Journal of Soil Science and Environmental Management Vol. 1(4), pp. 69-76, June 2010
Available online at http://www.academicjournals.org/JSSEM
ISSN 2141-2391 ©2010 Academic Journals

Full Length Research Paper

Enhancement of steel sheet-piling quay walls using grouted anchors

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Accepted 8 May, 2010

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 the 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. The use of additional anchored tie rods grouted into the backfill soil and arranged along the exposed wall height is one of the most appropriate solutions adopted for rehabilitation and upgrading of 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 sheet-piling quay wall. The influence of sheet-pile wall geometry, grout-ties area, inclination and location, length of grout, dredging depth and backfill soil angle of internal friction to enhance this type of walls are analyzed and the results are presented.

Key words: anchor, grouting-ties, harbor, marine, quay wall, sheet pile, retaining wall.

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 and 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 attempted to analyze and predict load carrying capacity of these types of walls. Some authors take into account the ability of sheet piles to deform and considered the wall as a flexible structure (Rymsza and Sahajda, 2008; McNab, 2002; Cherubini, 2000; Endley et al., 2000; and Schriver and Valsangkar, 1996). Others used finite element technique in their analysis to investigate behavior and failure mechanisms of the structure (Don and Warrington, 2007; Krabbenhoft et al., 2005; Krabbenhoft and Damkilde, 2003; Lyamin and Sloan, 2002 and Briaud and Lim, 1999). Full-scaled field tests have been also used to investigate the behavior of these structures (Briaud et al., 2000). Barley, 1997 provided considerable results to represent failure mechanisms of sheet-piling walls based on field observations.

Stability of sheet-piling wall depends on pressures excreted on its faces. They include the overturning, that results from active earth pressure; unbalanced water, acting upon the inner face of the wall and the passive pressure, acting on the wall's front embedment depth below the dredge line, so that the depth of penetration is the key of any sheet-piling wall's stability. In many cases, due to the growing number and size of vessels, there is increasing pressure to upgrade the existing berths that provide higher capacity to 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 the wall's safety against soil collapse and/or structural over-stressing. There are several possible failure mechanisms of grouted anchors. These are usually caused by excessive static loading of an anchor. Excessive loads can be related to: tension placed in the anchor during load testing or at lock-off, excavation sequence, surcharge by

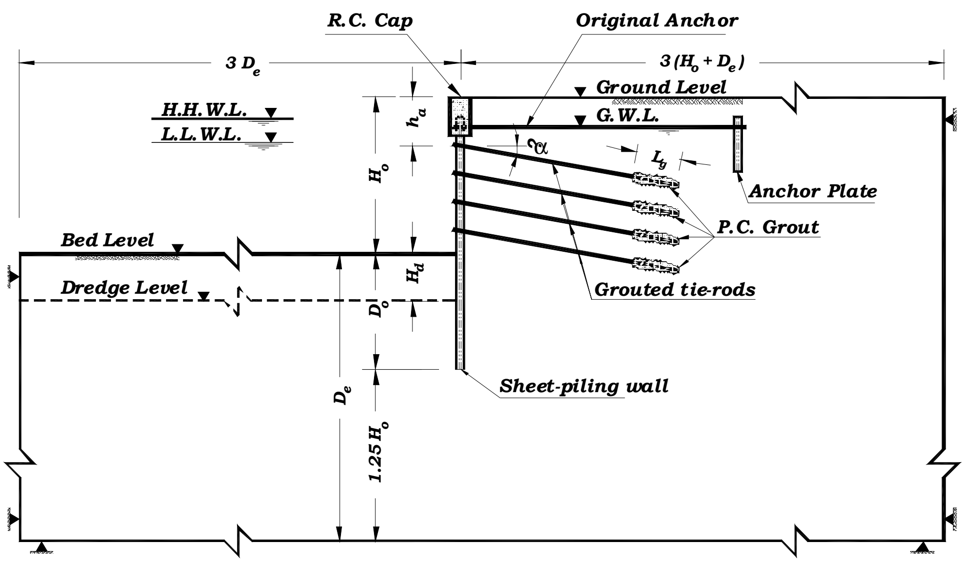

Figure 1. Geometry of Multi-Anchored-Sheet Pile System.

construction materials or equipment, construction of adjacent structures or a combination of these causes. Ground anchor failure mechanisms may involve the steel tendon, ground mass, ground-grout and grout-tendon zones (Sabatini et al., 1999).

Several methods can be used to increase the load-carrying capacity of the wall. The use of 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 of the existing quay wall (Ebeling et al., 2002 and Strom and Ebeling, 2001). To investigate the behavior of sheet-piling walls and to predict wall movements, the method of finite element has been used through its program, PLAXIS (Brinkgreve and Vermeer, 2002). PLAXIS is a finite element code for soil and rock plasticity and its version 8.2 has been employed in this study for the analysis of practical wall problems.

This paper describes the development of steel sheet-piling quay walls using grouted anchors technique and demonstrates the performance of this technique as a design tool of this type of walls under service loads. Several parameters, which affect the performance of sheet-piling quay wall, were considered and evaluated through predication of 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.

Parameters studied

The most previous studies showed that all parameters of sheet-piling wall improved the behavior of the structure. The influence of sheet pile wall geometry, grout-ties area, inclination and location, length of grout, dredging depth and backfill soil angle of repose are the most effective parameters in enhancing 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 in the current article are defined in Figure 1.

The backfill soil adopted in this work is homogenous sand with the following properties: modulus of elasticity, E_{SS}, 30 MPa; Poisson's ratio, V_S= 0.20; dry unit weight, γ_{sd} =18.0 kN/m^3; saturated unit weight, γ_{ss} = 20.0 kN/m^3 and angle of internal friction, ϕ, varies from 25 to 45^o. All steel elements are considered to be of high tensile steel, St-52. The allowable and yield stresses, f_a, f_y of the used steel are 210 and 360 MPa, respectively, and the modulus of elasticity, E_s is 210 GPa. In considering the analysis as a unit width of the wall, the cross-sectional area of the anchor, A, is prorated based on the anchor horizontal spacing, S, which is considered to coincide with four consecutive sheet-piling sections. Diameter of the 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-stressing force is taken into 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 varied from 0.20 to 0.50 of the wall's exposed height. The grouted concrete ties' angle of inclination ranged from 10 to 40^o. A reinforced concrete cap of constant dimension 1.00×2.00 m is used to represent the wall crown. The reinforced concrete is assumed to have 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, the concrete characteristic strength is 25 N/mm^2. The choice of the above parameter was based on the practical properties of the material required for marine structures.

Numerical modeling

As mentioned before, Figure 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. (2002). Finite element analyses were performed with

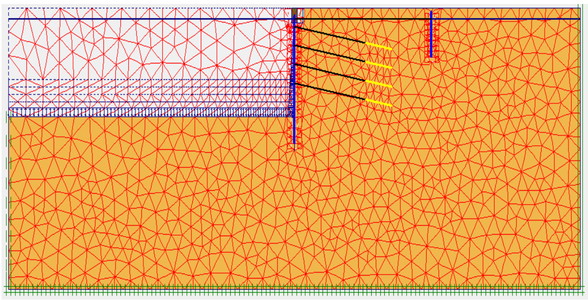

Figure 2. Finite Element Model as Generated by PLAXIS.

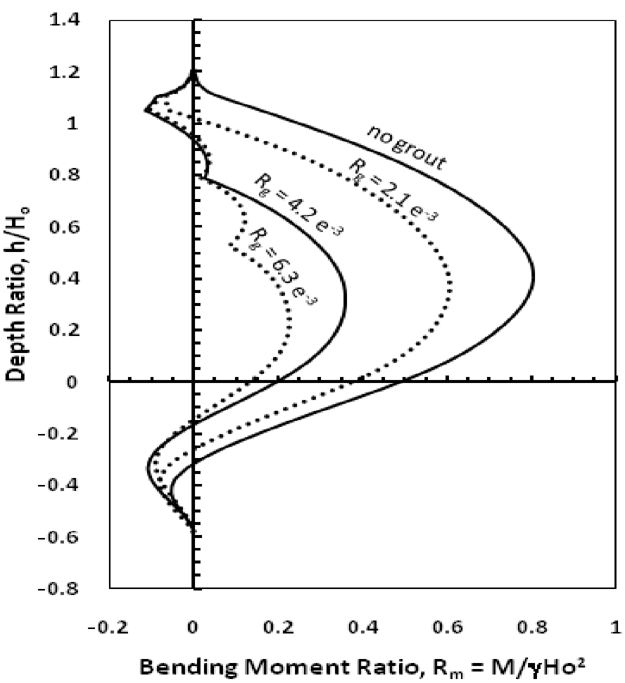

Figure 3. Bending moment ratios, R_m along sheet-piling quay wall due to various values of grouting area ratio, R_g.

PLAXIS and calculations were carried out by plane-strain analysis. Mohr-Coulomb failure criterion is currently the most widely used method for soil in practical applications. As a result, the soil was presented as an 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 anchor blocks have been modeled by 5-noded beam elements. Between the structure and soil elements, 5-noded interface elements of zero thickness were used. The original and grouted anchors are modeled by the node-to-node anchor element, while the grout body is simulated by the geo-grid element. All nodes on the vertical sides of the model 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 Figure 2.

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 and horizontal levels of the original anchor. The anchor plate is assumed to have a continuous sheet piling of the same section and positioned 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 penetration depth's determination, is assumed to act at 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 were verified and substantiated with the ones used by the limit equilibrium approach.

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

RESULTS AND DISCUSSION

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

Effect of grouted ties area ratio, R_g

Using grouting ties in the rehabilitation of 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 and maximum horizontal displacement of the sheet pile wall, ground surface settlement and existing anchor force.

To investigate such effect, 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 kept constant as, h_d/H_o= 0.30, h_a/H_o = 0.25, ϕ = 30^o, $\alpha = 10^\circ$, L_g/H_o= 0.30, $\gamma_{\delta\rho\psi}$ = 17 kN/m^3, P_v= 20 kN/m^2, P_h = 20 kN/m and E_s = 30000 kN/m^2.

To compare the results, no case of grouting ties was examined. Figures 3, 4, 5 and 6 present the effect of grouting ties area ratio on R_g, to reduce the R_m, R_{ux}, R_{uy} and R_F values 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 this 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}; ground surface settlement, R_{uymax} and anchor force, R_{Fmax} ratios dropped by 32, 56 and 67; 41, 69 and 78 and 30, 55 and 62% respectively. This reduction could be attributed to the contribution of grouting ties area, which

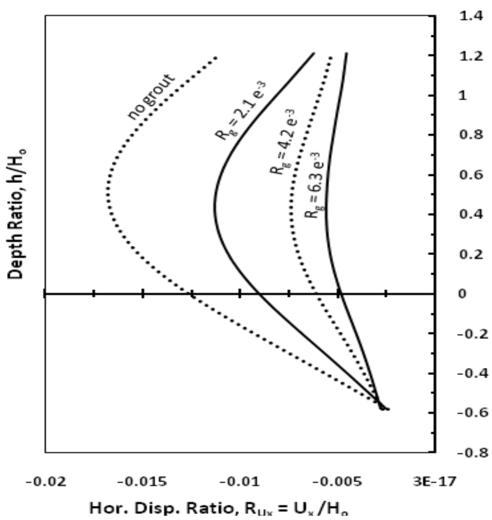

Figure 4. Horizontal displacement ratios, R_{ux} along sheet-piling quay wall due to various values of grouting area ratio, R_g.

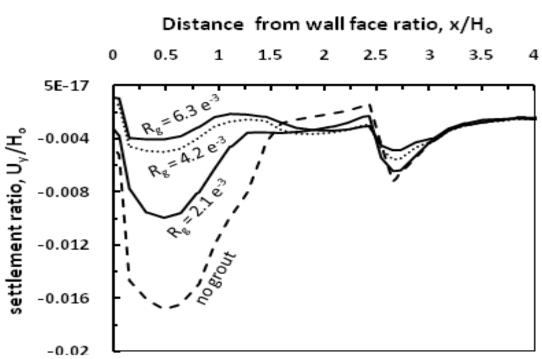

Figure 5. Ground surface settlement ratio, R_{uy} along sheet-piling quay wall due to various values of grouting area ratio, R_g.

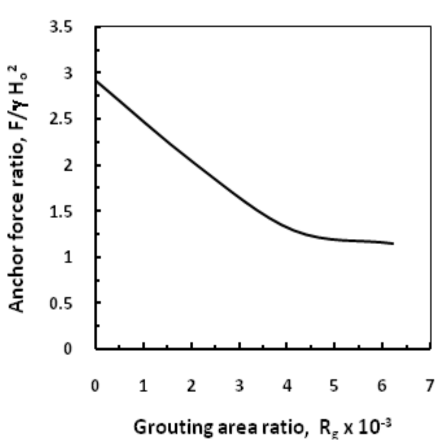

Figure 6. Anchor force ratio, R_F due to various values of grouting area ratio, R_g.

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.

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

To demonstrate the effect of the internal friction's angle 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^o, 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= 30000 kN/m^2. The results showed a considerable reduction in the internal forces of the structure due to an increase in the internal friction's angle of the backfill soil, ϕ see (Figures 7 - 10). When the backfill soil internal friction's angle, ϕ increases, the maximum bending moment ratio, R_{mmax} decreases significantly. It decreased by nearly 35, 70, 77 and 80% as ϕ increased from 25 to 30, 35, 40 and 45^o, 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 the internal friction.

The results also show that, further increase in ϕ can not reduce R_{mmax} very much for soils of high angle of internal friction. About 7% of ϕ increased from 40 to 45^o. Similar reductions were observed in R_{uxmax}, R_{uymax} and R_{Fmax} (Figures 8 - 10).

Effect of grout-ties inclination, α

Four different values of grouted ties inclination, α 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}, $\phi = 30^o$, 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= 30000 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 the maximum bending moment, R_{mmax}, original anchor force, R_{Fmax}; horizontal displacement of wall face, R_{uxmax} and ground surface settlement, R_{uymax} ratios. These observations indicate that, increasing the angle of grout-ties inclination α does not enhance the performance of the structure but generally

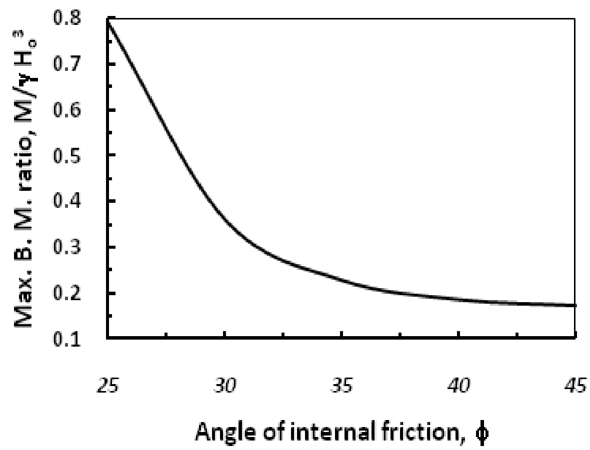

Figure 7. Maximum bending moment ratio, R_m versus backfill soil angle of internal friction, ϕ.

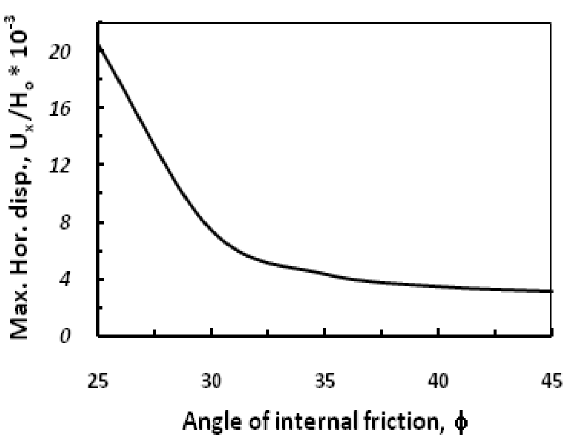

Figure 8. Maximum horizontal displacement ratio, R_{ux} versus backfill soil angle of internal friction, ϕ.

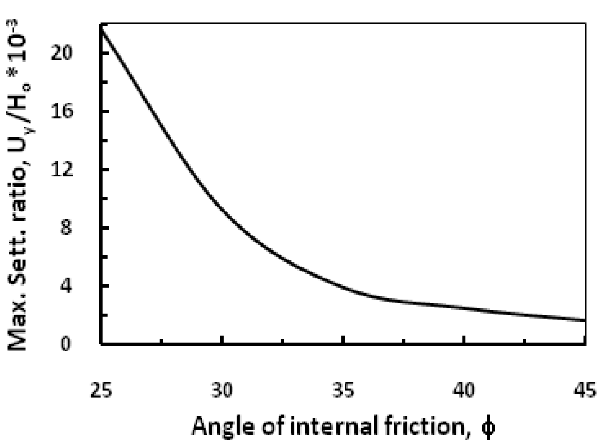

Figure 9. Maximum settlement ratio, R_{uy} versus backfill soil angle of internal friction, ϕ.

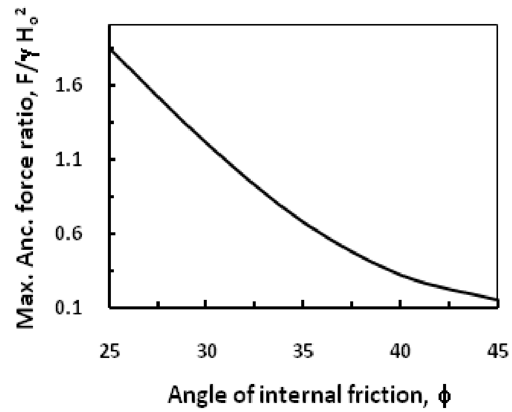

Figure 10. Maximum anchor force ratio, R_F versus backfill soil angle of internal friction, ϕ.

Table 1. Results of grout-ties inclination, α.

α	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

generally reduces the efficiency of wall enhancement. From the former results, the use of near horizontal grout-ties is more advisable for structure enhancement than using an inclined one. This is because the increase of grout inclination angle tends to decrease the horizontal reaction of grout-ties and increase tensile force within the original design which reduces the efficiency of the structure's enhancement.

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 were 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= 30000 kN/m^2.

Figures 11 - 14 illustrate the results obtained from non-grouted and grouted models. The finite element results showed that the grouted and non-grouted models failed when the dredging depth ratio, R_d was greater than 0.50 and 0.30, respectively. Compared with non-grouted walls, the results showed a considerable reduction in the

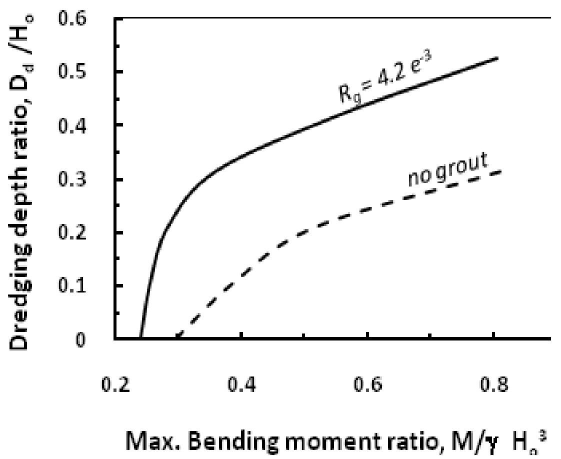

Figure 11. Maximum bending moment ratio, R_m versus dredging depth ratio, R_d.

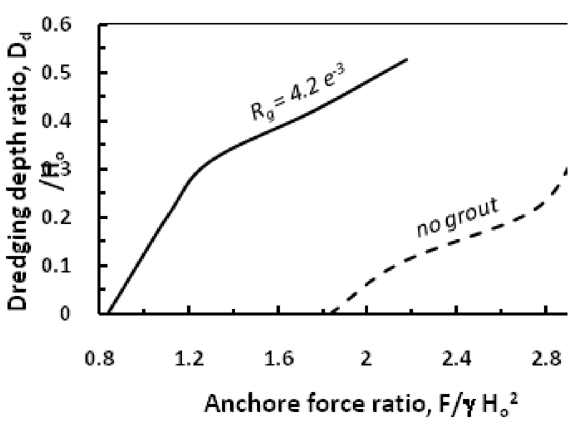

Figure 12. Maximum anchor force ratio, R_F versus dredging depth ratio, R_d.

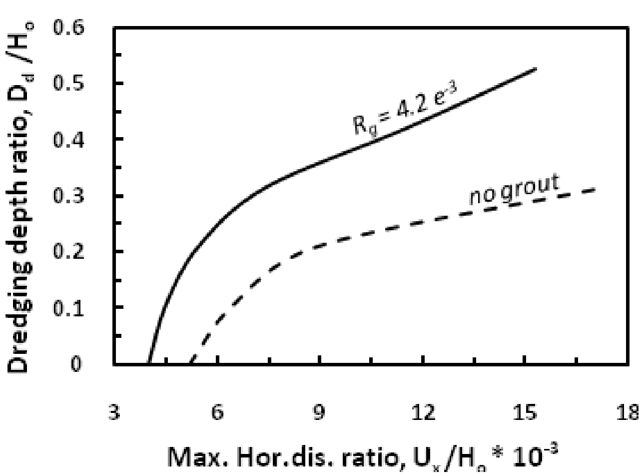

Figure 13. Maximum horizontal displacement ratio, R_{ux} versus dredging depth ratio, R_d.

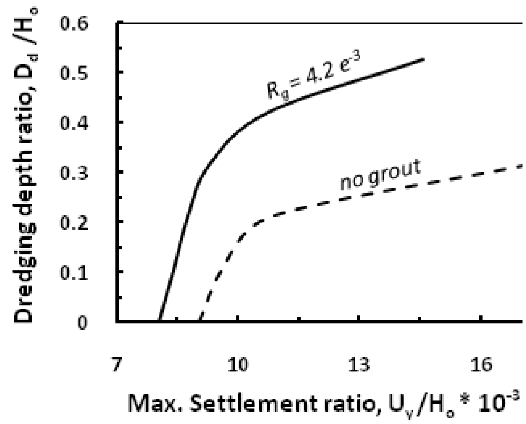

Figure 14. Maximum settlement ratio, R_{uy} versus dredging depth ratio, R_d.

internal forces of the structure due to the contribution of grout-ties in increasing the load carrying capacity of the system (Figures 11 - 14). At the point of failure of the non-grouted walls, the maximum bending moment, R_{mmax}; original anchor force, R_{Fmax}; horizontal displacement of wall face, R_{uxmax} and ground surface settlement, R_{uymax} ratios 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 and when it 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 to 0.30.

Effect of grout-tie depth ratio, R_t

Location of grout-tie from ground surface, h_a, plays a significant role in the performance of the steel sheet-piling quay walls. To investigate the role of grout-tie depth ratio, R_t; $[h_a/H_o]$ on the enhancement of steel sheet-piling quay walls, three values of h_a/H_o ratio have been investigated, (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}, $\phi = 30^o$, 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= 30000 kN/m^2.

Table 2 presents the results of different values of grout-ties depth ratio, R_a. The results present that an increase in grout-tie depth ratio, R_t reduces significantly the maximum bending moment, R_{mmax}, horizontal displacement of wall face, R_{uxmax} and ground surface settlement, R_{uymax} ratios. Unfortunately, this leads to the 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

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

structure, but a trade-off is required to balance the increase of original anchor force ratio, R_F.

Effect of grout length ratio, R_{lg}

To ensure that the active failure plan does not path throughout the grouted anchors, grout is installed away from the soil's active wedge of failure by a distance of one-and-half meter (Sabatini et al., 1999). To investigate the role of the grout-tie depth ratio, R_{lg}; [L_g/H_o] on the enhancement of steel sheet-piling quay walls, five 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}, $\phi = 30^o$, $h_a/H_o = 0.25$, γ_{dry}= 17 kN/m^3, P_v= 20 kN/m^2, P_h= 20 kN/m, and E_s= 30000 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. Also, it reduces the maximum bending moment and horizontal displacement of the sheet pile wall as well as it reduces the maximum ground surface settlement and force in the original anchor. These observations indicate that increasing the grout length ratio, R_{lg} leads to increase in 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 study's case, it is recommended that the value of R_{lg} should fall between 0.40 and 0.50.

Conclusion

Based on the results of presented parametric study, several conclusions can be drawn, which are designed guidelines recommended for enhancement of 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 surrounding soil show more stabilized behavior when the grouted anchors are used. Both the maximum bending moment and horizontal displacement exerted along the sheet pile wall have been considerably reduced by increasing the pertaining parameters of the system. Also, the maximum ground surface settlement and force in the original system anchor have been reduced. Results also show that the optimal length of the grout falls between; 0.40 and 0.50 of the quay wall original height. Furthermore, the grout-ties inclination has a great effect on the system's performance. 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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