Seismic effect on uplift bearing capacity of pile embedded in dry sand

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Abstract. The growing rate of occurrence of earthquakes in Iraq and the whole region has driven to conduct this experimental research aiming at evaluating the uplift capacity of piles under seismic influence. Shaking table was especially manufactured to simulate the seismic loading resulting from Halabjah earthquake with high accuracy. Pullout tests were carried out on piles embedded in dry sand to determine the ultimate uplift load capacity before and after applying the seismic loading for different length to diameter ratios (L/D) of pile model 20, 25 and 30 and for loose and dense dry sand. It has been found that the maximum pull-out load of the pile after applying only Halabjah seismic loading was reduced between (8.16%) and (10.46%) in loose dry sand. However, there is no clear effect on tension pile capacity in dense dry sand except in pile of L/D=30, that bearing capacity increased by about 15.94%. And when apply combined loading of Halabjah seismic loading and uplift loading equal to one-third of maximum tension capacity the reduction of maximum pull-out capacity was between (55.02% to 73.22%) in loose sand while in dense sand there is a reduction about 50% for pile with L/D=20 and 25% and a low reduction of 8.06% for pile with L/D=30.

Key word: seismic, uplift pile, shaking table, Halabjah earthquake.

1. Introduction
Earthquakes are broad-banded vibratory ground motions, resulting from a number of causes such as tectonic ground motions, rock bursts, landslides, volcanism, and man-made explosions. Of these, naturally occurring tectonic-related earthquakes are the largest and most important. Earthquakes initiate a number of phenomena or agents, termed seismic hazards, which can cause significant damage to the built environment, these include fault rupture, vibratory ground motion (i.e., shaking), inundation (e.g., tsunami, seiche, dam failure), various kinds of permanent ground failure (e.g., liquefaction), fire, or hazardous materials release. In a particular earthquake event, any particular hazard can dominate, and historically each has caused major damage and great loss of life in particular earthquakes [1].

Iraq is not out from seismic hazards. Earthquakes are likely to happen and may cause substantial damage. Actually, such hazards were happened and recorded after the last earthquake in November 2017 (Halabjah earthquake). Unfortunately, there is a lack of studies concerns the assessment of the earthquake hazard on the soil in Iraq. In November 2017, a major 7.3 magnitude earthquake struck the
Iraq–Iran border, killing over 530 people and injuring thousands in Iran alone. In Iraq, nine people were killed and 550 were injured, all in the north of the country (Kurdistan region), according to the United Nations [2].

When vertical piles are installed beneath buoyant structures such as dry docks, basements, and pumping stations they are required to resist uplift loads. Where the hydrostatic pressure always exceeds the downward loading, as in the case of some underground tanks and pumping stations, the anchorages are permanently under tension and cable anchors may be preferred to piles [3]. Foundation of many engineering structures like transmission towers, mooring systems, retaining walls, offshore structures, tall chimneys, jetty structures are subjected to uplift forces [4], [5] & [6]. In such structures, the induced overturning moments are transferred to the piles supporting the structure in the form of compression in some piles and pull out on others. Moreover, uplift forces may be exerted on piles due to swelling of the surrounding soils [7], several methods were used to analyze and evaluate the ultimate uplift capacity of pile in the sand layers such as [8], [9] and [10].

Many theoretical, numerical, and experimental studies have been conducted on evaluating the uplift capacity of piles subjected to static uplift forces. However, little work such as [11] have been conducted under seismic influence. This can be attributed to the fact that proper devices and software for accurate representation and measurements are only recently became available [12]. The growing rate of occurrence of earthquakes in Iraq and the whole region has driven to conduct this experimental research aiming at evaluating the uplift capacity of piles under seismic influence.

This research is devoted to study how the uplift capacity of pile embedded in dry sand is affected by seismic loading. Shaking was especially manufactured to simulate the horizontal movement and apply seismic loading resulting from earthquakes with high accuracy. The shaking table was equipped with a data acquisition device and neoteric sensors. Also, uplift device was used to apply uplift force on pile model which was placed on laminar shear box.

2. Research Methodology
After reviewing the previous studies, which were a large percentage of about static tests on piles models exposed to tensile forces and the lack of research and studies on the effect of dynamic forces on tension piles, the research was towards studying the effect of earthquakes on tension piles. Halabjah earthquake, the strongest earthquake that hit on the Iraqi Iranian borders were chosen. Effect of earthquakes on the tension bearing capacity of piles in dry sandy soils was the focus of the research. The study was conducted in a laboratory after manufacturing and preparing the necessary devices and equipment, and on a model for the pile to be placed in a model of soil with dimensions that facilitate the work of laboratory tests. Accuracy was taken into the manufacture of devices and equipment by conducting calibration for each sensor or device.

3. Experimental work
A laboratory model study of tension piles installed in sandy soil subjected to seismic loading was conducted. The objective of the study was to determine the effect of apply seismic loading on the ultimate bearing capacity of tension piles of L/D= 20, 25 and 30 in dry soil and for loose and dense soil. The soil sample was prepared in the laminar shear box by depositing very fine sand in a loose and dense condition using raining technique and tamping. A closed-ended steel pipe, 18 mm in diameter and 360,450 and 540 mm in length was placed into the dry soil mass.

4. Shaking table-pullout device system
Shaking table – pullout devices system was manufacturing locally to achieve a laboratory representation of the piles under effect of tensile and seismic loads. System consists of many devices, equipments and instruments as followings:

4.1 Shaking table
The shaking table is an indispensable testing facility for development of earthquake-resistant techniques [13]. Uniaxial Shake table device used was manufactured by author as shown in Figure 1 which consists of 10 mm steel plate thickness with dimension 1m x 1m act as the table of
shaking, two steel channels support bases for linear guides. A ball screw shaft with nut was fixed at the bottom of table to convert the rotational motion of the servo motor to a linear displacement, its total length is 1500 mm while, travel length is 500 mm.

4.2 Pull-out device for tension test

This device as shown in Figure 2 consist of steel frame, two smooth roles, steel wire, load cell (5 KN), rope displacement sensor and winch. It was used to apply tension force on model pile.

4.3 Laminar shear box (LSB)

LSB has been conducted as shown in Figure 2. LSB consist of 13 steel laminae stacked one above each other. The laminas were constructed from a hollow square steel tube (50 x 50 x 2mm). It is welded as a frame with inner dimensions of (570 x 620) mm and outer dimensions (670 x 720) mm and 50 mm in height for single laminae, the total height of the LSB was 650 mm and the tested soil specimen of 600 mm in depth, while remaining about 50 mm free space in the top of box consequently the tested soil model dimensions was (570 x 620 x 600) mm and the volume was 0.212m³.

5. Event selection

The event chosen for the study was Halabjah earthquake which was the highest earthquake happened during the last ten years in Iraq as recorded by the Iraqi Meteorological Organization and Seismology.
Table 1 Presents the information for Halabjah earthquake data while Figure 3 shows acceleration vs. time of this earthquake according to [14].

| Region                  | Iraq – Iran border, |
|-------------------------|---------------------|
| Date (UTC*)             | 12/11/2017 18:18:17 |
| Magnitude, (M)           | 7.3 MW              |
| Modified Mercalli Intensity, (MMI) | VIII- Moderated heavy |
| Epicenter depth, (Km)   | 19                  |
| Shake Duration, (sec)    | 180                 |
| Station distance to epicenter, (Km) | 218.8         |
| Sampling Frequency, (Hz) | 10                  |
| Acceleration direction   | E-W                 |
| Maximum acceleration, (g)| 0.1                 |
| Station code             | BHD                 |
| Reference                | Iraqi Meteorological Organization and Seismology |

6. Calibration of shaking table
One of the most important things that necessitate to known before any test is to check the ability of shaking table to produce and simulate real earthquake, the calibration was conducted by Linear variation displacement transducer (LVDT). LVDT is a sensor that measuring the displacement with capacity of 500 mm. It is fixed on the steel frame and connected with steel table of shaking table as shown in Figure 4, it is used to measure the horizontal displacement of shaking table during apply Halabjah earthquake by shaking table tests. The data of Halabjah earthquake has been converted into displacement vs. time and draw with the output of LVDT from shaking table tests as shown in Figure 5. The results of calibration indicated a high agreement with error% equal to 0.07% and the data of motion for real and experiment test was coincide.
Figure 4. LVDT fixed on shaking table tests.

Figure 5. Relationship between displacement and time for real earthquake and shaking table tests.

7. Software Programme Control
Controlling the motion of the servo motor was conducted by LabVIEW 2018 software, the LabVIEW 2018 program was used to create a virtual interface as shown in Figure 6. The Excel sheet file that contains the earthquake data in the form of acceleration vs. time was inserted into the program and converted into a distance vs. time by SeismoSignal software to become a form that LabVIEW program can use it.

8. Pile models
Pile models used in the tests of the current study were made of aluminium bar with a circular section with an external diameter with plastic cover of 18 mm (covered to increase the side friction of pile) as shown in Figure 7 with length 360, 450 and 540 mm so the length to diameter ratio (L/D) was 20, 25 and 30. Vertical displacement of pile was measured by a rope displacement sensor, rope displacement consist of a 1m flexible rope that was fixed on the pile cap. Rope displacement sensor can measure up to 1 m with a good accuracy up to 0.01 mm this sensor connected with data logger for monitor and store the data.
9. Physical and Chemical Properties of used Soil
Soil tests were carried out to find its properties, namely the specific gravity, grain size analysis, permeability, direct shear test, maximum and minimum dry density, and relative density. The materials used in this study are supplied from Karbala city. It is relatively poorly graded passing through sieve No.10 (maximum size is 2mm). The particle size distribution curve for backfill material is shown in Figure 8, from the figure the $D_{10}=0.185$, $D_{30}=0.285$, $D_{60}=0.425$, $C_u$ (Uniformity coefficient) was 2.3 and $C_c$ (Coefficient of curvature) =1.03. The backfill soil is classified as poorly graded sand (SP) according to the Unified Soil Classification System USCS. The physical and chemical properties of the sand are summarized in Table 2.
Table 2. Physical and Chemical Properties of Soil

| Soil Property                  | Loose Sand | Dense Sand | Standard of Test          |
|-------------------------------|------------|------------|---------------------------|
| Relative Density, $D_r$ (%)   | 35         | 70         | -                         |
| Max. Unit Weight, $\gamma_{\text{max}}$ (kN/m$^3$) | 17.7       |            | ASTM D 4253 (2000)       |
| Min. Unit Weight, $\gamma_{\text{min}}$ (kN/m$^3$) | 15.1       |            | ASTM D 4254 (2000)       |
| Dry Unit Weight, $\gamma_d$ (kN/m$^3$)           | 15.918     | 16.886     | -                         |
| Total Unit Weight, $\gamma_t$ (kN/m$^3$)          | 19.43      | 19.94      | -                         |
| Water Content, $W_c$ (%)      | 22         | 18         | ASTM D2216 (2010)         |
| Specific Gravity, $G_s$       |            | 2.64       | ASTM D854 (2014)          |
| Max. Void Ratio, $e_{\text{max}}$             | 0.689      |            | -                         |
| Min. Void Ratio, $e_{\text{min}}$               | 0.441      |            | -                         |
| Void Ratio, e                 | 0.601      | 0.516      | -                         |
| Sand %                         | 98         |            | ASTM D422 (2007)          |
| Fine sand %                   | 56.9       |            |                           |
| Medium sand %                 | 40.9       |            |                           |
| Coarse sand %                 | 0.2        |            |                           |
| Effective Size, $D_{10}$ (mm) | 0.185      |            |                           |
| Mean Size, $D_{50}$ (mm)      | 0.285      |            |                           |
| Mean Size, $D_{60}$ (mm)      | 0.425      |            |                           |
| Coefficient of Uniformity, $C_u$ | 2.297      |            |                           |
| Coefficient of Curvature, $C_c$ | 1.033      |            |                           |
| Soil Classification (USCS)     | Poorly-graded sand, (SP) | ASTM D2487 (2010) |
| Permeability Coefficient, k(cm/sec) | 2.53x10^{-3} | 1.38x10^{-3} | ASTM D2434 (2006) |
| Friction Angle, $\phi$        | 32°        | 38°        | ASTM D4767 (2011)         |
| $SO_3$, %                     |            | 1.6        | BS-1377 (1967)            |
| Gypsum content, %             | 1.59       |            |                           |
| T.S.S., %                     | 0.34       |            |                           |

10. Procedures of tests

In order to reach the aim of the research, which is to study the effect of earthquakes of Halabjah earthquake on the tension bearing capacity of the piles, the tests were divided into two kinds with different procedure. Each kind was conducted on three piles with $L/D = 20$, $25$ and $30$ installed in loose and dense sand soils as follows:

10.1 Procedure (1):

1. Prepare test model by install pile model into laminar shear box and deposit soil as six layers with tamping to achieve the soil density desired, then fix rope displacement and load cell on the head of pile. After that pullout test of piles before applying seismic loads was conducted by pullout device through applying pullout force on head of pile until reach failure which represent the force that pile becomes free. From the test the max pullout force (tension bearing capacity) and corresponding vertical displacement failure can be found.

2. Re-Prepare test model as 1.1 then apply seismic loading test from shaking table device for Halabjah earthquake data.

3. Conduct the pullout test of piles after finish of apply seismic loading until reach failure. From the test the max pullout force after applying seismic loading (ASL) can be found.

10.2 Procedure (2):

1. Re-Prepare model as 1.1 then apply combined loading (ACL) test from shaking table and pullout devices. Combined loading is seismic loading from shaking table and pullout force from pull-out device equal to max pullout force that was obtained from the static tests divided by three, this force value represents the allowable tension bearing capacity (T.B.C) of pile by taking safety factor =3. This case represents the critical state when allowable T.B.C and
horizontal seismic loading act together on piles.

2. Conduct the pullout test of piles after applying combined loading until reach failure. From this test the tension bearing capacity after applying combined loading can be found.

11. Results and discussions

Results of pull-out test before and after applying Halabjah earthquake loading is illustrate in Figures 9-14 as a relationship between pull-out force and vertical displacement for three pile model with L/D = 20, 25, and 30 placed into loose and dense sand soil.

Figure 9 show the results of pullout test for piles models installed in dry loose sand before shaking table tests. The maximum pullout forces were 164.91 N , 229.37 N and 313.67 N and the corresponding vertical displacement were 1.8 mm ,2.57 mm and 2.78 mm of pile model with L/D=20,25 and 30 respectively. Figure 10 shows the results in dry dense sand which were the max. pullout force were 339.85 N, 456.95 N and 677.62 N and the vertical displacement related to these values were 2.4 mm ,2.45 mm and 2.94 mm of pile with L/D=20, 25 and 30 respectively.

Figure 11 shows the dry tests results of pullout test of piles models installed in dry loose sand after apply seismic loading (ASL). The maximum pullout forces were 151.44 N , 206.28 N and 280.86 N and the corresponding vertical displacement were 2.53 mm , 3.2mm and 2.78mm of pile model with L/D=20,25 and 30 respectively. Figure 12 shows the results in dry dense sand for pile with L/D= 20, 25 and 30 which were the max. pullout force were 342.74 N , 466.06 N and 785.65 N and the vertical displacement related to these values were 2.3mm,2.66mm and 3.4 mm of pile with L/D= 20, 25 and 30 respectively.

Apply combined loading (seismic loading of Halabjah earthquake and pullout force) through shaking table and pullout devices have been conducted to study the effect of present combined loading ( apply tension force on head of pile during seismic loading) on pile model with L/D=20,25 and 30 to. In each test, pile –soil model was prepared and fixed the load cell on head of pile and installed the rope displacement sensor with the cap of pile model. Pullout device used to apply pullout force equal to one- third of maximum pullout force (Tension Bearing Capacity) that was obtained from static tests of pullout, this force represents the allowable load when assume safety factor equal to three, the value of pullout force used in combined loading for each test as shown in Table 3. Shaking table test conducted for six test on model pile placed in dry loose and dense sand for pile of L/D=20.25 and 30.

Table 3. TBC and allowable TBC used in combined loading.

| Soil type   | L/D | TBC (N) | TBC(N)/3 |
|-------------|-----|---------|----------|
| Loose sand  | 20  | 164.91  | 54.97    |
|             | 25  | 229.37  | 76.45    |
|             | 30  | 313.67  | 104.55   |
| Dense sand  | 20  | 339.85  | 113.28   |
|             | 25  | 456.95  | 152.31   |
|             | 30  | 677.62  | 225.87   |

Results of pullout test after apply combined loading in loose and dense sand as shown in Figure 14. Figure 14 shows that vertical displacement at failure was 1.92, 1.56 and 2.3 mm, while max. pullout force was 44.16N,103.16N and 132.15 N, the percentages of reduction were 73.22% ,55.02% and 57.87%. Unite skin friction was 1.23,2.29 and 2.44 for L/D=20.25 and 30 respectively. For dense sand, Figure 14 shows that in dry dense sand the vertical displacement at failure was 2.56 ,1.94 and 3.24mm, while max. pullout force was 170.41N,225.6N and 622N, unite skin friction was 4.73,5.01and 11.51(N/cm) for L/D=20,25 and 30 respectively. The percentages of reduction of max. pullout force due to apply combined loading as compared with max. pullout force before shaking table test were 49.86% , 50.62% and 8.06%.
Tables 4 and 5 illustrate the max. pullout force in newton, unite skin friction in newton/cm and the reduction in max pullout force percent (R%) before and after apply shaking table test for pile model with L/D =20,25 and 30 installed in loose and dense sand soil. Unit skin friction (N/cm) was calculate by divided the max pullout force on the length of pile while reduction percent (R) of tension bearing capacity was calculated according to equation (1) below.

\[
R\% = \frac{\text{Max. pullout force after ASL or ACL} - \text{Max. pullout force}}{\text{Max. pullout force}} \times 100 \quad \ldots \ldots \ldots \ldots (1)
\]

Where:
R% = reduction percent of max pullout force.
ASL = after apply seismic loading.
ACL = after apply combined loading.

In Table 4, the max. pullout force decrease from 164.91N to 151.44N, 229.37N to 206.28N and from 313.67N to 280.86N after apply seismic loading (ASL) and the R% were -8.16%, -10.07% and -10.46% while the max. pullout force decrease from 164.91N to 44.16N, 229.37N to 103.16N and from 313.67N to 132.15N and the R% were -73.22%, -55.02% and -57.87% for pile with L/D=20,25 and 30 installed in dry loose sand.

In Table 5 the max. pullout force changed from 339.85N to 342.74N, 456.95N to 466.06N and from 677.62N to 785.65N after apply seismic loading (ASL) and the R% were +0.85%, +1.99% and +15.94%, while the max. pullout force decrease from 339.85N to 170.41, 456.95 to 225.6N and from 677.62N to 622N and the R% were -49.86%, -50.62% and -8.06% for pile with L/D=20,25 and 30 installed in dry dense sand.

Unit skin friction also decrease from in all teats for pile installed in dry loose sand after apply seismic loading and after apply combined loading as shown in Table 5. For pile model installed in dry dense sand it is increased slightly after ASL for pile model L/D=20 and 25 and increase from 12.55 to 14.55N/cm for pile with L/D=30, while after ACL the unite skin friction decreased from 9.44N/m to 4.73N/m and from 10.15 to 5.01 N/cm and from 12.55 to 11.51N/cm.

Tables 6 and 7 show the results of vertical displacement in mm at failure and the percentages of these values to diameter of pile, results show that % diameter were 14.06%, 15.56% and 15.45% for loose sand and 12.78%, 14.78% and 18.89% for dense sand, values of vertical displacement ranges from 14.06-15.56% in loose sand and from 12.78-18.89% in dense sand.

### Table 4. Results of max. pullout force(N) in dry loose sand.

| L/D | L (cm) | max, pullout force(N) | Unit skin friction (N/cm) | Max. pullout force(N) after ASL | Unit skin friction (N/cm) | R% | Max. pullout force(N) after ACL | Unit skin friction (N/cm) | R% |
|-----|--------|-----------------------|---------------------------|---------------------------------|---------------------------|-----|-------------------------------|---------------------------|-----|
| 20  | 36     | 164.91                | 4.58                      | 151.44                          | 4.20                      | -8.16 | 44.16                          | 1.23                      | -73.22 |
| 25  | 45     | 229.37                | 5.10                      | 206.28                          | 4.58                      | -10.07 | 103.16                         | 2.29                      | -55.02 |
| 30  | 54     | 313.67                | 5.81                      | 280.86                          | 5.20                      | -10.46 | 132.15                         | 2.44                      | -57.87 |
Table 5. Results of max. pullout force(N) in dry dense sand.

| L/D (cm) | L | max. pullout force(N) | Unit skin friction (N/cm) | max. pullout force(N) after ASL | Unit skin friction (N/cm) | R% | max. pullout force(N) after ACL | Unit skin friction (N/cm) | R% |
|----------|---|------------------------|---------------------------|-------------------------------|---------------------------|----|-------------------------------|---------------------------|----|
| 20       | 36| 339.85                 | 9.44                      | 342.74                        | 9.52                      | +0.85| 170.41                        | 4.73                      | -49.86|
| 25       | 45| 456.95                 | 10.15                     | 466.06                        | 10.36                     | +1.99| 225.6                         | 5.01                      | -50.62|
| 30       | 54| 677.62                 | 12.55                     | 785.65                        | 14.55                     | +15.94| 622                           | 11.51                     | -8.06|

Table 6. Results of vertical displacement of pile model at failure VDF (mm) in dry loose sand.

| L/D (mm) | Diam. | VDF | % diam. | VDF | % diam. | VDF | % diam. |
|----------|-------|-----|---------|-----|---------|-----|---------|
| 20       | 18    | 1.8 | 10      | 2.53| 14.06   | 1.92| 10.67   |
| 25       | 18    | 2.57| 14.27   | 3.20| 15.56   | 1.56| 8.67    |
| 30       | 18    | 2.78| 15.44   | 2.78| 15.45   | 2.30| 12.78   |

Table 7. Results of vertical displacement of pile model at failure VDF (mm) in dry dense sand

| L/D (mm) | Diam. | VDF | % diam. | VDF | % diam. | VDF | % diam. |
|----------|-------|-----|---------|-----|---------|-----|---------|
| 20       | 18    | 2.40| 13.30   | 2.30| 12.78   | 2.56| 14.23   |
| 25       | 18    | 2.45| 13.61   | 2.66| 14.78   | 1.94| 10.78   |
| 30       | 18    | 2.94| 16.33   | 3.40| 18.89   | 3.24| 18.00   |

Figure 9. Relationship between Pullout force and vertical displacement for Pile L/D=20,25,30 in dry loose sand.
Figure 10. Relationship between Pullout force and vertical displacement for Pile L/D=20,25,30 in dry dense sand.

Figure 11. Relationship between Pullout force and vertical displacement for Pile L/D=20,25,30 in dry loose sand after apply seismic loading.

Figure 12. Relationship between Pullout force and vertical displacement for Pile L/D=20,25,30 in dry dense sand after apply seismic loading.
12. Conclusions

1. Results indicate that the max pullout force of piles models increases with increase L/D due to increase friction surface area in loose and dense sand, and in dense sand it is more than in loose sand for all L/D of piles this is due to increase relative density of soil which increase normal effective stress, lateral effective stress and shear strength between pile and soil.

2. Apply seismic loading (ASL) of Halabjah earthquake show that the max pullout force of pile model decreased about 8.16 to 10.46 in loose sand because of decrease the friction between pile and soil through of loosening of soil around the pile, while in dense sand there is a small effect of ASL on piles with L/D=20 and 25 while for L/D=30 the max pullout force increased after ASL due to increase density of soil around the pile and increased friction between pile and soil. Maximum effect on loose and dense sand was in long pile with L/D=30 which was the maximum decrease in max pullout force in loose sand and maximum increased in dense sand, this is possible to explain because the long pile is near to horizontal surface of source of shaking table movement and it is more affect as compared to piles with L/D=20 and 25.

3. High effect of ACL on the max. pullout force by reduction all values in all test of pile model in loose sand between 55.02% and 73.22% and dense sand between 49.86% and 50.62% except for pile model with L/D=30 in dense sand which was 8.06% ,this value is small as compared to others. Due to this result in dry loose and dense sand in case of critical state when uplift force reach to one-third of tension bearing capacity acts on pile and the present of seismic loading due earthquake, the structure will be under failure and high damage so the designer must take value of safety factor more than three.
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