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A study of sheet pile quay wall rehabilitation methods

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ABSTRACT

This paper studies numerically a tied-back sheet pile quay wall failure in Egypt, which started to collapse after the completion of the superstructure. The quay wall comprises a 20 m length sheet pile wall tied back to a 6 m length sheet pile wall. The failure of the tied-back sheet pile wall occurred in the tie rods, resulting in about 15 cm displacement. The explanation of failure required underwater dive inspection to investigate the cause. Investigations have revealed the absence of waler beams installation at the level of tie rods which led to their loss. And thus, the failure was attributed to the design errors and the tie rod bolts' poor material quality. This research aims to provide common rehabilitation strategies that are little disruptive. An inverted U-slab approach has been suggested to restrict the sheet pile wall's lateral displacement. The U-slab approach consists of a 40 cm thick slab connected to a beam from the seaside and a deadman from the landside which provides a tie-back mechanism and strengthens the defective sheet pile wall. The study also investigates the behavior of the sheet pile wall before and after the tie-rods numerically by PLAXIS 2D. Based on the analysis, the U-slab technique results in 2 cm lateral displacement of the defective sheet pile wall in the operational phase. This means that the technique controls the lateral movement of the displaced sheet pile wall. Eventually, the approach satisfies the factor of safety and increases the friction between the slab and soil.

Keywords: Quay Wall; Anchored Sheet Pile; Rehabilitation Techniques; PLAXIS.

1.INTRODUCTION

Sheet pile quay walls are one of the most challenging marine geotechnical structures, especially in port areas with poor ground conditions. Walls are embedded in soils and have a flexural stiffness that allows them to withstand horizontal earth pressures and water stresses. Depending on the wall stability and design function, the sheet pile wall can be cantilevered or anchored. Anchors can be used to enhance the load carrying capacity of sheet pile walls. Furthermore, the construction of sheet pile walls does not necessitate dewatering the site; hence, quay walls in coastal regions are the most practical (Tan et al., [14]).

Based on structural and geotechnical features (PIANC, [9]), there are many failure mechanisms for anchored sheet pile walls caused by general and seismic loading conditions: (a) Anchor failure, (b) Sheet pile wall/tie-rod failure, and (c) embedment failure. The consequences of failure due to a structural fault or structural ageing are often severe. Many quay walls have serious deterioration of anchors, cracks, wall movement, corrosion of reinforcement, or slip failure, etc. Researchers and design engineers face several challenges in this endeavor.

In many cases, the failure of the sheet pile walls has been attributed to the construction stages, poor maintenance works and improper design. One of the most important cases, the case of the bulkhead failure occurred in Taxis, USA. After a comprehensive site investigation, the geotechnical engineer assigned an incorrect safety factor of 2.0, higher than the realized safety factor in the range of 0.10 to 0.9 (Pilecki et al., [11]). Another case of design flaws leading to the failure was in the harbor in Portland, built on tidal mudflats along the riverbank. The damage caused by the anchored barrier was attributed to a design error caused by low tide conditions and incorrect soil characteristics estimations, resulting in anchors rupturing during dredging in front of the bulkhead (LaGatta. et al., [6]). In that way, engineers are confronted with the continuous challenge of developing new methods to repair, replace or rehabilitate these kinds of waterfront structures. Because replacing quay walls is costly, it's worth asking if the designer can extend their service life. Many case studies have detailed discussions on the signs and causes of sheet pile failures and cover a wide range of rehabilitation methods that can improve safety and performance. The deterioration of structural materials in a marine environment and how through innovation, the environmental impact on underground construction can be reduced using long-lasting, advanced technology of fiber-reinforced polymers (FRP) (Zhang et al., [17]; Lakomski et al., [7]; Littlejohn et al., [8]). The old diaphragm wharf at Mayport Station was retrofitted by installing a new wall in front of the failed wall with an anchor system and filling behind the wall (Mozo et al., [9]).Construction of relieving platforms or quay extension may be used to increase the resisting forces by placing anchors or to reduce the driving forces and imposed soil and water loads by constructing relieving platforms or quay extension (Douairi et al., [2]).

Numerical modelling is commonly utilized to simulate the behavior of quay wall upgrading systems. For example, PLAXIS, a Finite Element Analysis (FEA) software, was used to model and analyze the quay wall's stability (Brinkqreve et al., [1]). Another study had used PLAXIS 2D to upgrade an existing open-piled quay wall for a container terminal in Port-Said, Egypt (Galal et al., [4]). A study offers an approach of grouted anchors to improve the sheet pile wall resistance, and PLAXIS conducted an extensive parametric finite element analysis to investigate the solution (El-Naggar. [3]).

The present study focuses on understanding the real case study of the existing defective sheet pile quay wall before and after the tie-rods failure, using PLAXIS 2D. In addition, a numerical model has been conducted to simulate the sheet pile wall's displacement after the superstructure's completion and after applying the proposed inverted U-slab method as a rehabilitation technique to support the displaced sheet pile wall and work instead of the damaged ties.

2.CASE STUDY

2.1.Stucture Design

A cross-sectional view of the anchored sheet pile wall is shown in Figure 1. The frontal sheet pile wall is (LX-25) section. The final dredging surface was at an elevation of −7 m, and the wall penetration depth was 12.5 m. A 2.0 m high cap beam was built on the top of the sheet pile. The frontal sheet pile quay wall was tied back to a 6.0 m sheet pile wall. The back sheet pile wall is (LX-8) section. The tie rods are constructed of high tensile steel with a diameter of 50.80 mm and a spacing of 1.20 m (centre to centre), and they are all pre-tensioned with a force of 50 kN at a level (+0.300 m) above the low tide level. The anchored sheet pile quay wall satisfies the ultimate limit state. The distance between the front sheet pile wall and the back sheet pile is 18.0 m. The structure had been designed to resist 20 KN/m ultimate horizontal forces associated with the berthing of a ship and 50 KN/m^2 crane loads and surcharge ultimate loads.The soil improvement consists of a wedge of gravel-sand, stone and very dense clean sand. This improves the soil strength and increases the resistant forces as well.

2.2.Geotechnical Data

A site investigation program has been carried out in order to provide adequate information on the subsurface conditions at the site. The site investigation program comprises mechanical boreholes, field tests and laboratory tests. Two boreholes with a depth of 40.0 m were drilled below the existing ground level to investigate the stratigraphy of the site zone. The geotechnical data used in this research is shown in Figure 2 as a typical borehole, while soil characteristics are listed in Table 1. According to the geotechnical investigation, the sea-bed level is at a depth of (-5.5 m). The soft clay stratum runs from depth (-5.5 m) to (-13.5 m). The silty sand and medium to dense sand layers are located between depths (-14.5 m) and (-40.0 m). The Standard Penetration Tests (SPT) were analyzed in field to define the soil type of the

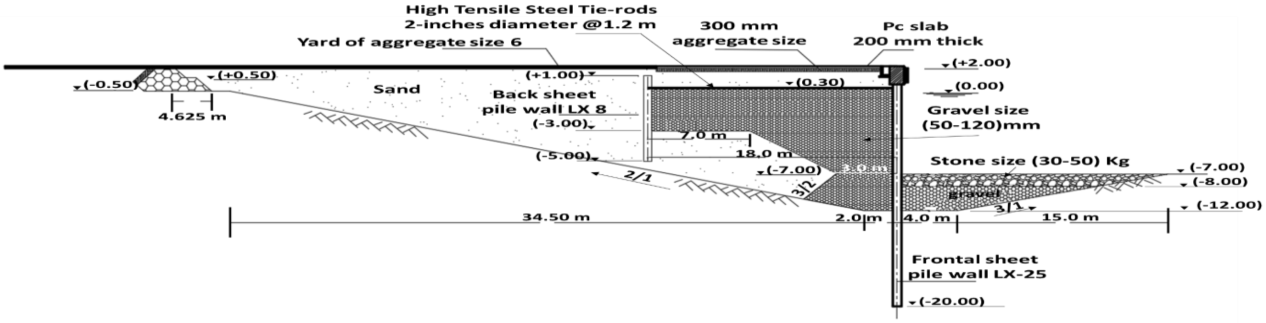

Figure 1: Typical cross-section of the case under-study of the sheet pile quay wall.

The silty sand and medium to dense sand layers are located between depths (-14.5 m) and (-40.0 m). The Standard Penetration Tests (SPT) were analyzed in field to define the soil type of the site zone.

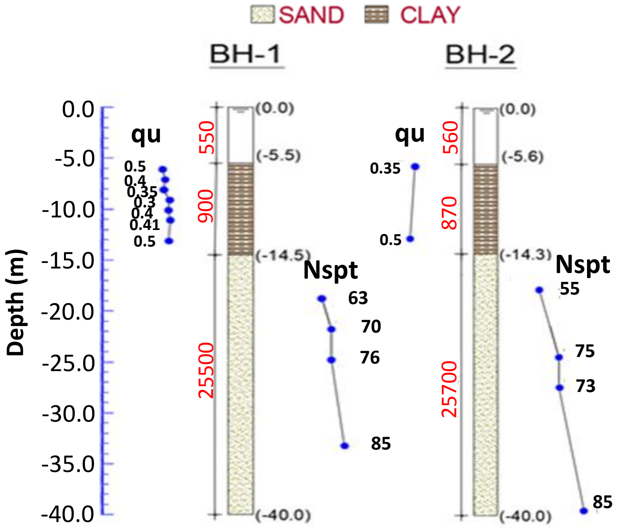

Figure 2: Geological cross section of the two boreholes for the area under-study.

Table 1: Soil parameters.

Layers	γ_b kN/m^3	ϕ_d	C_d kN/m
Soft clay	15.8	10	12.5
Medium dense sand	19	35	-
Very dense sand	19	40	-

2.3.Quay Wall Failure Description

The quay wall was thoroughly examined as part of the project's field assessment to determine its physical condition. The inspectors visually inspected the sheet pile quay wall for cracks, steel corrosion, wall movement, tie rod deterioration, and other quay issues. Figure 3 displays photos of the inspections carried out by the inspectors. The examination revealed that the top of the quay wall head had a significant displacement, tie rods had deteriorated at a level (+ 0.300 m) above sea level, the divers discovered the absence of waler beams, and lastly anchor heads had been damaged.

2.4.Choosing A Rehabilitation Strategy For The Defected Quay wall

Several rehabilitation techniques have been suggested to structurally improve the performance of the defective steel sheet pile quay wall. Choosing among the rehabilitation methods is based on the minimal interruption to the existing quay wall and services. Ultimately, the construction of bored piles behind the defect sheet pile wall would result in many challenges, significant disruption and add substantial costs to a repair operation, as shown in Figure (4-a). And thus, this technique has been excluded.

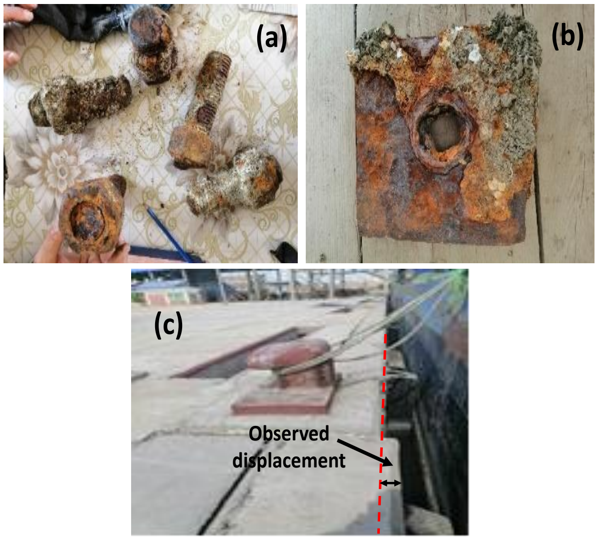

Figure 3: Sheet pile wall inspection photos: (a) anchor deterioration, (b) Plate failure, and (c) Lateral displacement at the top of the quay wall head.

Many contractors recommend installing a new sheet pile wall with a new bulkhead directly in front of an existing sheet pile wall, and filling the void between the sheet piles with backfill, as depicted in Figure (4-b). The good aspect of this rehabilitation technique is that installing the new wall can be done before failure or where the moderate movement has occurred. The disadvantages include the need for specialists to connect the cap beam as well as it is an expensive solution.

Others prefer to install grouted anchors as a rehabilitation technique, as shown in Figure (4-c). The installing of these grouted anchors can be executed either from the land-side or sea-side. The installing from land-side will be executed by excavating behind the wall and then installing anchors, while the installing from the sea-side is considered the best solution for the damaged quay wall. Establishing each grouted anchor from the sea-side requires a hole drilled through the sheet piling wall's head. The anchors must be pre-stressed to control the movements of anchored sheet piles. Unfortunately, in the case of the land-side construction process, the excavation is usually disruptive to property, the construction process takes more

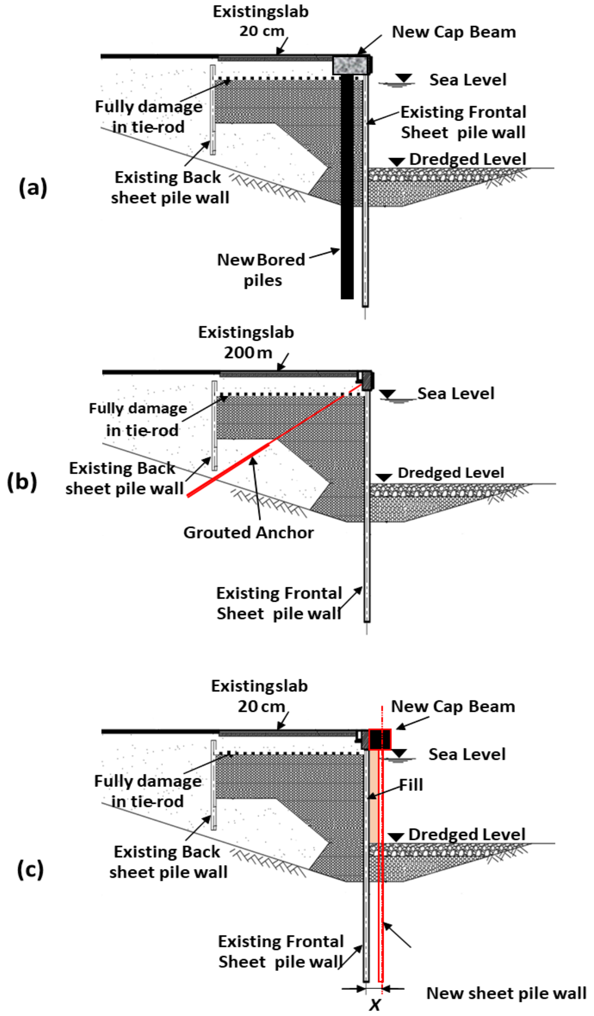

Figure 4: Quay wall rehabilitation technique examples: (a) Installing bored piles behind the existing wall. (b) Installing new sheet pile. (c) Installing ground anchors.

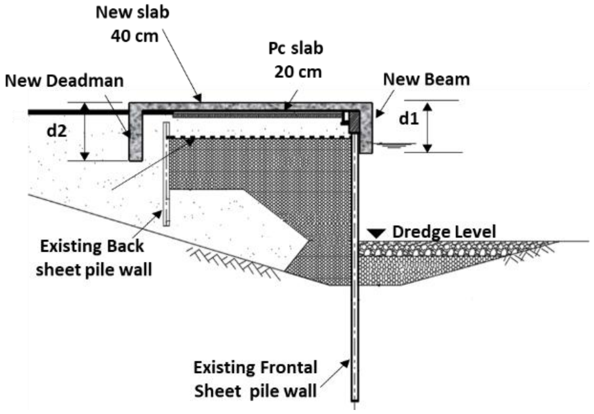

Figure 5: Details of the Suggested rehabilitation method of the inverted U-slab.

time, effort and increases the cost. While, in the case of the sea-side construction process, the grouted anchors technology is highly expensive in Egypt.

In this study, the recommended rehabilitation method of installing inverted reinforced concrete U-slab as a new tie-back system instated of the damaged tie-rod system was chosen to control/restrict the sheet pile wall's lateral displacement as shown in Figure 5. Ultimately, the selective approach consists of a 40 cm top slab connecting both ends to a beam and deadman from the sea-side and land-side, respectively. This slab cover and the sea-side beam will be attached to the old slab and the cap beam by shear connectors. The good point is easier to install and less costly. The disadvantages are that highly skilled specialists are required, berth operations will be disturbed, and surface drainage to the sea will be prevented due to the difference in levels.

3.NUMERICAL MODELING AND ANALYSIS

3.1.Numerical model

The effect of the suggested inverted U-slab rehabilitation technique on the behavior of the defective wall has been investigated numerically using the finite element method (PLAXIS-2D). The two-dimensional model was carried out to evaluate the displacement and internal forces in the stages of the construction sequence. PLAXIS-2D is a widely used finite element tool that can solve geotechnical problems ranging from simple linear analysis to very complicated nonlinear simulations that take into account the influence of soil-structure interaction (Brinkqreve et al., [1]. To set up the numerical model, several data must be defined, including model geometry, material modelling, elements, and analysis type. The FEA is employed in this study by using 15-noded elements. Hardening Soil Model (HSM) was chosen to represent the soil layers to highlight the important role of elastoplastic yielding. The hardening soil model (HSM) was developed, and formulated within the framework of the theory of plasticity (Schanz et al., [13]). The description of soil stiffness is more sophisticated for simulating the behavior of different types of soil in the HSM. This model accounts for shear hardening, compression hardening, stress-dependency of stiffness modulus, pre-consolidation, and finally, the distinction of elastic behavior during unloading and reloading. The yield conditions can be defined using the Mohr-Coulomb failure criterion. The soil stiffness in the primary loading condition is presented in Equation (1).

$$E_{50} = E_{50}^{ref}\left(\frac{\sigma_3'+c\,.\,cot\phi}{p^{ref}+c\,.\,cot\phi}\right)^{m} \qquad (1)$$

Where E_{50} is the elastic deformation modulus for mobilization of 50% of the maximum deviator stress (q_f). (E_{50}^{ref}) is the reference stiffness modulus corresponding to a reference confining stress, p^{ref}. c and ϕ are the drained shear strength parameters of the Mohr-Coulomb failure criterion. σ_3' is the effective confining pressure. m is a power exponent. A power law also describes the impact of unloading and reloading on soil stiffness, as illustrated in Equation (2).

$$E_{ur} = E_{ur}^{ref}\left(\frac{\sigma_3' + c \, . \, cot\phi}{p^{ref} + c \, . \, cot\phi}\right)^m \qquad (2)$$

Where *Eur* is the unloading-reloading deformation modulus; and is the reference unloading-reloading deformation modulus corresponding to a reference confining stress, *pref.*

Another basic characteristic of the HSM is the consideration of the plastic straining due to primary compression, which can be defined as in Equation (3).

$$E_{oed} = E_{oed}^{ref}\left(\frac{\sigma_1' + c \, . \, cot\phi}{p^{ref} + c \, . \, cot\phi}\right)^m \qquad (3)$$

E_{oed} is the tangent deformation modulus for primary loading, E_{oed}^{ref} is the reference tangent deformation modulus corresponding to a reference vertical stress p^{ref}, and σ_1' is the effective vertical pressure. m-values are used to assess the stress-dependent stiffness of the soil according to the power law in the HSM (Janbu, [5]; Von Soos, [14]). The triaxial loading stiffness (E_{50}), the triaxial unloading stiffness (E_{ur}), and the odometer loading stiffness (E_{oed}) are three input stiffness used to define soil stiffness accurately (Schanz et al. [12]). The stiffness parameters for the hardening soil model will be determined using the following fundamental assumptions:

- For soft clay m = 1 and for sand and silts m = 0.5 (Janbu, [4]).
- The reference pressure (p^{ref}) equals 100 kPa.
- The unloading/reloading modulus (E_{ur}) is five times the loading modulus for clay.
- The unloading/reloading modulus (E_{ur}) is three times the loading modulus for sand.
- The in-situ stress is calculated using the value of the at-rest earth pressure coefficient K_o.
- All soil types are assumed to have a drained behavior.

Table (2) presents the input soil parameters, while Table (3) shows the material input parameters for the sheet pile cross-sections used in PLAXIS-2D.

Table 2: Input soil parameters used in PLAXIS 2D.

Soil type	C_d	φ`	E_{50}^{ref} (Kpa) x 10^3	E_{oed}^{ref} (Kpa) x 10^3	E_{ur}^{ref} (Kpa)x 10^3
Backfill	0	30	16.0	28	60.0
Gravel-sand	0	40	64.5	65.1	194.5
Stone	10	30	65.0	59.2	283.0
Medium Sand	0	40	35	138	212.0
Soft clay	12.5	10	3.1	1.5	15.3
Very dense sand	0	40	62	246	283

Table 3: Input material parameters for sheet pile walls used in PLAXIS 2D.

Parameter	**Lx 25 x 10^3**	**Lx 8 x 10^3**	**unit**
EA`	4040	2320	kN/m`
EI	115.312	25.726	kN/m^2/m`

3.2.Quay wall structural modelling

This study adopts the same dimensions of the wharf in the field.The model's stratigraphic boundary is two times larger than the structural region, ensuring that the boundaries have no influence. PLAXIS-2D has been used to model the existing berthing structure using a plate element representing steel sheet pile wall, deadman, slab, and beam. Node to node anchor is how to tie rods are described. The interface element represents the shear connectors. Figure (6-a) shows the model setup and structural element representations before failure, while Figure (6-b) shows the suggested inverted U- slab's configuration as the rehabilitation technique.

3.3.Construction Stages

PLAXIS can simulate all stages of a construction process in the field, including failure. The phases of construction carried out in PLAXIS-2D can be summerized as follows: A) Phase 1: Deactivate the trapezoidal area and activate the frontal sheet pile wall; B) Phase 2: Activate the passive side with gravel to level -6.00 and stone to level -7.0 and the active side with stone to level -7.00; C) Phase 3: Activate the clean sand area; d) Phase 4: Activate the back sheet pie wall; E) Phase 5: Activate the tie-rods and adjust the pre-stress force to 50 KN; f) Phase 6: Activate the gravel layer between the two sheet piles to level (0.00); G) Phase 7: Activate the clean sand layer; H) Phase 8: Activate the slab; I) Phase 9: Activate the backfill; J) Phase 10: Activate the superstructure; and K) Phase 11: Deactivate the tie-rods. The rehabilitation procedure approach will then be introduced in PLAXIS 2D as follows: M) Phase 13: Activate the loads. L) Phase 12: Activate the U-slab and the slab interface.

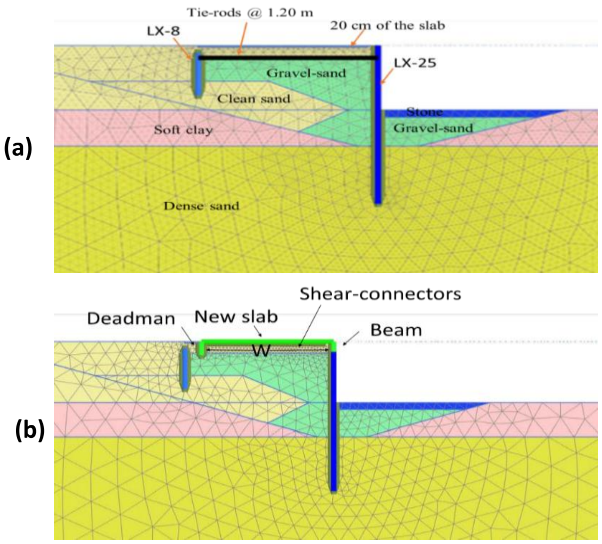

Figure 6: PLAXIS finite element model configuration for (a) Sheet pile quay wall berthing structure and (b) Suggested inverted U- slab rehabilitation technique.

4.RESULTS AND DISCUSSIONS

4.1.The behavior of the quay wall before and after failure

Figure 7 displays results on the behavior of the damaged quay wall before rehabilitating in terms of lateral displacement and bending moment for the case of superstructure completion and tie rod damage. The wall's displacement increases drastically from -2.10 cm to 14.50 cm at the position of the ties due to the tie rods' rupture in tension, as shown in Figure 7-a. As a result, the wall moved towards the sea-side and became a cantilever structure. As illustrated in Figure (7-b), the bending moment along the wall is reversed from +116 KN.m to –272 KN.m. Consequently, the wall is predicted to be safe in flexure, with maximum displacements of roughly 12.3 cm and 15.0 cm at the top of the wall and the slab level, respectively. Figure 8 indicates the deformed mesh of the wall post tie damage. At that time, the sheet pile wall worked as a cantilever wall due to the damage to the tie rods.

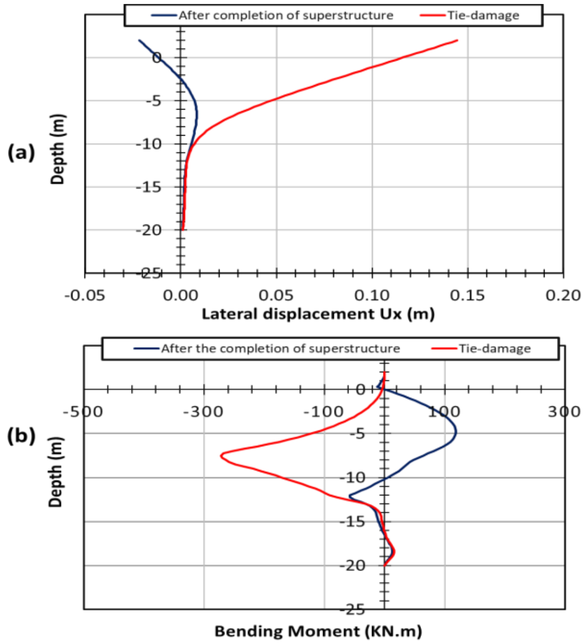

Figure 7: Comparison between sheet pile wall before and after the tie damage with respect to: a) The lateral displacement and B) The bending moment.

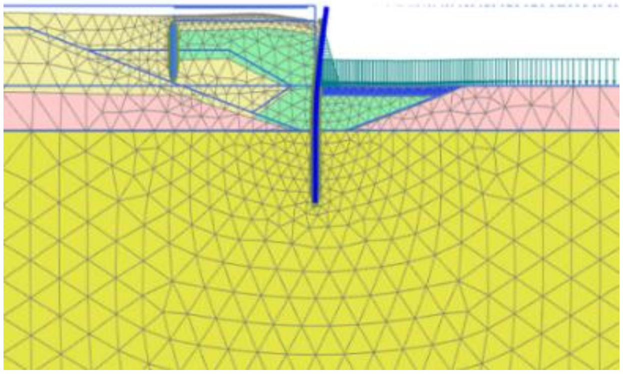

Figure 8: Deformed mesh of the quay wall after tie damage.

4.2.The behavior of the rehabilitated quay wall after installing U-slab technique

The rehabilitating approach works as a new tie-back system instead of the damaged system to support the defective sheet pile wall. It is executed by installing a new slab to the existing slab and connecting a new beam from the sea-side to the current cap beam by shear connectors. On the other side, the new deadman is connected to the new slab. Each component of the suggested approach has a specific function in reinforcing the sheet pile wall. The slab provides lateral support to the existing sheet pile wall while the deadman increases the system fixation and resists mobilization. The sheet pile is connected to the new system by the beam. In this study, a parametric numerical study for the slab's width (*W*), which defined as the distance between the centerlines of the beam and the deadman has been carried out assuming the slab thickness is 40 cm. The impact of various slab widths (*W*) of (16.0 m, 20. 0 m & 25.0 m) has been investigated by calculating the internal forces and the deformation of all system components.

4.2.1. The effect of the slab's width on the friction between slab and soil

The results of the normal forces for slab widths of (16.0 m, 20.0 m, and 25.0 m) have been studied to assess the friction between slab and soil, as shown in Figure(9-a). The results show that as the slab width increases, the tension force decreases while the compressive force increases. This is because as the slab's width increases, the friction between it and the soil increases, as shown in Figure (9-b). Shear dowels connect the new slab to the old slab, allowing them to work as one slab. As a result, the loads are transmitted to the soil by friction, as expected. For 16.0, 20.0 and 25.0 m, the maximum compression forces are 19.60, 70.20 and 91.80 KN/m', respectively, while the maximum tension forces are 63.90, 34.80 and 20.10 KN/m'.

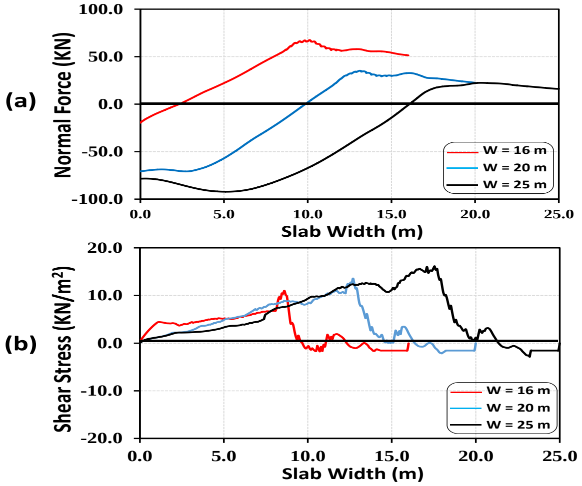

Figure 9: Effect of the slab's width on: (a) The normal force of the slab and (b) The friction between the slab and the soil.

4.2.2. Effect of slab's width on the sheet pile quay wall

In this section, the effect of the slab's width (*W* = 16, 20 and 25 meters) on the sheet pile quay wall has been analyzed, and the results of the displacement and the internal forces of the sheet pile wall are shown in Figure (10). The impact of varied slab widths on the wall's horizontal displacement *Ux* in metres is shown in Figure (10-a). The lateral displacements along the length of the sheet pile wall are relatively similar for different widths, with the most considerable value at the top of the wall, which is around 14.20 cm. Figure (10-b) shows the influence of varying slab widths on the bending moment of the wall in KN.m/m' for slab widths of 16.0 m, 20.0 m, and 25.0 m. The results reveal that the varying widths are identical over the length of the wall. The maximum positive bending moments are 200.20, 193.41, and 186.47 KN.m/m' at connecting the sheet pile wall and the beams, respectively.

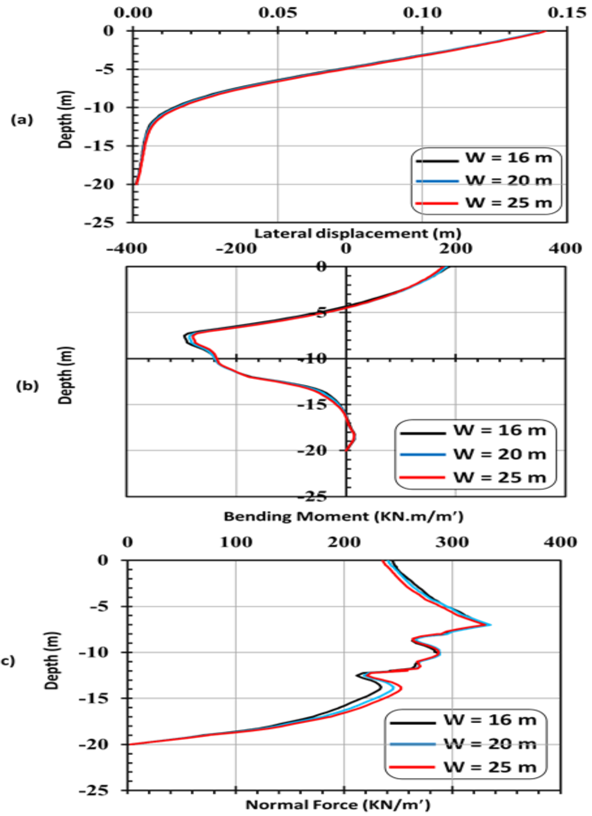

Figure 10: Effect of the slab's width on sheet pile: (a) Lateral displacement, (b) The bending moment, and (c) The normal force.

The maximum negative bending moments vary to reach peak values of 294.80, 285.50, and 279.80 KN.m/m' at -12.05 m depth, respectively. After that, the bending moment values decrease and fluctuate until they reach zero at the end of the wall.

Figure (10-c) illustrates the sheet pile wall's normal compressive force (NF) for slab widths of 16, 20 and 25. The maximum compression forces are 332.45, 335.50 and 330.40 KN/m' at -13.0 m depth for 16, 20 and 25 widths. The deformation, normal force, and bending moment do not change along the length of the existing wall with varying slab widths, according to previous findings.

4.2.3. Effect of slab width on the safety factor

A safety factor of 2.0 is recommended for the tie-back quay wall system (PIANC, [10]). Figure (11) shows that the change in the slab widths has a negligible impact on the safety factor. When the slab width increases, the passive earth pressure behind the deadman also increases which means that the deadman is located entirely in the passive zone. This explains why the safety factor of the inverted U-slab system changes from 2.332 to 2.53 when the slab width increases from 16.0 m to 25.0 m. In this case, the slab width of 16 m satisfies the design requirement.

4.2.4. Comparing the rehabilitating technique to the failure case

Figure (12-a and b) shows a comparison between the defected sheet pile quay wall after applying the U-slab technique and the operational stage with respect to lateral displacement in a meter and bending moment in KN.m/m`, respectively. There is a similar pattern in the horizontal movement for the defected wall and the strategy, as shown in Figure (12-a). The horizontal displacement at the top of the wall rises from 12.30 to 13.78 cm after the inverted U-slab installation. It climbs to 14.80 cm in the operational phase. The bending moment distribution along the wall in Figure (12-b) follows the same trend. Defected wall, U-slab installation, and the operational phase have positive bending moments of 0, 14.90, and 200 KN.m. After the U-slab system is installed, the structure’s weight causes displacement, and the deficient sheet pile wall fails without the additional system in the operational stage In terms of negative bending moments, the defective wall has a bending moment of 272 KN.m. The bending moments are 283 and 295 KN.m after activating the U- slab system and activating the loads, respectively. After damage, the wall's safety factor is 1.241, whereas it becomes 2.33 once the cover is applied.

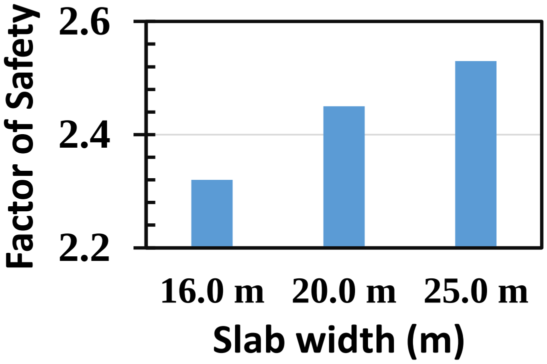

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Figure 11: Effect of the slab’s width on the quay wall safety factor.

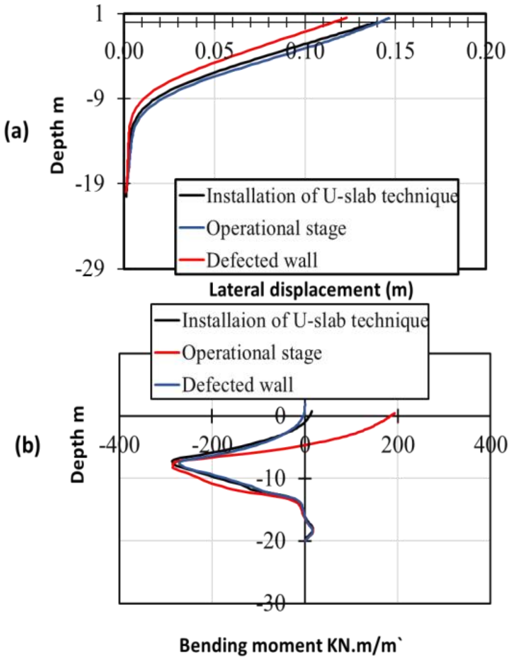

Figure 12: (a)- The comparison of the lateral displacement between the U-slab method and the defected wall. (b)-The comparison of the bending moment between the U-slab method and the defected wall.

5.CONCLUSION

This paper studies numerically a tied-back sheet pile quay wall failure in Egypt, which started to fail after the completion of the superstructure. The failure of the anchored sheet pile wall occurred in the tie rods, resulting in about 15 cm measured displacement at the cap beam level. Inspectors and designers extensively inspected the existing structure and have revealed the absence of waler beams installation at the level of tie rods which led to their loss. And thus, the failure was attributed to the design errors and the tie rod bolts' poor material quality.

The study has provided an overview of common rehabilitating techniques and has discussed its applicability to the current situation. As a result, the inverted U-slab approach was suggested to rehabilitation the system to control/restrict the sheet pile wall's lateral displacement. It consists of a 40 cm slab cover connecting both ends to a beam and deadman from the sea-side and land-side, respectively. This technique's mechanism plays a role as same as the old tied-back system. Instead of installing pretension ties to the sheet pile quay wall and tying them back to the short sheet pile wall, the slab shall work instead of the damaged ties by carrying the tension force. Moreover, the deadman shall provide the fixation and stability to the system instead of the short sheet pile wall. Lastly, the beam can connect the sheet pile quay wall to the system.

The behavior of the sheet pile quay wall before and after the lateral movement and after the application of the inverted U-slab technique were analyzed using PLAXIS 2D. Based on the results of the analysis, it can be concluded that:

- The wall's displacement increases significantly towards the sea at the tie-rods position after their failure.
- The sheet pile wall has been displaced about 2.0 cm after installing the U-slab in the operational phase. This means that the U-slab system restricts the movement of the defective sheet pile quay wall.
- The reduction in tension force was due to the increase in slab width. This is due to the increased stiffness of the slab and friction between the slab and the soil.
- The impact of varying slab widths on the sheet pile wall's internal forces and horizontal movement is negligible. With a slab width of 16.0 m, the safety factor was reached.

Credit Authorship Contribution Statement:

Doaa Essam: Literature review, Methodology, Software, Formal analysis, original draft preparation; and Investigation;

Ehab Tolba: Visualization, Conceptualization, Supervision, Investigation, and reviewing;

Elsayed Galal: Visualization, Conceptualization, Methodology, Original draft preparation, Supervision, Editing, and Reviewing.

6. RECOMMENDATIONS

It is recommended to extent this work including the followings:

- A dynamic analysis study for the U-slab system which is very important for determining whether the quay wall could be developed or not when considering the dynamic loads.
- Searching for creative engineering solutions for solving the problem which may be resulted due to deepening and increasing crane loads for both static and dynamic conditions.
- Conducting multi-criteria analysis on the suggested system.

REFERENCES

[1] Brinkqreve, R.B.J, Broere, W., and Watherman, D., (2004), “PLAXIS – 2D Version 8 Manual”, Plaxis BV, Delft, the Netherlands.

[2] Douairi, M., and De GIJT, J., (2013), "Upgrading Techniques for Quay Walls", IBSE Conference Rotterdam.

[3] El-Naggar, M.E. (2010). "Enhancement of steel sheet-piling quay walls using grouted anchors". Journal of Soil Science and Environmental Management, 1(4), 69-76.

[4] Galal, E. (2017). "A numerical study for upgrading the container terminal of port-said west port". Port-Said Engineering Research Journal, 21(2), 88-97.

[5] Janbu, N. (1963). "Soil compressibility as determined by oedometer and triaxial tests". Proc. ECSMFE, Wies- baden, v. 1, pp. 19-25.

[6] LaGatta, D.P., and Shields, D.R. (1984). "Failure of an anchored sheet pile bulkhead". In Proc., 1st Int. Conf. on Case Histories in Geotechnical Engineering (pp. 393-399).

[7] Lakomski, M., Tosik, G., & Niedzielski, P. (2021). Optical Fiber Sensor for PVC Sheet Piles Monitoring. Electronics, 10(13), 1604.

[8] Littlejohn, S., and Mothersille, D. (2008). "Maintenance and monitoring of anchorages: guidelines". Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 161(2), 93-106.

[9] Mozo, M., and McCullough N., (2013), "Improvements for an aging sheet pile wharf at Mayport Naval statio", American Society of Civil Engineers Journal.

[10] PIANC, (2001). Seismic Design Guidelines for Port Structures. Balkema,Tokyo.

[11] Pilecki, T.J., (1985). “Discussion of paper: Failure of Anchored Bulkhead" by Daniel and Olson, 1982. ASCE Journal of Geotechnical Engineering Division, Vol. III, No. 3.

[12] Sabatini, P.J., Pass, D.G., and Bachus, R.C. (1999), "Geotechnical engineering circular no. 4: Ground anchors and anchored systems”, FHWA Publication No. FHWA-IF-99-015, pp. 281.

[13] Schanz, T, Vermeer, P.A., and Bonnier, P., (1999), "The hardening soil model: formulation and verification". In: Beyond 2000 in computational geotechnics. Routledge, pp. 281-296.

[14] Tan, H., Jiao,Z., and Chen,J. (2018). "Field testing and numerical analysis on performance of anchored sheet pile quay wall with separate pile-supported platform. Marine Structures", 58, 382-398, DOI: 10.1016/j.marstruc.2017.12.006.

[15] Von Soos, P. (1990). "Properties of Soil and Rock (in German) ", Grundbau Taschenbuch Part 4. Ernst & Sohn, Berlin.

[16] Zekri, A., Ghalandarzadeh, A., Ghasemi, P., and Aminfar, M.H., (2015). "Experimental study of remediation measures of anchored sheet pile quay walls using soil compaction". Ocean Engineering, v. 93, PP: 45–63.

[17] Zhang, B., Benmokrane, B., and Chennouf, A. (2000). "Prediction of tensile capacity of bond anchorages for FRP tendons. Journal of Composites for Construction", 4(2), 39-47.