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MINIMIZING THE FAILURE RISK OF PILE BENT PIER UNDER SEISMIC LOAD USING GROUTING

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ABSTRACT

The need for speed construction increases the use of pile bent piers. The pile bent piers not only reduces the construction time, but also, reduces the construction cost. They reduce the pile cab required frameworks time and cost. However, the behavior of the pile bent pier under seismic load may cause the pile failure under maximum moment acting on the pile under the ground with 2 to 4.5 times the pile diameter.

In this research, a parametric study is performed to minimize the risks of pile failure under seismic loads by increasing the pile stiffnesses in the critical location using soil grouting. Different grouting widths (0.5, 1.0, and 1.5 m) are proposed and the effect of the grouting was compared in terms of acting forces on the pile. Grouting width 0.5 m around the pile decreases the seismic moment and increases the shear. However, increasing the grouting diameter than 0.5 m increases the pile stiffness and increases the acting forces.

Keywords: Pile Bent Pier, Drilled Shaft, Seismic Load, Grouting, FEA-Diana

1. Introduction

The use of pile bent piers helps in increasing the construction speed and cost , that the use of pile bent save the required formworks and the construction of the pile cap.The driven pile was firstly introduced as pile bent, and cab beam connects piles together at the top of the pile [1]. Precast concrete piles, steel pipe pile or H-pile may also be used for specific locations. The pile bent height is limited by the slenderness and buckling capacity of the pile. Pile bents may be designed to resist the lateral loads via the use of battered piles or by being rigidly cross braced or via cantilever action with moment-resistant deck connections. Bridge design manuals discussed the design of pile bents and its construction details. Manuals proposed a simplified method for the design for a specified range of axial loads. However, for the large bridges, the lateral loads as wind and seismic forces increase, and the corresponding moment cannot be neglected. Laterally loaded single pile or group pile should be designed not against geotechnical failure only but also, structural failure and excessive deflection. The excessive deflection may cause partial damage or structural failure [2]. The excessive deflection is related to soil-structure-interaction and related strongly to soil conditions. This research focuses on the structure considering P-Δ effect and seismic loads considering nonlinear analysis.

After the increase of using pile bent, various researchers studied the design of the pile bent and proposed various approaches for simplifying the design based on case studied or experimental works [3]. Also, an extensive numerical work conducted for enhancing the current methods [4], [1]. Most of these researches focused on soil modeling and determining the pile capacity (normal and bending) neglecting dynamic response of the pile. Simplified methods proposed for determining capacity and recommended in codes as Euro code-8, [5].

Evan and Duncan (1982) studied the behavior of laterally loaded piles under static loads for free and fixed head piles, and plotted dimensionless plots representing the relation between pile capacity (axial and bending) and the ratio between pile diameter and its depth. Later, Brettmann and Duncan (1998) proposed equations for calculating pile capacity in function of soil type, pile diameter and pile Young's modulus. Wang 1997 used finite difference method for developing the first commercial software analyzing the behavior of single pile under lateral loads [2].

George Mylonakis and Nikolaou 1997 [6], studied the kinematic and internal effects for soft soil pile-bridge numerically using multi-step superposition procedure. Single pile and group pile system subjected to vertical S-wave. The study concluded that the results should not be generalized to bridge piers that for, the soil deposits and seismic excitation are different from a case to another. However, the results helped in predicting the response of the system. Many quantitative researches recommended strong nonlinear analysis for generalizing results [6].

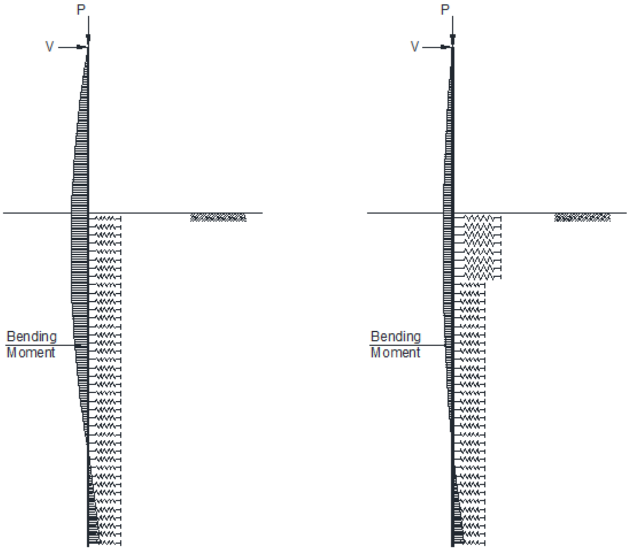
Jeong, et al 2006 [7], conducted extensive nonlinear parametric study for pile bent considering P-Δ effect and different soil parameters. Inelastic analysis is more sensitive for P-Δ effect and soil type; two plastic hinges may occur one locates at the bridge deck connection and the other locates underneath soil; this plastic hinge location depends on the soil characteristics and pile diameter. In addition, the pile-deflection is highly influenced by the inelastic analysis and P-Δ effect. The maximum bending moment occurred at 3.5D from the ground surface for inelastic analysis and it is reduced to 1.5D for elastic analysis; where D is the pile diameter [7].

In seismic analysis for pile bent, both soil and structure may cause structural failure. This interaction may be divided in two parts; one occurs due to ground excitation, known as kinematic interaction, the other occurs due to structural deformation, known as inertial interaction. Two methods are commonly used for modeling the kinematic and inertial interaction; direct and superposition method. Direct analysis is used for modeling the whole structure with the soil for determining more realistic results, however, it may be relatively cost based on required model sophistication. For simplifying the modeling, researchers developed simplified methods with reasonable accuracy. In superposition method, the model was divided into superstructure and substructure; each part modeled separately and the resultant force from each model is an input for the other. However, this method requires linearity.

The aim of this research is to study how to increase the pile stiffness at the zone of maximum moment during the earthquake by grouting the soil surrounding the pile with different widths and constant depth. This increase of the stiffness decreases the risk of the pile failure though distributing the forces on the surrounding grouted soil. The proposed method will be studied and analyzed in terms of forces acting moment and its corresponding shear forces.

In this study, the nonlinear seismic behavior of the unified system of a superstructure supported on the drilled shaft in sand soil is investigated using finite element software FEA-Diana. The model determines the forces acting on pile. The results were verified with literature results. Then, a parametric study discussing grouting the soil around the pile for increasing the pile stiffness at the location of maximum moment for redistributing the moment on the pile and the grouted soil, that decrease the forces acting on the pile. Also, the pile mode shapes were shifted.

The aim of this research is to convert the pile behavior above the ground from a cantilever supported by elastic springs and fixed at a certain point under the ground level [8] to an approximate fixed free pile by increasing the springs stiffnesses around the pile near the ground surface. Figure (1) shows a sketch for the effect of grouting surround the pile. The ground is grouted for 10 m depth with different diameters 0.5, 1.0, and 1.5m. The grouted soil around the pile will act as one unit against the soil and the area of soil resisting the pile movement increased and the spring's stiffnesses representing soil increased. The model mass was assumed to be 100 ton.



(a) reference pile (b) grouted pile

Fig. 1. shows Equivalent model parameters [4]

2. Numerical modeling

2.1. Model description

Figure (1) shows a simplified numerical model for a drilled shaft with 1.5 m diam. supporting a box girder bridge. The model was simplified for focusing of the pile behavior under seismic loads and the effect of the proposed grouting techniques on minimizing the risk of pile failure. The Model was 100x100 square meters with 50-meter depth. The increase of the model's depth and length is applied to ensure that the boundary conditions will not affect the stresses and the results. The pile was 25-meter depth with 10 meter above the ground. Figure (1) shows the numerical model for the pile. The pile mesh is fine for grantee results accuracy inner the pile and the mesh gets coarser by far of the pile, as shown in figure (2). The ground and pile were modeled by 35661, and 3991 solid elements, respectively.

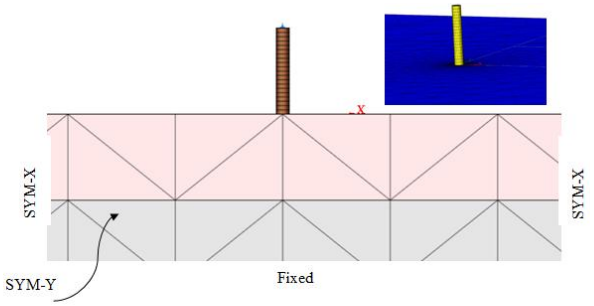


Fig. 2. shows drilled shaft extended from the ground.

2.2. Boundary conditions

The boundary conditions are fixed support to the bottom face of the model, and symmetric for representing the surrounding soil, (Figure 2). Symmetric -X restricts displacement in X- direction, and rotation in Y and Z rotation. Symmetric -Y restrict the sides displacement in Y- direction, and rotation in X and Z rotation [9], [10].

Figure (3) shows the input Aqaba 1995 earthquake time history used in the analyses. The earthquake loading was applied as a time-varying input ground acceleration to all of the base nodes. The stiffness of the ground, the piles, and the pier may be changed because of the nonlinearity of these materials. The viscous matrix calculated from the Rayleigh dampening is assumed to be constant, irrespective of the changes in the stiffness matrix, and the Rayleigh damping ratio was taken as 5% [11] for both soils and structure in the simulations. The direct integration method of Newmark-b was employed, and the time interval of the integration was 0.01 s in the dynamic analysis.

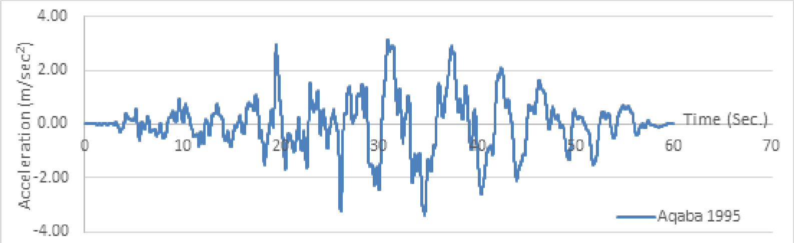


Fig. 3. Time history for Aqaba Seismic data Hz acceleration [12]

The sand modeled as mohr-coulomnb plasticity model with zero tension cutoffs and isotropic effective stresses. Table (1) shows the material characteristic used in the model.

Table 1.
Material Properties

Sand material							
Material	Young's Modulus	Poisson's ratio	Dry Density	Cohesion	Friction angle	Dilatancy angle	K_0
Sand	1.6 106 Ton/m2	0.3	1.7 Ton/m3	0.1 Ton/m2	30^{o}	0	0.485

Concrete material [11]			
Material	Young's Modulus	Poisson's ratio	Dry Density
Concrete	3.4 103 Ton/m2	0.2	2.4 T/m3

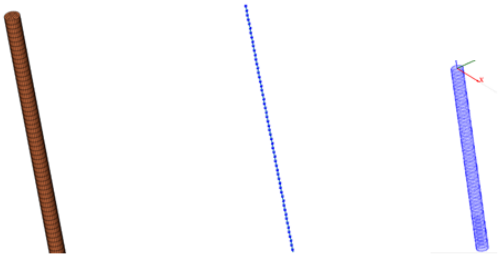
Pile soil Interface Material [11]

	Units	Interface
Normal stiffness	Ton/m^3	1.00E+6
Shear stiffness	Ton/m^3	1.00E+05
Cohesion	Ton/m^2	0
Friction angle		30
Dilatancy angle		0

Grout Material [11]			
Material	Young's Modulus	Poisson's ratio	Dry Density
Grout	2.0 10^3 Ton/m^2	0.2	2.4 Ton/m^3

A Composite beam solid element was modeled in the center line of the pile for extracting the internal forces generated in the pile under seismic load. The mesh of the solid elements may be unstructured and there are no topological constraints with the composed line elements. The local forces and bending moments are calculated and presented with reference to the composed line elements. The internal forces in the solid elements are integrated over the cross-section plane normal to the reference line. The pile was represented by 70 frame elements; that means each element is 0.5 m length for getting a reasonable accuracy, Figure (4).

The pile and the surrounding soil are not fully integrated, so the interface element was modeled for representing the friction surface, also, the interface element carry compression and friction, but not permitted to carry tension forces, (Figure 4). This interface was modeled by 1200 elements, and the material properties are summarized at Table (1)



(a) Pile (b) Embedded Frame (c) Interface mesh

Fig. 4. The pile, embedded Frame, and interface mesh.

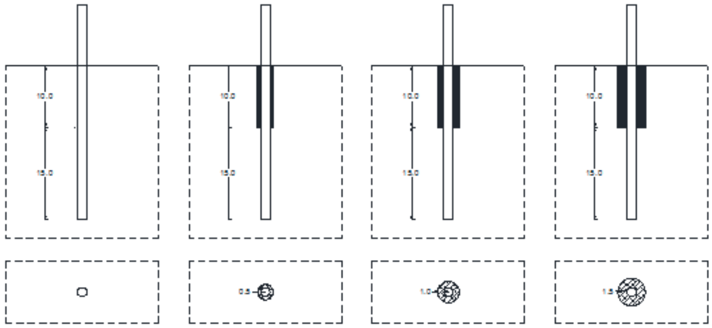
The bridge mass was modeled using mass element points. These point elements may be applied to add mass or damping to the finite element model without influencing the stiffness. A damping coefficient representing the bridge's stiffnesses and damping was considered as 10% assuming that the bridge deck and the pile have a monolithic joint.

3. Parametric study

As discussed in the literature, the pile critical section is located at the depth of 2.5 to 4.5 pile diameter depending on soil parameters [7]. The proposed solution may affect the critical section location, so the grouting depth is proposed to be approximately 6 times of the diameter and equals 10 m. The surrounding diameter of grouting is variable and changed from 0.5 to 1.5 meter with 0.5-meter step as shown in figure (5).

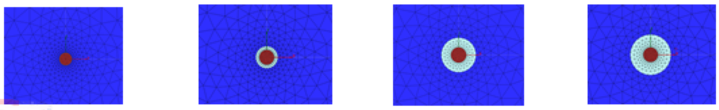
4. Results and discussion

The results are expressed in terms of moment and its shear forces acting on the pile. The forces acting on the pile is varied by the change in earthquake acceleration. So, the comparison was carried on the maximum moment and it corresponding shear forces acting on the pile during the earthquake. The maximum moment take place at 45.38 second. In comparing the feasibility of grouting the soil surrounding the pile, the moment and shear forces are compared with the reference case (Non grouted case).



Reference pile 0.5 m grout. 1.0 m grout 1.5 m grout

(a) Sketch



Reference pile 0.5 m grout. 1.0 m grout 1.5 m grout

(b) FE-Model View

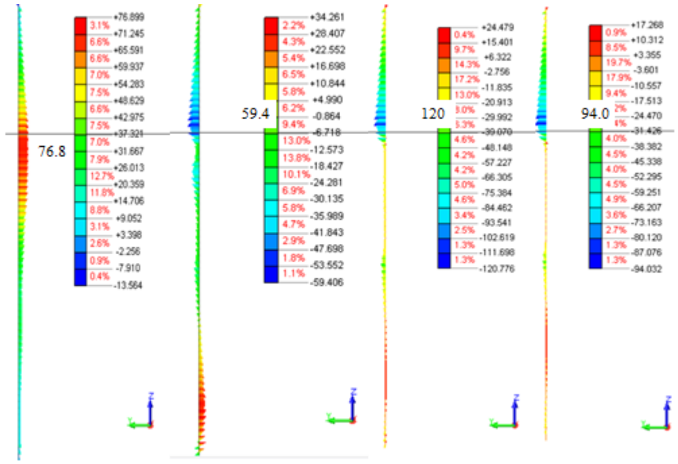
Fig. 5. shows schematic sketch for the parametric study.

By grouting 0.5 m around the pile, the maximum bending moment due to seismic load acting on the pile decreased by 22.7% from 76.80 Ton.m to 59.40 Ton.m. The moment direction has been changed due to the effect of generated rigidity of the grout. The corresponding shear forces decreased from 38 ton to -11.0 ton, (Figure 6). Also, the maximum moment location was moved from three times the diameter below the ground to one time above the ground by one times diameter (1D).

By increasing the grout width to 1.0 m, the seismic additional maximum moment acting on the pile increased by 56 % from 76.90 to 120.77 Ton.m, and its location was moved from three times the diameter below the ground to one time above the ground by a diameter (1D), that means the pile acts as fully fixed free with high fixation rigidity underground. Also, the corresponding shear forces increased by 57% from 38 to 60 ton.

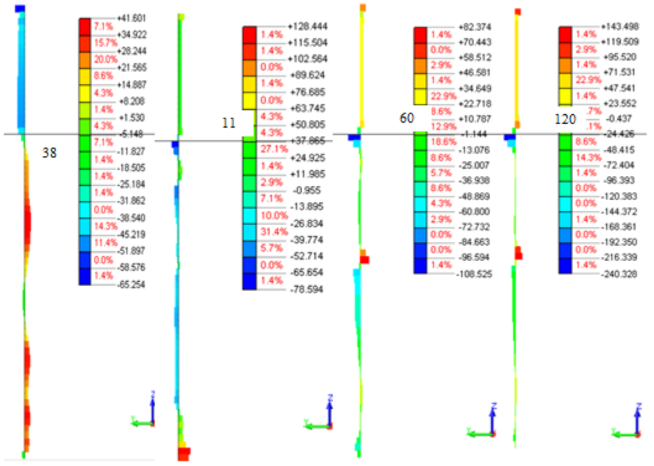
The moment and shear forces are decreased significantly under the ground level. By the end of grout layer, the shear forces acting on the pile increased, that means the pile and its surrounding soil are acting as a rigid unit.

By increasing the grout width to 1.5 m grouting around the pile showed a lower bending moment acting on the pile than 100 cm grout from 120 to 94 Ton.m, however, it is higher than the reference case (76.80 Ton.m). Also, the shear force is approximately doubled from 60, to 120 Ton for 1.0 m and 1.5 m grout respectively, figure (6). Moreover, the shear forces are higher than the reference case (38.0 ton).



Reference pile 0.5 m grout. 1.0 m grout 1.5 m grout

(A) Bending Moment Diagram



Reference pile 0.5 m grout. 1.0 m grout 1.5 m grout

(B) Shear Force Diagram

Fig. 6. Shows maximum Bending moment and corresponding Shear forces for different grouting cases

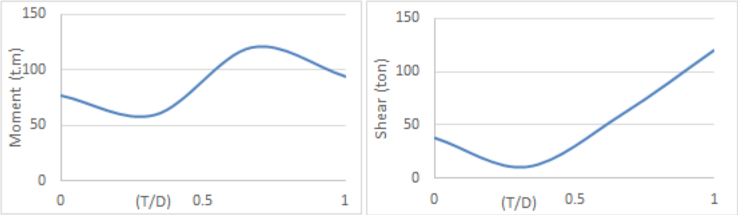
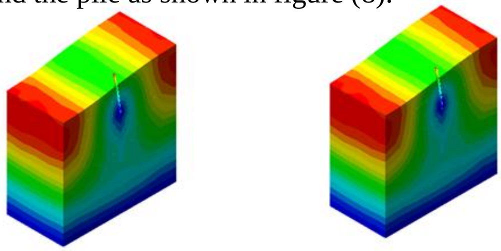
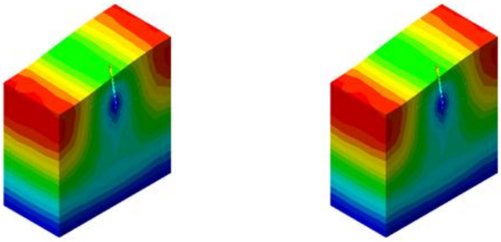


Fig. 7. shows maximum Bending moment and corresponding Shear forces comparing with the grouting to pile diameter

Figure (7) shows the relation between the grouting thickness to pile diameter and its effect on the moment and corresponding shear, and it can be concluded that the minimum bending moment and corresponding shear values were at grouting thickness equals the third of pile diameter and there is no significant effect on the pile natural frequency due to the sand grouting around the pile as shown in figure (8).



Reference pile (0.467631) 0.5 m grout (0.467634 Sec.)



1.0 m grout (0.467636 Sec.) 1.5 m grout (0.467637 Sec.)

Fig. 8. shows the first bending mode shapes under different grout widths.

5. Conclusions

The grouting around the pile stiffened the soil surrounding the pile and acts with the pile as a one unit that increases the cross section of the pile stiffness at that location. The passive pressure acting on the pile increases the generated forces (moment and shear) in the pile underground. However, the maximum moment location moves from underground to above the ground due to high rigidity of grouted soil. Grouting the soil around the pile has insignificant effect on the first mode shape.

The grouting has a significant effect in decreasing the moment and shear forces with the 0.5 m grouting diameter. The grout moves the maximum moment above the ground, and the pile acts as a fixed free cantilever. The increase of grouting around the pile than 0.5 m increase the moment and shear forces acting on the pile than the reference case (without grouting).The model analysis showed that the grouting is not a significant parameter for the pile and the pile acts as fixed free pile in the non-grouting case.

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التقليل من مخاطر انهيار امتداد الخوازيق تحت تأثير الحمل الزلزالي باستخدام الحقن للتربة

ملخص البحث

إن الحاجة الي سرعة تنفيذ الكباري دفعت الي استخدام امتداد الخوازيق كأعمدة للكوبري مما يؤدى الى توفير الوقت والجهد المطلوب لتنفيذ الشدات الخاصة بهامات الخوازيق والأعمدة وبالتالى تقل التكلفة، إلا أن حدوث بعض حالات الانهيار لامتدادت الخوازيق تحت تأثير أحمال الزلازل دفع الباحثين الي دراسة هذه الظاهرة، وتوصل الباحثون الي أنه تزداد العزوم المتولدة علي الخازوق تحت تأثير أحمال الزلازل لتصل أقصي قيمة لها علي عمق يتراوح من 2 الي 4.50 ضعف قطر الخازوق.

وقد قام هذا البحث بدراسة تاثير حقن التربة حول الخازوق بهدف زيادة جساءة التربة حول الخازوق بما يقلل من تأثير العزوم الناتجة عليه تحت تأثير أحمال الزلازل، وقد تم حقن التربة بسماكات (0.5، 1.0، 1.5 متر) وتمت مقارنة تأثير الحقن من حيث قوي العزوم والقص المتولدة علي الخازوق وأظهرت النتائج أنه عند حقن التربة حول الخازوق بسمك 50 سم (ما يناظر ثلث قطر الخازوق) فان العزوم المؤثرة علي الخازوق تقل وكذلك قوي القص.