OPTIMIZATION OF RETROFITTING AN ANCHORED SHEET PILE QUAY WALL USING SEPARATED RELIEVING PLATFORM

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1. **ABSTRACT:** In the maritime field, quay walls serve as vital components of port infrastructure, acting as pivotal linchpins in the maritime arena. Anchored sheet piles, a globally employed type of quay wall, play a crucial role in meeting the diverse service needs of seafaring vessels. As the maritime field experiences growth and vessels increase in size and tonnage, the necessity to upgrade existing quay walls becomes imperative to accommodate evolving demands. This paper focuses on optimizing the retrofitting process through the addition of a relieving platform structurally separated from the existing quay wall, utilizing finite element analysis for a comprehensive investigation. The research comprises dual-phase exploration, commencing with a verification stage followed by a parametric study. In the verification phase, field measurements conducted by others were employed to validate the numerical model. Subsequently, the validated model underwent expansion, encompassing various backfill soil types, number of piles supporting the platform, stiffness of the used piles, spacing of piles, bearing levels of piles, and different platform elevations. The results indicate that an increased number of piles supporting the platform is unfavorable when dealing with cohesionless soils, slightly reducing the maximum straining actions on the front wall and the tension affecting the tie rods. Conversely, straining actions on the pile rows were marginally reduced, regardless of the backfill soil type. Additionally, increasing the pile stiffness noticeably reduced the lateral displacement but increased the maximum bending moment on the front wall for all examined soil types, but the tie rod tension slightly decreased. Moreover, increasing the pile spacing has a modestly increased effect on the straining actions for the front wall and tie rods in cohesionless soils, with negligible effects in cohesive soils. Adjusting the pile bearing levels has a minor effect on the front wall and tie rods, whereas an increase in the bearing level results in heightened straining actions affecting those piles. Finally, modifying the platform elevation significantly increases the bending moment affecting the front wall, emphasizing the need for careful safety checks when adjusting the platform elevation.

2. INTRODUCTION

Anchored sheet pile walls are deemed essential type of soil retaining structures, distinguished by their swift execution, applicability across various soil types, and cost-effectiveness. Widely utilized globally, these walls are employed to resist the loads induced by the retained soil height, and the operation loads. Their versatility extends to maritime applications, finding use in both temporary works and permanent structures, such as quay walls.

Given the advancements in the maritime sector, particularly in vessel sizes and loads, upgrading existing quay walls has become essential to effectively handle the increased operational loads. To upgrade a quay wall, the prevalent local approach involves constructing another quay wall in front of the existing one that is specially designed for sustaining the anticipated loads. The area between the existing and the new quay walls is then filled. However, a notable drawback to this method is the substantial cost associated with building a new quay wall, coupled with the consequent reduction in the water surface area within the port.

This study aims to optimize the retrofitting method for anchored sheet pile quay wall introduced by Roushdy *et al.* (2023) [1] by incorporating a separate relieving platform supported on piles within the back yard of the existing quay wall. This approach has been demonstrated to markedly diminish straining actions affecting the entire system, facilitating the initiation of the upgrading process.

The present study entails finite element analysis of an upgraded anchored sheet pile quay wall with a separated platform. The investigation aims to determine the optimal configuration for this platform, considering factors such as pile bearing levels, platform elevation, pile spacing, and stiffness to achieve the highest efficiency for the upgrade.

Bilgin (2010) [2] investigated the construction methods of sheet pile walls, focusing on excavation and backfilling, and their impact on soil behavior, wall deformations, bending moments, and anchor forces. Using finite element modeling and analysis, the study specifically examined the behavior of anchored sheet pile walls in cohesionless soils. The findings revealed that walls constructed by poor backfilling method resulted in significantly higher bending moments and wall deformations. The paper also offers design recommendations for anchored sheet pile walls constructed by different methods.

Qu *et al.*, (2017) [3] proposed a simplified seismic design approach for anchored sheet pile walls and validated it through large shaking table tests. The results showed that the proposed approach is reliable and provides accurate calculations for earth pressures and cable tensions. They found a high correlation between theoretical results and experimental data, and recommended further research to study different pile-anchor dynamic interaction problems. The study aimed to provide a reliable basis for the application of this structure in high seismic intensity zones.

Tang *et al.*, (2014) [4] conducted a shake-table test on a 2x2 pile group behind a sheet-pile quay wall to investigate the behavior of the pile and the soil under liquefaction-induced lateral spreading. Their study found that the rear-row piles near the quay wall experienced larger bending moments than the front-row piles, indicating significant pile group effects.

Zekri *et al.*, (2015) [5] conducted shaking table tests to analyze the deformation of anchored sheet pile quay walls in a liquefaction susceptible layer. The study included improving the model in different scenarios and considering two normalized factors. They found that the seismic performance of sheet pile quay walls being highly dependent on liquefaction occurrence, with different modes of failure identified. The study also discussed the potential mitigation methods for liquefaction, such as soil improvement, water drainage paths.

Gazetas *et al.*, (2016) [6] reviewed current design practices for anchored steel sheet-pile walls in non-liquefiable ground and investigated the performance of a quay wall in sandy soil during strong earthquakes. They compared simplified design methods to finite element analysis and found that the latter provides more reliable results.

Tan *et al.*, (2018) [7] initiated field testing and numerical analysis of anchored sheet pile walls with separate pile-supported platforms. They used finite element modeling and instrumentation to monitor the behavior of the structures during construction. Their findings indicate that the separate pile-supported platform effectively reduces lateral earth pressures on the wall and transfers vertical loads to the piles. The researchers recommend considering the effects of construction steps, such as dredging and surface loading, and caution against relying solely on conventional calculation methods for earth pressure in such structures.

Singh and Chatterjee (2019) [8] investigated the effects of vertical upward seismic acceleration and surcharge on the stability of cantilever sheet pile walls in different types of sand. They used a pseudo-static approach and finite difference-based program FLAC2D for analysis, including numerical modeling, model validation, and a parametric study. They found that increasing the coefficient of horizontal seismic acceleration leads to increased deflection and settlement of the walls. It also observed the formation of heave on the ground surface due to the increase in seismic inertia force.

Zhao *et al.*, (2019) [9] performed field measurements and numerical studies of the behavior of anchored sheet pile walls constructed with excavating and backfilling procedures. The study found that the dredging process has considerable effect compared to the backfilling process on the sheet pile lateral displacement, and in the long term, the deflection increased accompanied by reduction in tie rod tension.

Qu *et al.*, (2016) [10] proposed a novel approach for the seismic design of anchored sheet pile walls, considering the non-linear behavior of soil using Mohr-Coulomb failure criteria. The study focused on identifying the effects of various parameters on the performance of tie-back sheet pile walls, suggesting potential directions for further research on seismic design and upgrade strategies.

An *et al.*, (2015) [11] Performed finite element analysis (FEA) on a sheet pile wharf with a separated relieving platform using ABAQUS to assess how the platform influences the overall internal forces in the system. The findings indicated a substantial reduction in the bending moment on the front wall and a decrease in tie rod tension due to the presence of the platform.

Cai *et al.*, (2015) [12] Conducted an FEA study with ABAQUS, examining two cases similar to An *et al.*, (2015) [11] but with a water depth of 11.80 m. Following Cai and his coauthors' approach, it was inferred that the lateral earth pressure distribution resembled the typical relieving effect. Consequently, all internal forces were lower in the case of the separated relieving platform in comparison to the conventionally anchored sheet pile wall.

Li *et al.*, (2012) [13] Conducted a one-year prototype observation of the new system featuring a front diaphragm wall during basin dredging to refine computational theories for this structure. The findings indicated that the platform's presence, along with the piles, led to a reduction in lateral earth pressure and all internal forces on the front diaphragm wall.

Tan *et al.*, (2014) [14] and Jiao *et al.*, (2015) [15] Explored the dynamic response of an anchored sheet-pile wall with a separated relieving platform to horizontal seismic loads through 2D finite element analysis (FEA). The investigation considered various earthquake characteristics, validating FEA results with field test observations. Both studies affirmed the effectiveness of the separated relieving platform system under seismic loads, highlighting the essential role of the tie rod in ensuring system functionality.

Chen *et al.*, (2018) [16] Created a numerical model derived from an engineering prototype to assess pile row optimization while maintaining a constant concrete volume. Findings indicated that increasing pile spacing and stiffness could diminish straining actions on the front wall, leading to a reduction in the front wall section.

El Naggar (2010) [17] examined the use of additional anchored tie rods grouted into the backfill soil to enhance the load-carrying capacity of steel sheet-piling quay walls. Through a parametric study using finite element analysis. The study analyzed various factors such as sheet-pile wall geometry, grout-ties area, inclination and location, length of grout, dredging depth, and backfill soil angle of internal friction. The findings emphasized the effectiveness of the grouted anchors technique in improving the load response of sheet-piling quay walls.

Zhang *et.al.*, (2015) [18] simulated design conditions before and after river channel dredging, examining earth pressure, settlement, and the shoring structure's horizontal displacement for a sheet pile wall. They found that the sheet-pile structures can effectively upgrade waterways without widening the water surface, thanks to their anti-overturning and sliding characteristics.

Mollahasani (2019) [19] investigated the use of submerged grouted anchors to enhance the load response of sheet-piling quay walls utilizing finite element analysis. The study assessed various factors like grout-ties area, length of the grouted body, anchor inclination, and location, and found that submerged grouted anchors effectively enhance the load response of sheet-piling quay walls.

Chen *et al.*, (2023) [20] employed centrifuge testing and three-dimensional finite element (FE) simulation, incorporating an advanced soil constitutive model, to assess the suitability and reinforcement effects of cement deep mixing (CDM) for stabilizing anchored sheet pile quays (ASPQ) in soft clay. They found that the effectiveness of CDM was closely tied to its strength, slenderness ratio, and excavation depth ratio and the influence of CDM block strength on quay wall response was significant under low rigidity conditions.

Roushdy *et al.*, (2023) [1] explored the behavior of anchored sheet piles under various separation gap widths and backfill soil types. The study revealed that incorporating a separated platform is notably effective for upgrading existing anchored sheet piles, irrespective of the backfill soil type. The research identified optimal performance when the separation gap width is minimized.

Building upon the existing literature, researchers have concentrated on understanding the behavior of sheet pile quay walls under both static and dynamic conditions, along with exploring potential enhancements. This study further contributes by conducting a thorough parametric exploration of the upgrade involving the addition of a separated relieving platform supported on piles to an anchored sheet pile wall.

3. CASE STUDY

The case under examination parallels the approach of Roushdy *et al.*, (2023) [1] that is based on the field measurements provided by Endley *et al.*, (2000) [21]. These measurements were conducted during the construction and dredging phases of a general cargo-type quay wall situated within the Port of Freeport, Texas. The structural system of the measured quay wall is an anchored sheet pile wall with an attached relieving platform, as depicted in Figure 1.

As provided by Endley, the soil deposits are comprised of stiff overconsolidated clay (OC clay) topped with a thin layer of recent river deposits. The front wall is of LARSSEN-VS type was installed to a depth of (-21.60m) below mean water level (MWL) with a section modulus of 970 cm^3/m. The sheet pile is anchored using Dywidag No.18 tie rods spaced at 2.00m center-to-center with a diameter of 57mm. The capacity of this tie rod section was calculated to be 1423 kN.

The platform was of 1.00m thickness, supported on 5 auger piles rows of a 60cm diameter bearing at (-21.00m) below MWL. These piles are spaced at an array of 4.40x2.00m for the in-plane and out-of-plane directions respectively. The draught of the quay wall was designed at (-11.60m) below MWL.

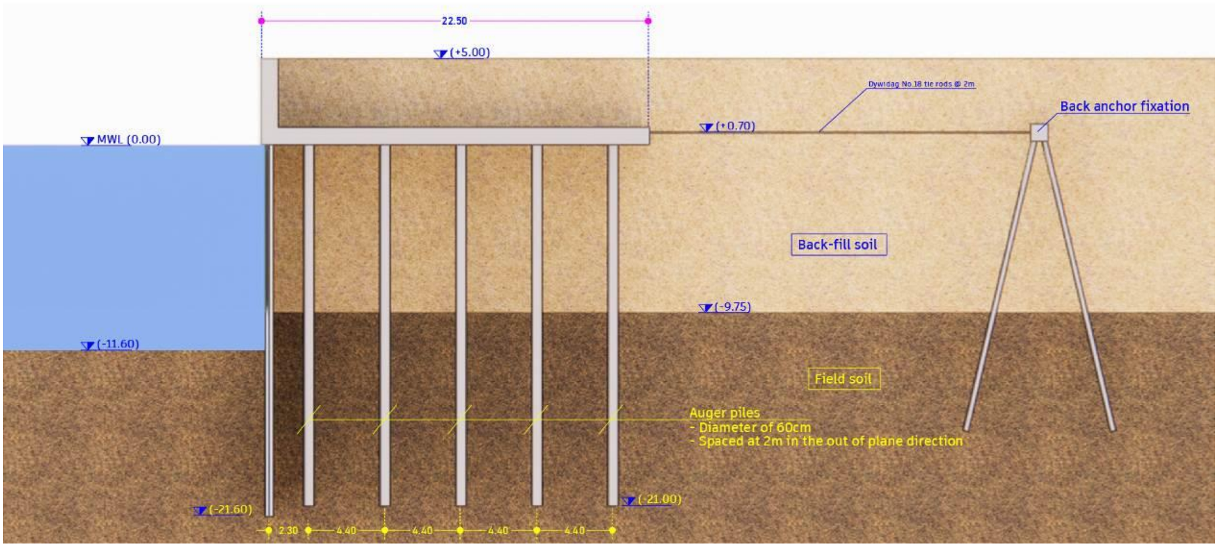


Figure 1: Cross-section of the measured quay wall

The measurements were conducted utilizing the instrumentations provided by Endley *et al.,* (2000) [21]:

1) For deflection measurement, a total of six inclinometers were installed on the sheet pile wall, distributed along six locations.
2) To measure the lateral earth pressure coefficient, three Earth Pressure cells were installed at three locations behind the sheet pile wall.
3) To detect strain affecting the sheet pile, three arrays were installed along the longitudinal direction of the quay wall. Each array comprises seven strain gauges equally spaced from MWL to -21.60m.
4) To measure tie rod tension, two load cells were installed at both ends of the tie rod, providing data for three of the tie rods.

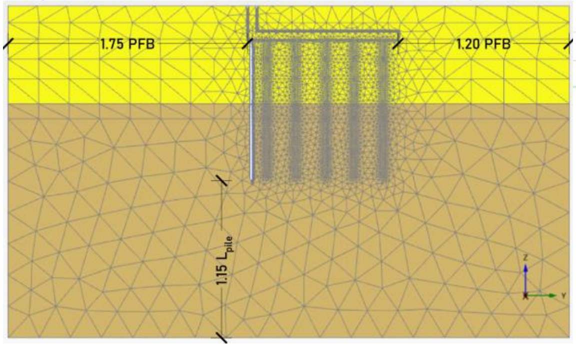
The construction commenced with the dredging of the soft soil layer, succeeded by the installation of the front sheet pile wall, whalers, and tie rods. Subsequently, the backfilling process was initiated, employing clamshell buckets to drop sand from a height of approximately 4 meters above the water line.

The first set of readings from the instrumentation was recorded after the backfilling process was completed in October 1986. This initial set indicated a noteworthy lateral displacement of approximately 13.0 cm towards the seaside, with the quay wall's draught measured at 9.70 m during that period. Following the backfilling, the auger piles were implemented, and a subsequent set of readings was taken in December 1986. The third and final set of readings was obtained after the completion of the superstructure in November 1987.

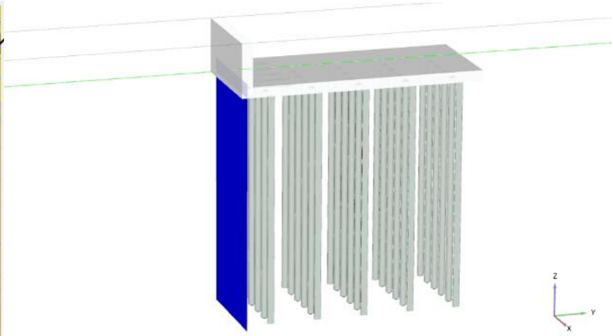
Inferred from the recorded readings, the researchers concluded that the substantial deflection observed in the front wall could be attributed to the backfilling method. They associated the act of dropping the backfilled sand from a considerable height into the water with the loss of a significant portion of the sand's shearing strength and stiffness, consequently causing extensive and unforeseen lateral movement.

4. NUMERICAL MODELLING

Utilizing the readings from the instrumentation within the measured quay wall illustrated in Figure 1, validation of the Finite Element Model (FEM) was conducted. The model was generated through the widely recognized Finite Element (FE) software PLAXIS, known for its capability to simulate various problems in both 2D and 3D. The validated model was developed in a 3D continuum using PLAXIS 3D and is presented in Figure 2.



(a)



(b)

Figure 2: Numerical model: (a) Adopted meshing configuration, (b) perspective view of the model components

4.1 Geometric representation

Within the validated Finite Element Model (FEM), the front sheet pile wall was represented as a plate element, while the associated tie rods were simulated as bar elements. The platform, capping beam, and auger piles were modeled as volume elements to model the stiffness characteristics of the concrete components in the model. Finally, the soil deposits were simulated using 3D solid elements.

Endley *et al.*, (2000) [21] did not provide information about the back anchor. Hence, it was modeled in the FEM as a Fixed end anchor, which accounts for the effect of the anchorage without delving into the details of the anchor structure. This approach was considered acceptable given that the primary focus herein is on the behavior of the front wall and ties. The equivalent length used for the fixed end anchor was 30m.

In an effort to limit mesh sensitivity, various mesh sizes were examined with, eventually refining the meshes to encompass 172,014 elements and 299,030 nodes. The boundary conditions illustrated in Figure 2 for the FEM cover a range from 0 to 10m in the X direction. They extend 1.75 of the Platform breadth (PFB) towards the sea-side and 1.20 of PFB towards the land direction.

Additionally, for the vertical direction, the boundary extends 1.15 of the Piles length below the bearing level of piles. These adjustments were made to minimize the impact of boundary fixation on the model results.

4.2 Material representation

The elasticity modulus for steel members was set at 210 GPa, while for concrete elements, it was set to 20 GPa.

The Mohr-Coulomb's failure criterion for plastic behavior defined all soil deposit layers. The selection of the Mohr-Coulomb's model was based on its widespread use and simplicity in geotechnical applications. Additionally, the study considered the impact of the backfilling methodology on the strength of the backfill soil. The analysis incorporated soil properties derived from Endley *et al.*, (2000) [21], and these properties are outlined in Table I.

The fill layer spanned from the berth level to a depth of -9.70m below MWL, with an underlying overconsolidated clay layer extending throughout the entire model, as specified in the reference paper [21]. The water line was considered to be at 0.00m.

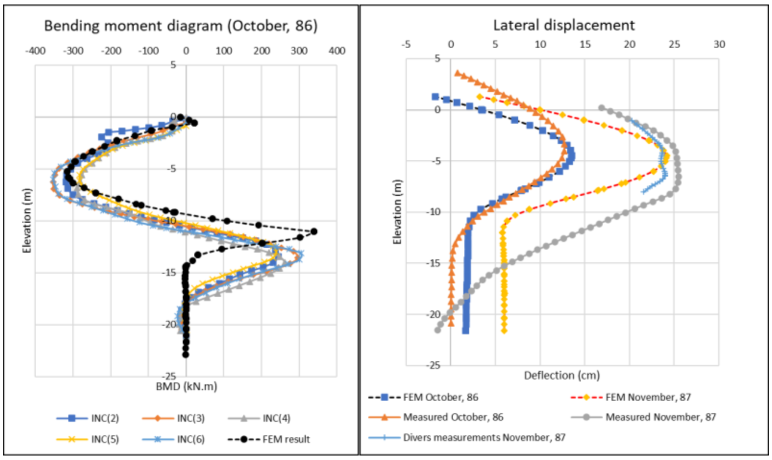
The interaction between the volume piles and the adjacent soil was simulated using interface elements, with interaction strength contingent on the characteristics of the surrounding soil. The coefficients for the soil layers' interfaces are provided in Table I.

Table I. Soil parameters employed in the verification

Soil	*Unit weight (kN/m^3)*	*Internal friction angle (deg.)*	*Undrained shear strength (kPa)*	*Elastic modulus (kPa)*	*Poisson's ratio*	*Interface*
OC Clay	19.50	---	100	30.00	0.40	1.00
Hydraulic sand	18.00	20	---	Less than 1.00	0.30	0.70

4.3 Verification of the numerical model

For the verification of the numerical model, the field measurements acquired by Endley *et al.*, (2000) [21] were juxtaposed with the FEM results during corresponding construction stages (instrument readings in October 1986 and November 1987) simulating the readings taken after backfilling, and after the completion of superstructure respectively.



(a) (b)

Figure 3: Front wall verification results: (a) Bening moments, (b) Lateral displacements

Figure 3 (a) illustrates the comparison initiated between the bending moment derived from the integration of the readings from the six inclinometers installed on the front wall and the bending moment resulted from the FEM. The agreement between the two bending moments is generally satisfactory, except at the anticipated interface between the two layers. This discrepancy could be attributed to uncertainties related to the top elevation of the overconsolidated clay layer.

Comparing the wall deflection measured throughout and after construction with the lateral displacement computed by the FEM, as presented in Figure 3 (b), reveals good alignment between the numerical predictions and the recorded field data during construction (October, 1986 readings). And there is a reasonable level of agreement at the completion of construction (November, 1987).

The maximum tension force recorded in the tie rods following the backfilling was around 106 kN/m, whereas the tension force derived from the FEM amounted to 118 kN/m.

5. PARAMETRIC STUDIES METHODOLOGY

The numerical analysis presented in this study seeks to extend the research introduced by Roushdy *et al.*, (2023) by refining the layout of the added separated platform supported on piles to upgrade anchored sheet pile wall. Consequently, the criteria utilized herein starts with the creation of two basic reference models dependent on the validated model, but having the platform separated and supported on two auger pile rows as shown in Figure 4, and the retained soil was changed to a cohesionless soil and a cohesive one (Sand fill, and Overconsolidated clay respectively). The properties of the two retained soils are illustrated in Table II.

The parametric study was initiated to explore the impact of adding rows of piles to the platform (with an extension of the platform to accommodate the added piles) on the internal forces affecting the primary elements, namely the front wall and the tie rods.

This study encompassed an examination of internal forces resulting from adjustments in pile stiffness, employing pile diameters of 80cm, 120cm, 150cm, and utilizing 1.20x2.00m barrettes. The spacing between these piles was set at a minimum of 3D to mitigate any pile group interaction effect.

Furthermore, the study considered the effect of increasing the spacing between piles used in the reference model (with a diameter of 60cm).

Additionally, the bearing level of the piles supporting the platform was scrutinized for b/B = 80% and b/B = 120%, where b represents the bearing level of the piles and B is the bearing level of the front wall.

Finally, the study assessed the impact of altering the elevation of the platform for top levels of 100%F, 80%F, 60%F, and 40%F, where F represents the freeboard measured from the top of the quay wall to the MWL.

The results of the Parametric studies of the front wall, tie rods, and the two pile rows were compared to the reference model. Simultaneously, the safety of the pile rows was assessed, particularly for the piles above the second row and those with different sections compared to the reference (60cm diameter).

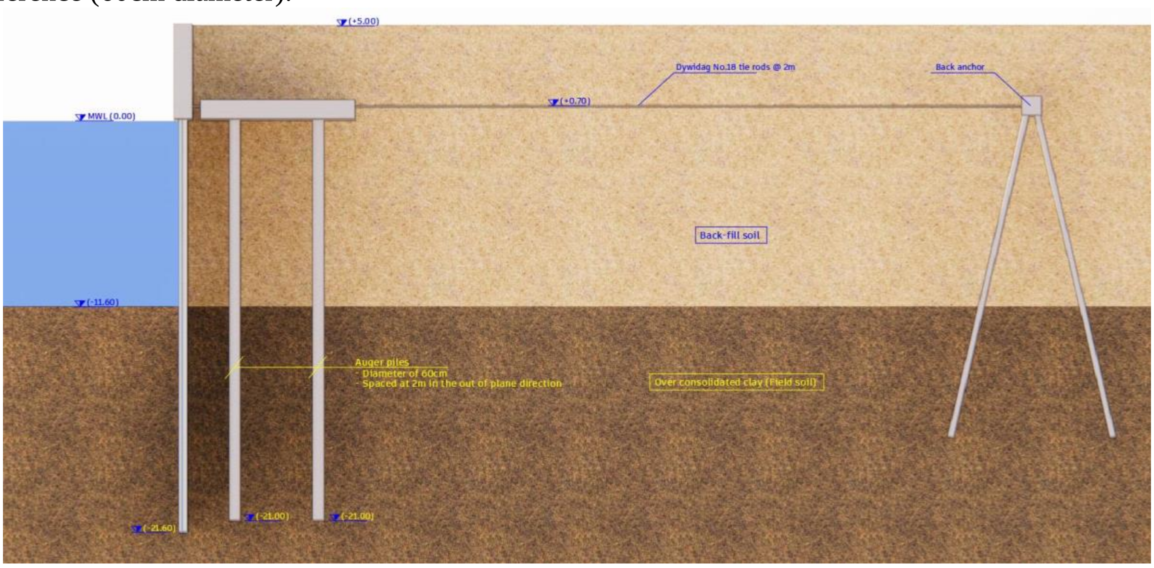


Figure 4: Typical cross-section of the basic reference models

6. BASIC REFERENCE QUAY WALL MODELS

6.1 Geometric representation

The geometry of the reference models was based on the validated model. The front wall extended from +1.30m to -21.60m from MWL. The capping beam was set to start from 0.00 to +5.00m (Berth level) with width of 1.00m. Tie rods were positioned at +0.70m, spaced at 2.0m in the out of plane direction.

The retained backfill soil, with properties illustrated in Table II, spanned from +5.00m to -9.75m. The field soil replicated the conditions of the validation model, beginning from -9.75m and continuing to the end of the model.

The depth of the dredging line in front of the quay wall was established at -11.60 m, mirroring the configuration in the validated model. Figure 4 depicts a representative cross-section of the reference model employed in this study.

The mesh employed in both of the reference models underwent refinement, resulting in 68220 elements and 119289 nodes. Boundary conditions for the model sides were exclusively fixed in the perpendicular direction, and the upper boundary was left free, while the lower boundary was fully constrained.

6.2 Material and interface representation

The material models employed in the reference model remained in line with those used in the validation model, encompassing reinforced concrete, steel members, and the native stiff overconsolidated clay. The sole exception pertained to the backfill material. The Mohr Coulomb failure criterion was applied to the soil layers, as elucidated earlier. The used Two backfill soils are presented in Table II. The soil-concrete and soil-front wall interfaces were designed to permit relative displacement, with specified interface strengths outlined in Table II. The friction angle between the soil and adjacent soil was assumed to be 2/3 of the soil's friction angle, and no strength reduction was applied to the stiff clay layer. Finally, full fixation was applied between capping beam and front wall.

Table II. Backfill soil parameters utilized in the reference models

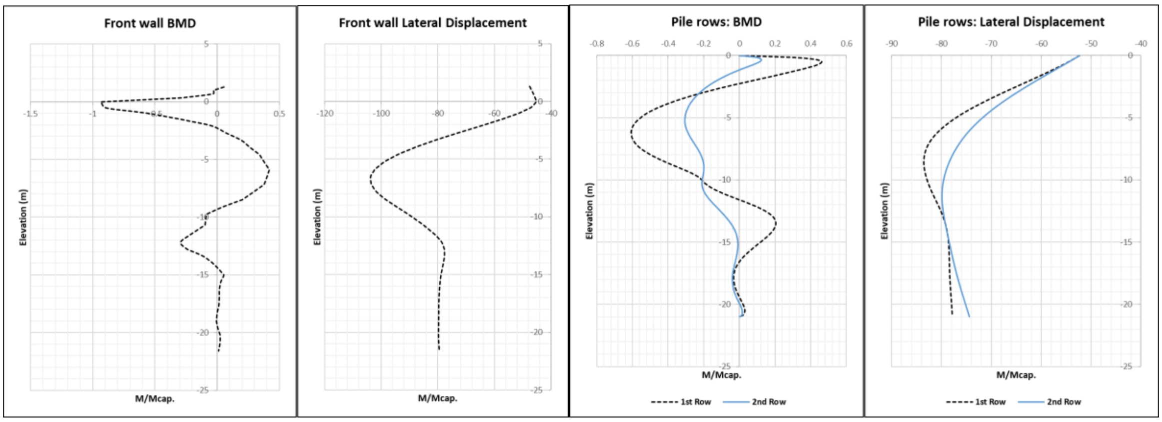
Soil	*Unit weight (kN/m^3)*	*Internal friction angle (deg.)*	*Undrained shear strength (kPa)*	*Elastic modulus (kPa)*	*Poisson's ratio*	*Interface*
Stiff OC Clay	19.50	---	100	30.00	0.40	1.00
Sand fill	19.00	30	---	38.00	0.30	0.70

6.3 Loading

The dead weights, and water uplift were considered by the software. Typical operational loads were applied to all of the models; surface load of 40 kPa simulating the operation of the quay wall, horizontal pulling load of 40 kN/m' mimics the mooring of vessels. Finally, vessels impact load was disregarded from the analysis as it affects towards the stability side of the quay wall.

6.4 Reference model 1: Using sand fill as retained soil

The maximum lateral deformation observed was 104mm. The peak utilization recorded for the front wall was 94% of the calculated capacity of 140.65 kN.m/m' at a yielding strength of 250 MPa. The tie rods utilization reached 58% of the estimated capacity of 1423 kN. Finally, the piles supporting the platform exhibited utilizations of 60%, and 31% of the calculated capacity of 241 kN.m for the first and second pile rows starting from the front wall side respectively. The results are shown in Figure 5.

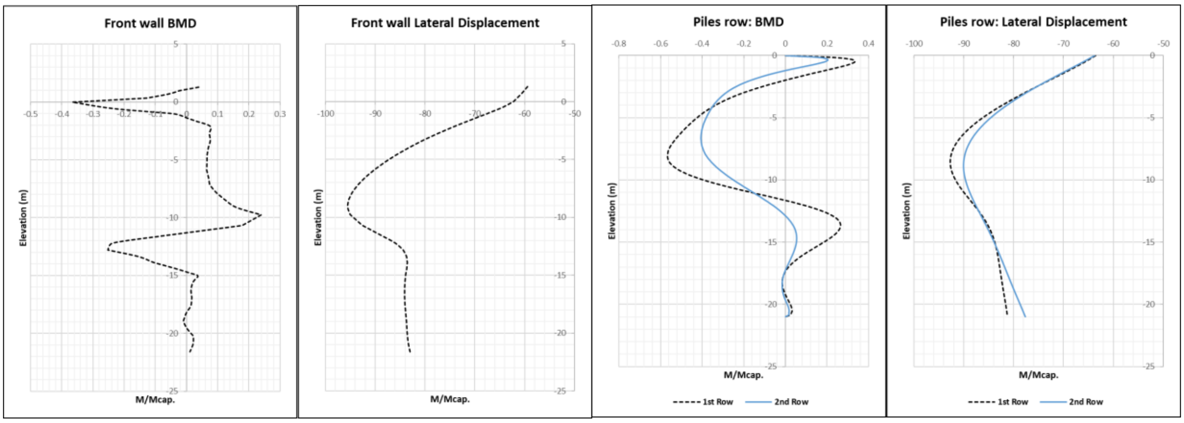


(a) (b) (c) (d)

Figure 5: Straining actions of reference model 01: (a) Front wall BMD, (b) Front wall deflection, (c) Piles BMD, (d) Piles deflection

6.5 Reference model 2: Using overconsolidated clay as retained soil

The maximum obtained lateral deformation was 96mm. The front wall shown a peak utilization of 37% relative to the calculated capacity. Utilization for the tie rods reached 76%. Additionally, the supporting piles for the platform displayed utilizations of 57% and 41% for the first and second rows, respectively, starting from the front wall side. The results shown in Figure 6.



(a) (b) (c) (d)

Figure 6: Straining actions of reference model 02: (a) Front wall BMD, (b) Front wall deflection, (c) Piles BMD, (d) Piles deflection

7. RESULTS OF THE PARAMETRIC STUDIES

Parametric studies were conducted on both of the basic reference models to explore the optimal configuration for the added platform and the most effective pile arrangement. The results of these parametric studies focus on determining the maximum utilization observed in the front wall section, the piles supporting the platform, and the tie rods.

7.1 Results of adjusting number of piles

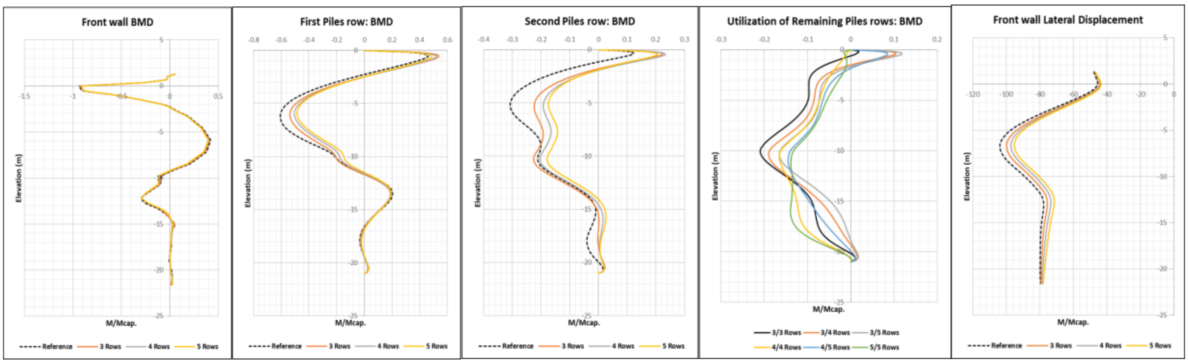
The impact of the considered parameters on the front wall, tie rods, and piles supporting the platform are illustrated in Table III, and Table IV. The negative sign refers to a decrease in force comparing to the reference case.

Table III. Effect of adjusting number of piles supporting the platform when sand fill is used as backfill soil

	Front wall		*Tie rods*	*1st Piles Row*		*2nd Piles Row*	
	Top	*Mid.*		*Top*	*Mid.*	*Top*	*Mid.*
3 Rows	-1.20%	-2.80%	-1.70%	+16.60%	-11.30%	+83.00%	-26.50%
4 Rows	-2.00%	-4.00%	-2.50%	+12.50%	-16.70%	+91.00%	-33.60%
5 Rows	-2.40%	-5.30%	-3.00%	+6.10%	-20.30%	+68.90%	-41.80%

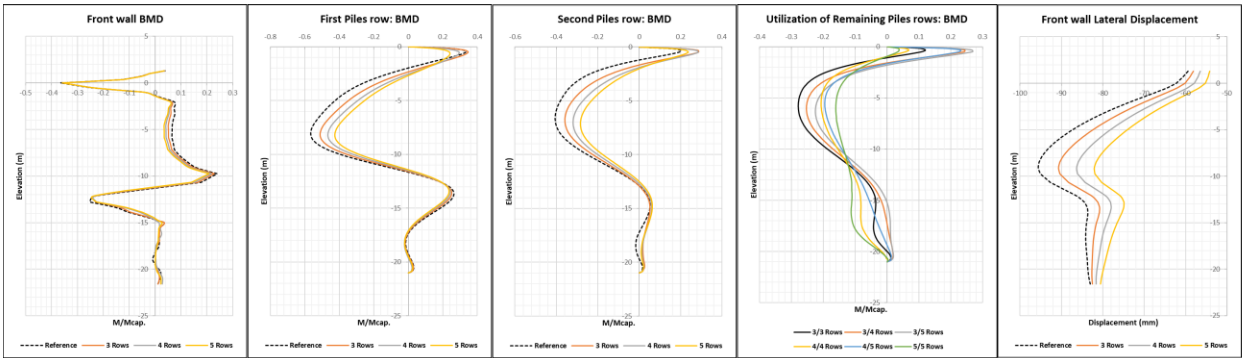
Table IV. Effect of adjusting number of piles supporting the platform when OC clay is used as backfill soil

	Front wall		*Tie rods*	*1st Piles Row*		*2nd Piles Row*	
	Top	*Mid.*		*Top*	*Mid.*	*Top*	*Mid.*
3 Rows	-2.30%	-4.70%	-2.70%	+3.71%	-9.40%	+42.10%	-11.50%
4 Rows	-2.00%	-9.00%	-6.00%	-11.90%	-17.50%	+40.90%	-21.40%
5 Rows	-2.40%	-12.80%	-10.00%	-27.70%	-24.80%	+16.80%	-30.00%



(a) (b) (c) (d) (e)

Figure 7: Impact of adjusting number of piles when sand fill is used as backfill soil: (a) Front wall BMD, (b) 1st piles row BMD, (c) 2nd piles row BMD, (d) utilization of the remaining piles, (e) system displacement



(a) (b) (c) (d) (e)

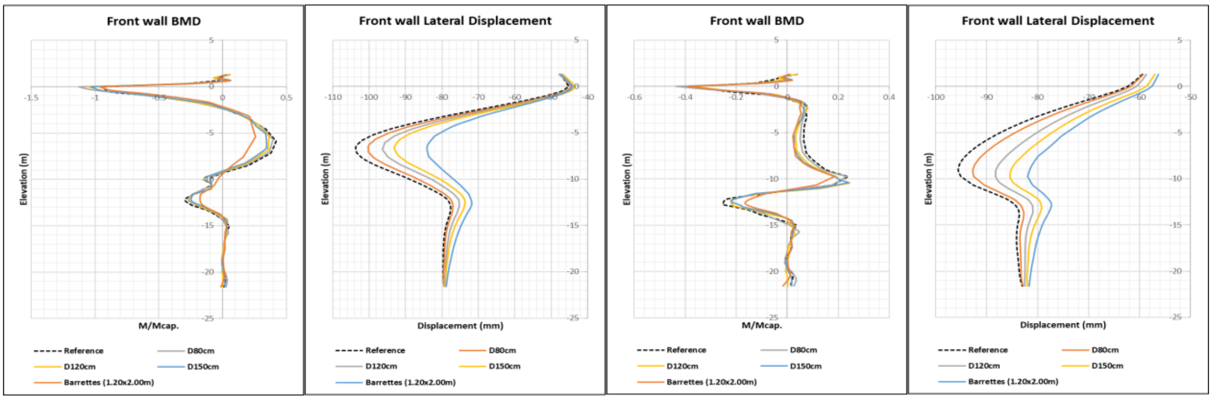
Figure 8: Impact of adjusting number of piles when OC clay is used as backfill soil: (a) Front wall BMD, (b) 1st piles row BMD, (c) 2nd piles row BMD, (d) utilization of the remaining piles, (e) system displacement

7.2 Results of adjusting stiffness of piles

The influence of changing the piles section was mainly investigated for the front wall, and tie rods while checking the safety of the used piles. All the larger piles than the references were deemed safe.

Table V. Effect of adjusting stiffness of piles supporting the platform

	Sand fill as backfill			*OC clay as backfill*		
	Front wall		*Tie rods*	*Front wall*		*Tie rods*
	Top	*Mid.*		*Top*	*Mid.*	
D80cm	+20.50%	-5.30%	-0.80%	+18.70%	-2.70%	-0.50%
D120cm	+12.50%	-12.70%	-0.70%	+1.71%	+2.00%	-2.00%
D150cm	+10.10%	-16.90%	-3.54%	+6.00%	+0.70%	-5.20%
Barrettes (1.20x2.00m)	3.00%	-37.80%	-2.40%	+5.80%	-22.70%	-6.60%



(a) (b) (c) (d)

Figure 9: Impact of adjusting stiffness of piles: (a) Front wall BMD when sand fill is backfill, (b) lateral displacement when sand fill is backfill, (c) Front wall BMD when OC clay is backfill, (d) Lateral displacement when OC clay is backfill

7.3 Results of adjusting spacing of piles

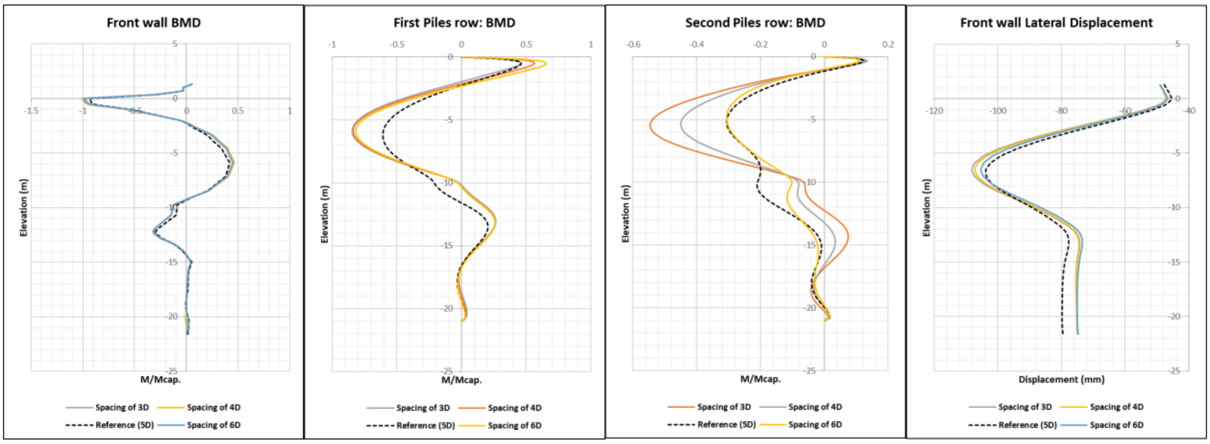
The effect of altering the spacing of piles was investigated for the various components constituting the quay wall. The utilized spacings ranged from 3 times the pile diameter to 6 times, with the note that the spacing in the reference model is 5 times the pile diameter.

Table VI. Effect of adjusting spacing of piles supporting the platform when sand fill is used as backfill soil

	Front wall		*Tie rods*	*1st Piles Row*		*2nd Piles Row*	
	Top	*Mid.*		*Top*	*Mid.*	*Top*	*Mid.*
3xD	+7.80%	+11.50%	+3.60%	+0.30%	+39.50%	+7.90%	+77.80%
4xD	+6.60%	+10.00%	+3.30%	+22.90%	+38.00%	+10.20%	+46.70%
6xD	+5.60%	+7.80%	+2.80%	+42.30%	+35.20%	-9.10%	-0.10%

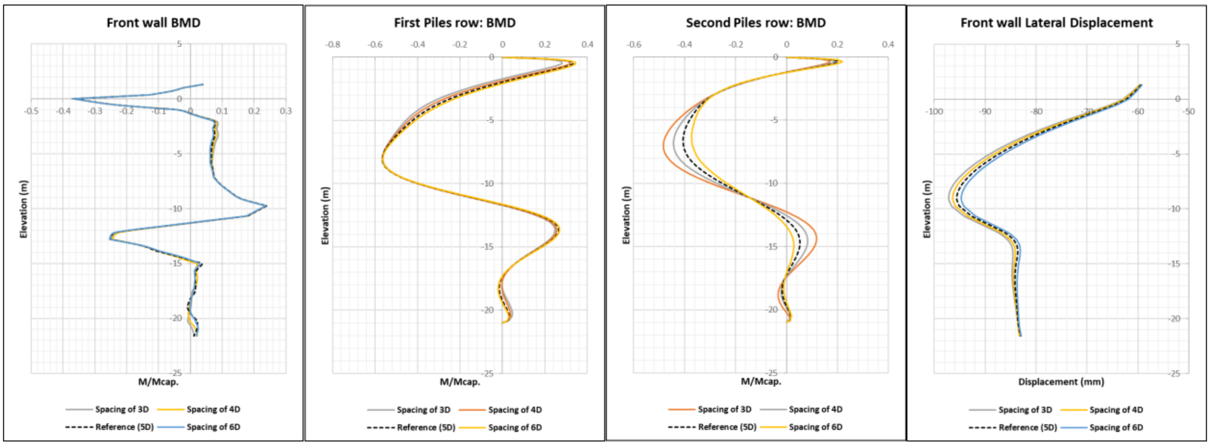
Table VII. Effect of adjusting spacing of piles supporting the platform when OC clay is used as backfill soil

	Front wall		*Tie rods*	*1st Piles Row*		*2nd Piles Row*	
	Top	*Mid.*		*Top*	*Mid.*	*Top*	*Mid.*
3xD	+1.80%	-0.30%	+0.80%	-15.80%	-0.40%	-15.60%	+18.90%
4xD	+0.60%	-0.20%	+0.50%	-4.40%	-0.10%	-6.30%	+9.20%
6xD	+0.80%	-0.90%	-0.50%	+3.30%	-0.30%	+7.40%	-8.30%



(a) (b) (c) (d)

Figure 10: Impact of adjusting spacing of piles when sand fill is backfill: (a) Front wall BMD, (b) 1st piles row BMD, (c) 2nd piles row BMD, (d) Lateral displacement



(a) (b) (c) (d)

Figure 11: Impact of adjusting spacing of piles when OC clay is backfill: (a) Front wall BMD, (b) 1st piles row BMD, (c) 2nd piles row BMD, (d) Lateral displacement

7.4 Results of adjusting bearing levels of piles

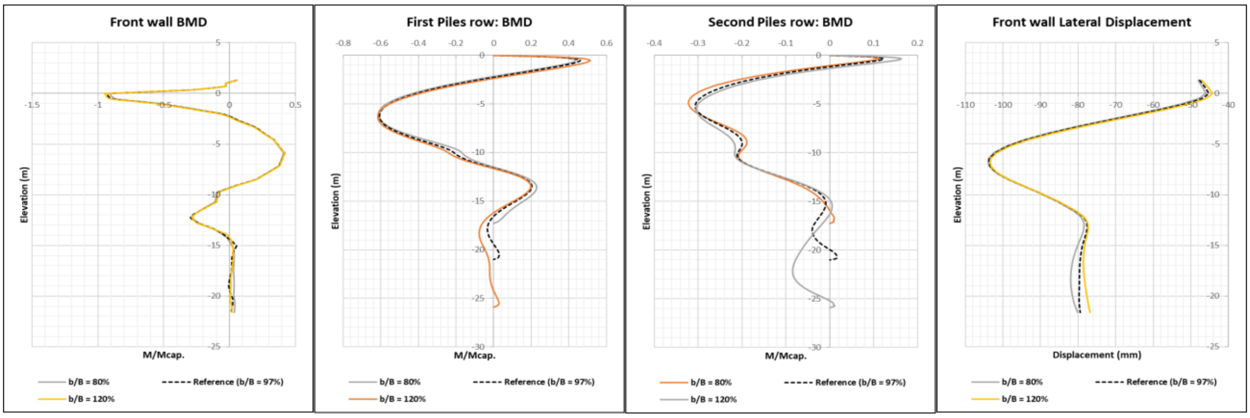
The influence of the modification in bearing level of the piles supporting the platform was examined. Note that the reference model has ratio of b/B = 97%.

Table VIII. Effect of adjusting bearing levels of piles supporting the platform when sand fill is used as backfill

	Front wall		*Tie rods*	*1st Piles Row*		*2nd Piles Row*	
	Top	*Mid.*		*Top*	*Mid.*	*Top*	*Mid.*
b/B = 80%	-2.30%	-1.60%	+1.40%	-4.80%	+0.90%	-8.00%	+4.80%
b/B = 120%	+2.00%	+0.80%	-1.80%	+11.40%	+1.40%	+33.00%	-1.00%

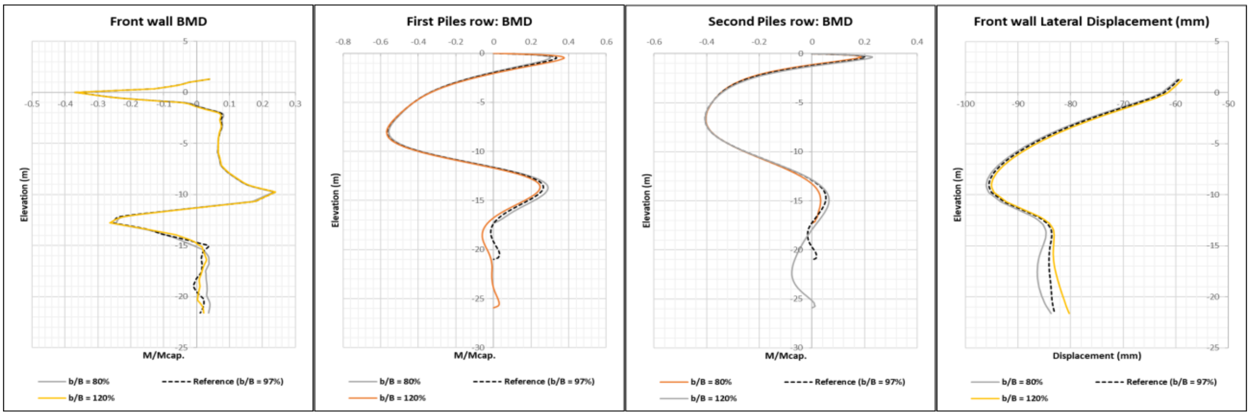
Table IX. Effect of adjusting bearing levels of piles supporting the platform when OC clay is used as backfill

	Front wall		*Tie rods*	*1st Piles Row*		*2nd Piles Row*	
	Top	*Mid.*		*Top*	*Mid.*	*Top*	*Mid.*
b/B = 80%	+1.10%	-2.10%	+0.60%	-9.40%	-1.40%	-8.10%	-0.50%
b/B = 120%	+0.90%	-0.10%	-1.10%	+12.70%	+0.60%	+12.90%	+0.30%



(a) (b) (c) (d)

Figure 12: Impact of adjusting bearing level of piles when sand fill is backfill: (a) Front wall BMD, (b) 1st piles row BMD, (c) 2nd piles row BMD, (d) Lateral displacement



(a) (b) (c) (d)

Figure 13: Impact of adjusting bearing level of piles when OC clay is backfill: (a) Front wall BMD, (b) 1st piles row BMD, (c) 2nd piles row BMD, (d) Lateral displacement

7.5 Results of adjusting the elevation of platform

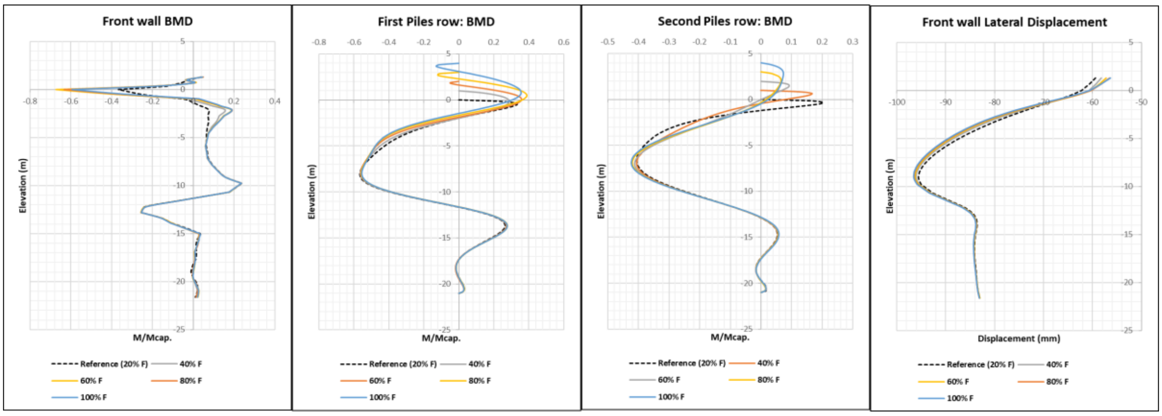
The obtained straining actions affecting the quay wall's components were investigated. Noting that, the reference model has the platform at 20% F.

Table X. Effect of adjusting platform level when sand fill is used as backfill

	Front wall		*Tie rods*	*1st Piles Row*		*2nd Piles Row*	
	Top	*Mid.*		*Top*	*Mid.*	*Top*	*Mid.*
40% F	+36.90%	-0.10%	-5.00%	-23.20%	+3.60%	-2.70%	-1.40%
60% F	+19.40%	-2.20%	-6.90%	-29.30%	+7.50%	+13.70%	-2.20%
80% F	+9.20%	-1.50%	-7.10%	-16.70%	+17.50%	+70.70%	-4.80%
100% F	+3.90%	+0.20%	-5.60%	-9.00%	+27.40%	+163.70%	-4.60%

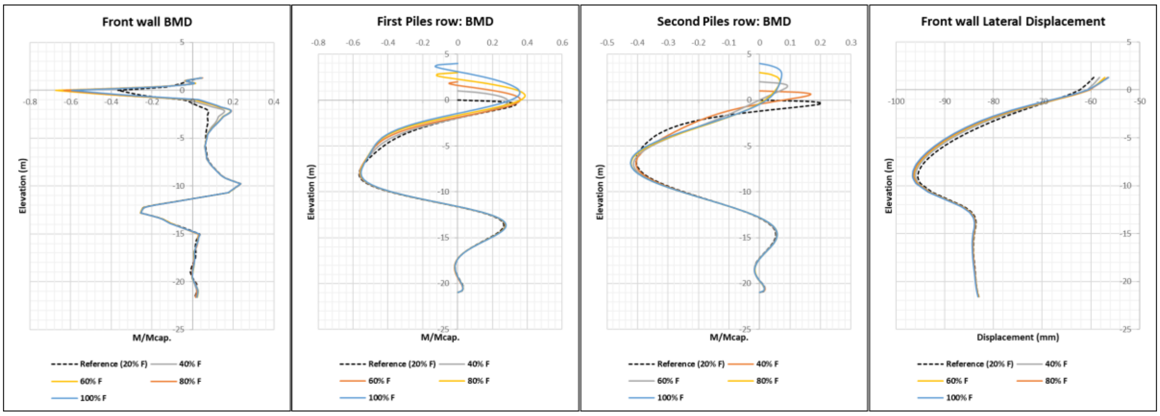
Table XI. Effect of adjusting platform level when OC clay is used as backfill

	Front wall		*Tie rods*	*1st Piles Row*		*2nd Piles Row*	
	Top	*Mid.*		*Top*	*Mid.*	*Top*	*Mid.*
40% F	+72.30%	-0.60%	-2.30%	-13.50%	-0.40%	-17.40%	-0.10%
60% F	+83.30%	-1.50%	-3.50%	+7.60%	-1.00%	-54.30%	+1.70%
80% F	+72.40%	-1.70%	-4.00%	+16.00%	-1.50%	-67.40%	+3.51%
100% F	+62.30%	-1.80%	-4.00%	+6.50%	-2.00%	-64.00%	+4.20%



(a) (b) (c) (d)

Figure 14: Impact of adjusting platform level when sand fill is backfill: (a) Front wall BMD, (b) 1st piles row BMD, (c) 2nd piles row BMD, (d) Lateral displacement



(a) (b) (c) (d)

Figure 15: Impact of adjusting platform level when OC clay is backfill: (a) Front wall BMD, (b) 1st piles row BMD, (c) 2nd piles row BMD, (d) Lateral displacement

7.5 Discussion of the results

The analysis carried out within the parametric study showed the following:

(1) Front wall behavior:

For all the examined cases, the peak bending moment took place at the connection zone to the capping beam.

- By increasing the number of piles supporting the platform and readjusting the extension of the platform to accommodate all the piles, a slight reduction of 2.40% in the maximum bending moment at the connection zone to the capping beam was observed when transitioning from 2 Rows to 5 Rows of piles, irrespective of the backfill soil type. This indicates that the lateral earth pressure affecting the front wall was not significantly influenced by the extension of the platform in conjunction with the number of piles. Consequently, the relieving effect was only marginally enhanced.

- Considerable care should be given to the front wall when dealing with the stiffness of piles. Increasing piles stiffness from 60cm to 150cm elevated the maximum bending moment affecting the front wall at different magnitudes as presented in Table V in the connection zone to the capping beam, regardless of the type of retained backfill soil. The increase arises from the spacing of piles (in the out-of-plane direction), which also increases with the heightened stiffness to maintain the minimum spacing between piles, thus avoiding pile group interaction. Consequently, this diminishes the earth lateral pressure blockage effect exerted by the piles, resulting in elevated bending moments at the front wall.

- Adjusting the spacing of piles along with the platform length had a slight effect on increasing the maximum bending moment at various magnitudes, as demonstrated in tables VI and VII, particularly noticeable in cohesionless backfill soils. However, this effect was deemed negligible for cohesive backfills. The increase in the maximum bending moment affecting the front wall when cohesionless backfills are used is attributed to the direct influence of changing pile spacing on the extension of the platform (which increases with the change in pile spacing) and the corresponding reduction in the platform stiffness (which decreases with the increase in pile spacing). This fluctuation in results occurs because the increase in platform extension relatively increases the mitigation of lateral earth pressure due to the relieving effect, while the increase in pile spacing results in less stiffness and less blockage effect for the lateral earth pressure exerted by the piles. Based on these findings, the optimal setup was determined to be at 5 times the diameter (5D) when the diameter of the piles is 60cm.

- Modifying the bearing level of the piles supporting the platform had a minor effect on the bending moment and deformation affecting the front wall for the examined backfill types. Increasing the bearing level of the piles supporting the platform provided moderately stiffer supports for the platform, resulting in a slight increase in bending moments on the front wall.

- Elevating the platform has a significant and potentially hazardous impact on the maximum moment affecting the front wall, particularly in cohesive backfill soils. The increase in bending moment reached 37% and 83% for cohesionless and cohesive soils, respectively. When the platform level is raised, the connection between the piles and the platform also rises, critically affecting the stiffness of piles at the maximum bending moment zone of the front wall (connection to the capping beam). Furthermore, the reduction in lateral earth pressure due to the relieving effect is severely compromised by raising the top level of the platform, resulting in a considerable increase in bending moments on the front wall. Therefore, it is strongly recommended to keep the platform at the lowest possible elevation to mitigate these effects..

(2) Tie rods:

- Augmenting the number of piles supporting the platform resulted in a minor reduction in tie rod tension for cohesionless backfill soil and a marginal decrease for cohesive soils. The tension decreased by approximately 3.00% and 10.00% for cohesionless and cohesive soils, respectively. This decrease can be attributed to the augmented stiffness of the platform, thereby slightly enhancing its capacity to transmit more lateral forces through piles while reducing the transmitted forces to the tie rods.

- Enhancing the stiffness of the piles supporting the platform caused reduction in tie rod tension. The reduction in tie rod tension can be ascribed to the bolstered rigidity of the platform, leading to a slight improvement in its ability to convey increased lateral forces through the piles, thus diminishing the load transmitted to the tie rods.

- Increasing the spacing of piles had a marginal effect on raising tie rod tension by 3.00% in the case of cohesionless backfill, while the effect is negligible for cohesive soils. The rise in tension is attributed to the reduction in rigidity of the platform caused by weakening its supports, resulting in more transmitted lateral loads to the tie rods.

- Adjusting the bearing levels of the piles supporting the platform had a negligible effect on the tie rod tension for all the examined backfill soils. The tension was reduced negligibly with the increase in bearing level of piles. The increase in bearing levels of piles provided a slight improvement for the platform supports, resulting in a relatively higher capability of transmitting lateral forces and minor reduction in tie rod tension.

- Modifying the platform elevation had a slight effect on decreasing tie rod tension, which reduced by approximately 6.00% and 3.00% for cohesionless and cohesive backfill soils, respectively. This reduction in tie rod tension is attributed to the increase in lateral loads transmitted to the platform system due to the difference in levels between the platform and ties.

(3) Pile rows, only the first piles row was discussed as it exhibited the highest straining actions:

- Using more piles to support the platform has a significant and reversed effect on the bending moment experienced by the piles, depending on the type of backfill soil. In cohesionless backfill, increasing the number of piles leads to a slight increase of approximately 6% in bending moment at the top of the pile, while it decreases by 20% in the middle zone. However, in cohesive backfill, the bending moment is reduced by 27% and 24% at the top and middle zones, respectively. In cohesionless soils, the increased stiffness in the connection between piles and platform causes a marginal increase in bending moment at the top level, while the distribution of lateral earth pressure among more piles reduces bending moment in the middle zones. Conversely, in cohesive soils, the high cohesion stabilizes the platform, leading to a redistribution of lateral earth pressure among more piles, thus reducing bending moment.

- Adjusting the spacing of piles had a considerable effect when dealing with cohesionless soils and a moderate effect for cohesive soils. For cohesionless soil, increasing the spacing of piles elevated the internal forces affecting the piles by up to 40%. On the other hand, this effect is reversed for cohesive soil, which decreased by around 10%. This indicates that the cohesion of the soil plays a considerable role in absorbing a portion of forces if it is high enough (as in the case of a stiff clay layer), while for cohesionless soils, the forces are distributed directly between the two piles at their different locations.

- By increasing bearing level of piles, internal forces at the connection zone to the capping beam fairly increase by almost 11.00%. This indicate that the increase in bearing level adds slight fixation to the supports of the platform resulting in more forces concentrated in the connection zone.

- Modifying the platform elevation overall resulted in significantly increased bending moments on the piles. This increase can be attributed to the upward lengthening of the piles, which led to the transmission of more lateral forces to the piles, consequently escalating the bending moments on them.

8. CONCLUSIONS

Optimizing the separated relieving platform is complicated. Therefore, the adjustment in the piles or the platform should be done with care. The study adopted within this research revealed that increasing the number of piles supporting the platform is ineffective, and not recommended for mitigating forces affecting the front wall, or the tie rods regardless the backfill soil type. Hence, using dual pile rows supporting the platform is preferable.

Piles supporting the platform should be carefully designed to handle the expected loads. Overdesigning these piles can lead to increased internal forces affecting the front wall, while tie rod tension is relatively reduced.

The spacing of the piles supporting the platform should be chosen carefully. In this research, a spacing of 5 times the diameter (5D) in the land/sea direction (using a diameter of 60cm) provided optimal mitigation for the front wall and tie rod tension for all soil types. Further research should be conducted to explore suitable spacing along different pile sections.

Bearing level of the piles supporting the platform should be designed carefully to avoid overdesign them, as they have minor effect on front wall, and tie rod tension.

Based on the findings, the optimal location for the platform is to be aligned with the bottom level of the capping beam. Internal forces affecting the front wall are severely affected by the elevation of the platform. The platform at a level other than the recommended elevation relatively reduces tension forces on tie rods but significantly elevates internal forces on the front wall.

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