3D FINITE ELEMENT ANALYSIS OF THE SEISMIC RETROFITTING OF EXISTING BRIDGES FOUNDATIONS BY MICROPILES*

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ABSTRACT

This paper concerns the seismic behaviour of soil-pile-superstructure reinforced by additional micro-piles. The analysis is carried out by a three–dimensional finite element modelling using the software Abaqus. The soil is assumed to be elastic with Rayleigh damping, while the micro-piles are modelled as 3D elastic beam elements. The bridge deck slab is represented by a concentrated mass at the top of the pier column. Interaction between micropiles and the existing piles as well as the performance of the retrofitted soil-pile-superstructure system are investigated for different configurations of additional micropiles (number, position, inclination). Numerical simulations show that additional micropiles constitute an efficient retrofitting solution. Analysis of results also shows that spacing between existing piles and retrofitting micropiles has little effect; while it is observed a substantial improvement with reducing of the inclination angle of retrofitting micro-piles.

KEY WORDS: micropiles; retrofitting; seismic; elastic; finite element.

* For the paper in Arabic see pages (35).

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1. Introductio:

The post earthquake observations from the recent earthquakes in the Loma Prieta earthquake (1980) in United States of America and the Kobe earthquake (1995) in Japan have imposed the need of revising the seismic design codes for highway bridges and developing new technologies to perform seismic retrofitting for bridge foundations. Therefore, micro-piles are increasingly adopted for retrofit (to retrofit or for retrofitting) bridge foundations because of theirs high flexibility during the seismic conditions and their superior execution properties in addition to the ability to be installed in all types of soils and ground conditions with minimal vibration and disturbance to adjacent traffic or structures (Mascardi,1982) in low overhead clearance (less than 3.5 m), without suspending the traffic of the bridge and of course to their capability to resist grand axial and lateral loads (Armour et al,2000). Most of the dynamic analysis carried out on the micro-piles focused on the use of micro-piles as new foundations or for soil strengthening and protection .Ousta and Shahrour (Ousta and Shahrour, 2001) studied the seismic behaviour of micro-piles in saturated soils .Sadek and Shahrour analysis (Sadek and Shahrour, 2003) showed that the inclination of micro-piles)results in an improvement of the lateral stiffness, the bending moment and the axial force. Alsaleh and shahrour (Alsaleh and shahrour, 2006) confirmed that the Non-linearity of (both of) the soil and micro-piles -soil interface have significant effect on the seismic response of the micro-piles group as well as that of structure. Only few studies have been conducted on the use of micro-piles as an effective and economical method for retrofitting the existing foundations under severe working restrictions. Field studies such as studies performed by Jiehan et al.(Han et al.2006) and centrifuge tests carried out by Fukui et al. (Fukui et al.2005) showed that retrofitting pile foundations using micro-piles leads to effective retrofitting effects .Kishishita et al. (Kishishita et al. 2002) confirmed the positive effect of inclined micro-piles on pile foundations in liquefiable ground. In this paper, we propose to study the seismic behaviour of bridge foundation retrofitted by micro-piles using a three dimensional finite element modelling with an elastic constitutive relation for the soil behaviour.

2. REFERENCE EXAMPLE:

This section deals with the analysis of the influence of executing micro-piles near to existing pile foundation on both the seismic performance of the foundation and the interaction of the soil-pile-superstructure. The foundation consists of group of (4) piles and (4) micro-piles embedded in a soil layer .The thickness of the soil layer (Hs) is equal to 15m.The behaviour of the soil is assumed to be elastic with Rayleigh material damping. Numerical simulations were performed with (soil) young's modulus (of)E_{s0}=10 MPa .The poisson's ratio of the soil wasν_s=0.35.The computed natural frequency of the soil layer was equal to f_1=0.67 Hz. The superstructure was modelled as a single degree of freedom system composed of a concentrated mass represents the bridge deck, slab M_{st}=240 T, and a pier column with a height Hst=3.5 m figure (1).its fixed base fundamental frequency is equal to f_{st}=1.72 Hz. The interface between the (piles/micro-piles) and the soil are assumed to be cohesive (C = 50 kpa).

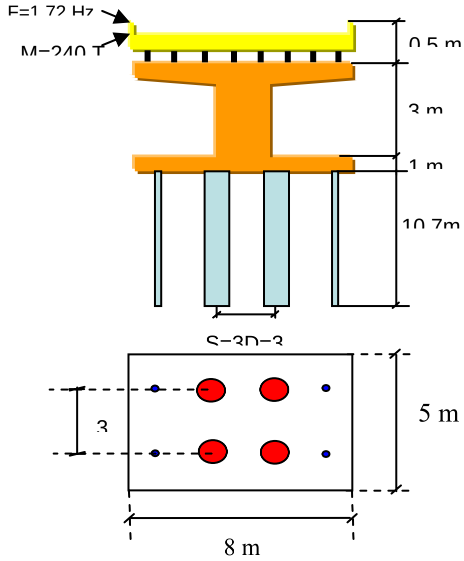
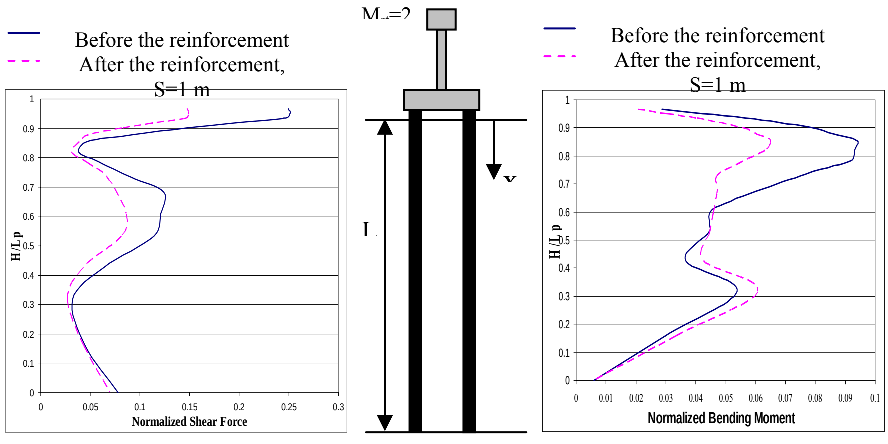


Figure 1.The reference example

The piles and micro-piles were modelled as 3D beam elements. They are connected to the cap, which is assumed to be rigid. The thickness of the cap is equal to (1m).Numerical simulations were conducted with the following characteristics for micro-piles: length L_m = 10.72 m, diameter D_m = 0.25 m, axial stiffness E_mA_m=12500 MN, flexure stiffness E_mI_m= 65.10 MN m^2.The pile's characteristics: length L_p=10.72 m, diameter Dp=1 m, axial stiffness E_pA_p=20000 MN, flexure stiffness E_pI_p= 1666.67 MN m^2.The spacing between the piles (S=3D =3 m).The results of the reference example figure (2) for the case of spacing between the pile-micropile (S=1) m confirmed the great retrofitting effects of the additional micro-piles. The distribution of the normalized shear force in figure (2) shows a significant retrofitting effects with a drop of about (45%) of the maximum shear force .Furthermore, the figure (2) reveals a decrease of about (39%) of the maximum bending moment after the addition of the micro-piles .While the maximum shear force is (12%) and the maximum bending moment is (4.5%) of the micro-pile.



Normalized envelope of Shear Force and Bending Moment along the pile
Figure 2. the retrofitting effects of the addional micropiles

3. PRESENTATION OF THE MODEL

The example concerns a three dimensional finite element model has been realised using the code of ABAQUS **.**The model consists of system soil-pile-micropile-superstructure. The soil is assumed to be elastic with Rayleigh damping. The foundation is represented by (4) piles then retrofitted by (6) micropiles figure (3). The piles and micropiles length is (10.72 m) and their cross diameters (1 m), (0.25m) respectively .The piles and micro-piles are established in layer of homogenous soil with (15 m) thickness .The spacing between the piles is (S=3D=3 m)

The behaviour of the system of soil-pile-micro-pile-superstructure is supposed to be elastic with damping of the Rayleigh type .The bridge deck slab is represented by a concentrated mass (240 t)at the top of the pier column with length (3.5 m) , the mass was calculated for bridge consists of (2) spans with span length (11 m) and two lanes for the traffic (7 m) .the fundamental frequency of the pier column is (Fst =1.72 Hz) , while the fundamental frequency of the soil layer is F=0.67 Hz .The set of parameters used for the description of the system is presented in table(1).

Material	Mass density (kg/m^3)	Young's Modulus (MPa)	Poisson's rate	Damping coefficient (%)	Axial stiffness (MN)	Flexure stiffness ($MN.m^2$)
Soil	1800	10	0.35	5 %		
Pile	2500	20000	0.2	2 %	20000	1666.67
Micropile	7800	200000	0.2	2 %	12500	65.10

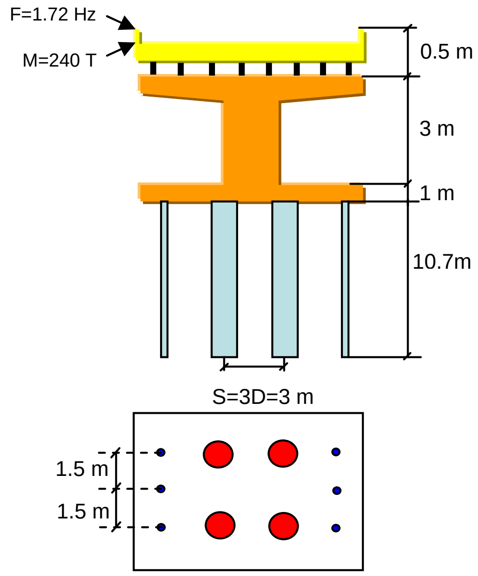
Table1. Set of parameters used in the model

The piles and micropileswere embedded in a one meter thickness rigid foundation without contact the ground .The interface between the soil mass and micro-piles is assumed to be cohesive (C = 50 kpa) .The seismic loading is applied at the base of the soil mass as a harmonic displacement made up of (10 cycles) whose amplitude and frequency are equal to (Ag=0.2 g) and (F=0.67 HZ) respectively.Numerical simulations are carried out with the following boundary conditions:

-The base of the soil mass is assumed to be rigid.

-The lateral boundaries of the soil mass were placed at a sufficient distance to neglect the reflexions on the lateral boundaries.

-equal boundary conditions are imposed at the lateral boundaries.



The finite element mesh used in the numerical simulations for verticals micro-piles is illustrated in figure (4); it involves 3490 (20-node) elements.

Figure 3.The model

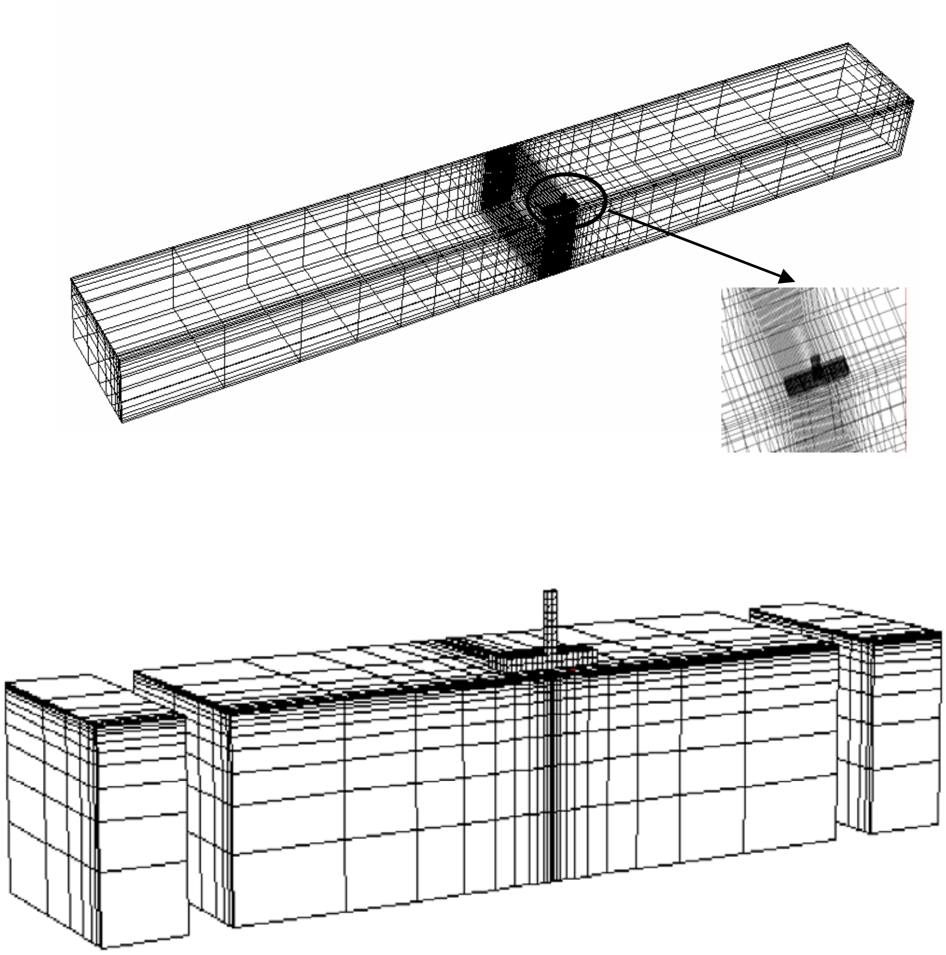
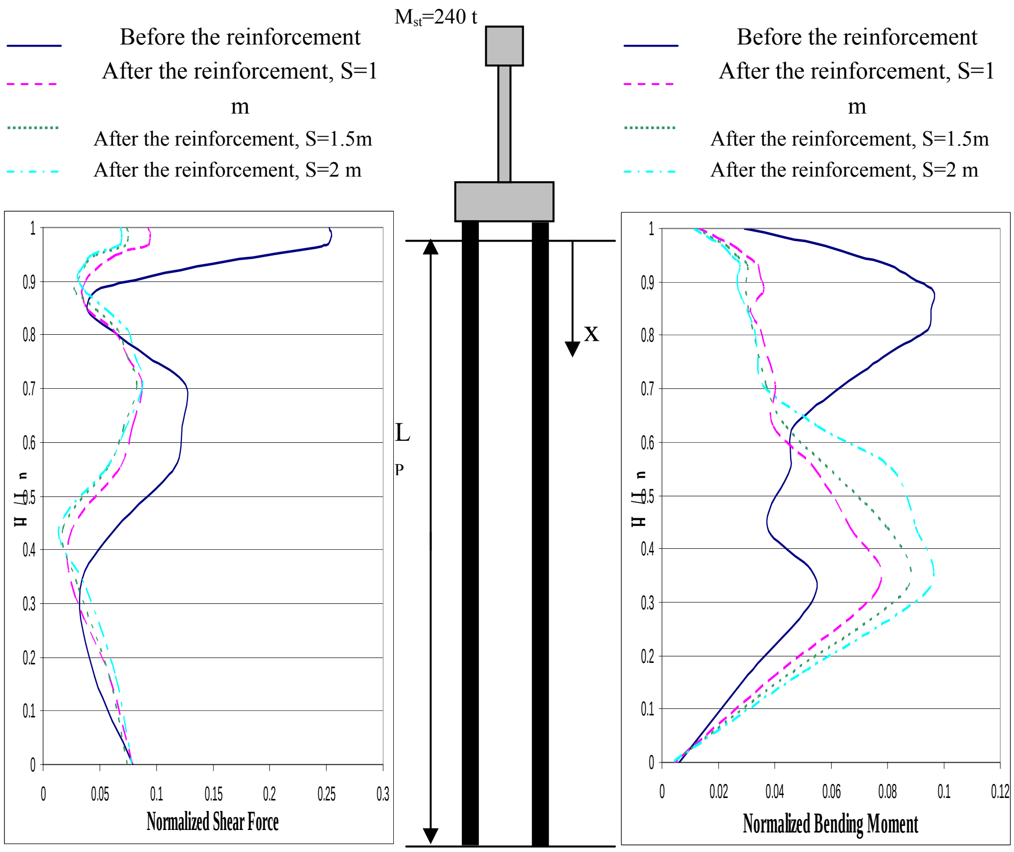


Figure 4.Finite element mesh used in the numerical simulations for vertical micrpiles(3490 hexahedral elements of 20-node and 66 beam elements 3D).

4. INFLUENCE OF PILE –MICROPILE PACING AND MICROPILES NUMBER:

In order to study the influence of the spacing between the existing piles and retrofitting micropiles on the system of soil-pile-micropile-structure interaction, the numerical simulations were performed considering the previous model with various spaces S=(1,1.5,2) m.Figure (5) illustrates the normalized envelops of the shear force and

bending moment in the piles due to the input motion which composed of harmonic sinusoidaldisplacement(10 cycles, Ag=0.2g, F=0.67HZ).Numerical simulations presented herein, clearly show the interesting retrofitting effects of the additional micropiles on the soil-pile-micropile-structure response to earthquake. The maximum shear forces are obtained at the pile head in both cases : befor and after the reinforcement. This indicates the dominant role of the inertial forces .It can also be observed that the increase of spacing between piles-micropiles induces a increase of the maximum bending moment in piles.In fact, this increase appears at the lower third part of the pile after the reinforcement which be attributed to the weak interface between the piles-soil . In other word the separation of the



head of piles from the soil leads to reduce the bending moment at the head of pile.The distribution of the shear force is depicated in figure (5).It shows a great retrofitting effect of the micro-piles on the maximum shear force developed in the piles . on the other hand, the maximum bending moment increases (2-20%) with the increase of the spacing .Also,it can be observed the little effect of the spacing on the maximum shear force about (7-10%) and bending moment about (12%) induced in the retrofitted micro-piles

Theseresults agree with those obtained by the centrifuge model test carried out by (Itani et al. 2002).

For convenience, internal forces are normalized with respect to the internal forces at the base of the superstructure (Mst and Tst) as follows:

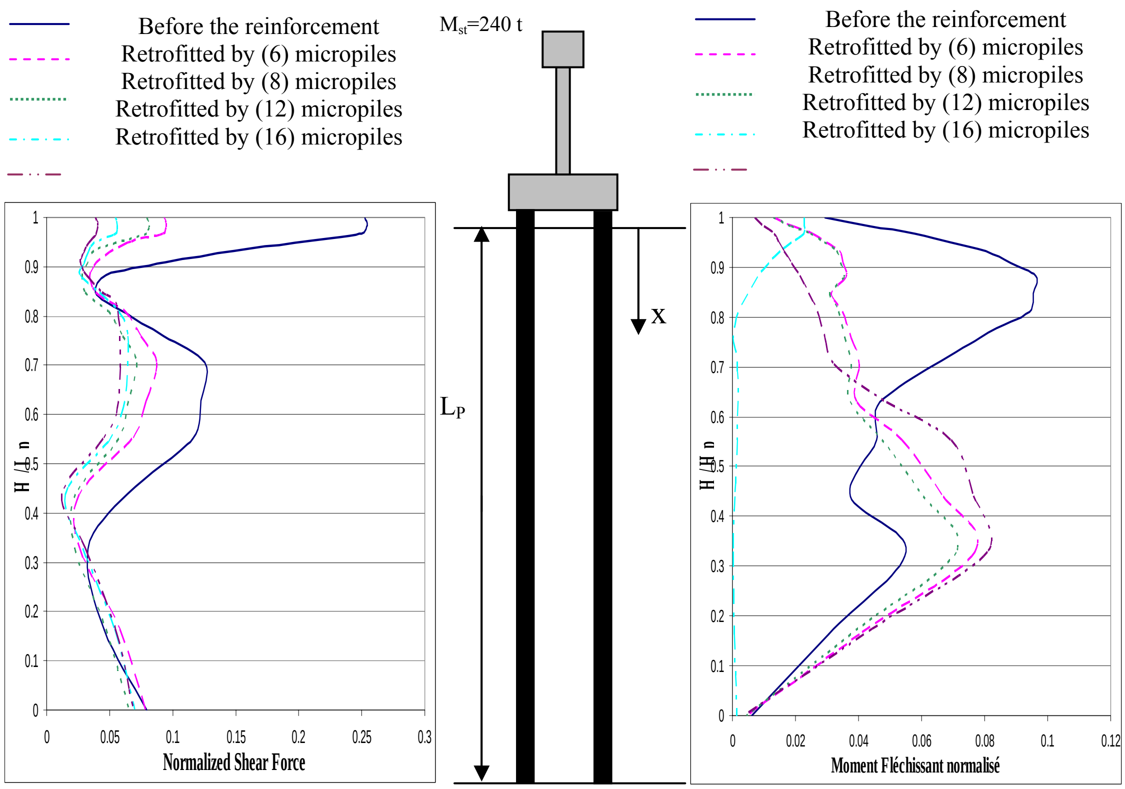
$$T^*=T/Tst$$
$$M^*=M/Mst$$
$$Mst=my, T_{st}=my$$

Where T*, M* are dimensionless internal forces in (piles/micropile); m: the mass of the superstructure. .. the acceleration of the superstructure .l:the arm leverage over the base of the foundation.

Normalized envelope of Shear Force and Bending Moment along the pile.

Figure 5. Influence of the spacing between the existing piles and retrofitting micropiles

To study the influence of the number of the retrofitting micro-piles,we analyzed the results of the simulations for the previous model conducted by varing the number of micropiles.The treated cases concern the following configurations (6,8,12,16) micropiles. The influence of the number of micropiles on the retrofit effect is presented in figure (6).It can be seen that the maximum shear force decreases with the increase in the number of micropiles



Normalized envelope of Shear Force and Bending Moment along the pile
Figure 6. Influence of the number of micropiles on the retrofitting effects

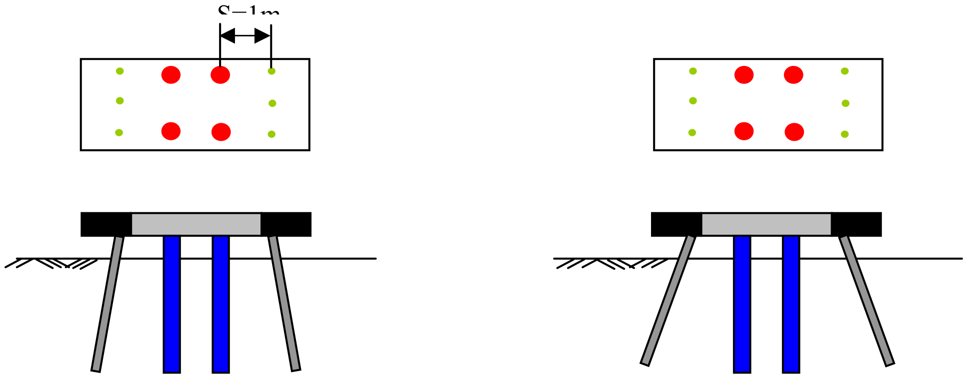
Also, it can be observed significant reduction of the shear force up to (40%) for the case of (16) micropiles.It is worth noting that the maximum shear force is obtained at the upper part of the pile .Likewise, the maximum bending moment decrease for the cases of (6),(8)and(12) micropiles , while it returns to augment for (16) micropiles .The maximum bending moment is obtained in the proximity of the the lower third part of the pile.

5. INFLUENCE OF MICROPILES INCLINATION:

This section presentes the results of calculations realized on a group of (4) piles and (6) micropiles for two cases of inclination (10°,20°). Figure (7) shows the foundation configurations for (6) inclined micropiles. While, figure (8) and table (2) summarize the

results of numerical simulations obtained for two values of micro-piles inclination namely, α=10°, 20° with respect to the vertical axis α=0°. Table (2) indicates that the increase in the piles inclination from 0 to 20° induces a regular increase in the amplification of the lateral acceleration (a/ag), which attains 29% and 37% at the cap (superstructure-base) and the superstructure-mass level, respectively.It can be noted that the increase in micropile inclination strongly affects on the distribution of internal forces in piles .Indeed, the inclination of micropiles induces notable augmentation of the maximum shear force of the pile up to (20%).As well as ,it can be observed the great augmentation of the maximum bending moment of the pile (48%)with the increasing of the inclination angle.contrariwise,the results indicates a considerable reduction of the maximum shear

force and the bending moment induced along the corner micropile with the augmentation of the inclination angle.



(10%) **(20%)**

Figure7. foundation configurations

Normalized envelope of Shear Force and Bending Moment along the pile

While , the maximum shear force and bending moment induced along the central micropile augmente with the rise of the inclination angles (0°, 10°, 20°).Also, it is important to indicate that the maximum shear force is always obtained at the upper part of the pile , while , the maximum bending moment is obtained in the proximity of the pile centre. Thisresult disagrees with those obtained by (Itani et al. 2002). Which can be attribute to the contact rigid in the centrifuge test , while we use in this numerical model weak interface (C = 50 kpa) between the (piles/micro-piles) and the soil.

It is worth noting that the increase in the maximum internal forces is expected to be overestimated because of the elastic constitutive relation used in this study and the weak adhesion between the(piles /micropiles) and the soil.

Table 2. Influence of inclination of the amplification of the lateral acceleration

Figure 8. Influence of micropile inclination on the retrofitting effects Inclination (α)	0 °	10 °	20 °
acap/ag	14.17	18.27	23.56
ast/ag	16.28	22.3	30.55

6. ONCLUSION:

This paper included a numerical analysis of the seismic behavior of micro-piles used for the reinforcement of pile foundation of bridge .It was performed using a three–dimensional implicit dynamic analysis by finite element program ABAQUS .A number of conclusion can be drown from this study .The main results of this study can be summarised as follows :

- Confirm the effective seismic retrofit effects of using the micro-piles for retrofitting the pile foundation of bridge .
- The increase of the spacing between the existing piles and the retrofitting micropiles has little effect on the retrofitting effects of the micropiles .
- A significant reduce of the maximum shear force up to (40%) is obtained fromthe case of (2*8) micro-piles , while the maximum bending moment reduce by different percentage according to the case .
- The retrofitting effects of the micropiles drops considerably with the augemntation of the inclination angle of the micropiles.

REFERENCES*

1. H. Alsaleh, I. Shahrour, “Three-dimensional nonlinear finite – difference analysis for seismic soil-micropile-structure interaction: effects of nonlinearity of soil and micropile-soil interface”, Don J. et al., Atlanta, Georgia, USA, February 26-March 1, 2006, Proceedings of Geocongress, 2006.
2. http://www.pwri.go.jp/eng/ujnr/joint/37/paper/82fukui.pdf.
3. J.Fukui, M.Ishida, M.Takeguchi, “Seismic retrofitting sites for existing foundations”.Technical Memorandum of Public Works Research Institute,vol**. No.3983**; **Page.337**-350(2005).
4. Han, J. and S. L. Ye, "A field study on behavior of an underpinned foundation by micropiles." Canadian Geotechnical Journal, 43(1), 2006.
5. Itani.M,Kawamura. T,Onodera.S and Oshita,T "Centrifuge model test on pile group effect of pile foundation reinforced by micropile" Works Research Institute , Japan, 2002.
6. M.Sadek, I.Shahrour, “Influence of piles inclination on the seismic behavior of groups of flexible piles”, Washington, DC, 12-16 January 2003, *82nd Annual Meeting of the Transportation Research Board,* pp.1-14, 2003.
7. Mascardi, C. A, “Design criteria and performance of micropiles.”Recent development in ground improvement techniques, Balkema, Rotterdam, (1982).
8. R.Ousta, I.Shahrour, Three-dimensional analysis of the seismic behaviour of micropiles used in the reinforcement of saturated soil, *International journal for numerical and analytical methods in geomechanics,*25, 183-196,2001.
9. T. Armour, P. Gronck, J. Keely, S. Sharma, “Micropile design and construction guidelines implementation manual” U.S department of transportation federal highway administration, U.S.A, 2000.
10. T.Kishishita, T. Oshita, J. Fukui, E. Saito, M.Sagara, “Liquidizing model shaking table test of an existing foundation reinforced with micropiles“, Proceedings of the Japan earthquake engineering symposium, Japan, 2002, Vol.11, pp.1087-1090, 2002.

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