Enhancement of steel sheet-piling quay walls using grouted-ties technique

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Steel sheet-pilings are one of the most common types of quay walls used in the construction of ports and harbors facilities, especially for berths of small crafts which have small dimensions and capacity. Due to growing market of marine traffic around the world, an increasing number of these berths are required to be upgraded to meet the requirements of permanently growing dimensions and capacity of vessels. Several methods can be used to increase the load-carrying capacity of steel sheet-piling walls. Rehabilitation using additional anchored tie rods grouted into the backfill soil and arrange them along the exposed wall height is one of the most appropriate solutions adopted for rehabilitation and upgrading the existing quay wall. An extensive parametric study through the finite element program, PLAXIS, version 8.2 was carried out to investigate the enhancement of using grouted anchors technique on the load response of the sheet-piling quay wall. The influence of sheet pile wall geometry, grout-ties area, grout-ties inclination, length of grout, location of grout-ties, dredging depth and backfill soil angle of internal friction to enhance this type of walls are analyzed and the results are presented.

تستخدم حوائط الارصفة ذات المرابط الخلفية لرسو السفن بانواعها المختلفة وخصوصاً اذا كانت تربة الموقع ضعيفة والسفن ذات غاطس صغير، ونظراً للتطور السريع في بناء سفن بأحجام كبيرة وبالتالي ذات غاطس كبير وحمولات ذات كثافة عالية مما يتطلب إعادة تأهيل هذا النوع من الأرصفة حتي يمكن إستخدامها لشحن وتفريغ البضائع بأمان، وذلك يتطلب دراسة هذه المنشآت بعناية للتأكد من أتزانها نتيجة القوي المؤثرة عليها والناتجة من تأثير أحمال السفن والشد علي مدافع الرباط والصدمات والضغوط الجانبية للتربة. ويهدف هذا البحث إلى دارسة وتحليل هذا النوع من الحوائط وتحديد العوامل المختلفة والتي تؤثر علي تحسين أدائها وذلك بأستخدام تقنية حقن مرابط إضافية بالأسمنت عند مناسيب مختلفة علي إرتفاع الحائط وذلك بهدف زيادة اتزانها وتقليل الازاحات الأفقية لها ومن ثم تحديد القوي الداخلية للحائط والشد علي المرابط الخلفية. ولتحديد تاثير العوامل المختلفة والمؤثرة علي اتزان الحائط فقد تم استخدام نظرية العناصر المحددة لدراسة كل عامل علي حده ومن ثم تحديد تأثير كل العوامل مجتمعة.

Keywords: Anchor, Grouting-ties, Harbor, Marine, Quay wall, Sheet pile, Retaining walls

1. Introduction

Generally, quay walls play a crucial role in the operational capacity of ports, marinas, shipyards and other waterside facilities. Steel sheet-pilings are one of the most common types of quay walls used in port construction. They are widely used in the construction of container and dry-bulk terminals; as well as for sea walls, reclamation projects; where a fill is needed seaward of the existing shore and for marinas and other structures where deep water is needed directly at the shore. Many authors in the literature have been attempted to analysis and predict the load carrying capacity of these types of walls. Some of them take into account the ability of sheet piles to deform and considered the wall as a flexible structure [1-5]. Others used the finite element technique in their analysis to investigate the behavior and failure mechanism of the structure [6- 10]. Full-scaled field tests have been also used to investigate the behavior of the structure [11]. Barley K. [12] provided considerable results to represent failure mechanism of sheet-piling walls based on field observations.

Stability of sheet piling wall depends on the pressures excreted on its faces. These pressures include the overturning pressure, that resulting from active earth pressure, unbalanced water pressure acting upon the inner face of the wall, and the passive pressure acting on the front of the wall embedment below the dredge line. So that depth of penetration is the key of the stability of any sheet-piling wall. In many cases, due to the growing number and size of vessels, there is increasing pressure to upgrade the existing berths to provide more efficiently of the existing sheet pile wall. As a result of upgrading the existing facilities through deepening the quay wall, rehabilitation is required to accommodate these larger vessels. Under these new serviceability conditions, the sheet-piling quay wall should be strengthened to ensure an adequate factor of safety of the wall against soil collapse and/or structural overstressing.

Several methods can be used to increase the load-carrying capacity of the wall. Rehabilitation using additional anchored tie rods grouting to the backfill soil and arranged along the exposed wall height is one of the most practical solutions adopted for rehabilitation and upgrading the existing quay wall [13, 14]. To investigate the behavior of sheet-piling walls and to predict wall movements, finite element method through finite element program, PLAXIS, [15]. PLAXIS is a finite element code for soil and rock plasticity. PLAXIS version 8.2 has been employed for the analysis of practical wall problems.

This paper describes the development of such model and demonstrates its performance as a design tool under practical conditions. Several parameters, which affect the performance of sheet-piling quay wall, were considered and evaluated through the predication of the horizontal displacements and bending moments induced along the sheet-piling wall as well as ground surface settlements and the original anchored force due to the effect of different system parameters.

2. Parameters studied

The most previous studies showed that all the parameters of the sheet-piling wall improved the behavior of the structure. The influence of sheet pile wall geometry, grout-ties area, grout-ties inclination, length of grout, location of grout-ties, dredging depth and backfill soil angle of repose are the most affected parameters used to enhance this type of walls. In the present study, these parameters are analyzed and the results are presented. Geometry of the sheet-piling quay wall and different parameters studied are defined in fig. 1.

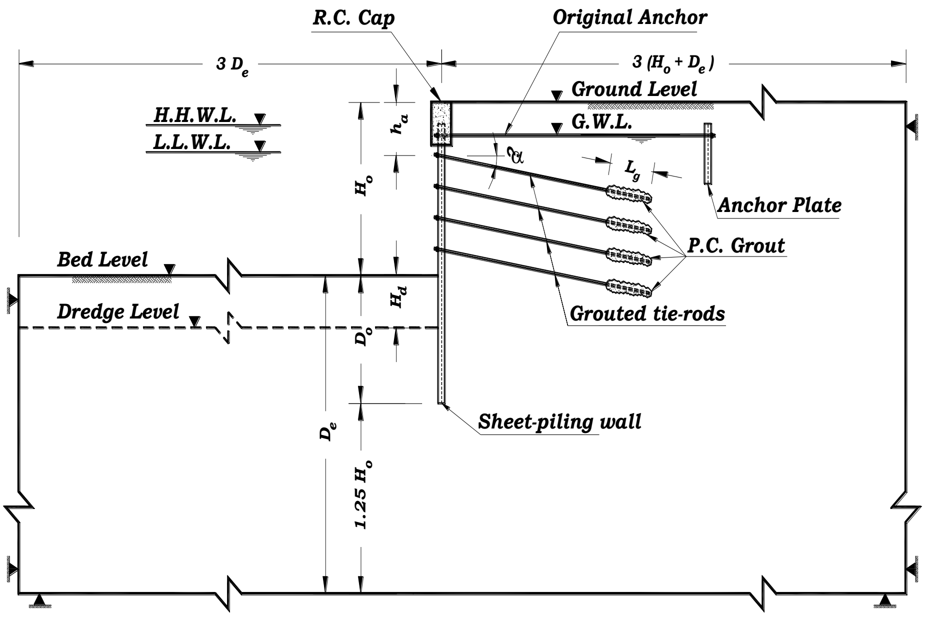

Fig. 1. Geometry of multi-anchored-sheet pile system.

The backfill soil adopted in this work was assumed to be homogenous sand, as in the most sea-bed soil and it has the following properties: modulus of elasticity, E_{ss}, 30 MPa; Poisson's ratio, ν_s = 0.20; dry unit weight, γ_{sd} 18.0 kN/m^3; saturated unit weight, γ_{ss} unit weight 20.0 kN/m^3 and angle of internal friction, ϕ, varies from 25^o to 40^o. All steel elements are considered of high tensile steel, St-52. The allowable and yield stresses, f_a, f_y of the used steel are 210 MPa and 360 MPa, respectively, and modulus of elasticity, E_s is 210 GPa. As the analysis will be considered a unit width of the wall, the cross-sectional area of anchor, A, is prorated based on the anchor horizontal spacing, S, which is considered to be coincide with four consecutive sheet-piling sections. Diameter of original anchor-tie rods considered for limit equilibrium design is 80 mm. In the finite element model, the additional tie rods are pre-stressed by a force of 175 kN/m. This pre-stressed force is taken equal two thirds of the allowable tie load. The grouted anchors are assumed to transfer loads via the grouted concrete body by friction with adjacent soil mass. The average diameter of grouted concrete body is 200 mm for the whole parametric study; whereas its lengths are varied from 0.20 to 0.50 of the wall exposed height. Angle of inclination of the grouted concrete ties is ranged from 10^o to 40^o. A reinforced concrete cap of a constant dimension 1.00×2.00 m is used to represent the wall crown. The used reinforced concrete has the following properties: modulus of elasticity, E_p = 20 GPa; Poisson's ratio, ν_c=0.20 and its dry unit weight γ_{cd}= 24 kN/m^3 according to the Egyptian code of practice ECCS 203-2001 assuming a characteristic strength of 25 N/mm^2. The choice of the above parameter was based on the practical properties of the material required for marine structures.

3. Numerical modeling

As mentioned before, fig. 1 presents a general layout of the physical model considered throughout this work. The dimensions of the model were assumed to agree with the values suggested by Briaud et al, [13]. Finite element analyses were performed with PLAXIS [15]. Calculations were carried out by plane-strain analysis. Mohr-Coulomb failure criterion is currently the most widely method used for soil in practical applications. As a result, the soil was presented as elastic-perfectly plastic material based on Mohr-Coulomb failure criterion. 15-noded triangle elements were used for modeling the soils and concrete cap. The sheet-pile wall and the anchor block have been modeled by 5-noded beam elements. Between the structure elements and the soil elements, 5-noded interface elements of zero thickness are used. The original and the grouted anchors are modeled by the node-to-node anchor element. The grout body is simulated by the geo-grid element. All nodes on the lateral boundaries of the structure are restrained from moving in the horizontal direction to represent the rigid-smooth lateral boundaries. And to represent the rough-rigid surface boundaries, all nodes on the bottom surface are restrained in both horizontal and normal directions. The finite element mesh used for the present work is shown in fig. 2.

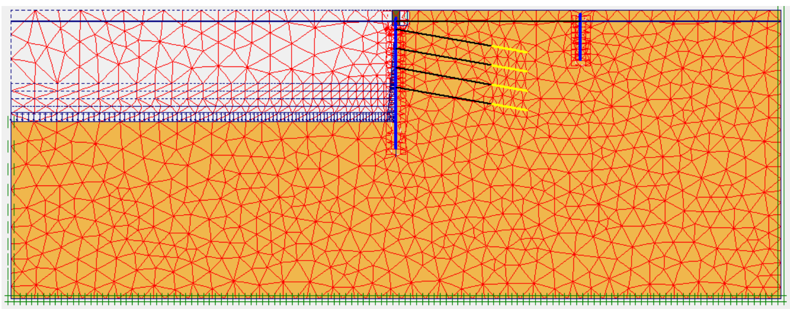

Fig. 2. Finite element model as generated by plaxis.

To simulate the oscillation of water level between the front and rear of the wall, a constant hydrostatic unbalanced head of half meter is considered. The position of the original anchor is considered to be coinciding with the ground water level. As considered in the most practical quay walls, a constant distance of 1.50 m is taken into account between the ground surface level and the horizontal level of the original anchor. The anchor plate is assumed to a continuous sheet piling of the same section of the sheet piling wall and positioned to be outside the backfill soil failure plan behind the wall. The bollard force, which is used only in the calculation of both the maximum moment and the determination of the penetration depth, is assumed to act at a 0.40 m above the horizontal terrain.

An extensive parametric study through the finite element model was carried out to investigate the enhancement of using grouted anchors technique on the load response of the sheet-piling quay wall. The results obtained from the finite element model was verified and substantiated by the results used limit equilibrium approach.

The results of the parametric study are presented in terms of the following non-dimensional parameters. Anchor force ratio, $R_F = F_a/[\gamma_w (H_o)^2]$, bending moment ratio, $R_m = M/\gamma_w(H_o)^3]$, grouting length ratio, $R_{Lg} = L_g/H_o$, ground surface settlement ratio, $R_{uy} = U_y/H_o$; and horizontal displacement ratio, $R_{ux} = U_x/H_o$.

4. Results and discussions

It has been found from the parametric studies that all the parameters pertaining to the steel sheet-piling quay walls system have a significant effect on the behavior of the structure. The following subsections represent the results of the steel sheet-piling quay walls obtained from different parameters.

4.1. Effect of grouted ties area ratio, R_g

Using the grouting ties to rehabilitation steel sheet-piling quay walls leads to a considerable reduction in the maximum bending moment ratio exerted in the quay wall as well as the corresponding maximum horizontal displacement of the sheet pile wall, maximum ground surface settlement and maximum of existing anchor force.

To investigate this role, three values of R_g, $(A_g/S.H_o]$ have been adopted, (R_g= 2.1, 4.2, and 6.3e^{-3}). The other parameters of the model were considered constant as, h_d/H_o= 0.30, h_a/H_o= 0.25, ϕ=30°, α= 10° L_g/H_o= 0.30, γ_{dry}= 17 kN/m^3, P_v= 20 kN/m^2, P_h= 20 kN/m, and E_s= 3000 kN/m^2.

To compare the results, case of no grouting ties was also examined. Figs. 3-6 present the effect of grouting ties area ratio, R_g to reduce the R_m, R_{ux}, R_{uy} and R_F exerted along the sheet-piling quay wall. The plots show that as the grouting area ratio, R_g increased, the maximum bending moment ratio, R_{mmax} decreased. Comparing with the case of no grouting-ties, it decreased by approximately 25, 55 and 72% as R_g increased from 2.07 to 4.14 and 6.21e^{-3}, respectively. Similarly, the maximum horizontal displacement, R_{uxmax} dropped by 32, 56 and 67%, the maximum ground surface settlement ratio, R_{uymax} by 41, 69 and 78%, and the maximum anchor force ratio, R_{Fmax} by 30, 55 and 62%. This reduction could be attributed to the contribution of grouting ties area, which helps to increase the overall stiffness of the structure and thus decrease the internal forces induced in the steel sheet-piling quay wall system. The results also, show that the maximum horizontal displacement, R_{uxmax} occurred approximately, at the same point for different grouting area ratios, R_g, approximately at a depth ratio, h/H_o= 0.50 from the dredging line and the maximum ground surface settlement ratio, R_{uymax} takes place at the same distance from the wall face.

4.2. Effect of the angle of internal friction of backfill soil, ϕ

To demonstrate the effect of the angle of internal friction of the backfill soil, ϕ on the internal forces of this type of marine structure, five values of ϕ were considered, (ϕ=25, 30, 35, 40 and 45). The other variables of the system were considered constant as, h_d/H_o= 0.30, h_a/H_o= 0.25, R_g = 4.2e^{-3}, α =10° L_g/H_o= 0.30 γ_{dry}= 17 kN/m^3, P_v= 20 kN/m^2,

P_h= 20 kN/m, and E_s= 3000 kN/m^2. The results showed a considerable reduction in the internal forces of the structure due to an increase of the angle of internal friction of the backfill soil, ϕ, see figs. 7-10. When the

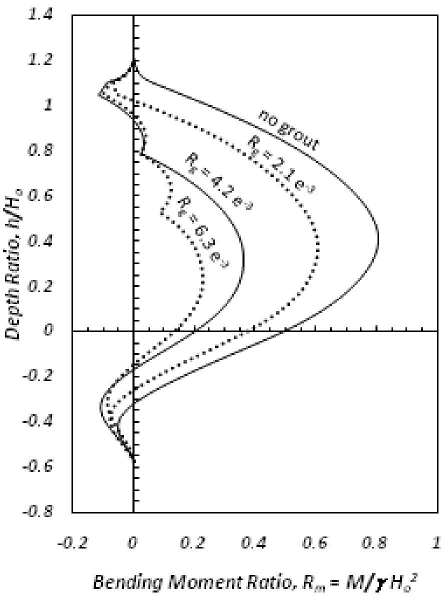

Fig. 3. Bending moment ratios, R_m along sheet-piling quay wall due to various values of grouting area ratio, R_g.

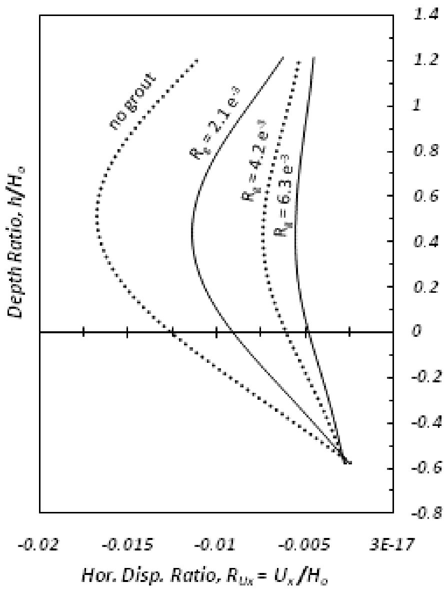

Fig. 4. Horizontal displacement ratios, R_{ux} along sheet-piling quay wall due to various values of grouting area ratio, R_g.

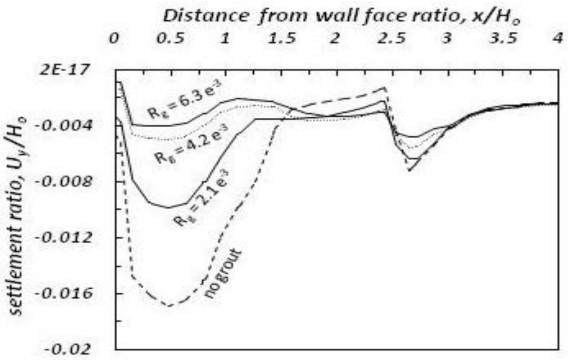

Fig. 5. Ground surface settlement ratio, R_{uy} along sheet-piling quay wall due to various values of grouting area ratio, R_g.

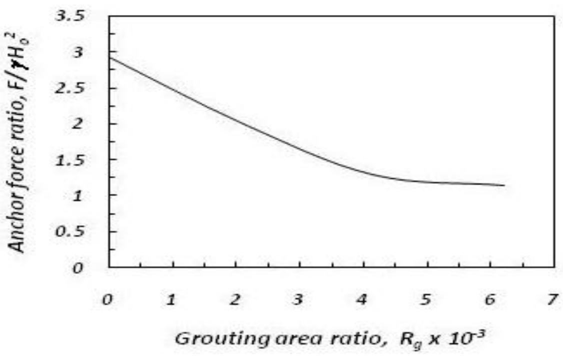

Fig. 6. Anchor force ratio, R_F due to various values of grouting area ratio, R_g.

backfill soil angle of internal friction, ϕ increases, the maximum bending moment ratio, R_{mmax} deceases significantly. It decresed by nearly 35, 70, 77 and 80% as ϕ increased from 25° to 30°, 35°, 40° and 45°, respectively. This reduction could be expected since an increase in the backfill soil angle of internal friction, ϕ helps to reduce the active earth pressure and increase the passive earth pressure and thus reduces the internal forces induced in the sheet-piling quay wall system. This means that the efficiency of the enhancement techniques is more effective for higher values of soil's angle of internal friction.

The results also show that, for soils of high angle of internal friction, further increase in ϕ can not reduce R_{mmax} very much. It is about 7% as ϕ increased from 40° and 45°. Similar reductions were observed in R_{uxmax}, R_{uymax}, and R_{Fmax}, see figs. 8-10.

4.3. Effect of grout-ties inclination, α

Four different values of grouted ties inclination are examined, (α = 10°, 20°, 30° and 40°). The other variables of the system were considered constant as, h_d/H_o= 0.30, h_a/H_o= 0.25, R_g= 4.20e^{-3}, ϕ= 30° L_g/H_o= 0.30 γ_{dry}= 17 kN/m^3, P_v= 20 kN/m^2, P_h= 20 kN/m, and E_s= 3000 kN/m^2.

Table 1 summarizes the results of different values of grout-ties inclination, *α*. The results show that an increase of *α* leads to an increase in both the maximum bending moment ratio, R_{mmax}, the maximum original anchor force ratio, R_{Fmax}, the maximum horizontal displacement of wall face, R_{uxmax}, and the maximum ground surface settlement, R_{uymax}. These observations indicate that the effect of increasing the angle of grout-ties inclination, *α* does not enhance the performance of the structure but it generally reduces the quality of wall enhancement. From the former results, using near horizontal grout-ties is more advisable for the enhancement of structure than using an inclined one. This is because the increase of the grout inclination angle tends to decrease the horizontal reaction of the grout-ties and then increase of tensile force within the original design which reduces the quality of the enhancement of the structure.

4.3. Effect of dredging depth ratio, R_d

Dredging depth ratio, R_d, is the most dominant factor affecting the behavior of the anchored sheet pile quay wall. The internal forces of the structure increase as the dredging depth ratio, R_d; [h_d/H_o] increases. To study the enhancement of the structure due to the use of grouting ties technique, six different values of dredging depth ratio, R_d are used, (R_d = 0, 0.10, 0.20, 0.30, 0.40 and 0.50). The other variables of the system were considered constant as, *α* = 10°, h_a/H_o= 0.25, R_g= 4.2e^{-3}, ϕ= 30 °, L_g/H_o= 0.30, γ_{dry}= 17 kN/m^3, P_v= 20 kN/m^2, P_h= 20 kN/m, and E_s= 3000 kN/m^2.

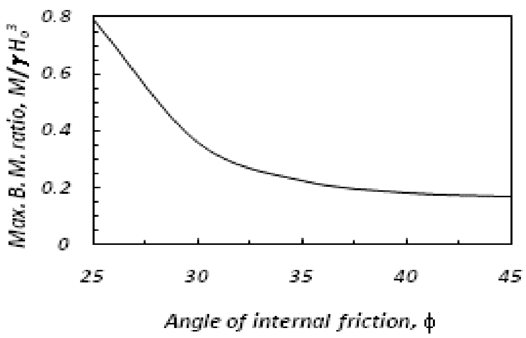

Fig. 7. Maximum bending moment ratio, R_m versus backfill soil angle of internal friction, ϕ.

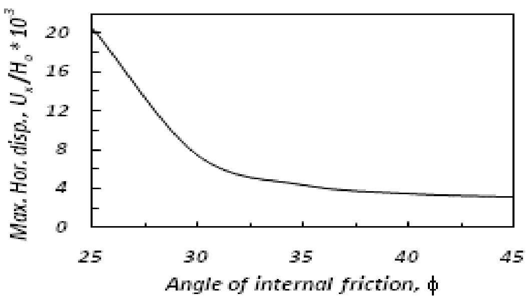

Fig. 8. Maximum horizontal displacement ratio, R_{ux} versus backfill soil angle of internal friction,ϕ.

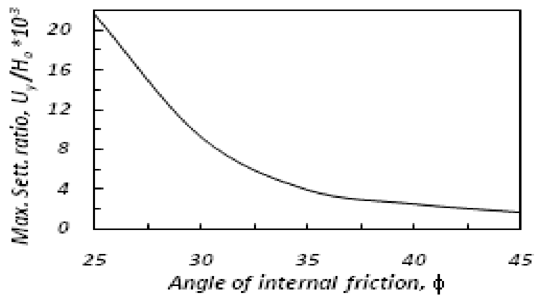

Fig. 9. Maximum settlement ratio, R_{uy} versus backfill soil angle of internal friction,ϕ.

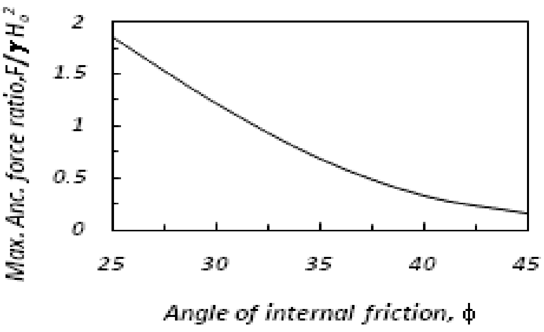

Fig. 10. Maximum anchor force ratio, R_F versus backfill soil angle of internal friction, ϕ.

Table 1
Results of grout-ties inclination, *a*

a	R_{mmax}	R_{Fmax}	R_{uxmax} * 10^{-3}	R_{uymax} * 10^{-3}
10	0.361	1.295	7.299	5.884
20	0.372	1.365	7.391	6.042
30	0.414	1.601	7.867	6.709
40	0.536	2.168	9.561	9.489

Figs. 11-14 illustrate the results obtained from un-grouted and grouted models. The finite element results showed that the grouted models failed when the dredging depth ratio, R_d was greater than 0.50 and the un-grouted models failed when the dredging depth ratio, R_d was greater than 0.30. Compared with un-grouted walls, the results showed a considerable reduction in the internal forces of the structure due to the contribution of grout-ties to increase the load carrying capacity of the system, see figs. 11-14. At the point of failure of the un-grouted walls, the maximum bending moment ratio, R_{mmax}, , the maximum original anchor force ratio, R_{Fmax}, the maximum horizontal displacement of wall face, R_{uxmax}, and the maximum ground surface settlement, R_{uymax} decreased by nearly 55, 55, 57 and 48%, respectively.

The results also show a linear relationship, for all internal forces, as the dredging depth ratio reached 0.30. As the dredging depth ratio increased beyond 0.30, all the internal forces increased significantly. As a result, it can be advised that the efficiency of the enhancement techniques is more reliable when the dredging depth ratio, R_d is less than or equal 0.30.

4.4. Effect of grout-tie depth ratio, R_t

Location of grout-tie from the ground surface, h_a plays a significant role in the performance of the steel sheet-piling quay walls. To investigate the role of the grout-tie depth ratio, R_t; $[h_a/H_o]$ on the enhancement of

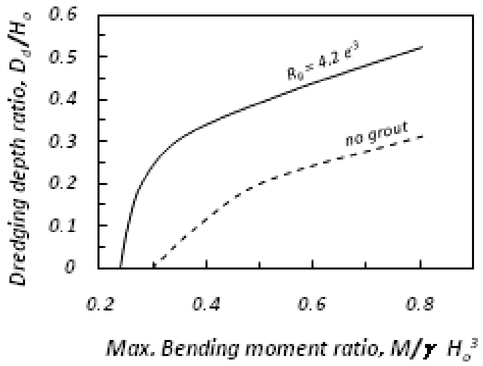

Fig. 11. Maximum bending moment ratio, R_m versus dredging depth ratio, R_d.

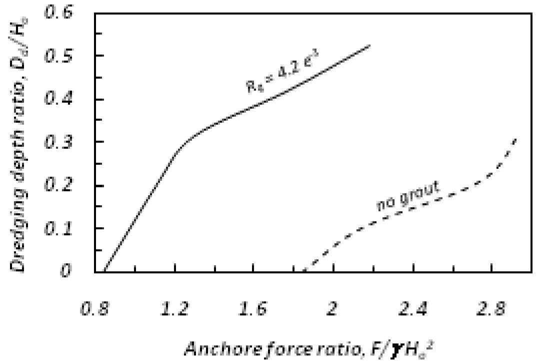

Fig. 12. Maximum anchor force ratio, R_F versus dredging depth ratio, R_d.

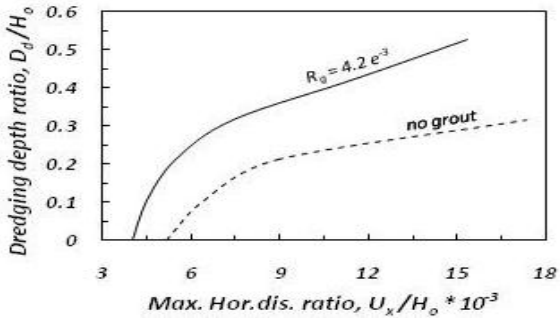

Fig. 13 Maximum horizontal displacement ratio, R_{ux} versus dredging depth ratio, R_d.

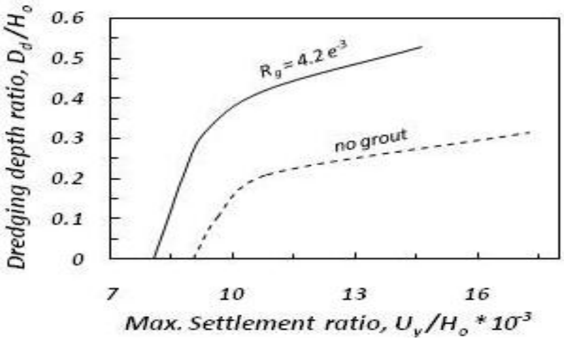

Fig. 14. Maximum settlement ratio, R_{uy} versus dredging depth ratio, R_d.

the steel sheet-piling quay walls, three values of h_a/H_o ratio have been conducted, (h_a/H_o= 0.25, 0.50 and 0.75). The other variables of the system were considered constant as, h_d/H_o= 0.30, R_g= 2.1e^{-3}, ϕ=30° L_g/H_o= 0.30 γ_{dry}= 17 kN/m^3, P_v= 20 kN/m^2, P_h= 20 kN/m, and E_s= 3000 kN/m^2.

Table 2 presents the results of different values of grout-ties depth ratio, R_a. The results present that an increase of the grout-tie depth ratio, R_t reduces significantly both the maximum bending moment ratio, R_{mmax}, the maximum horizontal displacement of wall face, R_{uxmax}, and the maximum ground surface settlement, R_{uymax}. Unfortunately, this increase leads to significant increase of the maximum original anchor force ratio, R_{Fmax}, as shown in table 2. The former observations indicate that increasing the grout-tie depth ratio, R_t generally enhances the performance of the structure but a trade-off is required to balance the increase of the original anchor force ratio, R_F.

4.5. Effect of grout length ratio, R_{lg}

In this study, grout is installed away from the soil's active wedge of failure by a distance of one and half meter. To investigate the role of the grout-tie depth ratio, R_{lg}; [L_g/H_o] on the enhancement of the steel sheet-piling quay walls, three values of h_a/H_o ratio have been tested, (L_g/H_o=0.20, 0.30, 0.40, 0.50 and 0.60). The other variables of the system were considered constant as, h_d/H_o=0.30, R_g=4.2e^{-3}, ϕ=30° h_a/H_o= 0.25 γ_{dry}= 17 kN/m^3, P_v= 20 kN/m^2, P_h= 20 kN/m, and E_s= 3000 kN/m^2.

Table 3 presents the results of different values of grout length ratio, R_{lg}. From these results, it can be noticed that the increase of R_{lg} enhances the performance of this type of marine walls. It reduces the maximum bending moment and the maximum horizontal displacement of the sheet pile wall as well as it reduces the maximum ground surface settlement and the maximum original anchor force. These observations indicate that increasing the grout length ratio, R_{lg} leads to increase the fixity of the structure and then enhances the performance of the wall. The results also show that the reductions in the internal forces are not significant when the grout length ratio, R_{lg} is greater than 0.40. In this case of study, it is recommended the value of R_{lg} to fall between 0.40 to 0.50.

Table 2
Results of grout-ties depth ratio, R_t

R_a	R_{mmax}	R_{Fmax}	R_{uxmax} * 10^{-3}	R_{uymax} * 10^{-3}
0	0.802	1.815	16.499	16.641
0.25	0.593	2.185	10.874	10.112
0.50	0.491	2.437	9.474	8.865
0.75	0.428	2.669	8.909	8.445

Table 3
Results of grout-ties length ratio, R_{lg}

R_{lg}	R_{mmax}	R_{Fmax}	R_{uxmax} * 10^{-3}	R_{uymax} * 10^{-3}
0.20	0.378	1.450	8.140	10.442
0.30	0.368	1.418	7.742	9.256
0.40	0.363	1.350	7.473	8.889
0.50	0.360	1.295	7.315	8.778
0.60	0.358	1.258	7.221	8.736

5. Conclusions

Based on the results of presented parametric study, several conclusion can be drawn which can be used as a design guidelines to enhancement the steel sheet-piling quay walls. The rehabilitation of steel sheet-piling quay walls using additional grouting tie-rods has a significant role on the performance of anchored quay wall system. The anchored wall and the surrounding soil show more stabilized behavior when the grout techniques used. The maximum bending moment and the maximum horizontal displacement exerted along the sheet pile wall have been considerably reduced by increasing the pertaining parameters of the system. The maximum ground surface settlement and the maximum original design anchor force have been also reduced. Results also show that the optimal length of the grout falls between 0.40 to 0.50 of the quay wall original height. Furthermore, the grout-ties inclination has a great effect on the performance of the system. Minimum practical angle of grout-ties inclination increases the enhancement performance of the system.

Notations

A	cross-sectional area of original anchor,
S	anchor horizontal spacing,
f_a	steel elements allowable stress,
f_y	steel elements yield stress,
h_a	location of grout-tie from the ground surface,
h_d	dredging depth,
E_p	reinforced concrete modulus of elasticity,
H_o	quay original height,
L_g	grouted concrete body length,
P_h	mooring load,
P_v	vertical distributed load,
R_d	dredging depth ratio,
R_f	anchor force ratio,
R_g	additional grouted ties area ratio,
R_m	bending moment ratio,
R_t	grout-tie depth ratio,
D_{ot}	original anchor diameter,
E_{ss}	backfill soil of elasticity,
R_{Lg}	grouting length ratio,
R_{Ux}	horizontal displacement ratio,
R_{Uy}	ground surface settlement ratio,
R_{Fmax}	maximum original anchor force ratio
R_{mmax}	maximum bending moment ratio,
R_{uxmax}	maximum horizontal displacement of wall face,
R_{uymax}	maximum ground surface settlement,
α	Inclination of grouted concrete ties,
ϕ	backfill soil angle of internal friction,
ν_c	reinforced concrete Poisson's ratio,
ν_s	backfill soil Poisson's ratio,
γ_{cd}	reinforced concrete dry unit weight,
γ_{sd}	backfill soil dry unit, and;
γ_{ss}	backfill soil saturated unit weight.

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