/	5	110	200	Layer 3

F-1 was chosen for modeling and analysis in the 3D Gts-Nx program, located approximately in the middle of the bridge, because the soil in this area is weak, meaning the weakest soil at the bottom of the bridge is below the F-1 pile cap.

6. GTS-NX SOFTWARE

GTS NX from Midas company is a simulation program developed for evaluating soil-structure interaction based on the finite element method. GTS NX helps engineers perform step-by-step analysis of excavation, banking, structure placement, loading, and other factors that directly affect design and construction. The program supports various conditions (soil characteristics, water level, etc.) and analytical methodologies to simulate natural phenomena. Settings for all types of field conditions can be simulated using non-linear analysis methods (such as linear/non-linear static analysis, linear/non-linear dynamic analysis, seepage and consolidation analysis, and slope safety analysis) and various coupled analysis (such as seepage-stress, stress-slope, seepage-slope and non-linear dynamic-slope coupled analysis).
The interface of GTS NX provides easy summoning of modeling and analysis tools, creating an intuitive working environment for general and novice designers. The 64-bit OS-supported next-generation platform base and new graphic engine allow the best modeling performance for object calculation and element generation. In contrast, the 64-bit integrated solver considerably reduces the analysis time for large models (Midas Company).

7. BRIDGE PILE FOUNDATION MODELING

The bridge's foundations were modeled in the Midas Gts-Nx program in a three-dimensional form based on the structural designs obtained from the **Engineering Consultancy Bureau** at the University of Diyala. The Bridge foundation consists of three parts: columns, pile caps, and piles, as shown in **Fig. 3**. With free field boundary conditions of the soil's layers and automatic generating size of the mesh for all elements.

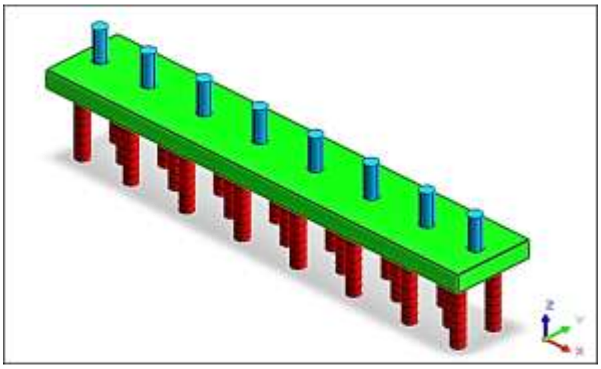


Figure 3. Three-dimensional modeling of Baqubq–AL Mafraq bridge foundation.

8. USED MATERIALS CHARACTERISTICS

The input properties of each type of material required for dynamic analysis for the bridge of the AL Mafraq intersection located in the Diyala Governorate are given in **Table 2.**

Table 2. Properties of the soil and material of the AL Mafraq bridge foundation **(Engineering Consultancy Bureau, 2011).**

Material		Unit weight kN/m3	C kN/m2	Ø degree	E kN/m2	Poisson ratio	Void ratio (e)
columns		24	/	/	20000000	0.2	0.15
Pile cap		24	/	/	20000000	0.5	0.15
Piles		24	/	/	20000000	0.5	0.1
soils	Layer 1	16	40	20	120000	0.3	0.68
	Layer 2	16	45	25	120000	0.33	0.68
	Layer 3	15.18	75	0	150000	0.33	0.6

9. DYNAMIC LOAD

The earthquake record data were obtained from the Iraq Meteorological Organization (**Iraq Meteorological Organization and Seismology, 2017)** after completing the foundation geometry and inputting the material properties, boundary conditions, and static loads of the AL-Mafraq bridge foundation. The data of Halabjah, EL-Centro, and Kobe Earthquakes were used for analysis in the Gts-Nx. The earthquake acceleration time charts are shown in **Fig. 4**. Also, the earthquake data is shown in **Table 3**. In addition, 25 seconds were added to the time of each earthquake used during the analysis.

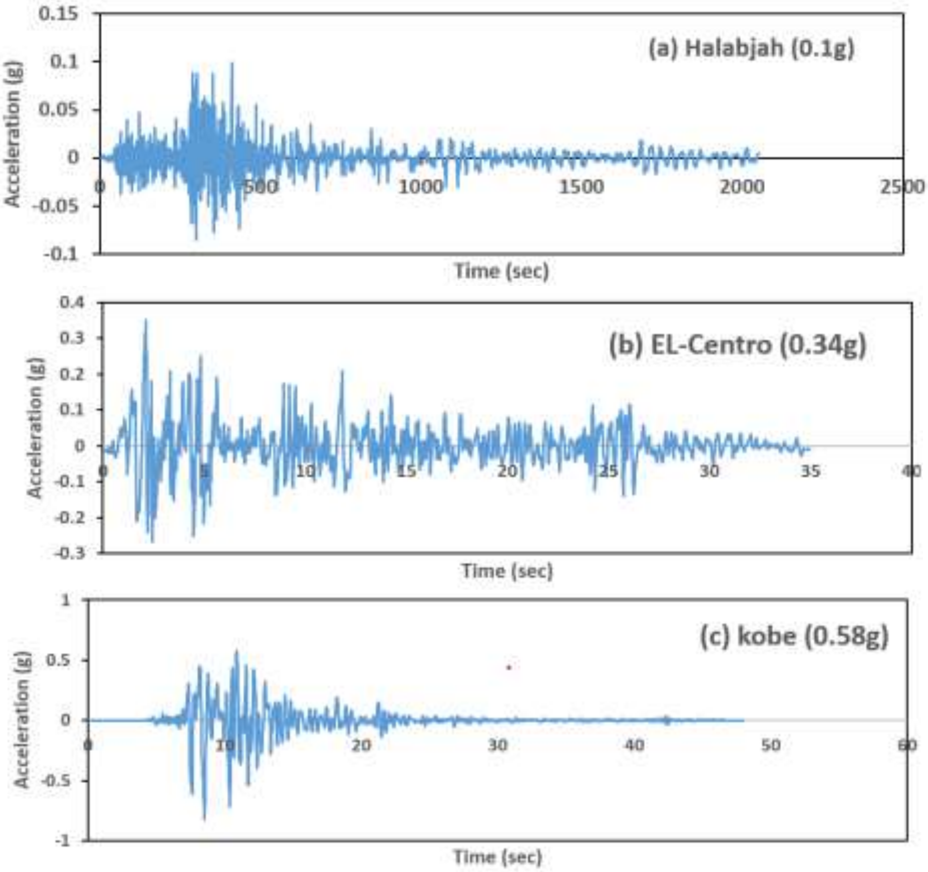


Figure 4. The earthquake's acceleration time that is used in the analysis, (a) Halabjah, (b) EL- Centro, (c) Kobe.

Table 3. Explain data of the Earthquakes using.

Earthquakes types	Acceleration (g)	Time of Earthquake (sec)	Time using in analysis (sec) +25	Increment Time	Time Steps (sec)
Halabjah	0.1	205	230	0.1	2300
EL- Centro	0.34	35	60	0.02	3000
Kobe	0.58	48	73	0.02	3650

10. STATIC LOADS

Because the bridge consists of six roads, three going and three coming, the concentrated loads were represented on the foundation with a weight of 6 army tanks, three on each side standing directly above the foundation F-1, which is subject to the conditions of the earthquake when analyzing. Where the weight of each army tank was imposed 70ton, equivalent to 700 kN, and the total loads equal to 4200kN (6 × 700 = 4200kN) were divided into the eight columns and therefore, the load equal to 525 kN on each column (4200÷8=525kN), and than divided on the area of the one circular column. The columns transferred the loads from the bridge to the pile cap. As a result, the stress equals 668.45 kN/m2, approximately 700 kN/$m^{2,}$ as given in **Table 4**. It is found that this method gives more accurate results in calculating the static loads.

Table 4. Explain the maximum static load applied on the columns of the AL Mafraq bridge.

Weight of army tank (kN)	700 (70 ton)
Number of the army tank	6
Total weight of the army tank (kN)	6 × 700 = 4200
Number of circular columns	8
Weight on each column (kN)	4200 ÷ 8 = 525
Area of the one circular column (m^2) $\boldsymbol{A = \pi r^2}$	$\pi \times 0.5^2 = 0.7854$
pressure (p) on each column (kN/m^2)	525÷0.7854 = 668.45 ≈ 700

11. RESULTS AND DISCUSSION

The numerical analysis results of the bridge foundation piles will be discussed under the influence of Halabjah, EL-Centro, and Kobe earthquakes with 0.1, 0.34, and 0.58 acceleration (g), respectively, as shown in **Fig. 4** to compute Z-Displacements (settlements) for all the mentioned earthquakes at nodes 1,2,3 and 4 for pile cap as shown **in Fig. 5a**, also at nodes 5,6,7,8 and 9 for piles as shown in **Fig. 5b**.
Based on Terzaki's conclusion in 1943, which states that a pile failure occurs if the settlement exceeds 10% of the pile diameter). Thus, the diameter of the Al-Mafraq bridge piles is 1000mm, So the allowable settlement is equal to 100mm (1000mm×10%=100mm) depending on the **(Terzaki, 1943).**

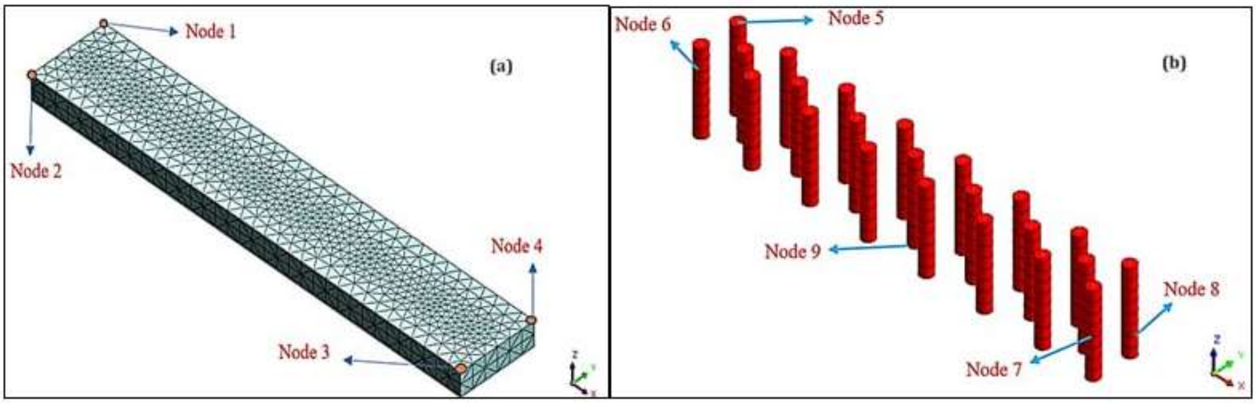


Figure 5. Nodes of the Al-Mafraq bridge pile foundation were taken to explain the results: (a) Four Nodes on the edges of the pile cap and (b) Five Nodes on the piles.

11.1 Halabjah Earthquake

11.1.1 Pile cap (Vertical displacement)

Fig. 6 shows the Z-Displacement (mm) with time (sec) at nodes 1,2,3,4 in the edges of the pile cap. The maximum displacement equals 11.95 mm with a time of 443 sec at node 3, and the minimum displacement equals -11.06 mm with a time of 446 sec at node 4.

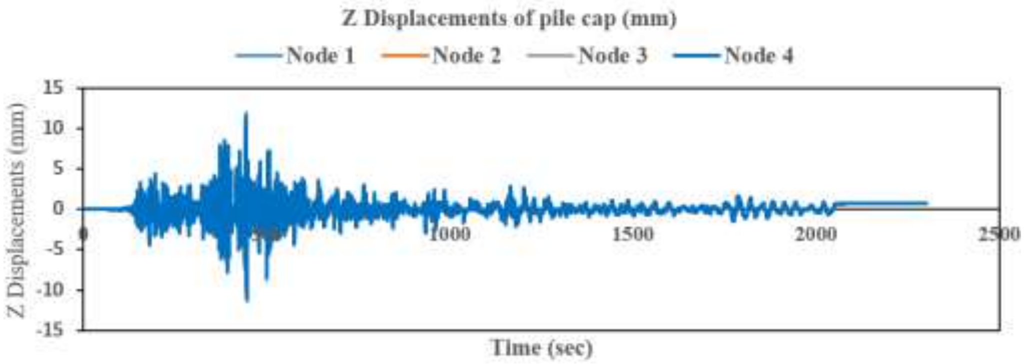


Figure 6. The Z-Displacement(mm) with time (sec) at nodes 1, 2, 3, and 4 that result from the Halabjah earthquake.

11.1.2 Piles (Vertical displacement)

Fig. 7 shows the Z-displacement (mm) with time (sec) at the nodes 5,6,7,8,9 of the piles. The maximum displacement is equal to 11.86 mm with a time of 443 sec at node 7, and the minimum displacement is equal to 11.14 mm with a time of 446 sec at node 5.

11.2 El-Centro Earthquake

11.2.1 Pile cap (vertical displacement)

Fig. 8 shows the Z-displacement (mm) with time (sec) at nodes 1,2,3,4 on the edges of the pile cap. The maximum displacement is equal to 49.47 mm with a time of 254 sec at node 3, and the minimum displacement is equal to -35.59 mm with a time of 106 sec at node 1.

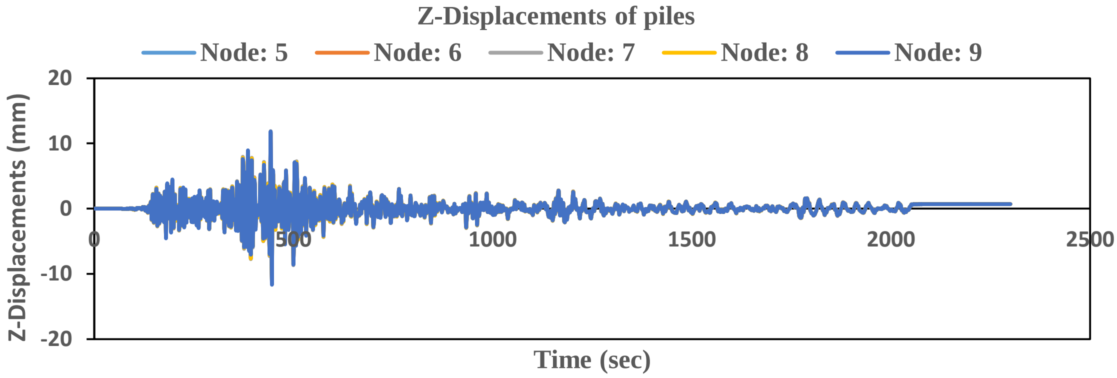


Figure 7. Z-Displacements(mm) with time(sec) at nodes 5, 6, 7, 8, and 9 that result from the Halabjah earthquake.

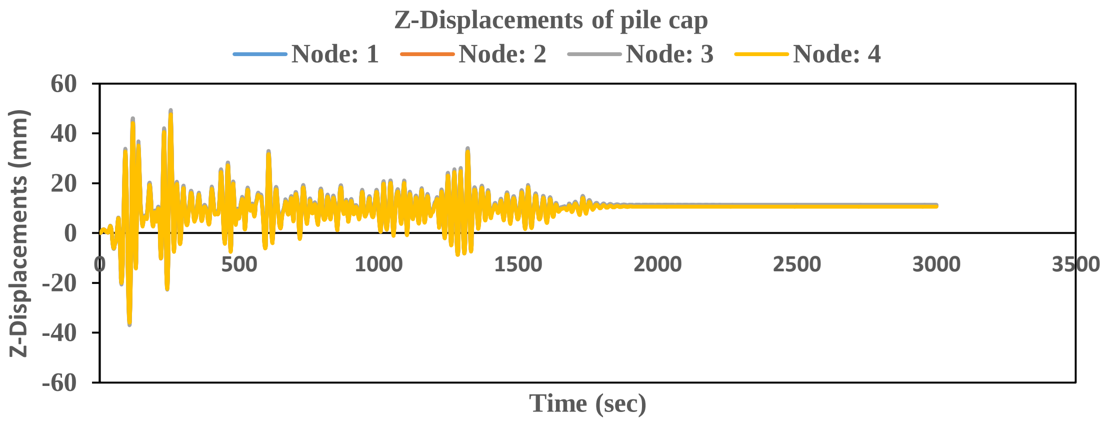


Figure . 8 The Z-Displacement(mm) with time (sec) at nodes 1, 2, 3, and 4 that result from EL-Centro earthquake.

11.2.2 Piles (vertical displacement)

Fig. 9 shows the Z-displacement (mm) with time (sec) at the nodes 5,6,7,8,9 of the piles. The maximum displacement is equal to 48.5 mm with a time of 254 sec at node 7, and the minimum displacement is equal to -35.73 mm with a time of 106 sec at node 5.

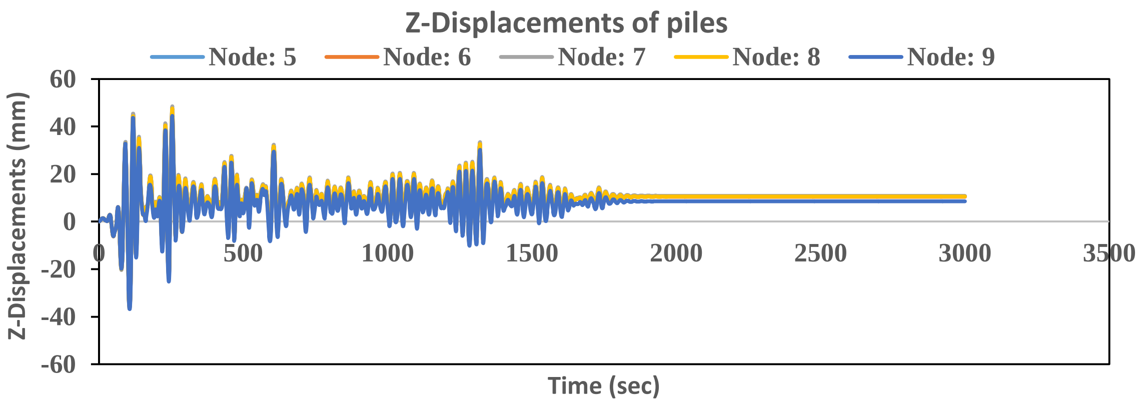


Figure 9. Z-Displacements(mm) with time(sec) at nodes 5, 6, 7, 8, and 9 that result from EL-Centro earthquake.

11.3 Kobe Earthquake

11.3.1 Pile cap (vertical displacement)

Fig. 10 shows the Z-displacement (mm) with time (sec) at nodes 1,2,3,4 at the edges of the pile cap. The maximum displacement is equal to 359.99 mm with a time of 565 sec at node 3, and the minimum displacement is equal to -30.64 mm with 372 sec at node 4.

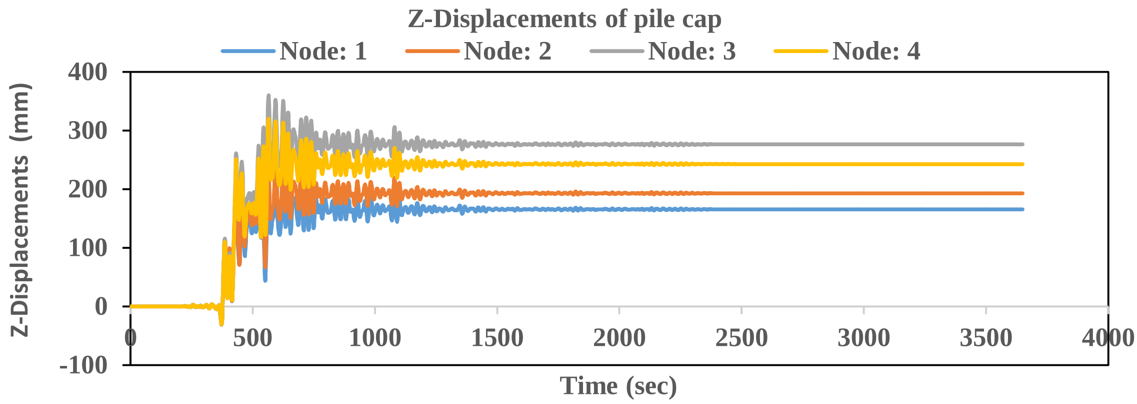
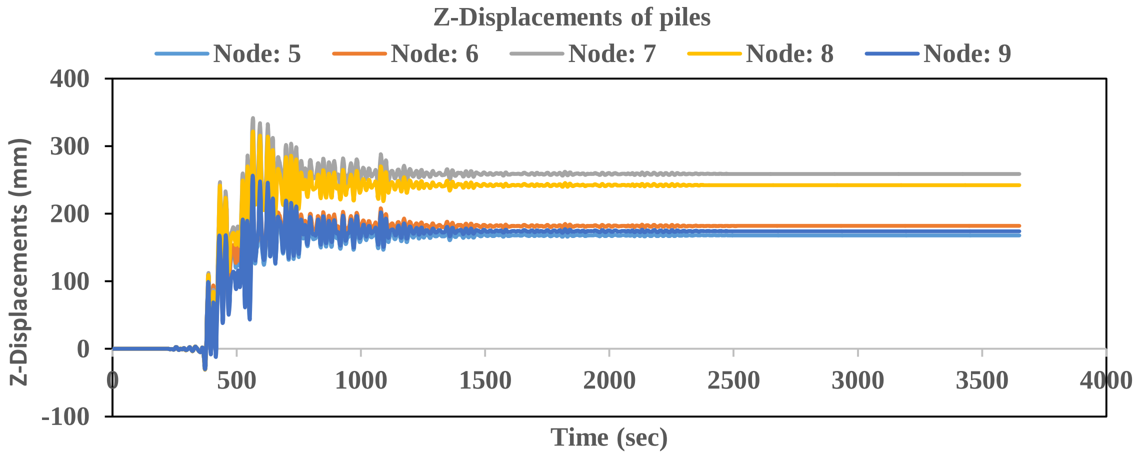


Figure 10. The Z-Displacement(mm) with time (sec) at nodes 1, 2, 3, and 4 that result from the Kobe earthquake.

11.3.2 Piles (vertical displacement)

Fig. 11 shows the Z-displacement (mm) with time (sec) at the nodes 5,6,7,8,9 of the piles. The maximum displacement is equal to 341.56 mm with a time of 565 sec at node 7, and the minimum displacement is equal to -30.34 mm with 372 sec at node 9.



11.3.3 Figure 11. Z-Displacements(mm) with time(sec) at nodes 5, 6, 7, 8, and 9 that result from the Kobe earthquake.

After 3D modeling using the Gts-Nx program and analysis of the AL-Mafraq bridge pile foundations. **Table 5** gives the results of maximum settlement (mm), and **Fig. 12** shows the Comparison of the maximum settlement (mm) between the Halabjah, EL-Centro, and Kobe earthquakes, which were calculated at nine nodes. nodes 1,2,3 and 4 for pile cap as shows in **Fig. 5a** also, nodes 5,6,7,8 and 9 for piles as shows in **Fig. 5b**.

Table 5. The results of the maximum settlements (mm) of the AL-Mafraq bridge foundation under earthquakes (g) effect.

		Nodes of Pile Cap Edges				Nodes of Piles				
Seismic (g)	Maximum Movements (mm)	1	2	3	4	5	6	7	8	9
Halabjah	Settlements	11.69	11.78	11.95	11.58	11.69	11.71	11.86	11.66	11.85
EL-Centro	Settlements	48.37	48.38	49.47	47.63	47.56	47.50	48.50	47.51	44.52
Kobe	Settlements	227.61	256.80	359.99	320.15	231.49	246.09	341.56	321.66	256.21

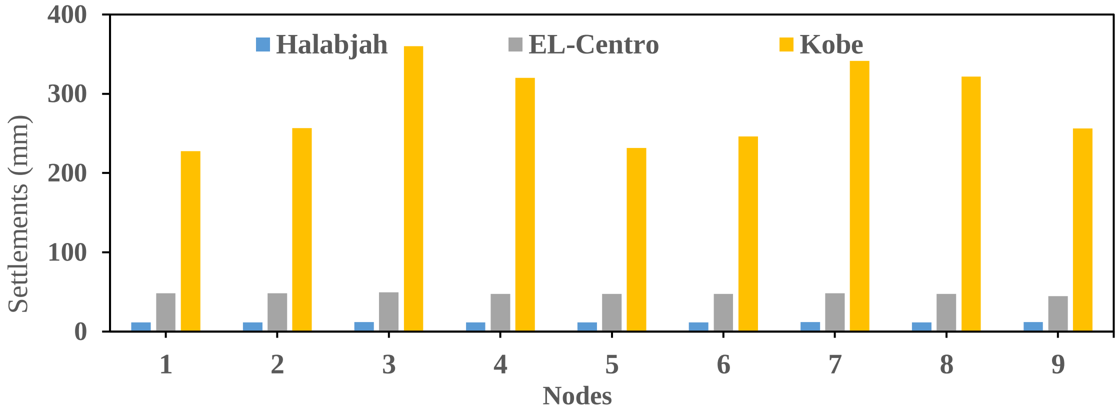


Figure 12 Comparison results of the maximum settlement of Halabjah, EL-Centro, and Kobe earthquakes.

When analyzing the Halabjah earthquake with 0.1g for piles foundation. I found the maximum settlement equal to 11.95mm at node 3 and a minimum settlement equal to 11.58mm at node 4. At the same time, the analysis of the EL-Centro earthquake with 0.34g was the maximum settlement of 49.47mm at node 3 and a minimum settlement of 44.52mm at node 9. These displacements are slight, almost do not affect the foundation, and are very close to each other. But the maximum settlement and minimum that resulted from the Kobe earthquake with 0.58g are equal to 359mm and 227mm at node 3 and node 1, respectively. Under the influence of the Kobe earthquake, the bridge's foundation was exposed to significant risks.

12. CONCLUSIONS

In this work, the effect of different earthquake intensities on the AL-Mafraq Bridge was studied to show their impact on the bridge's safety. These earthquakes are the Halabjah, EL-Centro, and Kobe earthquakes. By applying these intensities on the bridge, the settlement amount was studied at different locations on the pile cap and along the piles. The maximum settlement was determined and compared to the allowable settlement based on Terzaki's conclusion in 1943: *The allowable settlement in the piles is equal to 10% of the pile diameter*. It compares the values of the maximum settlements with the allowed settlement rate of 100 mm. In the Halabjah earthquake, with an acceleration of 0.1g, the maximum settlement rate

was equal to 11% of the allowed settlement, which is within the tolerable limits. When the earthquake's intensity was increased using the EL-Centro earthquake with the acceleration of 0.34g, the settlement percentage rate increased to 49%, also within the permissible limits. However, when applying Kobe seismic with the acceleration of 0.58g, the settlement percentage was equal to 359% of the allowed settlement, which exceeded the tolerable limit. This work shows that the earthquake of Halabjah and EL-Centro does not affect the bridge's stability. On the contrary, the Kobe earthquake led to the bridge's failure because the maximum settlement exceeded the tolerable limit.
Meanwhile, this analysis appears clear when earthquakes approach from 0.5g, must carry out maintenance work for the Bridge if possible, and treatment of the failure places. Through the Gts-Nx program, it is possible to identify the most dangerous places due to the impact of earthquakes.

NOMENCLATURE

Symbole	Description	Symbole	Description
C	Cohesion, kN/m^2.	g	Earthquakes acceleration, m/sec^2.
D	Diameter, m.	Gts-Nx	Geotechnical Analysis System-New Experience.
E	Elastic modulus, kN/m^2.	X	Width, m.
e	Void ratio, dimensionless.	Y	length, m.
F-1	Symbol of pile caps plan.	Ø	The angle of internal friction, deg.

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