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Numerical Investigation on Anchored Sheet Pile Quay Wall with Separated Relieving Platform

Mahmoud Roushdy, Mohamed El Naggar, Ahmed Yehia Abdelaziz

***Abstract*—**Anchored sheet pile has been used worldwide as front quay walls for decades. With the increase in vessel drafts and weights, those sheet pile walls need to be upgraded by increasing the depth of the dredging line in front of the wall. One of the upgrades for the sheet pile wall is to add a separated platform to the system, where the platform is structurally separated from the front wall. The platform is structurally separated from the front wall. This paper presents a numerical investigation utilizing finite element analysis on the behavior of separated relieve platforms installed within existing anchored sheet pile quay walls. The investigation was done in two steps: a verification step followed by a parametric study. In the verification step, the numerical model was verified based on field measurements performed by others. The validated model was extended within the parametric study to a series of models with different backfill soils, separation gap width, and number of pile rows supporting the platform. The results of the numerical investigation show that using stiff clay as backfill soil (neglecting consolidation) gives better performance for the front wall and the first pile row adjacent to sandy backfills. The degree of compaction of the sandy backfill slightly increases lateral deformations but reduces bending moment acting on pile rows, while the effect is minor on the front wall. In addition, the increase in the separation gap width gradually increases bending moments on the front wall regardless of the backfill soil type, while this effect is reversed on pile rows (gradually decrease). Finally, the paper studies the possibility of deepening the basin along with the separation to take advantage of the positive separation effect on piles, and front wall.

***Keywords*—**Anchored sheet pile, relieving platform, separation gap, upgrade quay wall.

I. INTRODUCTION

ANCHORED sheet-pile walls are commonly used as retaining structures in civil engineering applications because they are easy and fast to execute, can be embedded in most soil deposits, and are relatively inexpensive. These walls were used to withstand the lateral earth pressure caused by the retained height and superimposed loads. In marine structures, sheet pile walls are used for decades either in temporary works or as permanent quay wall structure.

However, owing to the development of marine works, especially vessel types and loads, there is a need for deeper quay walls that can sustain larger operational loads. The common way, especially in Egypt, to upgrade the quay wall is by constructing larger quay wall in front of the existing one to sustain the required new vessels draught and extra operation loads. The main drawbacks of this solution are the cost of constructing a new quay wall and the corresponding reducing in the water surface area of the basin inside the harbor.

This study presents another method to retrofit existing sheet pile and anchored sheet pile quay wall to withstand growing demands on deeper quay walls. The new method to rehabilitate and upgrade existing sheet pile wall comprised of installing a platform (namely relieving platform) supported on piles at the backyard of the existing wall. This platform will significantly reduce the lateral earth pressure acting on anchored sheet piles, allowing deeper depths and design loads to be resisted with the existing wall. The main challenge in installing the new platform is its connection with the existing capping beam of the existing sheet pile wall. The study presented hereby relaxes this condition by separating the new platform structure from the existing quay wall. The sheet pile wall with a relieving platform is a traditional anchored sheet pile wall, however, separating the relieving platform from the front wall capping beam is considered the new method in upgrading the existing quay wall.

This current study utilizes numerical investigation on an anchored sheet pile wall with and without a reliving platform to evaluate the effect of the proposed addition on the overall performance of the system. The main objective of this study was to determine the optimal configuration of the new addition platform including its dimensions, type of attachment to the front wall, under any retained soil type and for many basin depths in front of the wall.

The anchored sheet pile with separated relieving platform was successfully constructed for the first time at Tangshan Port in China in 2010 Cai et al. [2]. Because the structure is still new, corresponding studies are lacking, and researchers have focused on studying the internal forces of this new type of wharf and comparing it to the traditional anchored sheet-pile to examine the relieving effect of the platform.

Li et al. [5] made a prototype observation of the new system with a front diaphragm wall for a period of one year during basin dredging to enhance the computational theories for this structure. They concluded that the existence of the platform with the piles reduced lateral earth pressure and all internal forces on the front diaphragm wall.

Tan et al. [7] and Jiao et al. [4] investigated the dynamic response of an anchored sheet-pile wall with a separated relieving platform under horizontal seismic loads using finite element analysis (FEA) in 2D. The study analyzed the influences of different earthquake characteristics and compared the results of the FEA with field test observations to verify the accuracy of the calculations. Both studies concluded that the separated relieving platform system was effective under seismic

Mahmoud Roushdy is with Alexandria University, Egypt (e-mail: roushdy_mmr@yahoo.com).

loads, and the tie rod was crucial for ensuring the functionality of the system.

An et al. [1] conducted FEA of a sheet pile wharf with a separated relieving platform using ABAQUS to examine the effect of platform existence on the overall internal forces affecting the system. The studies concluded that the existence of the platform had a significant effect on reducing the bending moment on the front wall, as well as reducing the tie rod tension.

Cai et al. [2] performed FEA study using ABAQUS on two cases similar to An et al. [2] but for water depth of 11.80 m. Cai and his coauthors deduced that distribution of the lateral earth pressure is similar to the ordinary relieving effect; accordingly, all internal forces were lower in the case of the separated relieving platform compared to the conventionally anchored sheet pile wall.

Chen et al. [3] developed a numerical model based on an engineering prototype to examine the optimization of pile rows using a constant concrete volume. The results showed that increasing the spacing of piles and their stiffness could reduce the straining actions acting on the front wall, resulting in a smaller front wall section.

Tan et al. [8] employed a numerical model using ABAQUS, which was verified by field measurements conducted by Tan et al. [7] to study the performance of the structural members of an anchored sheet pile with a separated relieving platform. They found that the relieving effect was caused by partially blocking the soil mass by piles along with the sustained part of vertical loads by the platform. In addition, the dredging phase has the greatest effect on the front wall, while the surface loading phase has the maximum effect on the anchor wall.

Based on the available literature, the majority of researchers focused on studying the internal forces by means of comparing them with that in a traditional anchored sheet pile system. Few studies, e.g. [1] and [8], have investigated the effect of the separation gap width between the front wall and the platform, the type of backfill soil, and the effect of deepening the dragging line in front of the wall on the new system. This study provides a parametric study to optimize those parameters through comprehensive numerical investigation. A design guideline for installing a separated relieving platform is provided based on the results of the numerical investigation.

II. Field Case Study

The field case study employed here was adopted from Endley et al. [6]. Endley and his coworkers provide field measurement during and after construction of an anchored sheet pile quay wall attached to a relieving platform, with no separation. The quay wall is located within Port Freeport, Texas, USA. The typical cross section of the anchored sheet pile wall used in their study is illustrated in Fig. 1.

As given in the paper, the soil stratigraphy consisted of stiff over-consolidated clays and dense sands overlain by approximate 60 cm of recent river deposits. The underwater bank of the channel mildly sloped up to land from a maximum channel depth of 9.7 m below MLW (Mean Low Water) level.

The front wall is comprised of sheet pile wall of Larssen-VS type until depth of -21.6 m below MWL. As provided by Endley et al. [6], the sheet pile has a section modulus of 970 cm^3/m. the front wall was attached to a back anchor by Dywidag No. 18 tie rods with a diameter equal 57 mm spaced at 2 meters. The breaking load of the tie road was estimated to be equal to 1423 kN.

The attached platform was 1.0 m thick and supported on 5 rows of auger piles. The auger piles had a diameter of 60 cm and were placed at a 2-meter center-to-center spacing. The piles supporting the relieving platform were installed until depth equal -21.00 m below the MWL. The dredge line front of the wall was designed at elevation -11.6 m below MWL, as shown in Fig. 1.

The anchored sheet pile wall system and the relieving platform were provided with the following instrumentation, as provided by Endley et al. [6]:

1) Six Inclinometers distributed at six locations along the longitudinal direction of the quay wall used for deflections measurement.
2) Three Earth Pressure Cells behind the sheet pile were installed at three locations along the quay to capture the earth pressure variations.
3) Strain gauges were installed at three locations along the quay while each point of the three is an array of seven strain gauges equally spaced from 0.00 m to -21.60 m below MLW.
4) Load cells were installed for three of the tie rods. Each tie rod had two load cells one at the sheet pile location and the other at the back anchor location.

The construction process was initiated by dredging the soft soil layer, followed by installing the front sheet pile wall, whalers, and tie rods. Afterwards, the backfilling process began using clamshell buckets that dropped sand from approximately 4 meters above the water line.

The first set of instrumentation readings was taken after completing the backfilling process (October 1986), which revealed significant lateral displacement of around 13.0 cm towards the seaside (the draught of the quay wall at the time was 9.70 m). Following the backfilling process, the auger piles were executed, and another reading set was taken in December 1986. A third and final set of reading was taken after completing the superstructure in November 1987.

Based on the recorded readings, we concluded that the excessive deflection affecting the front wall was caused by the backfilling methodology. They attribute that dropping the backfilled sand from a remarkable height into water resulted in the loss of the majority of sand’s shearing strength and stiffness, leading to huge, unexpected lateral movement.

III. Numerical Model

The readings obtained from the instrumentation installed within the quay wall presented in Fig. 1 were employed to verify a Finite Element Model (FEM). The model was created using the well-known Finite Element (FE) software PLAXIS which is capable of modeling different problems in 2D and 3D geometric configuration. The verified model was created in a 3D pattern using PLAXIS 3D.

A 3D slice of the structure was modeled in PLAXIS 3D. Fig. 2 depicts the main geometric components of the 3D FE Model.

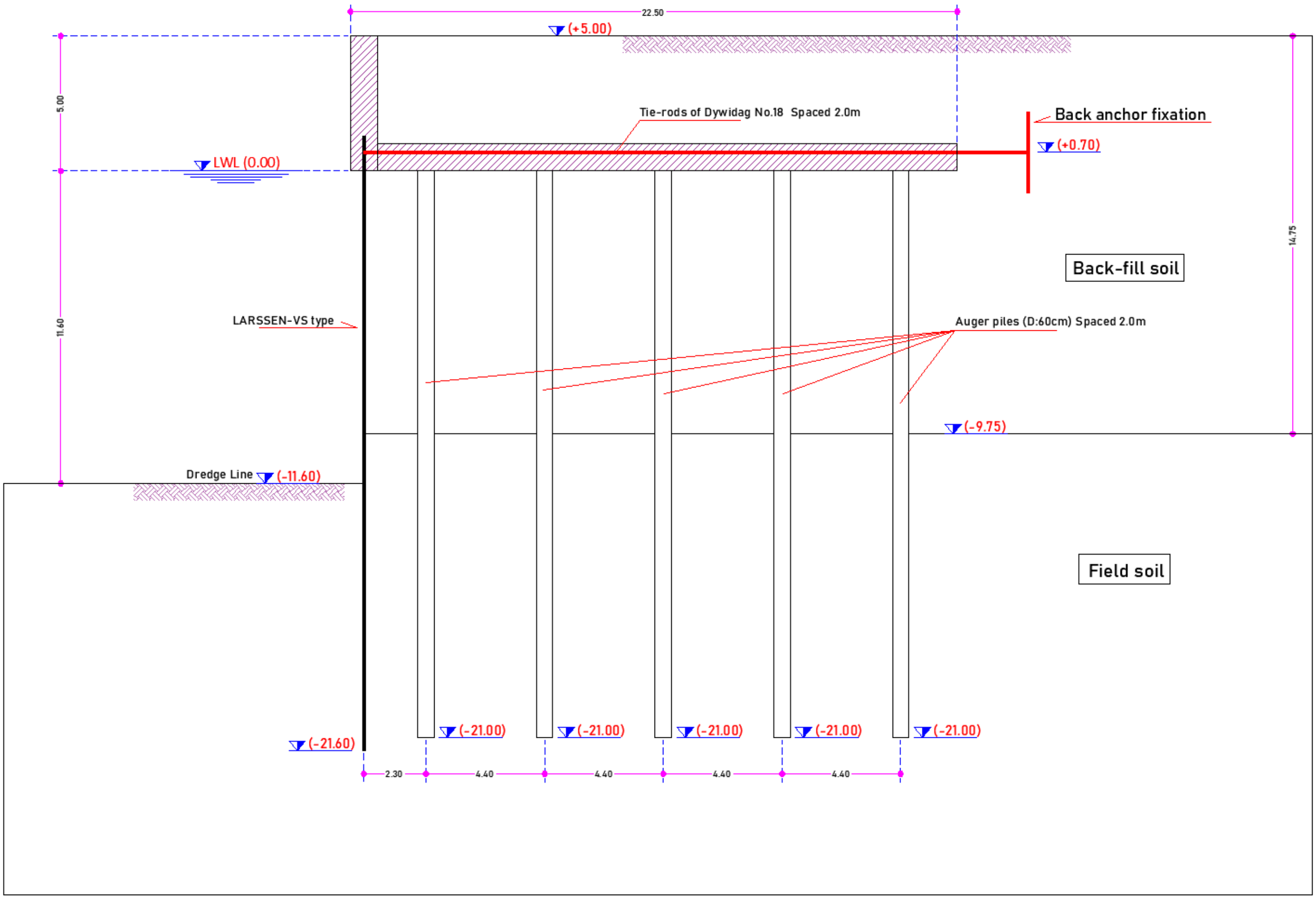


Fig. 1 Cross-section of calibration quay wall

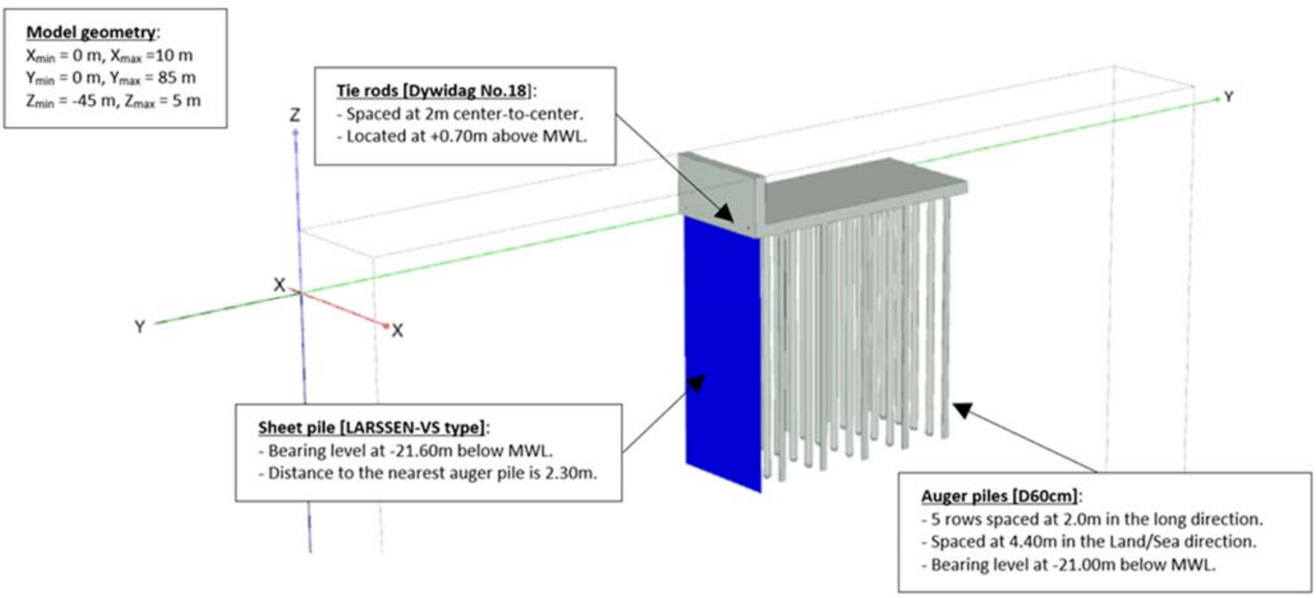


Fig. 2 Geometry of the structure employed within the FE model

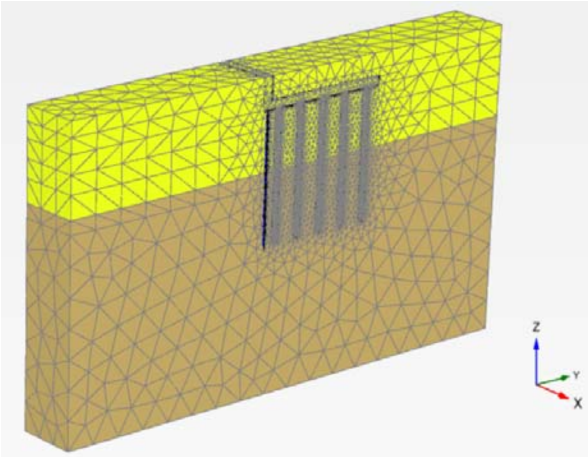


Fig. 3 Meshing configuration used in the FE model

A. Geometric Modeling

In the verified FEM, the front sheet pile wall was modelled as a plate element and the attached tie rods were modeled as bar elements. The platform, capping beam, and the auger piles were modeled as volume elements to simulate the stiffness of the concrete elements in the model. The soil deposits were modeled using 3D solid elements.

To reduce the mesh sensitivity, several meshing sizes were tried and the meshes were refined up to 172014 elements and 299030 nodes. The boundary conditions and meshes are shown in Figs. 2 and 3.

B. Material Modeling

The elastic modulus of all steel members in the model was taken equal to 210 GPa, and the elastic modulus of concrete elements was assumed equal to 20 GPa.

All soil deposit layers were defined using the Mohr-Coulomb's failure criterion for the plastic behavior. Mohr-Coulomb's model was chosen because of its simplicity and widespread geotechnical applications. The effect of the backfilling methodology on the backfill soil's strength was also considered. The soil properties based on Endley et al. [6] used in the analysis are summarized in Table I.

The fill layer extended from the top level down to depth equal -9.70 m below MWL, underlain by over consolidated clay layer extended to the end of the model, as given in the reference paper [6]. The MWL water line was assumed at 0.00 m.

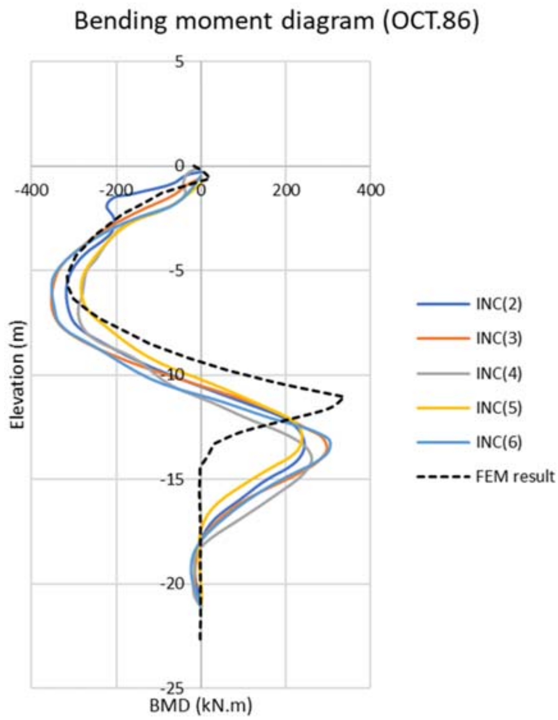
The interface between the volume piles and the surrounding soil was modeled using interface elements with interaction strength that depends on the surrounding soil. The interface coefficients for the soil layers are given in Table I.

TABLE I
SOIL PARAMETERS USED IN CALIBRATION

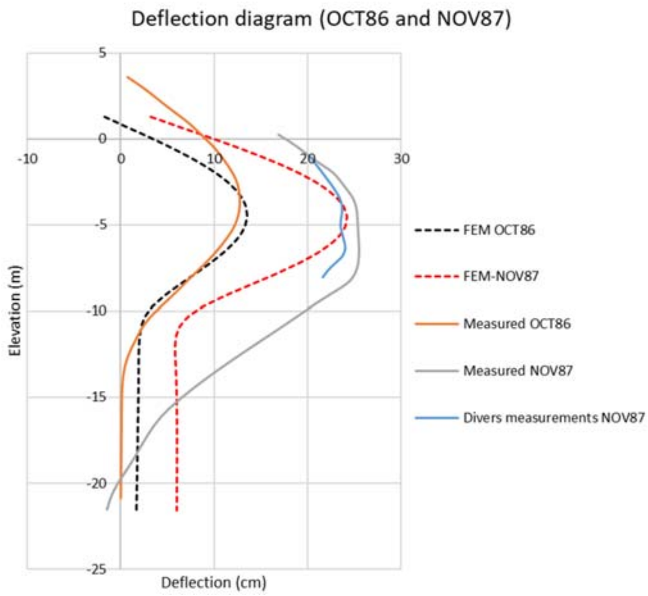
Soil	Unit weight (kN/m^3)	Internal friction angle (deg.)	Cohesion (kPa)	Elasticity modulus (MPa)	Poisson's ratio	Interface
Stiff clay	19.50	0	100	30.00	0.40	1.00
Hydraulic sand	18.00	20	1.00	**≤1.00**	0.30	0.70

C. Calibration of the Numerical Model

To calibrate the created numerical model, the field measurements obtained by Endley et al. [6] were compared to the model results at the same construction stages (instruments readings in October 1986 and November 1987).



(a)



(b)

Fig. 4 Front wall calibration results: (a) bending moments, (b) deformations

Fig. 4 (a) presents a comparison between the bending moment developed on the front wall as integrated from the six inclinometers installed behind it and the bending moment obtained from the numerical model. Both bending moments are in a good agreement except on the anticipated interface between the two layers, which may be attributed to the uncertainty of the over consolidated clay layer top elevation.

The deflection of the wall measured during and after the end of construction was compared with the lateral deflection calculated by the FE model and given in Fig. 4 (b). The results show a very good agreement between the numerical model and the measured field data during construction (October 1986 readings) and fair agreement at the end of construction (November 1987).

The maximum tension force measured in the tie rods after backfilling was approximately 106 kN/m as per Endley et al. [6], while the tension force obtained from the FE model was equal to 118 kN/m.

IV. Methodology of Parametric Studies

The numerical investigation presented in this study aims to examine the effectiveness of adding a relieving platform to upgrade an existing ordinary anchored sheet pile quay wall. Accordingly, the criteria used in the numerical parametric study commence with creating a set of four basic reference models based on the validated model but without the platform supported on piles (ordinary anchored sheet pile system). The main constant parameter in each reference model is the retained backfill soil (loose sand, compacted sand, dense sand, and overconsolidated clay). The properties of the three backfill materials employed in this study are presented in Table II. All reference models have the same structure similar to the validated model, except for the existence of platform supported on auger piles, and the type of retained backfill soil.

The parametric study was conducted to examine the effect of adding a platform supported on piles on the internal stability of the system elements. The added platform on piles may be attached to or separated from the capping beam with certain distances.

The effect of adding the platform was simultaneously examined with deepening the dredging line in front of the sheet pile front wall to examine the increasing in the operation loads on the wall due to upgrade. As per the validated model, the dredging line was considered at 11.60 m below the mean low water level (MLWL) in all four reference models. MLWL was considered at elevation 0.0.

The results of the parametric study for the front wall and tie rod tension were compared to the reference model, whereas pile rows safety was considered during the analysis to examine the effect of the platform location on the piles capacity.

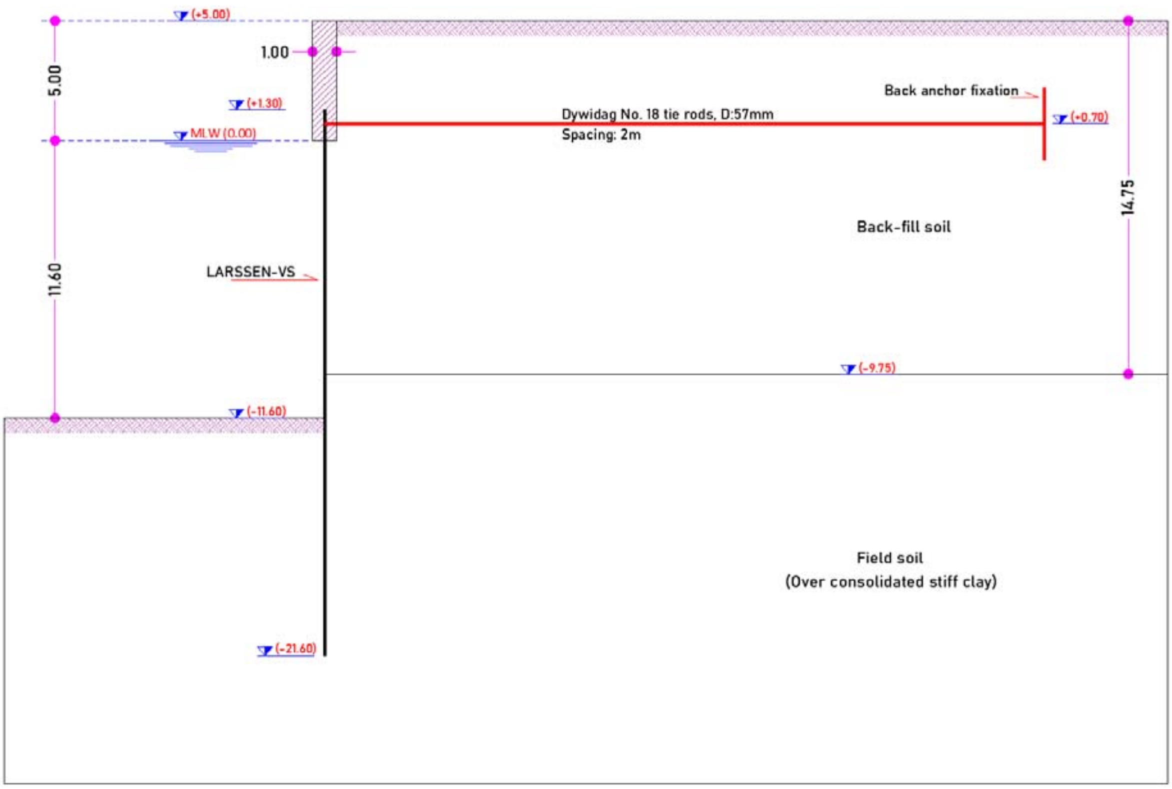


Fig. 5 Cross section of the reference model

V. Reference Quay Wall Models

A. Geometric Modeling

The geometric configuration of the reference models was adopted from the validated model. The front wall was set at the top from level +1.30 m until the bearing level of -21.60 m from MLWL. The capping beam was taken from elevation 0.00 m to +5.00 m (top level of the quay wall) with 1.0 m width. Tie rods were adjusted at +0.70 m with 2.0 m spacing center-to-center along the wall length.

The retained backfill soil of its different types (loose sand, compacted sand, dense sand, and stiff over-consolidated clay) started from +5.00 m to -9.75 m. The native soil was adopted from the validation model as the stiff over-consolidated clay from elevation -9.75 m until the bottom end of the model.

The depth of the dredging line in front of the quay wall was set equal to -11.60 m, similar to the validated model. A typical cross section of the reference model used in this study is shown in Fig. 6.

The mesh used in all reference models was refined to 4331 elements and 8457 nodes. The boundary conditions for the model sides were fixed only in the perpendicular direction and were set as free for the upper boundary, whereas they were fully fixed for the lower boundary.

B. Material Modeling

The same material models used in the validation model (for reinforced concrete, steel members, and native stiff over-consolidated clay) were employed in the reference model except for the backfill material. For the soil layers, the Mohr–Coulomb failure criterion was used, as previously explained. The four backfill soils were used as listed Table II.

All the concrete elements were assumed to have an elastic modulus of 20 GPa, unit weight of 25 kN/m^3, and Poisson's ratio of 0.15. All the steel members were assumed to be in an elastic state with an elastic modulus of 210 GPa.

TABLE II
SOIL PARAMETERS USED AS BACKFILL SOILS IN THE REFERENCE MODELS

Soil	Unit weight (kN/m^3)	Internal friction angle (deg.)	Cohesion (kPa)	Elasticity modulus (MPa)	Poisson's ratio	Interface
Stiff clay	19.50	---	100	30.00	0.40	1.00
Loose sand	18.00	27	---	18.00	0.30	0.70
Compacted sand	19.00	30	---	35.00	0.30	0.70
Dense sand	21.00	20	---	70.00	0.30	0.70

C. Interface Modeling

The interface between the soil-concrete and soil-front wall was considered to have the interface strengths presented in Table II to allow relative displacement (gapping/slippage) to take place between the soil and the structure. The friction angle between the soil and adjacent soil was assumed to be 2/3 of the friction angle of the soil, whereas no strength reduction was considered for the stiff clay layer.

The connection between the front wall and tie rods was considered as fixed. In addition, no interface element was considered in the embedded part of the front wall inside the capping beam to simulate a full fixation.

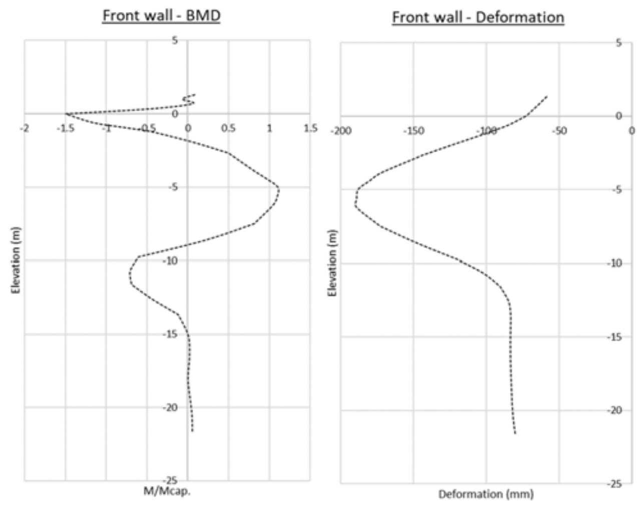
D. Loading

The weights of different materials were considered by the software. Besides, water uplift was considered for the submerged portions. The typical operation loads on a quay wall are comprised of the following:

- External surface load: to mimic the loads of the personnel and equipment atop the quay wall surface. Surface load equal to 40 kPa acting on the top of the quay wall was considered in the analysis;
- Mooring load: the horizontal tension force on the mooring lines pulling the vessels to the bollard after vessel berthing. The direction of the pull-out load is away from the quay wall. A load of 40 kN/m' was considered in the current analysis; and
- Impact load: the dynamic impact of the vessels during berthing on the quay wall. The impact load is absorbed by the fenders system and the rection due to fender compression is transferred to the quay wall structure. This reaction force is applied towards the quay wall and generally resisted by the passive earth pressure of the retained soil. An impact load of 89.6 kN/m' was taken in the current study.

E. Reference Model 1: Loose Sand as Backfill

The maximum lateral displacement of the sheet pile wall was found equal to 189 mm, which is considered significant. The maximum bending moment calculated (at the connection to the capping beam) delivered utilization of 1.50 which surpasses the calculated front wall capacity of 140.65 kN.m/m at yield strength equal 250 MPa. On the other hand, the tie rods reached a utilization of 0.82, which is acceptable considering a breaking load of 1423 kN. The results for the front wall are shown in Figs. 6 (a) and (b).

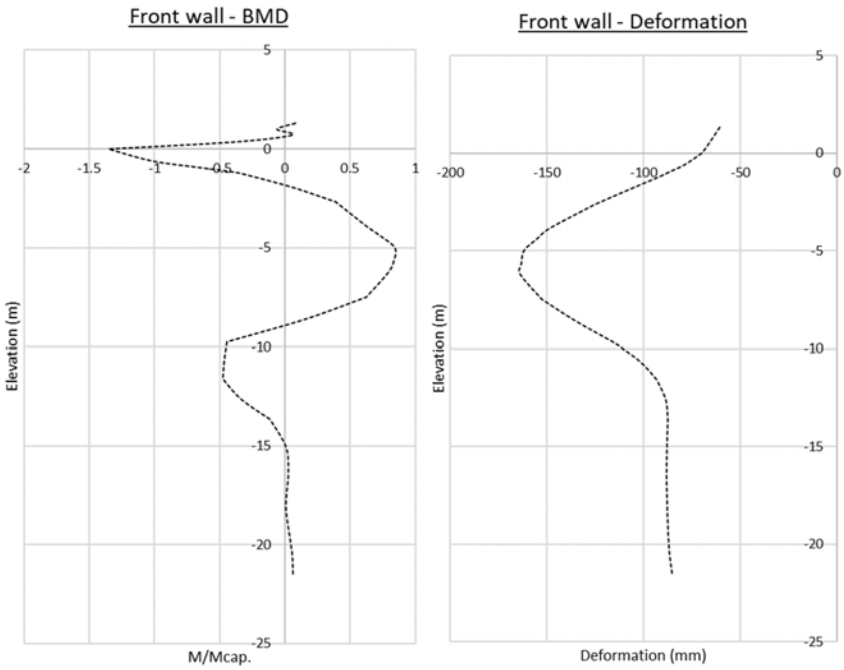


(a) (b)

Fig. 6 Front wall of the reference model-1: (a) Bending moment, (b) Deformation

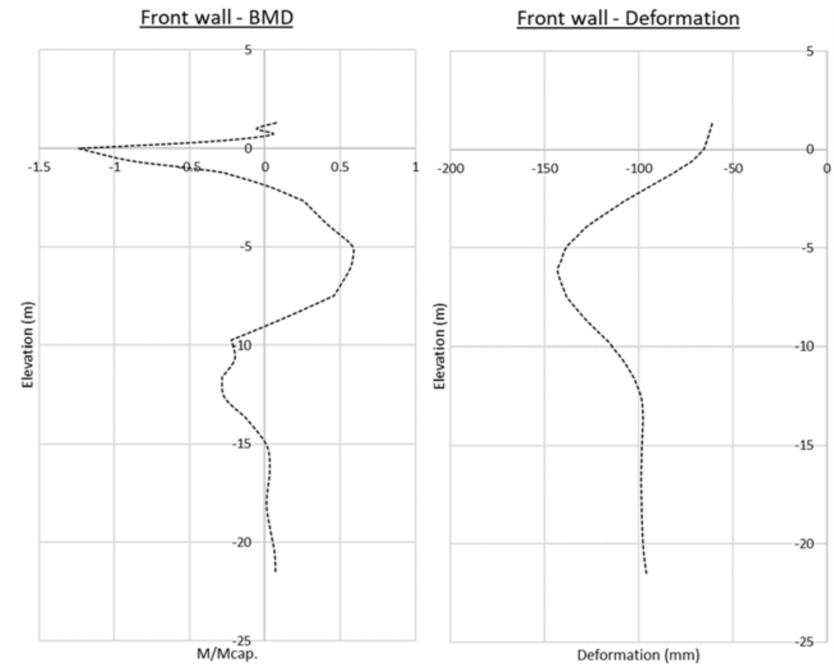
F. Reference Model 2: Compacted Sand as Backfill

The maximum lateral displacement of the sheet pile reached 164 mm, that still is considered huge. The utilization factor due to the maximum calculated bending moment (at the connection to the capping beam) reached is 1.35 that exceeds the calculated capacity of 140.65 kN.m/m' using yield strength of 250 MPa. On the contrary, utilization of the tie rods is 0.81 that is below the considered breaking load of 1423 kN. The results for the front wall are presented in Figs. 7 (a) and (b).



(a) (b)

Fig. 7 Front wall of the reference model-2: (a) Bending moment, (b) Deformation



(a) (b)

Fig. 8 Front wall of the reference model-3: (a) Bending moment, (b) Deformation

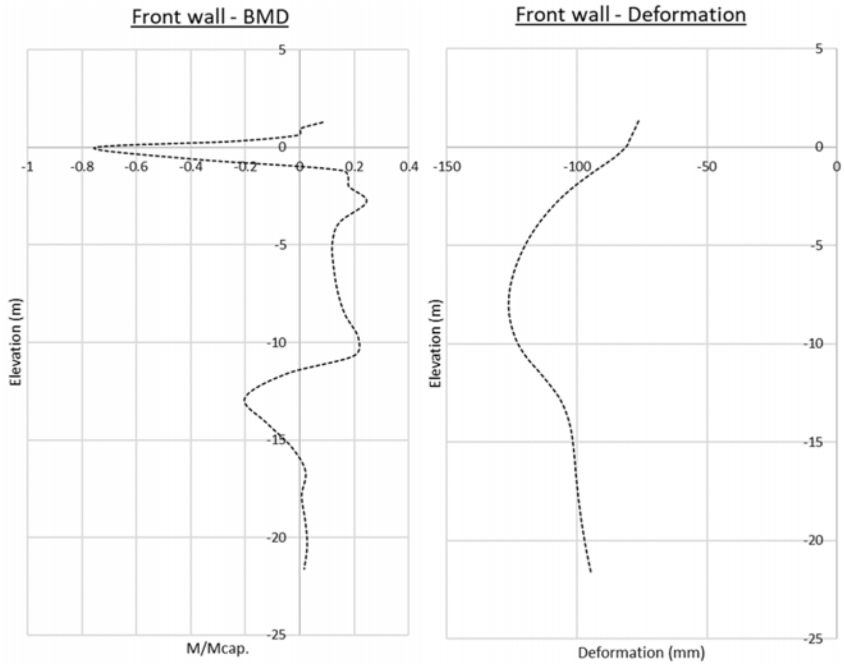
G. Reference Model 3: Dense Sand as Backfill

The maximum obtained lateral displacement was 143 mm, which is immense. The maximum bending moment result is 1.24, still higher than the calculated sheet pile capacity of 140 kN.m/m employing a 250 MPa yield strength. Nevertheless, tie rod's utilization reached 0.79 that is lower than the breaking load of 1423 kN. The results of the front wall are shown within Figs. 8 (a) and (b).

H. Reference Model 4: Overconsolidated clay as Backfill

The maximum spotted lateral displacement was 126 mm, that is slightly large value, while the maximum bending moment (at the connection to the capping beam) resulted in a utilization of

0.75 which is considered safe regarding a capacity of 140.65 kN.m/m. Tie rod tension exhibited utilization of 0.98 which is critically acceptable considering breaking load of 1423 kN. The results for the front wall are illustrated in Figs. 9 (a) and (b).



(a) (b)

Fig. 9 Front wall of the reference model-4: (a) Bending moment, (b) Deformation

VI. Parametric Study Results

For each of the four reference models, the parametric study was carried out to explore the effect of platform addition either attached to the capping beam or separated by a given ratio of the freeboard, S/F (the ratio between the separation width, S, and the freeboard, F). The addition of the platform was studied concurrently with the effect of deepening the dredging line in front of the quay wall to simulate the anticipated increases in the draft of the visiting vessels.

The outputs from the parametric study considered hereby are:

- The maximum bending moment in the front sheet pile wall (to examine the available utilization of the front wall section);
- The maximum lateral deflection of the system;
- The maximum tension force in the tie rod; and
- The utilization of the piles supporting the platform under the effect of those parameters was also investigated. From the analysis of the pile rows, the adjacent pile rows (closest to the front wall) exhibited the maximum straining actions in all cases. Therefore, only the first piles row is considered representative of the safety of the used pile section.

A. Results of Loose Sand as Backfill Soil

The effect of the parameters considered in the current study on the maximum bending moment in the front wall, maximum lateral deflection, and maximum tension force in the tie rod are summarized in Tables III, IV, and V respectively. The maximum utilization ratios and the corresponding lateral deformation of piles under the platform for all the analyzed cases are given in Tables VI and VII, respectively.

TABLE III
Ratio of Decreasing in Maximum Bending Moment in Front Wall for Different Parameters Reference Case 1 - Loose Sand as Backfill

Front wall	Draft of ref. model		Draft increased by 20%		Draft increased by 40%	
	Top	Mid.	Top	Mid.	Top	Mid.
S/F = 0%	67.55%	65.58%	66.03%	67.75%	64.03%	68.36%
S/F = 4%	35.43%	61.55%	34.73%	62.72%	32.92%	62.24%
S/F = 10%	29.26%	59.44%	27.64%	60.49%	24.37%	59.93%
S/F = 20%	22.06%	57.18%	19.96%	59.27%	15.25%	58.68%

TABLE IV
Ratio of Decreasing in Front Wall Lateral Deformation for Reference Case 1 - Loose Sand as Backfill

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	49.74%	44.60%	39.54%
S/F = 4%	49.18%	43.67%	38.33%
S/F = 10%	48.34%	42.93%	37.42%
S/F = 20%	47.11%	41.58%	36.14%

TABLE V
Ratio of Decreasing in Maximum Tension in Tie Rod for Reference Case 1 - Loose Sand as Backfill

Tie rod	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	28.22%	18.34%	8.26%
S/F = 4%	29.82%	21.05%	12.01%
S/F = 10%	30.83%	22.36%	13.67%
S/F = 20%	32.20%	24.27%	15.97%

TABLE VI
PLATFORM PILES UTILIZATION RATIO FOR REFERENCE CASE 1 - LOOSE SAND AS BACKFILL

Piles	Draft of ref. model		Draft increased by 20%		Draft increased by 40%	
	Top	Mid.	Top	Mid.	Top	Mid.
S/F = 0%	0.96	0.62	1.11	0.56	1.24	0.54
S/F = 4%	0.75	0.55	0.84	0.52	0.93	0.48
S/F = 10%	0.73	0.53	0.84	0.51	0.91	0.47
S/F = 20%	0.72	0.49	0.78	0.44	0.84	0.41

TABLE VII
PLATFORM PILES DEFORMATION FOR REFERENCE CASE 1 - LOOSE SAND AS BACKFILL

Piles	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	74.98 mm	88.16 mm	100.42 mm
S/F = 4%	74.04 mm	87.62 mm	100.43 mm
S/F = 10%	73.06 mm	86.75 mm	99.76 mm
S/F = 20%	71.34 mm	85.21 mm	98.61 mm

B. Results of Compacted Sand as Backfill Soil

The maximum bending moment in the front wall, maximum lateral displacement, and maximum tension force in tie rods when use compact sand as backfill material behind the front wall are summarized in Tables VIII, IX, and X respectively. The peak utilization ratio, and the corresponding lateral displacement of piles under the platform for all the considered cases are shown in Tables XI and XII, respectively.

TABLE VIII
RATIO OF DECREASING IN MAXIMUM BENDING MOMENT IN FRONT WALL FOR DIFFERENT PARAMETERS, REFERENCE CASE 2 - COMPACTED SAND AS BACKFILL

Front wall	Draft of ref. model		Draft increased by 20%		Draft increased by 40%	
	Top	Mid.	Top	Mid.	Top	Mid.
S/F = 0%	65.49%	54.26%	65.26%	57.65%	63.28%	57.84%
S/F = 4%	31.80%	53.15%	33.67%	56.44%	33.64%	57.13%
S/F = 10%	23.88%	53.14%	25.41%	56.08%	23.63%	56.44%
S/F = 20%	15.62%	49.73%	14.92%	54.21%	13.72%	54.42%

TABLE IX
RATIO OF DECREASING IN FRONT WALL LATERAL DEFORMATION FOR REFERENCE CASE 2 - COMPACTED SAND AS BACKFILL

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	41.79%	36.39%	30.13%
S/F = 4%	43.19%	37.45%	31.25%
S/F = 10%	43.23%	37.17%	30.90%
S/F = 20%	42.08%	36.35%	30.30%

TABLE X
RATIO OF DECREASING IN MAXIMUM TENSION IN TIE ROD FOR REFERENCE CASE 2 - COMPACTED SAND AS BACKFILL

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	29.83%	19.01%	7.75%
S/F = 4%	31.84%	21.68%	11.31%
S/F = 10%	33.71%	23.70%	13.52%
S/F = 20%	35.81%	26.17%	16.26%

TABLE XI
PLATFORM PILES UTILIZATION RATIO FOR REFERENCE CASE 2 - COMPACTED SAND AS BACKFILL

Front wall	Draft of ref. model		Draft increased by 20%		Draft increased by 40%	
	Top	Mid.	Top	Mid.	Top	Mid.
S/F = 0%	0.63	0.43	0.77	0.38	0.90	0.36
S/F = 4%	0.49	0.39	0.59	0.37	0.69	0.34
S/F = 10%	0.48	0.39	0.56	0.37	0.65	0.34
S/F = 20%	0.50	0.35	0.54	0.31	0.60	0.29

TABLE XII
PILES DEFORMATION FOR REFERENCE CASE 2 - COMPACTED SAND AS BACKFILL

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	74.74 mm	87.55 mm	101.98 mm
S/F = 4%	74.88 mm	87.17 mm	101.81 mm
S/F = 10%	74.64 mm	86.71 mm	101.32 mm
S/F = 20%	74.15 mm	85.68 mm	100.32 mm

C. Results of Dense Sand as Backfill Soil

The effect of the two main parameters on the maximum bending moment of the front wall, the maximum lateral displacement, and the maximum tie rod tension when the retained soil behind the front wall is dense sand is presented in Tables XIII, XIV, and XV. The utilization ratios and lateral displacement of the pile rows for all the analyzed scenarios are given in Tables XVI and XVII.

TABLE XIII
RATIO OF DECREASING IN MAXIMUM BENDING MOMENT IN FRONT WALL FOR DIFFERENT PARAMETERS, REFERENCE CASE 3 - DENSE SAND AS BACKFILL

Front wall	Draft of ref. model		Draft increased by 20%		Draft increased by 40%	
	Top	Mid.	Top	Mid.	Top	Mid.
S/F = 0%	61.30%	34.00%	61.16%	39.35%	58.49%	38.98%
S/F = 4%	40.62%	32.32%	45.08%	36.68%	43.28%	37.16%
S/F = 10%	24.78%	35.02%	26.65%	39.92%	23.78%	40.58%
S/F = 20%	14.87%	31.55%	14.14%	38.65%	12.78%	39.79%

TABLE XIV
RATIO OF DECREASING IN FRONT WALL LATERAL DEFORMATION FOR REFERENCE CASE 3 - DENSE SAND AS BACKFILL

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	31.29%	24.51%	16.38%
S/F = 4%	31.65%	24.70%	16.94%
S/F = 10%	32.61%	25.63%	17.72%
S/F = 20%	32.34%	25.47%	17.69%

TABLE XV
RATIO OF DECREASING IN MAXIMUM TENSION IN TIE ROD FOR REFERENCE CASE 3 - DENSE SAND AS BACKFILL

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	27.00%	14.67%	1.76%
S/F = 4%	28.09%	16.04%	3.80%
S/F = 10%	31.02%	19.06%	6.69%
S/F = 20%	33.08%	21.49%	9.38%

TABLE XVI
PLATFORM PILES UTILIZATION RATIO FOR REFERENCE CASE 3 - DENSE SAND AS BACKFILL

Front wall	Draft of ref. model		Draft increased by 20%		Draft increased by 40%	
	Top	Mid.	Top	Mid.	Top	Mid.
S/F = 0%	0.39	0.27	0.59	0.35	0.78	0.36
S/F = 4%	0.35	0.26	0.51	0.37	0.67	0.38
S/F = 10%	0.31	0.23	0.41	0.34	0.54	0.37
S/F = 20%	0.33	0.19	0.37	0.34	0.48	0.34

TABLE XVII
PILES DEFORMATION FOR REFERENCE CASE 3 - DENSE SAND AS BACKFILL

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	83.39 mm	93.25 mm	109.91 mm
S/F = 4%	83.49 mm	92.76 mm	109.45 mm
S/F = 10%	83.27 mm	92.49 mm	108.92 mm
S/F = 20%	82.74 mm	91.58 mm	107.75 mm

D. Results of Overconsolidated Clay as Backfill Soil

The maximum bending moment, the maximum lateral displacement affecting the sheet pile wall, and maximum tie rod tension for reference model No. 4 are presented in Tables XVIII, XIX, and XX. The maximum corresponding utilization ratios, and lateral deformation acting on the pile rows below the platform are summarized in Tables XXI and XXII.

TABLE XVIII
RATIO OF DECREASING IN MAXIMUM BENDING MOMENT IN FRONT WALL FOR DIFFERENT PARAMETERS, REFERENCE CASE 4 – OVERCONSOLIDATED CLAY AS BACKFILL

Front wall	Draft of ref. model		Draft increased by 20%		Draft increased by 40%	
	Top	Mid.	Top	Mid.	Top	Mid.
S/F = 0%	68.98%	18.83%	65.72%	14.40%	65.87%	8.41%
S/F = 4%	51.84%	19.44%	51.95%	9.54%	51.24%	5.05%
S/F = 10%	45.12%	26.39%	44.33%	14.13%	42.81%	4.18%
S/F = 20%	37.72%	24.19%	35.57%	9.78%	33.34%	2.81%

TABLE XIX
RATIO OF DECREASING IN FRONT WALL LATERAL DEFORMATION FOR REFERENCE CASE 4 - OVERCONSOLIDATED CLAY AS BACKFILL

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	37.41%	30.09%	20.18%
S/F = 4%	37.30%	30.27%	20.42%
S/F = 10%	37.50%	30.46%	20.58%
S/F = 20%	37.68%	30.76%	20.93%

TABLE XX
RATIO OF DECREASING IN MAXIMUM TENSION IN TIE ROD FOR REFERENCE CASE 4 - OVERCONSOLIDATED CLAY AS BACKFILL

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	37.25%	32.33%	27.51%
S/F = 4%	37.41%	32.70%	28.03%
S/F = 10%	37.97%	33.32%	28.80%
S/F = 20%	39.09%	34.55%	30.17%

TABLE XXI
PLATFORM PILES UTILIZATION RATIO FOR REFERENCE CASE 4 - OVERCONSOLIDATED CLAY AS BACKFILL

Front wall	Draft of ref. model		Draft increased by 20%		Draft increased by 40%	
	Top	Mid.	Top	Mid.	Top	Mid.
S/F = 0%	0.23	0.33	0.22	0.33	0.24	0.35
S/F = 4%	0.17	0.31	0.18	0.33	0.16	0.36
S/F = 10%	0.15	0.32	0.16	0.31	0.16	0.34
S/F = 20%	0.17	0.27	0.16	0.28	0.17	0.29

TABLE XXII
PILES DEFORMATION FOR REFERENCE CASE 4 - OVERCONSOLIDATED CLAY AS BACKFILL

Front wall	Draft of ref. model	Draft increased by 20%	Draft increased by 40%
S/F = 0%	76.78 mm	84.96 mm	97.16 mm
S/F = 4%	76.71 mm	84.46 mm	96.50 mm
S/F = 10%	76.39 mm	83.79 mm	95.73 mm
S/F = 20%	75.74 mm	83.21 mm	94.29 mm

E. Results Discussion

The analysis results of the parametric study carried out for different backfill material show the following:

1) For the front wall:

- The bending moment and corresponding lateral deformation were significantly reduced by adding the platform for all backfill types. However, by increasing the separation gap distance between existing caping beam and the new platform slab, the effect of adding the new platform gradually decreases (Tables III, VIII, XIII, and XVIII), indicating a simultaneous reduction in the relieving effect of the platform. The increasing of the separation gap gradually decreases the reduction in utilization of the bending moment from 67% to 15% when using loose or compact sand as backfill soil, while this reduction gradually decreased from 61% to 15% when dense sand was used. No doubt, the best mitigation is to attach the new reliving platform to the existing wall capping beam, but this mitigation may be difficult from construction point of view and may require full reconstruction of the existing capping beam of the quay wall.
- The addition of the platform while maintaining the ratio (S/F) equal to 4%, allowed for deepening the basin in front of the quay wall by 40% from its original value while maintaining the utilization ratios for the used sheet pile section below 1.00 for all types of backfill soils. It should be noted that the front wall section was not safe at the original draft without the platform.

2) For the tie rod tension:

- The tension force in the tie rod was significantly reduced by the addition of the platform for all proposed gap distances ratios and using any type of backfill material. Nevertheless, the increases in the separation gap width decrease the tension force in the rod, as the platform contribution to the fixation of the front wall is reduced. The reduction in the fixation of the system causes more relaxation in the deformation of the front wall (increase in deformation) accompanied by a decrease in tension force.

This was observed for the sandy and clayey backfill materials employed in the parametric study.

- All studied platform separation ratios allowed for deepening the basin while maintaining the tie rod tension below the capacity limit and below the value in the reference case in the original draft.

3) For the pile rows:

- The behavior of the pile's rows carrying the platform slab was similar to the tie rod tension forces. As expected, the forces in the piles decreased with the increase in the separation gap width, confirming that the contribution to the fixation is reduced, resulting in lower straining actions in piles.

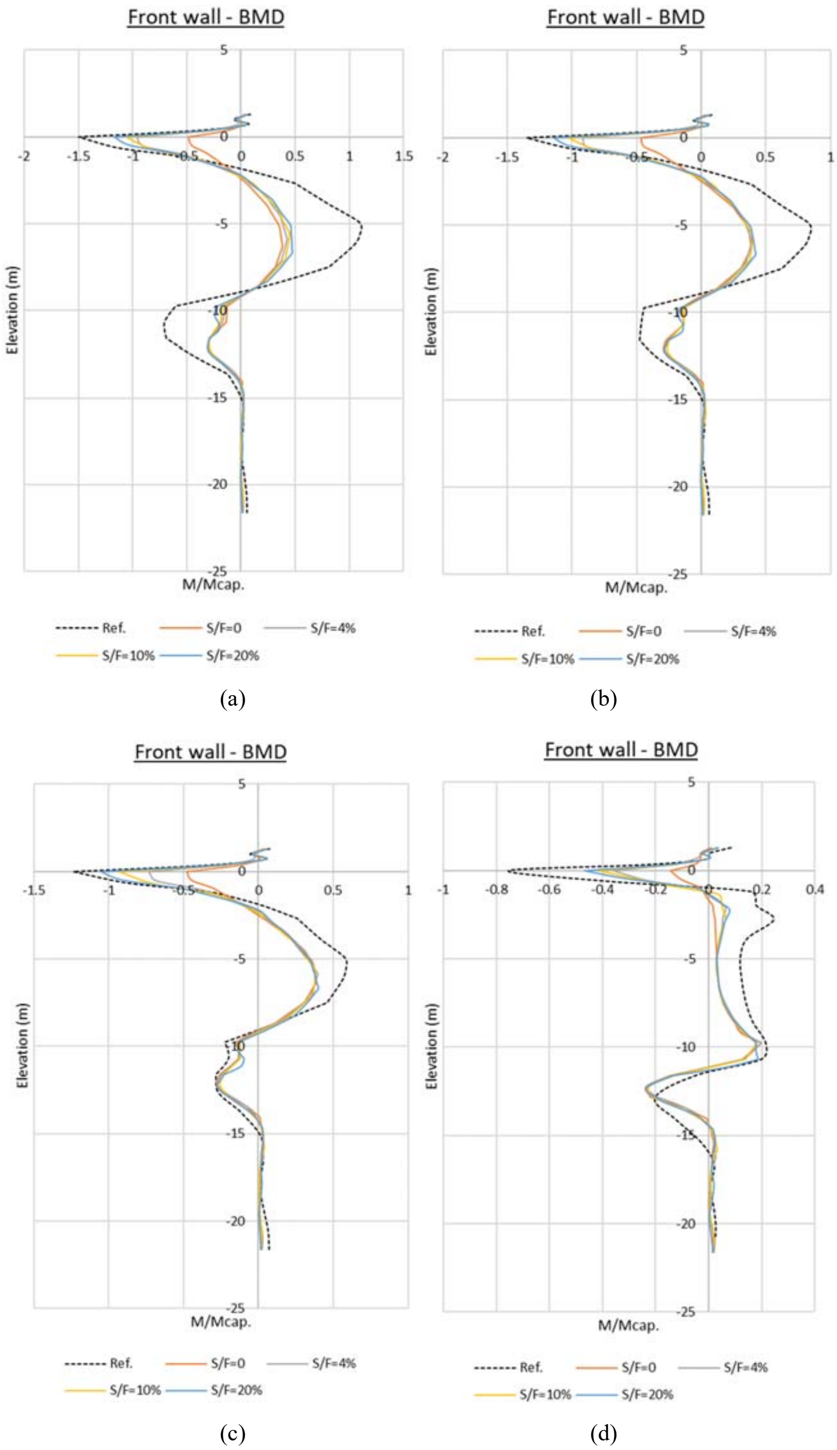


Fig. 10 Front wall bending moment at original depth; (a) Loose sand as back fill, (b) Compacted sand as backfill, (c) Dense sand as backfill, (d) Overconsolidated clay as backfill

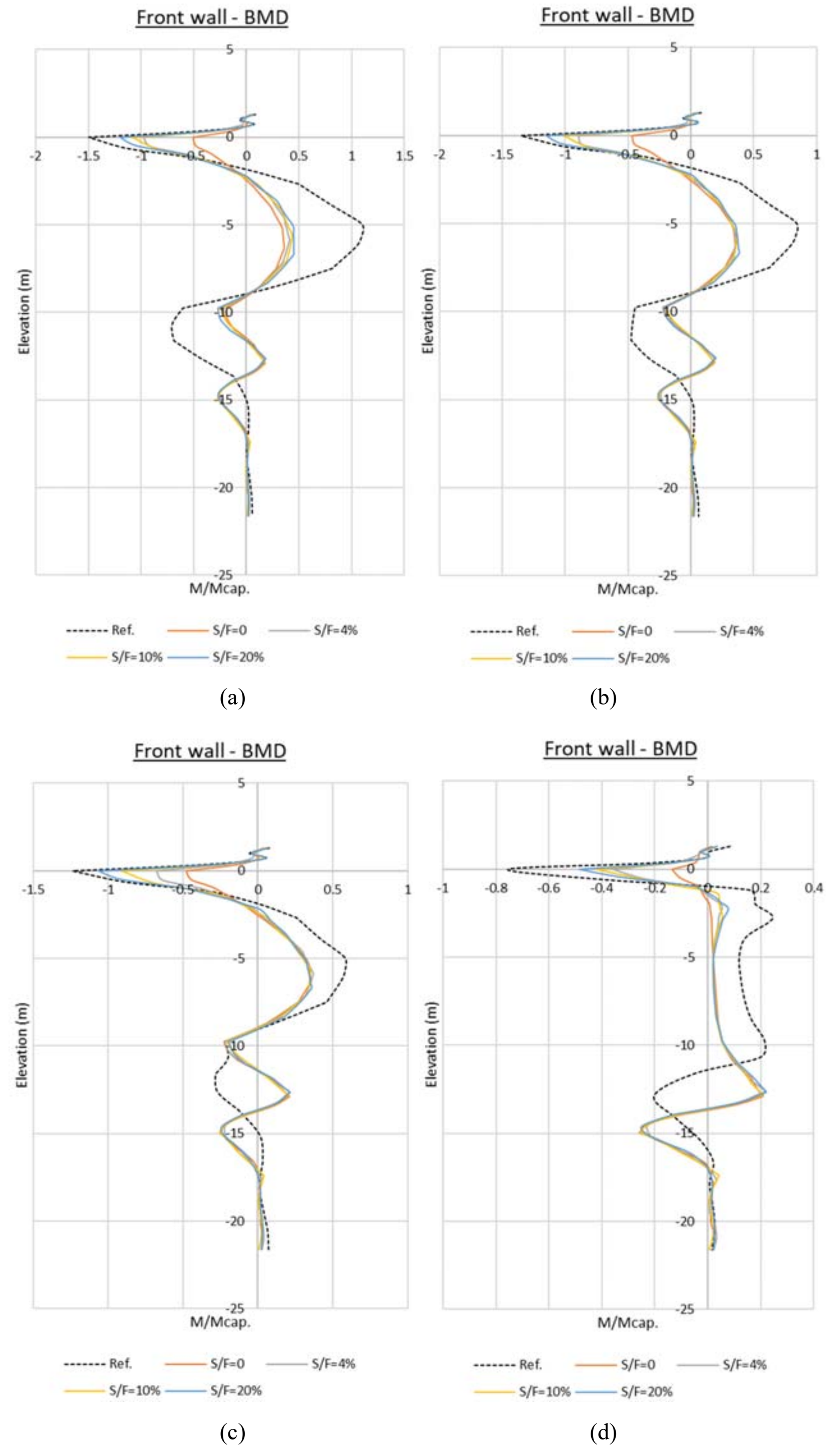


Fig. 11 Front wall bending moment at depth increased by 20%; (a) Loose sand as back fill, (b) Compacted sand as backfill, (c) Dense sand as backfill, (d) Overconsolidated clay as backfill

- The deepening of the basin in front of the quay wall has considerable effect on the utilization ratio of the pile based on the type of backfill material. For piles embedded in loose to compact sand, as given in Tables VI and XI, increasing the depth in front of the wall by 20% elevated the utilization ratio of the pile between 7% and 22%. For piles embedded in dense sand (Table XVI), deepening by 20% resulted in an increment of 11% to 49% in the internal forces depending on the location of the row. While for piles embedded in stiff clay, deepening of the basin by 40% resulted in an increment of only 7% to 16% (Table XXI) in the utilization ratios of piles. At same S/F ratio, the increase in the piles' utilization reached 144%, 127%, 110%, and 72% as ratio of the draft increases for S/F equal 0%, 4%, 10%, and 20%, respectively as presented in Figs. 16 (a)-(c).

- The results of the analysis carried here indicate that the piles carrying the platform should be adequately designed (in section and in length) to carry the anticipated loads after upgrading the quay wall and selecting the appropriate separation distance of the new relieving platform to sustain the increase in the dredge line depth.

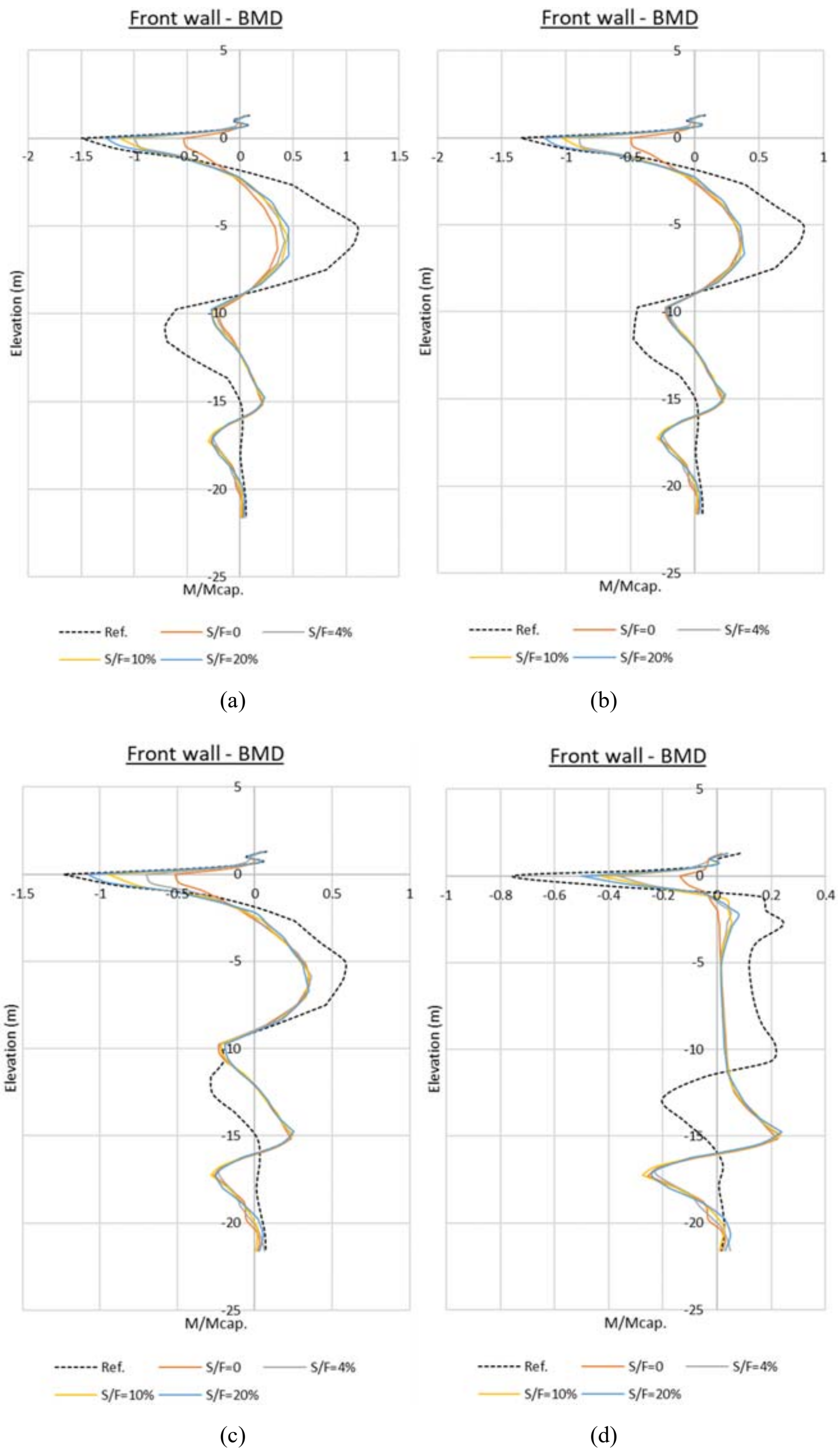


Fig. 12 Front wall bending moment at depth increased by 40%; (a) Loose sand as back fill, (b) Compacted sand as backfill, (c) Dense sand as backfill, (d) Overconsolidated clay as backfill

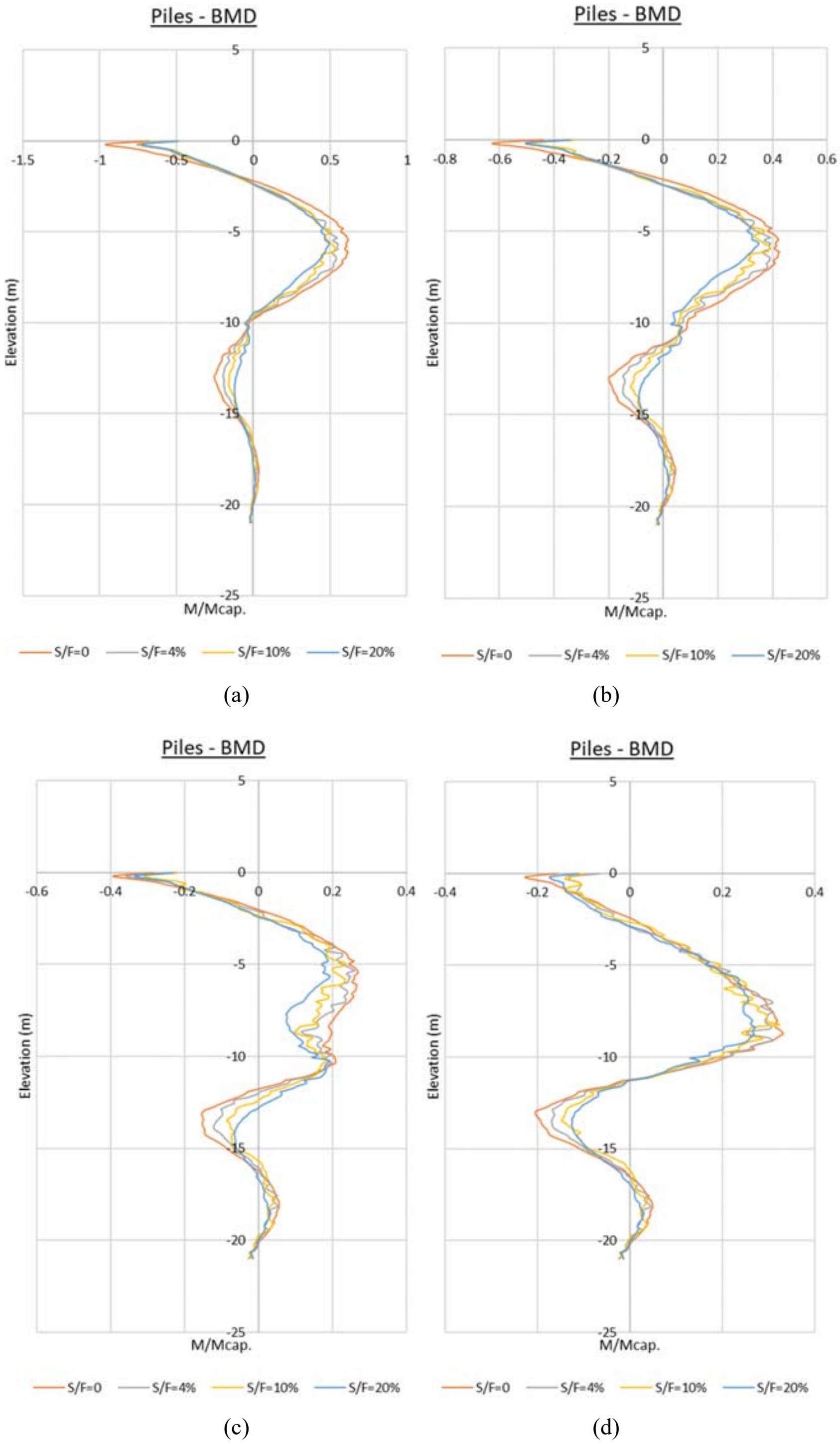


Fig. 13 Piles bending moment at original depth; (a) Loose sand as back fill, (b) Compacted sand as backfill, (c) Dense sand as backfill, (d) Overconsolidated clay as backfill

4) The impact load case was analyzed to examine the deformation of the front wall with respect to the separation gap width at the platform location (0.00 MLW). For all analyzed cases under the impact load case, the lateral deformation was found to be away from the separation gap, as shown in Figs. 17 (a) and (b). The resultant lateral deformation of the front wall under the impact load and the lateral earth pressure from the retained soil was in the opposite direction of the proposed separation gap. Based on that, the impact load of the vessel's during berthing does not control the proposed width of the separation gap.

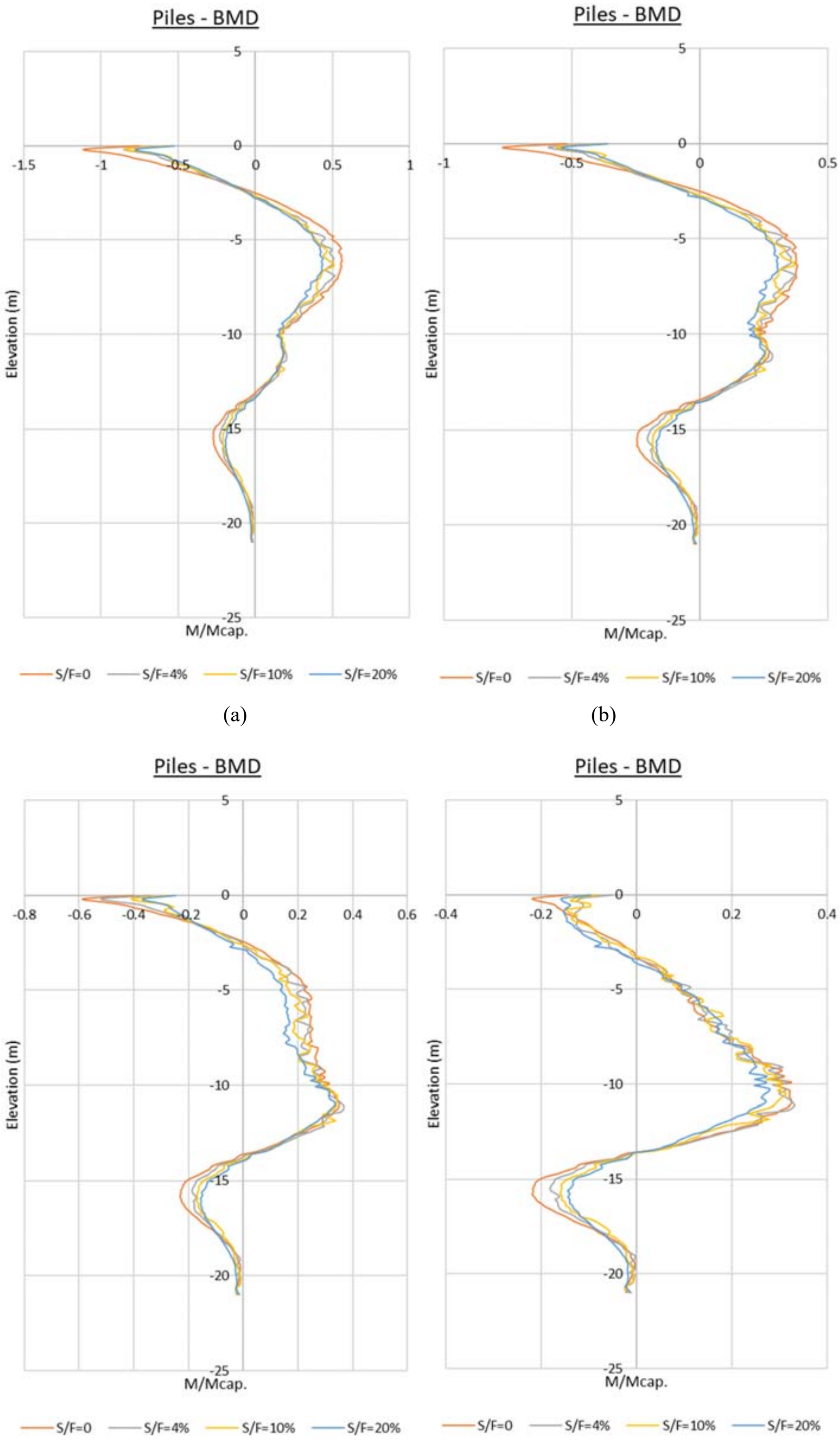


Fig. 14 Piles bending moment at depth increased by 20%; (a) Loose sand as back fill, (b) Compacted sand as backfill, (c) Dense sand as backfill, (d) Overconsolidated clay as backfill

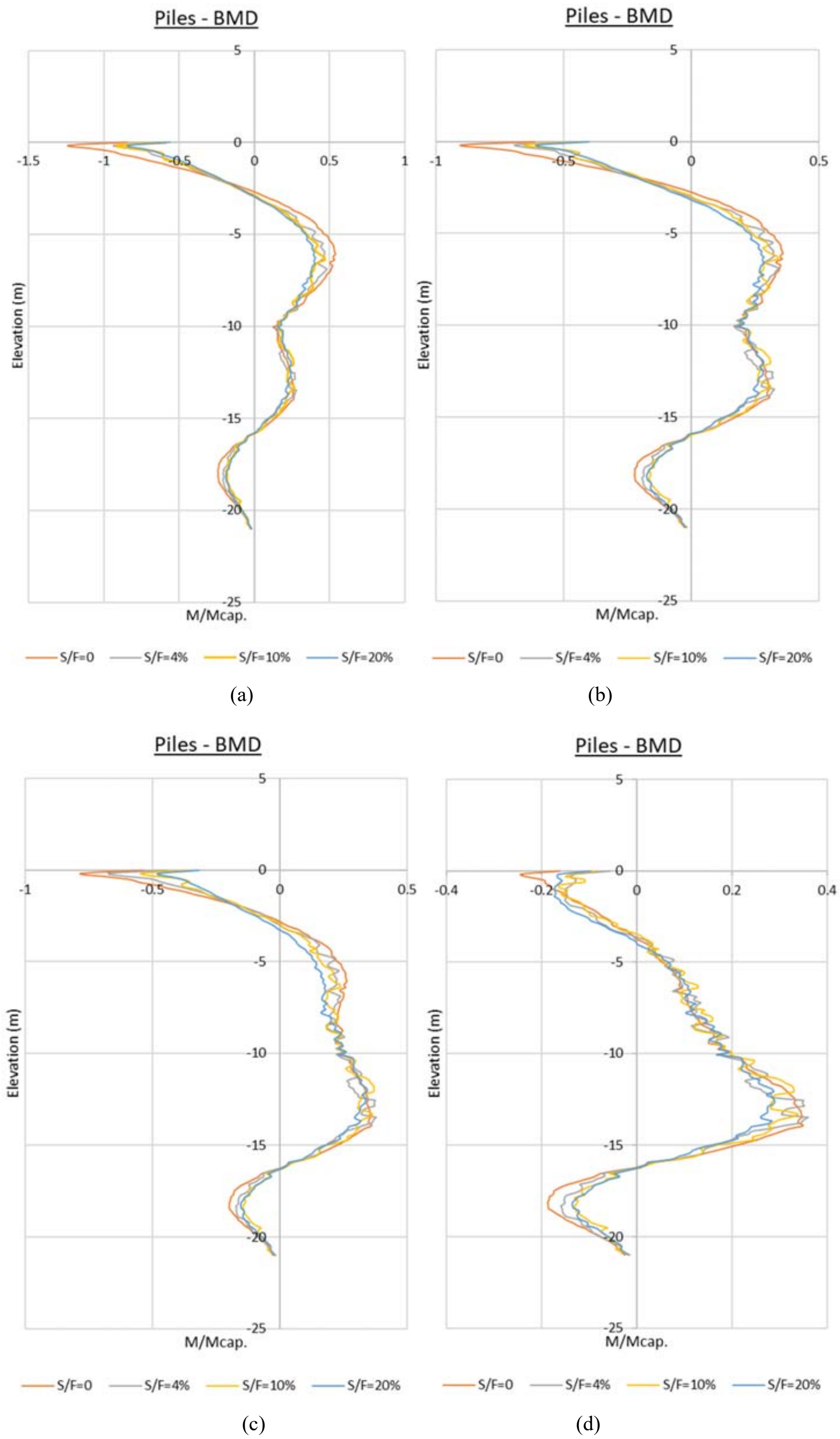
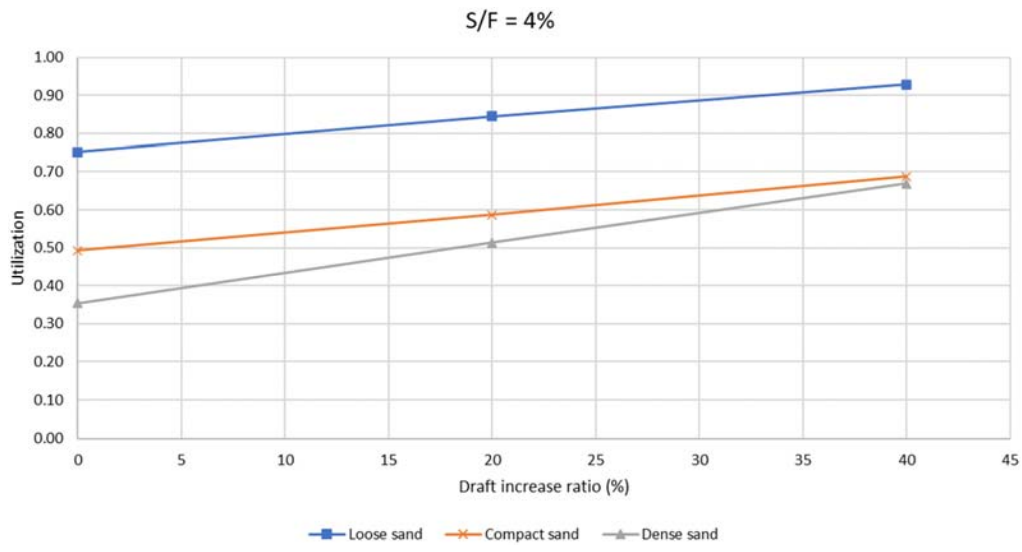
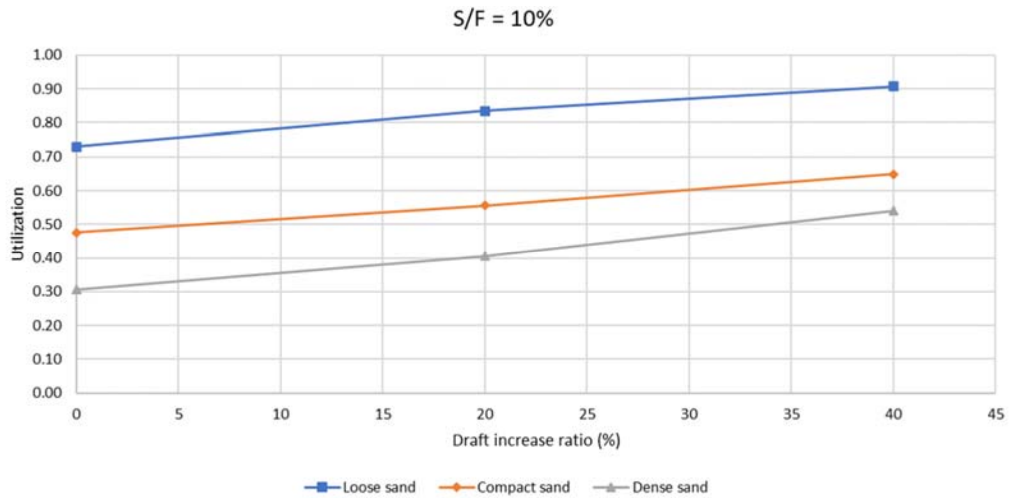


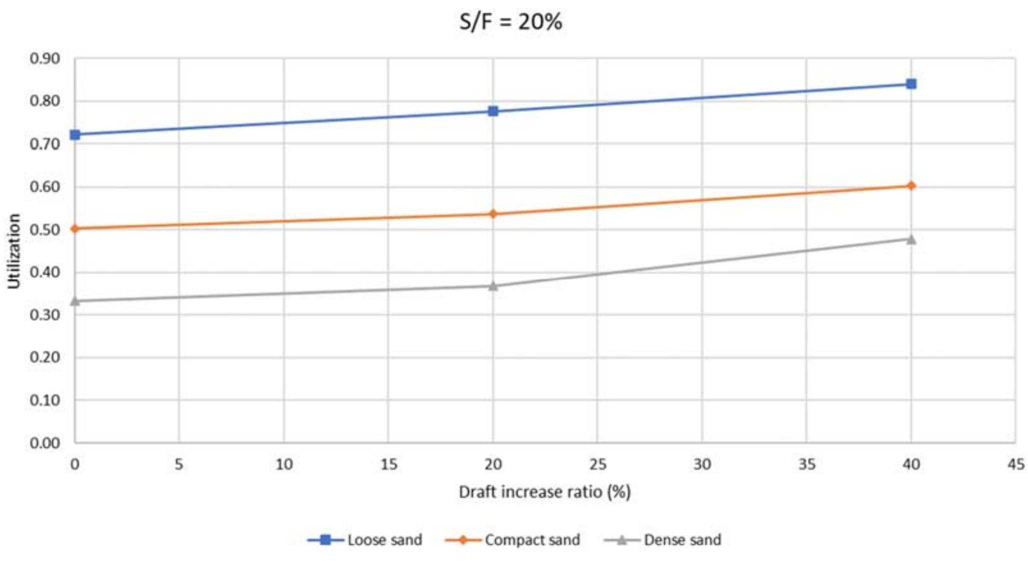
Fig. 15 Piles bending moment at depth increased by 40%; (a) Loose sand as back fill, (b) Compacted sand as backfill, (c) Dense sand as backfill, (d) Overconsolidated clay as backfill



(a)

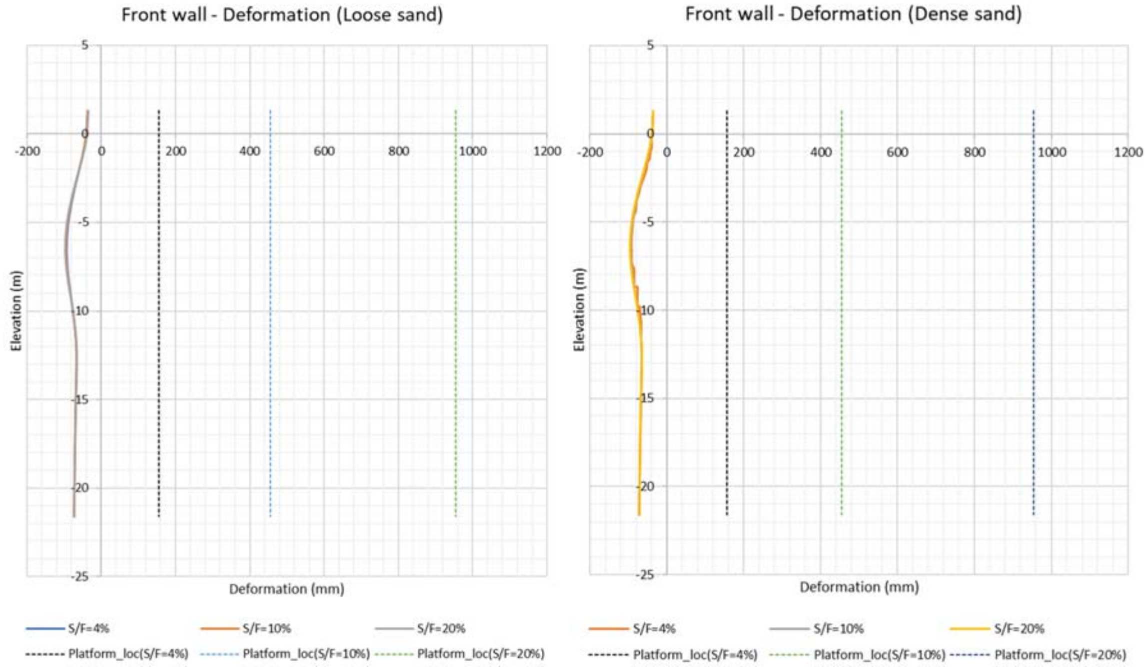


(b)



(c)

Fig. 16 Piles utilization trends for sandy backfill soils; (a) S/F = 4%, (b) S/F = 10%, (c) S/F = 20%



(a) (b)

Fig. 17 Front wall deformation considering impact load; (a) Loose sand backfill, (b) Dense sand backfill

VII. Conclusion

Adding a platform supported on piles at the backyard of an existing sheet pile or anchored sheet pile quay wall is considered a successful mitigation to upgrade the quay wall. Usually, the added platform is connected to the existing capping beam, however, this option may require reconstruction of the capping beam. The numerical investigation presented in this study demonstrated that the platform can be added at the back side of the front sheet pile wall with a separated distance from the existing capping beam. Adding a new platform on piles is a cost-effective option compared to constructing a new quay wall system in front of the old wall to upgrade the existing quay wall.

The analysis carried out in this paper shows that adding a platform will relax the lateral earth pressure on the front wall and the tension force in the tie rod, allowing to increase the dredge line depth in front of the wall based on the required upgrade of the quay wall (receiving bigger and deeper vessels).

The numerical investigation reveals also that constructing a platform on piles at a separated distance from the quay wall can be used for all types of retained soils either loose sand, compact sand, dense sand, and stiff clay. Based on the parametric study given results, using stiff clay as a backfill soil gives slightly better performance for the front wall and the first adjacent pile row than sandy backfills, if the native soil is comprised of stiff clay.

The added platform is supported on several rows of piles. Those piles should be designed to sustain the existing and the anticipated increase in the operation loads after upgrading the quay wall to receive heavier vessels. Design of supported piles under the platform including section, length, and number depends mainly on the depth of the dredge line in front of the wall in addition to the operational loads (surface live loads, mooring tension load, and impact loads).

Based on the results of the numerical investigation presented in this study, optimization of upgrading the quay wall should be achieved to select the maximum separation distance at certain new dredge line depth for the existing retained soil behind the quay wall followed by a full design of the new platform and its supported piles.

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