The International Maritime Transport and Logistics (MARLOG 14) - ISSN 2974-3141
http://dx.doi.org/10.21622/MARLOG.2025.14.1.84
Artificial Intelligence Implementations Towards Shaping the Future of Digital World

OPTIMIZING THE DRAFT OF A QUAY WALL TO THE ANCHOR LENGTH RATIO USING FINITE ELEMENT NUMERICAL MODEL

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ABSTRACT

This research studied the effect of varying the distance between the front wall and the back anchor of a quay wall located in Abu Qir, Alexandria, Egypt. The quay wall was built to serve as a multipurpose terminal, the front wall is a combined wall system (tubular steel pipes connected by intermediate sheet piles) and the back (deep) anchor is a barrette pile. Researchers often study quay wall optimization and how various structural and operational changes could affect an existing quay wall's performance. However, the relation between a quay wall's draft and the back anchor length using pile anchors was not studied previously. The added value of this research is providing several ratios between the quay wall draft and the back anchor length.

The analysis was performed by varying the distance of the barrette piles, bringing them closer to and further apart from the front wall to conclude how this variation affects the quay wall elements. The numerical model was calibrated and verified using previous numerical models in two separate locations with different structure systems prior to conducting this research. The analysis was performed by conducting a three-dimensional numerical model using PLAXIS 3D V21 which is a finite element analysis software that models soil/structure interface. The results revealed that as the distance between the front wall and the back anchor increases, the moment increases on the combined wall while decreasing on the barrette, meanwhile, the front wall deflection decreases. The decrease in deflection is limited by the at rest and active plane of failures. It was concluded that the decrease in the front wall's deflection becomes minimal after a draft to anchor length (d/L) ratio of 0.71 and the effect varying the d/L ratio has an immensely greater effect on the back anchor than on the front wall.

Keywords: Quay wall, combined wall, barrette, deep anchor, PLAXIS 3D, Abu Qir Port

1. INTRODUCTION

Quay walls are retaining structures that are used for berthing ships and transporting cargo from ships to shore using cranes and other heavy equipment. The structure system of a quay wall depends on the type of vessel, quay draft as well as the geotechnical conditions and operational loads. Existing ports are expanding to accommodate new generations of commercial containerships [1], therefore, quay walls must be optimized by selecting an appropriate structure system. This paper is organized as follows: Section 3 explores the historical evolution of supply chains and current challenges. Section 4 introduces the methodology and structure of the proposed approach, highlighting the role of AHP and its practical implementation. Section 5 details the use of AnyLogistiX tools in modeling and optimizing supply chains. Section 6 discusses AI's role in scenario generation for sustainability enhancement. Finally, Section 7 evaluates the AS-IS and TO-BE scenarios, offering actionable insights into achieving sustainability objectives and last section 8 concludes the study with limitations and future suggestions.

Al-Jubair and Al-Salih [2] evaluated a proposed design for a 200 m open-berth quay wall using finite element analysis. Two loading scenarios were analyzed: lateral thrust from container, crane, traffic, bollard and earth pressure loads (with and without water level differences) and ship impact loads combined with earth pressure. The results showed the initial design was inadequate, with safety factors approaching unity and excessive displacements and stresses in the sheet piles under both scenarios.

Bildik, S. [3] addressed the strengthening of a port structure in Guinea to accommodate increased maritime trade capacity while preserving ongoing operations and existing infrastructure. Geotechnical analysis was performed using PLAXIS 2D with nonlinear soil modeling. The results demonstrate that hybrid solutions combining reinforced and unreinforced piles can be effectively modeled using finite element methods, ensuring safe capacity increases with appropriate geotechnical precautions.

ElGendy et al., [4] evaluated the structural performance of the quay wall under scenarios involving deepening and increased crane loads at Port Said East Port in Egypt, one of the deepest diaphragm walls, extending 62.5 m below LAT, supports a quay wall with an existing water depth of 18 m. Results indicate that the diaphragm wall can safely withstand a 4 m deepening with current crane loads but that crack width limitations constrain the ability to increase crane loads further.

Galal et al., [5] investigated the failure of a tied-back sheet pile quay wall, which began collapsing after superstructure completion due to tie rod rupture, resulting in 15 cm lateral displacement. To rehabilitate the wall, the research proposed an inverted U-slab technique, comprising a 40 cm thick slab connected to a seaside beam and a landside deadman, providing a tie-back mechanism. Numerical analysis using PLAXIS 2D showed that this method effectively reduces lateral displacement to 2 cm.

Gamal et al., [6] explored structural options for deepening existing quays. A numerical modelling research was conducted on a block-type quay wall at Alexandria Port, Egypt, comparing two techniques for deepening. The first involved an anchored diaphragm wall with a tie to a back barrette, while the second featured a diaphragm wall anchored by a relief slab supported by two rows of piles and a barrette.

Hamet et al., [7] numerically investigates the 3D interaction between Port-Said Clay and a quay wall at East Port-Said Port using the Hardening Soil Model (HSM) and Soft Soil Creep Model (SSCM). Results emphasize the importance of accounting for secondary consolidation effects, which contributed to 25% and 139% increments in horizontal and vertical movements, respectively.

Kamal et al., [8] examined the displacement behavior of a quay wall system using PLAXIS 3D and compared its predictions with field measurements from a case study at Rotterdam Port, South Holland. The numerical performance of the quay wall was analyzed over five years, highlighting the causes of horizontal displacement increments at the wall's top.

Kamal et al., [9] presented a sensitivity analysis of soil interaction using 3D finite element modelling (FEM) for an existing diaphragm quay wall at East Port, Port Said, Egypt. The analysis focuses on the impact of soft clay layer parameters on FEM results for the quay wall. A parametric study was conducted across three different soil profiles, considering strain-hardening constitutive model (HSM) parameters and clay layer thickness.

Kamal et al., [10] proposed a new quay wall system, the Open Cell Sheet Pile (OCSP), designed to replace the existing diaphragm quay wall at East Port Said Port, Egypt. A parametric study with 24 cases using the Hardening Soil Model (HSM) and PLAXIS 3D software was conducted to assess the system's behavior. The results showed that the OCSP system is effective, allowing for an increase in seabed depth by up to four meters, and includes a group of bored piles to support heavy gantry crane loads.

Ku et al., [11] pioneered the numerical modeling of the dynamic behavior of port structures using performance-based seismic design. It evaluates cellular and sheet pile quay walls using three analysis methods. Effective stress analysis, incorporating pore pressure generation and soil-liquid coupling, was employed to assess dynamic responses and soil liquefaction potential.

Premalatha *et al.,* [12] presented a numerical study on pile groups supporting berthing structures subjected to berthing/mooring forces and dredging-induced forces. A 2D finite element model developed using PLAXIS was validated against theoretical solutions, considering three slope configurations to replicate field conditions. The research investigated the bending moment variation, load-deflection behavior of piles and the effects of tie-rod anchors.

Roushdy *et al.,* [13] investigated the performance of separated relief platforms as an upgrade for anchored sheet pile quay walls to accommodate increased vessel drafts and weights. A finite element analysis explored the effects of backfill soil type, separation gap width and the number of supporting pile rows. Results show that stiff clay backfill enhances the performance of the front wall and adjacent pile rows compared to sandy backfill.

Roushdy *et al.,* [14] examined the optimization of retrofitting anchored sheet pile quay walls by adding a relieving platform structurally separated from the wall, using finite element analysis. The research was conducted in two phases: a verification phase using field measurements to validate the numerical model, followed by a parametric study.

Tan *et al.,* [15] examined the performance of a diaphragm quay wall anchored with barrette piles, focusing on long-term field-test results from its first practical application. Key performance metrics, including settlement, lateral deflection, bending moment, tensile force and lateral earth pressure were analyzed. The maximum lateral displacement was 0.23% of the wall height, with barrette piles effectively bearing lateral loads due to their blocking and anchoring mechanisms.

Tolba *et al.,* [16] examined the stability and optimum design of concrete block quay walls, focusing on replacing solid blocks with hollow precast blocks to evaluate potential benefits. Four optimization stages were analyzed for factors of safety against overturning, sliding, bearing capacity and slip failure.

Results indicate that reducing the backfill internal angle of friction (ϕ) from 40° to 30° significantly lowers safety factors for bearing capacity and slip failure, while increasing subsoil cohesion (c) improves bearing capacity stability.

Yajnheswaran *et al.,* [17] examined the effectiveness of diaphragm walls and anchor rods in supporting open berth structures in marine soil conditions, with a focus on the deep draft berth at New Mangalore Port. Diaphragm walls face soil-induced loads, while anchor rods are introduced to improve stability and mitigate lateral loads, thus reducing deflection. The paper utilizes PLAXIS 3D, a finite element software, to analyze the diaphragm wall's performance, specifically measuring displacement, shear force and bending moment with and without anchor rods.

This paper discusses the finite element analysis of a quay wall located in Abu Qir, Alexandria, Egypt. The aim of the research is analyzing the effect of increasing/decreasing the distance between the front wall and the anchor system of the quay wall and how this distance (anchor length) affects the behaviour of the quay wall elements.

2. EXISTING QUAY WALL

2.1. Structure system

The quay wall is a multipurpose terminal with draft 17 m, the front wall is a combined wall consisting of steel tubular piles 2250/18 mm with an RC bored pile connected by double AZ 26-700 sheet piles spaced at 3.71 m. The back anchor is a barrette 2.8 x 0.8 m spaced at 7.42 m and the distance between the combined wall and barrette centerlines is 13 m.

The platform consists of a capping beam 2.3 x 2.5 m and a reinforced concrete deck 0.5 m thick supported by transverse beams 2.3 x 1.5 m spaced at 7.42 m. An overview of the quay wall structure system is shown in **Figure 1**.

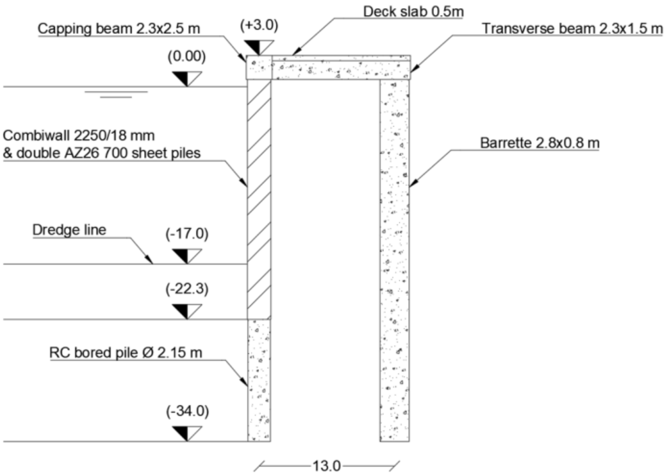

Figure 1: *Quay wall cross section*

2.2. Geotechnical data

Geotechnical data was gathered from the site from several boreholes and the geotechnical parameters were determined from field tests such as SPT and CPT as well as laboratory tests such as direct shear test and triaxial test. Soil stratigraphy is shown in **Table 1**.

Table 1. *Soil layers and their corresponding levels*

Soil layer	Top level (m LAT)	Bottom level (m LAT)	Soil layers	Top level (m LAT)	Bottom level (m LAT)
Reclaimed sand 1	3.0	-5.0	Silt	-36	-38.5
Reclaimed sand 2	-5.0	-10	Clay	-38.5	-42
Reclaimed sand 3	-10	-15	Silty sand	-42	-43.5
Silty sand	-15	-36	silt	-43.5	-60

2.3. Operational loads

The quay wall serves as a bulk/multipurpose terminal, therefore, the operational loads acting on the quay is a surcharge of 60 kN/m2 on the platform and the stacking yard behind it and a bollard load of 480 kN.

3. METHODOLOGY

The analysis was performed by conducting a three-dimensional numerical model using PLAXIS 3D V21 which is a finite element analysis software that models soil/structure interface. The numerical model was calibrated and verified using previous researches that studied similar topics. After verifying the model, different alternatives were proposed for the distance between the front wall and the back anchor as shown in **Table 2** to assess how it impacts the quay wall elements in terms of straining actions and deflection. An optimum draft to anchor length ratio was determined and an equation was developed to estimate the moment acting on the quay wall substructure elements corresponding to any anchor length.

Table 2. *Anchor length alternatives*

Alternative	*Anchor length (m)*	*Alternative*	*Anchor length (m)*	*Alternative*	*Anchor length (m)*
1	6.0	4	12.0	7	16.0
2	8.0	5 (existing)	13.0	8	18.0
3	10.0	6	14.0	9	20.0

4. VERIFICATION OF THE NUMERICAL MODEL

In order to assess the modelling capabilities prior to conducting the research, a finite element analysis was performed based on researches that studied similar topics and the results were compared in order to calibrate and verify the numerical model.

4.1. East Port Said Port

Hamed et al. [7] performed a numerical study on the three-dimensional interaction between Port Said clay and an existing quay wall at East Port Said Port. All barrette dimensions are 3 x 1 m spaced at 7 m along the quay and extend down to -60 m LAT. The diaphragm walls thickness is 1 m, the front and back diaphragm walls extend down to -32 m LAT and -8 m LAT respectively. The capping beam is 3.5 x 3 m, transverse beam is 3 x 0.8 m, the back beam is 3 x 3 m and the deck slab is 0.75 m thick.

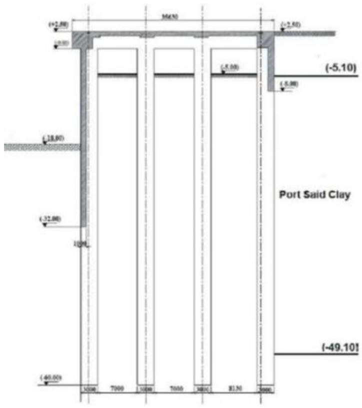

Figure 2: *East Port Said Port quay wall cross section [7]*

The loads acting on the deck included a surcharge of 60 kPa [7], two vertical line loads of 800 kN/m representing the gantry cranes were applied on the front and back beams [7], a mooring line load of 95 kN/m was applied on the front beam, a surcharge of 20 kPa was applied behind the deck for a 30 m wide road and a surcharge of 60 kPa was applied until the end of the boundary [7].
The numerical analysis performed by Hamed et al. [7] studied the undrained (short term) and drained (long term) behavior of East Port Said quay wall. The verification was performed for undrained (short term) behavior. The same geometry, soil parameters, construction phases and operational loads were applied. **Figure 3** shows the deformed mesh for Hamed et al. [7] and the deformed mesh for the analysis performed for the first verification while **Figure 4** shows the horizontal movement due to operational loads.

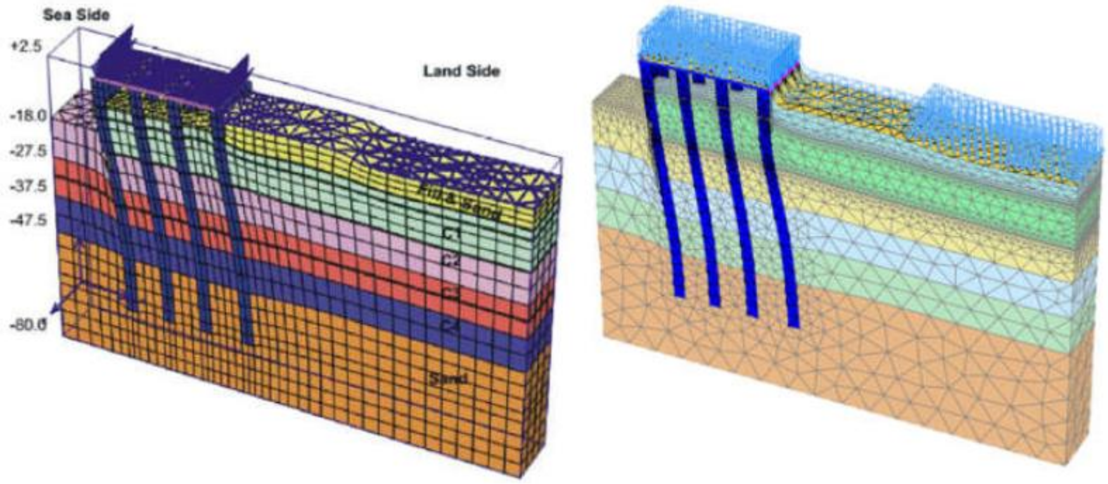

Figure 3: *Deformed mesh comparison, Hamed et al. [7] (left) and verification 1 (right)*

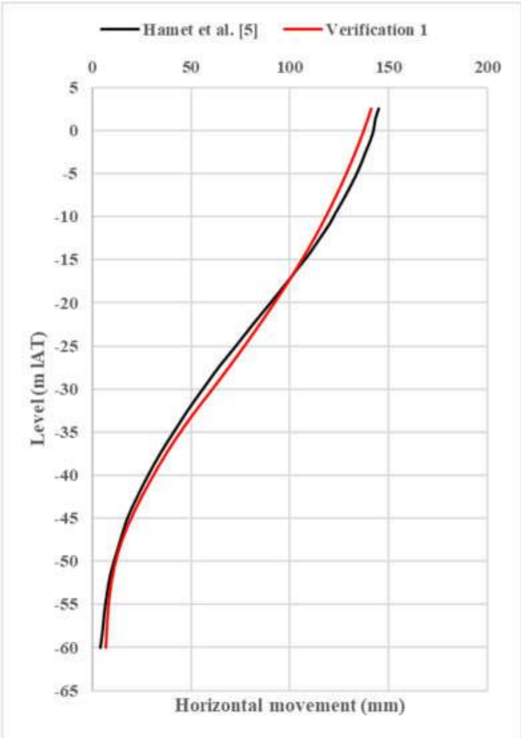

Figure 4: *Horizontal movement comparison, Hamed et al. [7] and verification 1*

4.2. Rotterdam Port

Kamal et al. [8] calculated the horizontal displacement for an existing quay wall located in Rotterdam Port in South Holland and compared it to the horizontal displacement measurement over five years. Rotterdam Deep Sea quay wall consists of combined tubular sheet piles with diameter 1420 mm connected by triple sheet piles. New concrete piles with dimensions 450 x 450 mm were constructed down to -26 m NAP and the back anchor is a steel sheet pile wall AZ36 located 38 m from the quay wall situated between +4.0 m NAP and -4.0 m NAP with a concrete wailing 1.7 x 1.7 m [8]. The dredge line in front of the quay wall is at -12.65 m NAP. The tie rod is a 24 strand FeP 1860 tendon with a strand diameter 15.7 mm and attached to the tubular piles at +1.75 m NAP and ends at 0.0 m NAP at the anchor wall [8]. The anchor centerline spacing is 3.28 m and is as stressed at 1,320 kN with an angle of two degrees [8]. Fig. 6 shows the quay wall as described by Grotegoed et al. [18].

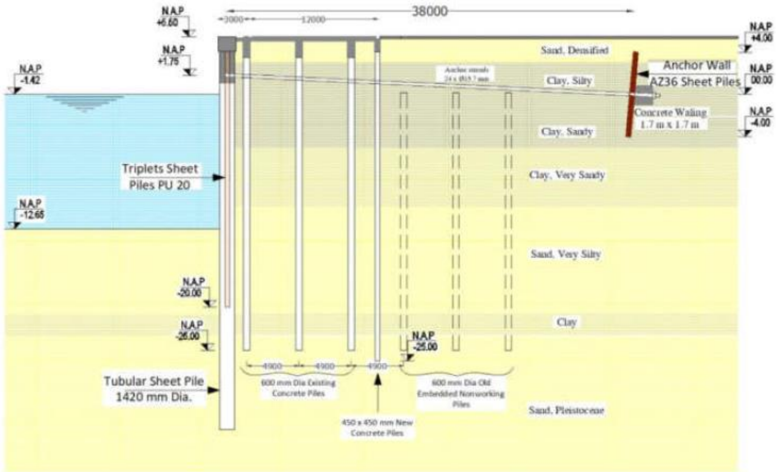

***Figure 5:** Deep Sea quay wall cross section [18]*

The operational design loads acting on the deck included a surcharge of 50 kPa and a line load of 80 kN/m representing the bollard load. Kamel et al. [8] performed the numerical analysis using the Hardening Soil and Mohr-Coulomb failure criteria.

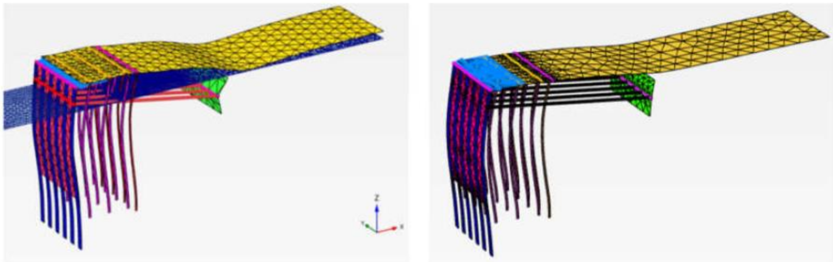

***Figure 6:** Deformed mesh comparison, Kamal et al. [8] (left) and verification 2 (right)*

5. NUMERICAL MODEL OF ABU QIR PORT

5.1. Model input

After calibrating the numerical model using previous researches that studied similar topics and verifying that the author is capable of producing a numerical model with reliable results, a three dimensional numerical model was built using PLAXIS 3D V21, a model width of 14.84 m was adopted which represents the spacing of the bollards installed on the quay wall.

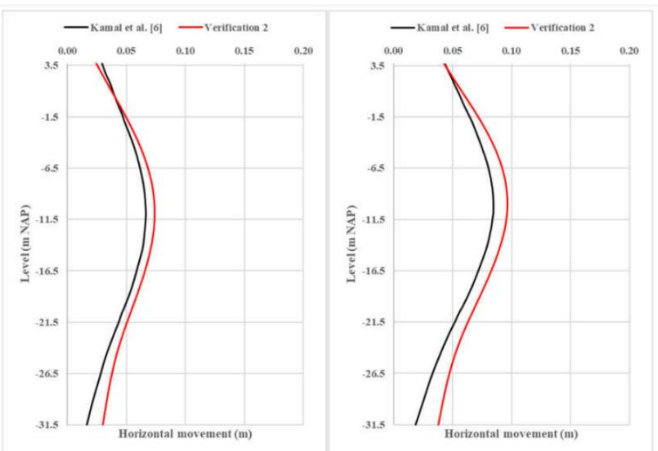

***Figure 7:** Horizontal movement comparison due to dredging (left) and operational loads (right),*

Kamal et al. [8] and verification 2

Table 3. *Numerical model boundaries*

Boundary	Length (m)	Fixity
X_{max}	+100	Normally fixed
X_{min}	-100	Normally fixed
Y_{max}	7.42	Normally fixed
Y_{min}	-7.42	Normally fixed
Z_{max}	+3.0	Free
Z_{min}	-90	Fully fixed

Table 4. *Soil parameters*

Soil layers	*Material model*	*Drainage*	*γ unsat/sat (kN/m3)*	*E (MPa)*	*v*	*C (kN/m²)*	*φ(°)*	*ψ*
Reclaimed sand 1	Mohr-Coulomb	Drained	18/20	$20 + 1.5\,^{a}z_0$	0.33	-	31	1.0
Reclaimed sand 2	Mohr-Coulomb	Drained	18/20	$20 + 1.5\,^{a}z_0$	0.33	-	34	4.0
Reclaimed sand 3	Mohr-Coulomb	Drained	18/20	$20 + 1.5\,^{a}z_0$	0.33	-	38	8.0
Silty sand	Mohr-Coulomb	Drained	18/20	$50 + 2\,^{b}z_1$	0.3	-	38	8.0
Silt	Mohr-Coulomb	Drained	17/17	50	0.3	-	34	4.0
Clay	Mohr-Coulomb	Drained	18/18	50	0.3	-	21	0

$^{a}z_0$ is the depth below ground level
$^{b}z_1$ is the depth below natural seabed level

Table 5. *Material properties*

Material	*Material model*	*γ (kN/m³)*	*E (GPa)*	*v*
Concrete	Linear elastic	25	31	0.2
Steel	Linear elastic	78.5	210	0.2

All concrete elements were modelled as volume elements which is the most suitable choice of modelling for laterally loaded embedded structures [19]. The Rinter values for soil/steel interface and soil/concrete interface were set at 0.67 and 1.0 respectively [20].

Stages of construction started by initializing the K0 procedure which is the direct generation of initial effective stresses, pore pressures and state parameters followed by activating the substructure then the superstructure in the geometry. Dredging was performed by deactivating the soil on the sea side of the quay down to -17 m LAT then down to -19 m LAT which allows for scour protection rock installation. After dredging, soil is activated up to -17 m LAT and the material is changed to scour protection rock. Operational loads are then applied which consist of 60 kN/m2 surcharge on the platform and the stacking yard until the end of the boundary and a concentrated point load of 480 kN was applied which represents the bollard pull force. The stages of construction are shown in **Table 6**.

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Table 6. *Stages of construction*

Construction phase	*Phase description*
Initial phase Initial	phase (initializing K_0 procedure)
Phase 1	Substructure construction
Phase 2	Superstructure construction
Phase 3	Dredging seaside in front of the quay wall down to -17 m LAT
Phase 4	Dredging seaside in front of the quay wall down to -19 m LAT
Phase 5	Installing scour protection
Phase 6	Operational loads (60 kN/m^2 surcharge + 480 kN bollard load)

6. RESULTS

6.1. Deformations

Quay wall deformation due to operational loads is shown in **Figure 8**.

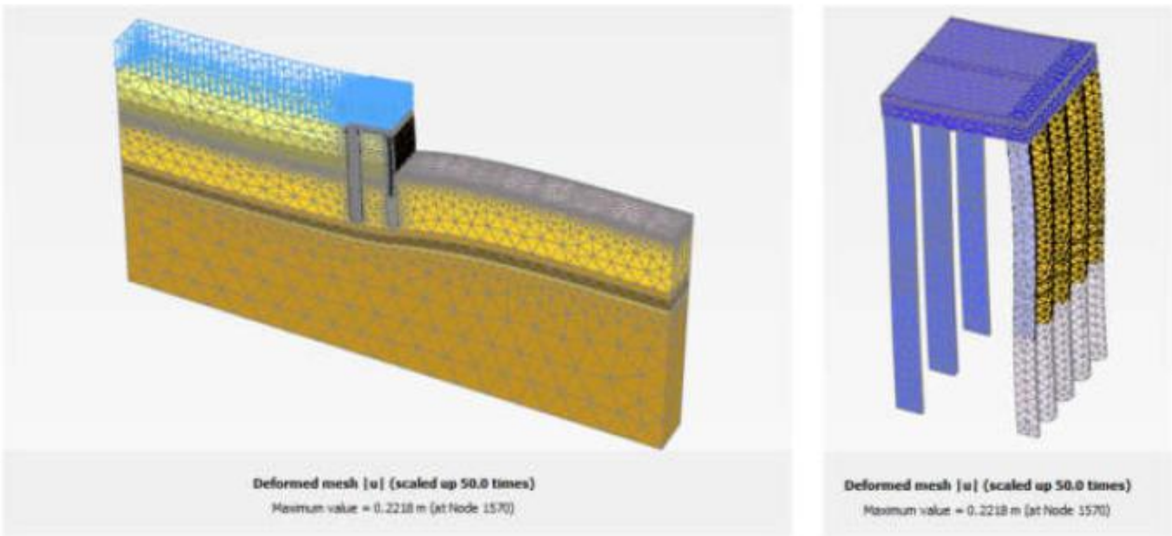

Figure 8. *Quay wall deformation due to operational loads*

Nine alternatives were modelled as shown in Table 2 to conclude how the anchor length affects the quay wall elements in terms of deformation and straining actions. As the distance between the front wall and the back anchor decreases, the front wall movement increases. This is due to moving the barrettes away from the active soil wedge and into the passive soil zone which aids in anchoring the barrettes. The decrease in the front wall's deflection becomes minimal after a draft to anchor length (d/L) ratio of 0.71. The front wall horizontal movements and the draft to anchor length ratios are shown in **Figure 9**.

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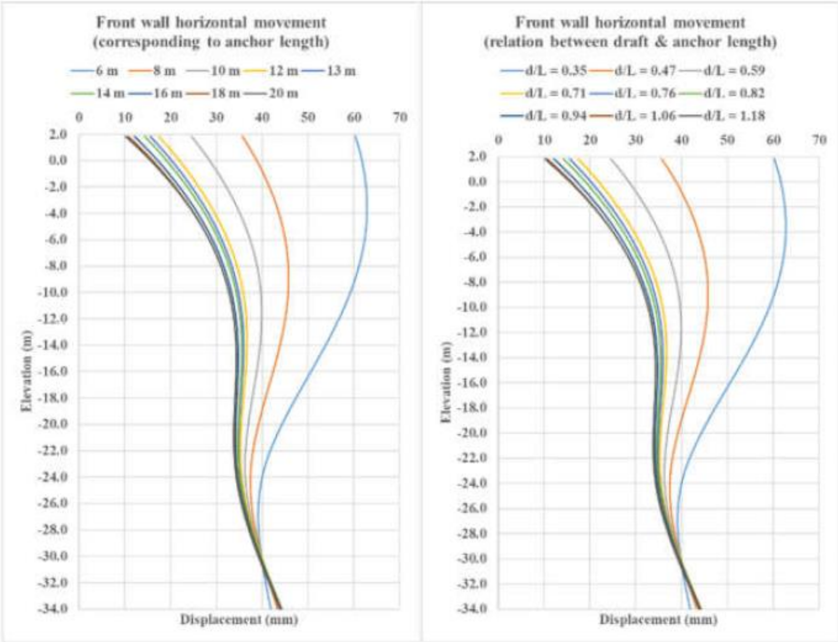

Figure 9. *Front wall horizontal move*

6.2. Straining actions

6.2.1. Combi-wall

Straining actions for the combi-wall are shown in **Figure 10**. Maximum differences of 4.6%, 11.1% and 34.8% were obtained for normal, shear forces and bending moment respectively. The comparison was made between the 6 m and 20 m anchor lengths.

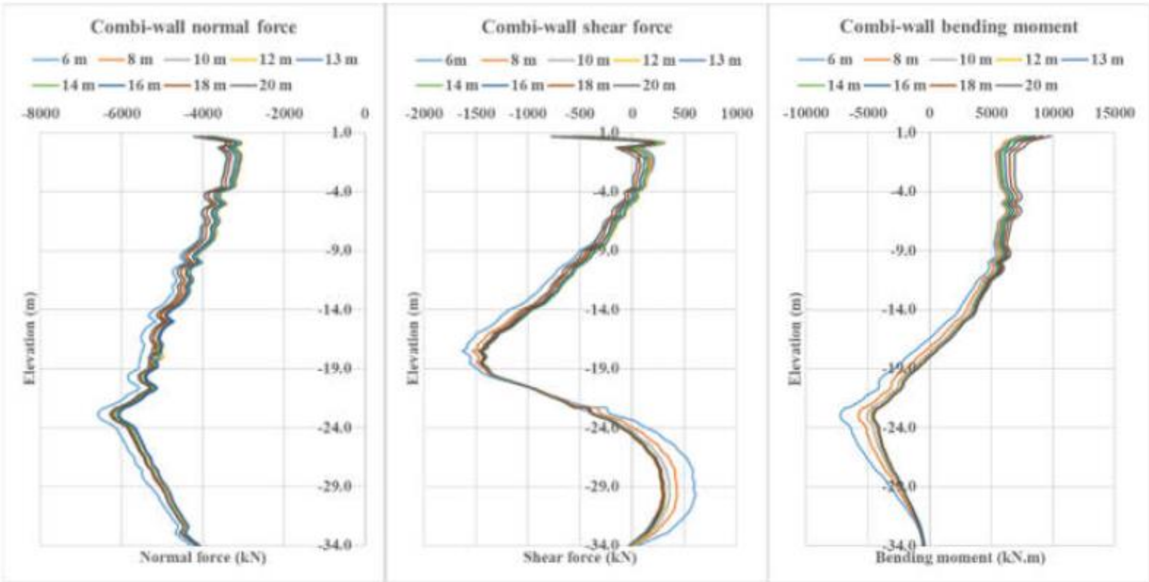

Figure 10. *Front wall bored pile straining actions*

6.2.2. Barrette

The same analysis was performed for the barrette as shown in **Figure 11**. Maximum differences of 950%, 412% and 690% were obtained for normal, shear forces and bending moment respectively. The comparison was made between the 6 m and 20 m anchor lengths.

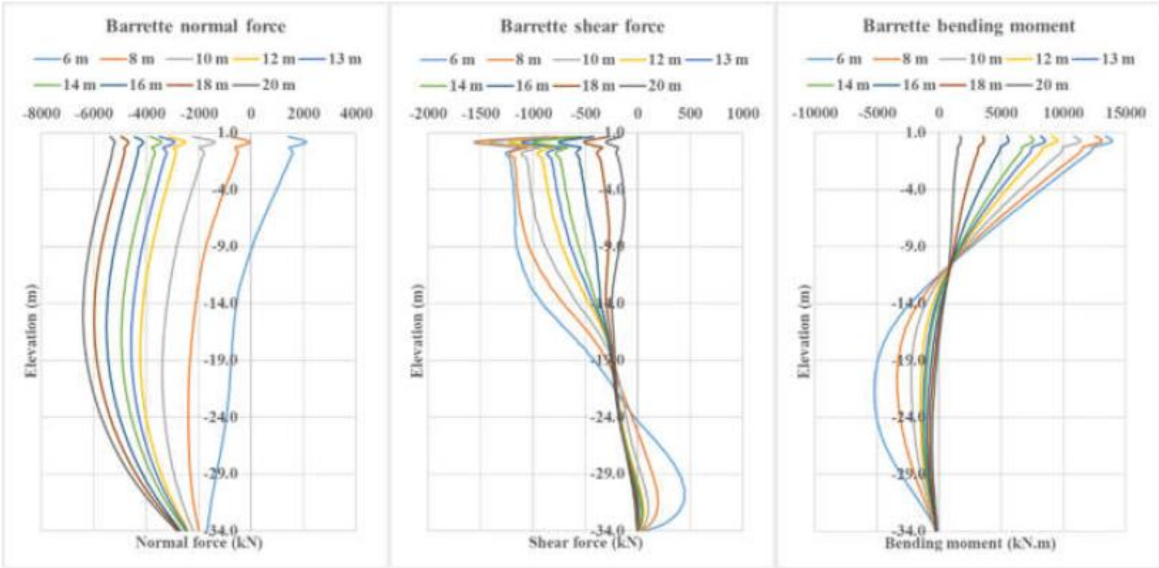

Figure 11. *Barrette straining actions*

The analysis showed that varying the d/L ratio affects the combi-wall moderately (34.8% difference in bending moment) but affects the barrette immensely (690% difference in bending moment). Bending moments acting at the top of the quay wall elements were extracted for each alternative and plotted in order to obtain a formula which estimates the value of the bending moment for any anchor length as shown in **Figure 12**. The bending moment for the combi-wall was almost stable from 6 m to 10 m anchor lengths and started increasing at 12 m anchor length while the barrette bending moment changes considerably for every anchor length.

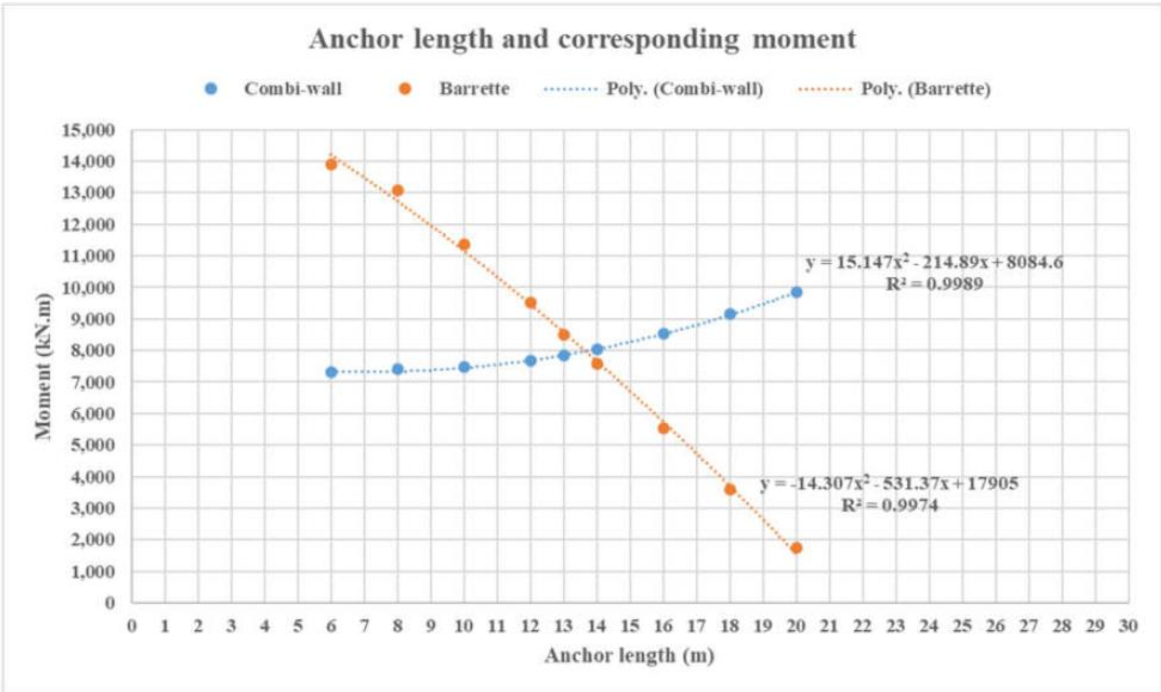

Figure 12. *Anchor length and corresponding moment*

7. CONCLUSION

The research concluded that choosing an anchor length of 13 m was the optimal approach for designing this multipurpose quay wall where the straining actions and deformations were optimized for the combi-wall and the barrette. The following conclusions were obtained from this research;

- The location of a pile back anchor requires optimization through trial and error.
- As the anchor length increases, the front wall deformation decreases.
- As the anchor length increases, the bending moment increases on the front wall element and decrease on the barrette.
- The most significant deformation value is governed by a draft/length (d/L) ratio of 0.71, this ratio may be used by future designers for multipurpose quay walls with similar soil profiles and similar structure systems.
- The front wall element is not affected as substantially as the back anchor element while varying the anchor length.

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