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Artificial Intelligence Implementations Towards Shaping the Future of Digital World

A PARAMETRIC ANALYSIS TO INVESTIGATE THE SOIL-STRUCTURE INTERACTION ON QUAY WALLS USING FINITE ELEMENT MODELING

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ABSTRACT

Structural strengthening is an effective and feasible approach for preserving the functionality of degraded structures safely and reliably while also upgrading their capacity to sustain extra loads. As a cost-effective and practical solution necessitates the development of methodologies that simulate the real conditions to assess the soil structure interaction, additional loads, and their impact on structures, as well as to evaluate the strengthening system properly. The overall aim of this research is to develop finite element models using PLAXIS 3D to investigate the influence of various material models on an existing quay wall with diverse soil profiles, along with a parametric analysis to evaluate the impact of extra loads. A case study in Port Said East Port, the diaphragm quay wall of the container terminal operated by Suez Canal Container Terminal (SCCT), which is located to the north of Egypt on the Mediterranean Sea, was chosen in this regard. For the purpose of verification, two case studies were chosen: the Deep-Sea quay wall at Rotterdam, which provides essential field results and a 3D PLAXIS finite element model, along with the diaphragm quay wall of the Port Said East Port container terminal, which provides 3D PLAXIS finite element models. Most comparisons between the author's models and the three referenced cases show a percent error of less than 10%, indicating an acceptable margin of error. A comparative study of two soil profiles employing two material models was conducted, revealing that the Mohr-Coulomb material model is more conservative than the Hardening Soil model, since it yields higher results. A parametric analysis was performed on the effects of increased crane loads and deepening in front of the quay wall, revealing that deepening has a greater influence than the increment of crane loads, especially for horizontal displacement.

Keywords: Numerical modeling, Egyptian Port, Quay walls, PLAXIS 3D, Strengthening.

1. INTRODUCTION

Maintaining degraded structures safely and reliably with structural strengthening is efficient and profitable. Structural strengthening may repair structures damaged by earthquakes or impact and extra loads. Also applies to structures built to earlier code standards that no longer match current criteria. Existing reinforced concrete (RC) constructions for gravity loads or earlier regulations may be non-ductile. Such structures are vulnerable to collapse during large earthquakes due to their low lateral load-carrying capability and ductility. Due to long-term degradation from the hostile marine corrosive environment, reinforced concrete (RC) structures lose load-carrying capability and become more prone to structural collapse.[1-6]

Marine structures, such as quay walls, require reinforcement due to the harsh marine environment and its impact on them. Additionally, they need to be upgraded to accommodate additional loads resulting from the increasing crane loads or the deepening of the area in front of the quay wall, which is caused by the increase in the weight and variety of cargo, as well as the development of related buildings and storage areas. Multiple research initiatives have examined case studies on how to strengthen for quay walls using conventional methods with concrete and steel materials. These studies have incorporated additional elements from these materials for purposes such as deepening, increasing crane loads, augmenting deck loads, ship collision incidents, and seismic. Numerical analysis has been conducted using a variety of software, including ABAQUS, ANSYS, MIDAS, and PLAXIS, to investigate the behavior of structures under the aforementioned loads and to develop strengthening techniques.[7-13]

Elsayed M. Galal (2017) performed a numerical study utilizing the PLAXIS 2D model to assess the feasibility of upgrading the current quay wall structure which is open berth at Port Said West container terminal, Egypt. In order to sustain the additional weights from the new container cranes and enable berth deepening, a rehabilitation approach incorporating new fender piles and box sheet pile panels has been selected. The assessment was conducted by reviewing the initial design and subsequent upgrade assessments under two defined scenarios: pre-upgrading and post-upgrading situations. The findings indicated that the upgraded structure maintained soil stability at levels comparable to those before the improvement, and the quay wall elements effectively withstood the effects of depth and increased crane loads.[14]

Joel Aguilar et al. (2019) conducted a study on the aging wharf structure (deck on piles) at Pier J, Berths 245-247, Port of Long Beach (POLB), necessitating the enhancement of the carrying capacity of the landward crane rail to support modern and larger ship-to-shore (STS) cranes for bigger ships. This research delineates the assessments and analyses conducted, together with the design possibilities contemplated for the enhancement at Pier J. Option 1 involves increasing the thickness of the deck between two rows of piles, whereas Option 2 entails the installation of a new row of piles. Option 1 was the preferred solution, offering significant construction cost savings and mitigating construction risks.[15]

A study by Premalatha, P.V. et al. (2011) presents a numerical analysis of piling groups that support berthing structures, which experience forces from berthing/mooring operations and dredging works. A two-dimensional finite element model is developed using Plaxis and is varified against the theoretical solution. The influence of berthing and mooring forces, as well as dredging activities, on pile groups is analyzed with and without the presence of tie-rod anchors. An analysis of a berthing structure in India is conducted to determine the optimal tie-rod length necessary for its installation. The results demonstrated that the lateral deflection of the berthing structure caused by mooring or towing forces is greater than that caused by berthing forces. Furthermore, the influence of the tie rod significantly mitigates the deflection of the berthing structure by approximately 8.72% to 15.43% as the length of the tie rod is incrementally increased from 6 m to 18 m, thereby decreasing the required length of the pile, as well as the materials and reinforcement utilized in construction.[16]

Lu Zhu et al. (2019) investigated a novel foam-filled lattice composite bumper system (FLCBS), comprising fibre-reinforced polymer (FRP) layers and a foam-web core, intended to protect bridge piers against maritime collisions. FLCBS comprises FRP face sheets, FRP lattice webs, and polyurethane (PU) foam cores, which may be concurrently produced using the vacuum-assisted resin infusion process (VARIP). FLCBS demonstrates exceptional energy-absorbing capabilities and wide customizable alternatives. A comprehensive numerical model for assessing achievement was created using the explicit finite element program ANSYS/LS-DYNA. An investigation was conducted to experimentally examine two foam-filled lattice composite panels subject to low-velocity impact, aiming to validate the computational model for FLCBS. The finite element models of the composite panels exhibited substantial concordance with the impact load history and mid-span deflection history of the experimental data. Diverse simulations of impact angles, velocities, and locations were conducted. Quantitative statistics illustrate the specific benefits of FLCBS by contrasting peak impact force and impact duration.[17]

2. Problem statement

Maritime transportation underpins economic development and contemporary civic infrastructure. The maritime transportation industry requires larger vessels to accommodate containers and freight. This raises storage areas, weights, crane capacity, and quay wall loads. This requires the improvement of quay walls and the enlargement of quay yards. Moreover, unforeseen incidents may damage quay walls, incurring expenses and hindering port operations. Restoring the quay wall is essential to safeguard and enhance its functionality. In this regard, it is crucial to develop methodologies that can precisely simulate real circumstances in a detailed yet simplified manner, without wasting resources, to assess soil-structure interaction under current conditions and potential alterations. Finite Element Models (FEM) are the suitable methodology for this context; hence, constructing the FEMs to examine the proper definitions for soil characteristics and structural descriptions, as well as the impact of various loads on them, is essential.

3. RESEARCH OBJECTIVE

This research aims to evaluate the soil structure interaction for an existing quay wall that necessitates upgrading to accommodate extra loads due to higher crane loads or deepening of the quay wall. To accomplish this objective, FEM were developed to validate the case study and investigate the influence of different material models along with different soil profiles on the mentioned case study in addition to conduct a parametric analysis on the increase in loads and quay wall depth. FEM conserves time, resources, and effort compared to experimental or field tests; furthermore, it provides a range of methodologies and effectively represents real conditions.

4. RESEARCH methodology

4.1. Data Collection

Two case studies were selected for verification purposes: the Deep-Sea quay wall at Rotterdam, which provides essential field results and a 3D PLAXIS finite element model result, along with the diaphragm quay wall of the Port Said East Port container terminal, which provides a 3D PLAXIS finite element model result from two research studies by M. ElGendy et al. (2016)[18] and Omaima M. Hamed et al. (2017)[19]. FEM in this research have been developed using PLAXIS 3D to compare the mentioned research findings with the model's results in order to validate the selected model for the comparative and the parametric study in this research.

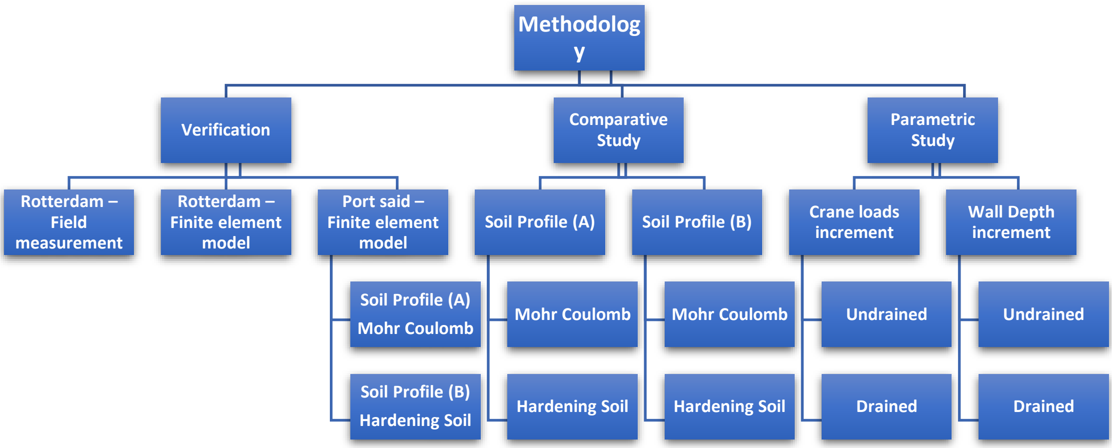


Figure 1: Research Methodology Plan.

4.1.1. Deep-Sea quay wall at Rotterdam

The port is located in Rotterdam, Netherlands. In 2003, a logistics company named Gevelco refurbished a quay wall at Rotterdam Port, located near Brittanie Harbor, to enhance its capacity for accommodating big vessels. Due to port improvements, an old jetty has been replaced by a new 319-meter quay wall, referred to as the Deep-Sea Quay Wall. Seven (07) spots have been monitored along the deep-sea quay wall, with systematic field measurements performed from the commencement of the operating phase in 2004 until 2010.[20]

The deep-sea quay wall in Rotterdam comprises tubular piles with diameter 1420 mm and three sheet piles PU20, ranging from a height of +5.50 to -31.50 m and -20 m respectively. Existing hollow section concrete piles with a 4.9-meter spacing between them provide the foundation for the quay wall concrete slab. New concrete piles, measuring 450mm x 450mm, have been erected to a depth of NAP - 26.0 meters. The seabed elevation adjacent to the quay wall is at NAP 12.65 meters. The anchor wall consists of steel sheet piles AZ36 positioned 38 meters behind the quay wall. A concrete wall is employed for anchoring purposes. A 24-strand tie rod (FEP 1860 tendon) is secured to the tubular piles. Figure 3 depicts the Deep-Sea Quay Wall as described by J. K. Vrijling et al. (2010) cited in M. A. Kamal (2021).[20].

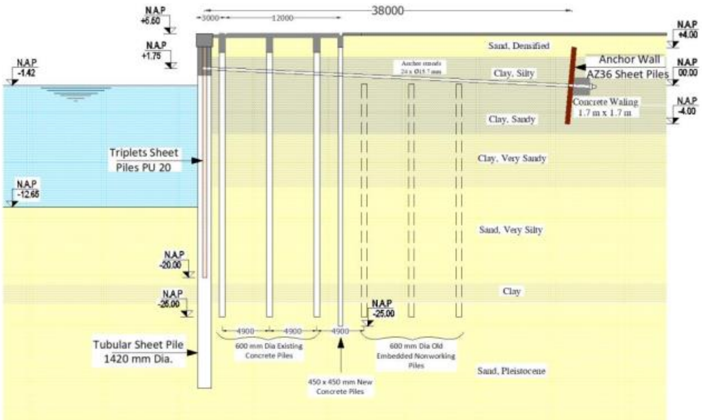


Figure 2: *Section elevation for deep sea quay wall system[20].*

The finite element program PLAXIS 3D was employed to develope a finite element model of the Rotterdam quay wall. The quay structural elements, soil parameters, and external loads are specified in the software input. PLAXIS utilizes the Hardening Soil Model (HSM) as an isotropic hardening model to simulate the nonlinear behavior of loose sands, dense sands, and over-consolidated clays, which is employed in this case study. In Table 1, the parameters for the hardening soil model are presented. In the unloading-reloading condition, a default Poisson's ratio (v_{ur}) of 0.3 is employed for all soil strata, as suggested by J. K. Vrijling et al. (2010) and cited in M. A. Kamal (2021). [20]

Table 1 : *Soil properties for Rotterdam Hardening Soil model [20].*

Layer	Type	Level		Unit weight [KN/m³]		Kx m/day	Ky m/day	C [kPa]	ϕ° [deg]	Ψ [deg]	E_{50}^{ref} [kN/m²]	E_{oed}^{ref} [kN/m²]	E_{ur}^{ref} [kN/m²]	m [-]	R_{inter} [-]
		Start	Finish	γ_{unsat}	γ_{sat}										
Sand, densified	Drained	+5.50	-3.00	18	20	1	0.1	0.01	35	5	57000	57000	171000	0.5	0.7
Clay, silty	Undrained	-3.00	-2.00	14	18	0.1	0.01	6	34	0	4500	3600	50841	0.8	0.6
Clay, sandy	Undrained	-0.50	-5.00	12	17	0.001	0.001	15	35	0	5400	2700	43390	0.8	0.6
Clay, very sandy	Undrained	-2.00	-10.50	12	17	0.01	0.01	15	35	0	5100	4080	41338	0.8	0.6
Sand, very silty	Drained	-5.00	-20.50	18	20	0.1	0.01	0.01	32.5	3	6800	5440	81600	0.5	0.7
Clay	Undrained	-10.50	-22.50	11	17	0.01	0.001	10	34	0	6200	3100	27047	1.0	0.5
Sand, dense	Drained	-20.50	-60.00	18	20	1	0.1	0.01	35	5	50000	50000	150000	0.5	0.7

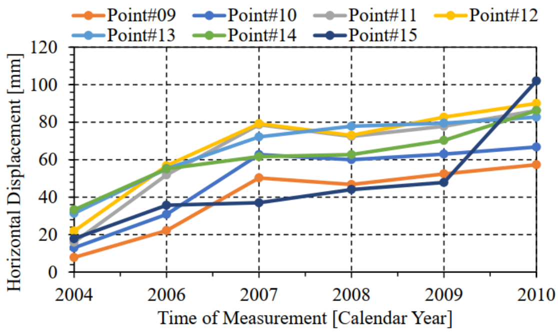
The 3D model incorporates a surcharge load of 50 kN/m^2 in accordance with the design requirements of the quay wall. Furthermore, J. K. Vrijling et al. (2010), as cited in M. A. Kamal (2021), reference a total equivalent surcharge load of approximately 150 kN/m^2 for the substantial steel cylinders, which have been stowed at a height of approximately 2 meters, in addition to a bollard load of 80 kN/m. To verify the model approach in software (PLAXIS 3D), the phases developed in this instance are presented herein. The results are checked with the field-measured values and to the results ***of*** (PLAXIS 3D) by M.A. Kamal. [20]

Table 2 : *Construction Stages [20].*

Construction Phase Number	Phases Description
Phase 0	Initial phase calculation based on the defined at rest pressure coefficient value (Ko) for each soil layer, where the quay wall system is not simulated yet.
Phase 1	Construction of substructure quay wall system
Phase 2	Excavation in front of the combi wall up to -0.50 [m NAP]
Phase 3	Prestressing of tie anchors by 1320 [kN]
Phase 4	Dredging up to level -12.65 [m NAP]
Phase 5	Applying of operation design loads [50 kPa Surcharge load + 80 [kN/m] Bollard loads
Phase 6	Applying of operation overdesign loads [150 kPa]
Phase 7	consolidation analysis with time intervals of 365 days after overloading

According to Vrijling et al. (2010), as quoted by M. A. Kamal (2021), the measured displacement data for seven places along the deep-sea quay wall over a five-year period are illustrated in Figure 3. As per Figure 3, the annual maximum values range from 33 mm to 102 mm, while the minimum values range from 7 mm to 57 mm. The measurement values and the PLAXIS 3D results from M. A. Kamal (2021) are compared to the PLAXIS 3D calculated results, which will be further discussed in the subsequent section.

Figure 3: *Horizontal displacements of the wall top for five years [20].*



4.1.2. Diaphragm quay wall of the Port Said East Port container terminal

The Port Said East Port container terminal, which is located in northern Egypt on the Mediterranean Sea, initiated the design and building of the quay wall in 1998 completing it in 2002. The quay wall deck, measuring 1200 meters in length and 35 meters in width, is underpinned by deep T-shaped and rectangular barrettes, each having a cross section of 3x1 meters, and reaches an average elevation of -60.0 meters. Each seaside and landside barrette is connected to wall extends to -32 m and -8 m respectively. The four barrettes are interconnected transversely by a top beam measuring 3 x 0.8 m. The longitudinal distance between the supporting structure created by the four barrettes and the top beam is 7 meters. In the same orientation, there are front and back beams that support the crane, and the front beam designed to bear bollard weights.

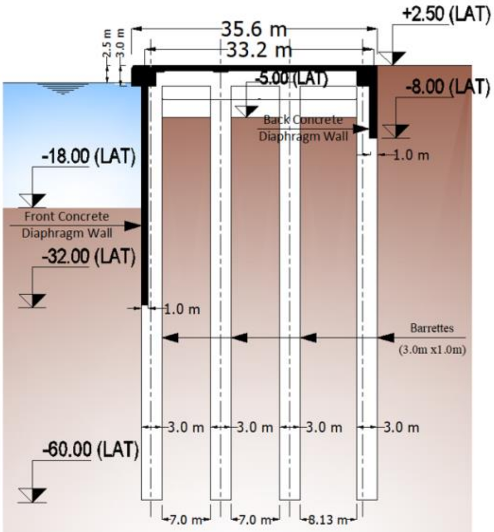


Figure 4 : *Quay wall cross section [20].*

Two soil profiles (A and B) are presented by M. ElGendy et al.(2016) – Soil profile (A) and Omaima M. Hamed et al.(2017) – Soil profile (B) used in modelling the selected quay wall under study by PLAXIS3D. The soil profile (A) is the original soil profile for the quay wall devoloped by the Norwegian Geotechnical institute and presented by Hamza and Hamed in (2000) [21] and M. ElGendy et al. in (2016) [18] where the finite element models are based on the Mohr Coulomb (MC) material model criteria by FLAC3D and PLAXIS3D software respectively. The soil profile (B) presented by Omaima M. Hamed et al. in (2017) [19, 22] after investigating another area near the quay wall location, field and laboratory tests were carried out on Port-Said Clay by the Suez Canal Authority Research Center (SCARC), the tests results have been devoloped to get the required parameters for numerically modelling the behavior of PortSaid Clay using the hardening soil material model (HSM) for undrained (short term) and drained (long term) conditions along with the Soft soil creep (SSC) for drained (long term) condition. [19, 22]

Table 3 : *Soil Profile (A) used in Mohr Coulomb model (MC) [18].*

Type	Thick (m)	γ_b KN/m³	C' Kpa	Φ' Deg	C_u Kpa	G Mpa
Clay(A)	5	17	0	24	-	1
Sand(B)	8.5	18.5	0	35	-	12
Clay(D)	15	15.5	0	24	1*	2*
Clay(E)	30	15	0	20	1*	2*
Clay(G)	34	17.5	20	20	150	25
Sand(F)	Inf.	20	0	35	-	60

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Table 4 : *Soil Profile (B) used in Hardening soil model (HSM) [19].*

Layer	Top level (m LAT)	Unit weight (kN/m^3)	K_0	C' (kPa)	ϕ' (deg)	$E_u^{ref}{}_{50}$ (MPa)	m (undrained)	$E^{ref}{}_{50}$ (MPa)	m (drained)	$E^{ref}{}_{oed}$(Mpa)
Fill & Sand	+2.5	17	0.52	0	29	…	…	20.0	0.5	20.0
C1	-5.5	16	0.59	0	22	4.66	0.81	3.12	0.59	2.1
C2	-17.5		0.64							
C3	-27.5		0.68							
C4	-37.5		0.72							
Sand	-47.5	18	0.43	0	35	…	…	30.0	0.50	30.0

Table 5 : *Construction Stages [19].*

Phase number	Description
1	Initial stresses calculated based on the assigned K_0 value for each layer
2	Construction of diaphragm walls
3	Construction of beams
4	Construction of slabs
5	Excavation under deck and in front of it to +0.0 m LAT
6	Excavation under deck and in front of it to -2.5 m LAT
7	Excavation under deck and in front of it to -5.0 m LAT
8	Dredging in front of the deck to -8.0 m LAT
9	Dredging in front of the deck to -11.0 m LAT
10	Dredging in front of the deck to -14.5 m LAT
11	Dredging in front of the deck to -18.0 m LAT
12	Application of operational loads over the deck
13	Application of operational loads behind the deck

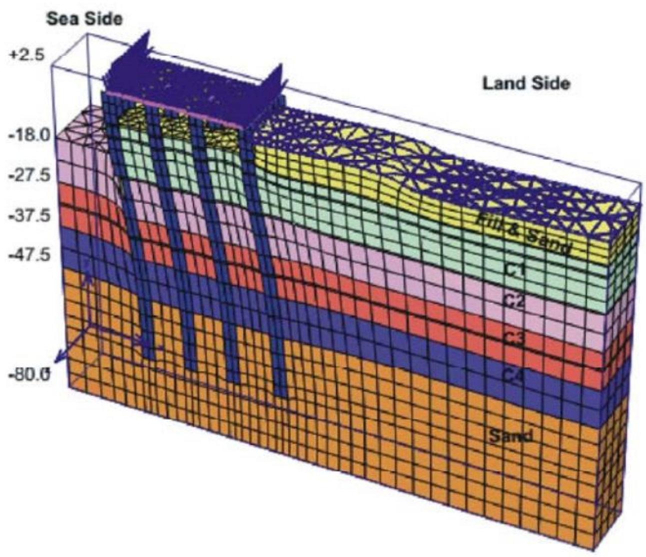

Figure 5 : *Finite element mesh for Omaima M. Hamed et al.(2017) [19].*

5. Case Study Verification

5.1. Deep-Sea quay wall at Rotterdam

The developed 3D PLAXIS model for Rotterdam quay wall was analyzed to compare its results with the research results and the field measurements in displacement of the soil and displacement of the front wall over all phases and after updated the phases by splitting the overloading stage into unloading / reloading stages.

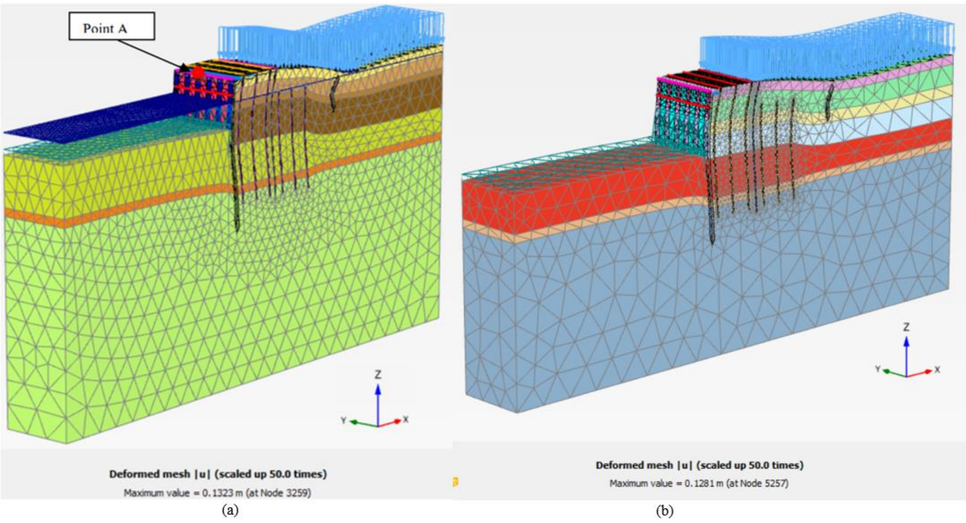

Figure 6 : Deformed mesh a) M. A. Kamal [20] b) F.E. study.

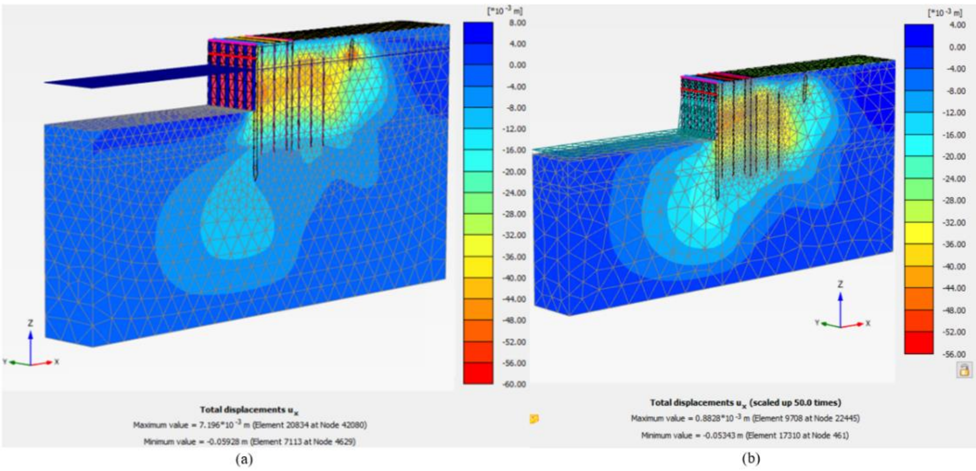

Figure 7 : Soil Horizontal Displacement a) M. A. Kamal [20] b) F.E. study.

The total soil displacement is reported as 132 mm, whereas the PLAXIS calculation yields 128 mm, resulting in a discrepancy of around (-3%). In terms of horizontal displacement, the published value is 59 mm, while the calculated value is 53 mm, indicating a divergence of nearly (-9.5%).

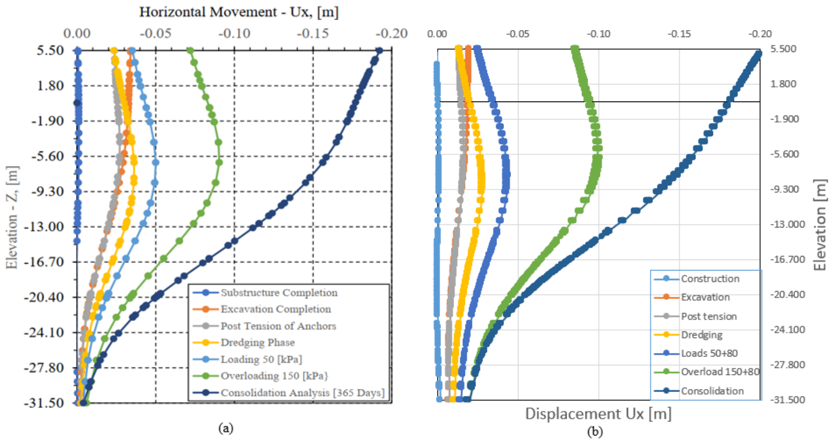

***Figure 8 :** Front Wall Horizontal Displacement for all phases a) M. A. Kamal [20] b) F.E. study.*

Upon comparing the horizontal displacement derived over the front wall depth in the preceding chart, it is evident that while the disparity in the initial stages is substantial, it diminishes significantly in the later stages. Following the overloading phase, the computed displacement is 101 mm, whereas the published value is 90 mm, resulting in a difference of approximately (11%).

***Table 6 :** Front Wall Top Horizontal Displacement Error after updated phases.*

Type of analysis	Top horizontal displacement					
Year	2004	2006	2007	2008	2009	2010
Max horz disp Field mm [20]	33.24	56.76	79.19	77.84	82.7	102
Plaxis 3d phases-M. A. Kamal [20]	Phase 5	Phase 6a	Phase 6b		Phase 6c	
Plaxis 3d disp-M. A. Kamal mm [20]	35.16	51.21	72.07	72.07	62.6	62.6
Plaxis 3d disp-F.E. study mm	25.44	47.75	72.66	72.66	68.13	68.13
Error M. A. Kamal [20] with Field % [20]	5.8	-9.8	-8.99	-7.4	-24.3	-38.63
Error F.E. study with Field % [20]	-23.47	-15.87	-8.25	-6.65	-17.62	-33.21
Error F.E. study with M. A. Kamal % [20]	-27.65	-6.76	0.82	0.82	8.83	8.83

From comparing the computed horizontal displacement at the top of the front wall with the results presented by M. A. Kamal [20] after the overloading phase, it is obvious that the calculated value is 86 mm, while the published figure is 72 mm, resulting in an error of approximately (19%). Additionally, the field measurement reported by M. A. Kamal [20] as an average value is 79 mm, indicating a difference of about (8.8%). However, after splitting the overloading phase into three stages corresponding to the unloading and reloading processes, the computed displacement is 72.66 mm, whereas the published value is 72.07 mm, resulting in a discrepancy of around (0.8%). While the field measurement is 77.84 mm, indicating a difference of nearly (-6.6%).

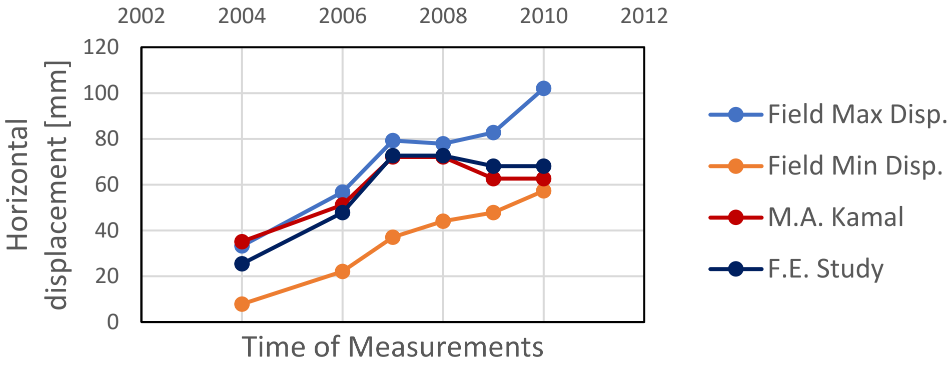

***Figure 9 :** Front Wall Top Horizontal Displacement Error after updated phases.*

Figure 9 illustrates that the computed results lay between the maximum and minimum measured values and closely align with the estimated outcomes in the published research.

5.2. Port Said East Port the diaphragm quay wall container terminal

The developed 3D PLAXIS models for the diaphragm quay wall of the Port Said East Port Container Terminal were analyzed to compare their results with prior research findings, incorporating various soil profiles and their corresponding material models: Mohr-Coulomb (MC), Hardening Soil Model (HSM), and Soft Soil Creep (SSC). Each model was constructed with dimensions similar to those of the respective study model, along with its construction stages. The data for the original soil profile (A) and its corresponding model characteristics are relatively limited; however, soil profile (B) and its associated model characteristics provide more comprehensive data necessary for modeling.

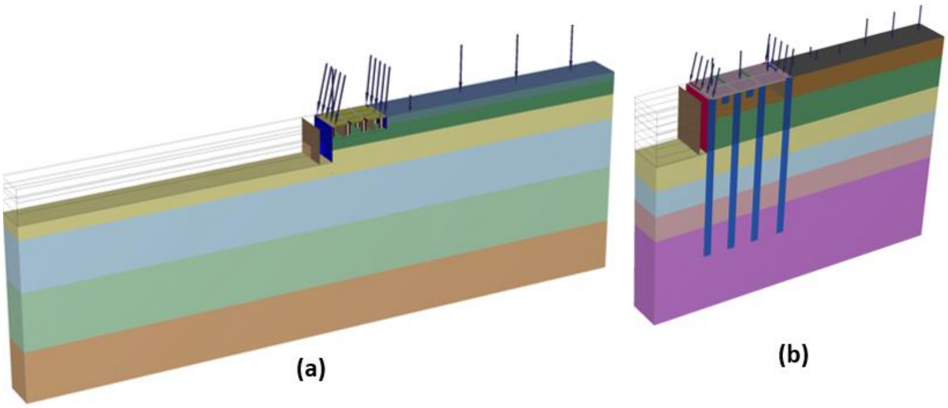

***Figure 10 :** The Developed 3D PLAXIS Model for a) soil profile (A) and b) soil profile (B).*

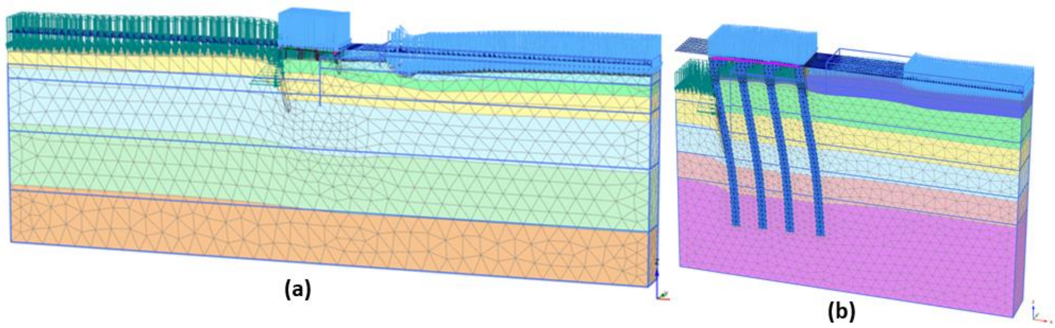

***Figure 11 :** The Deformed Mesh of the 3D PLAXIS Model for a) soil profile (A) and b) soil profile (B).*

5.2.1. Verification result for soil profile (A)

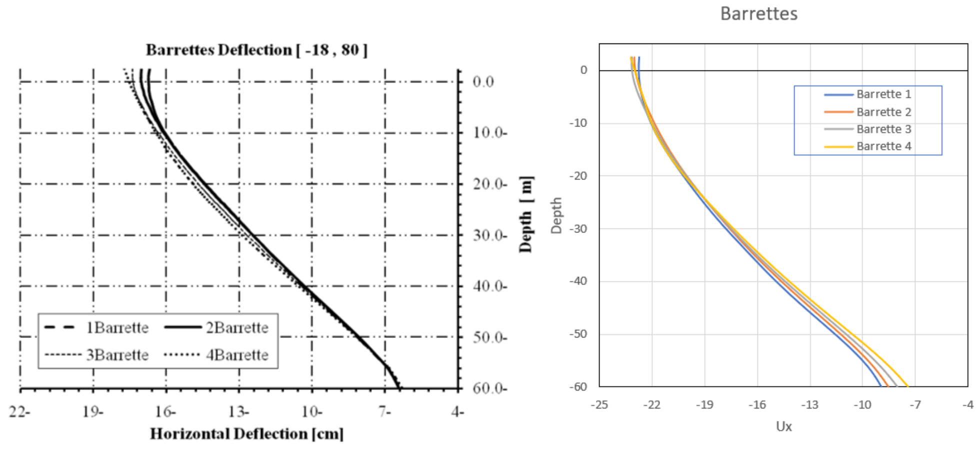

Figure 12 : Horizontal Displacement of Barrettes a) M. ElGendy et al. [18] b) F.E. study.

The above chart indicates that the reported maximum horizontal displacement is around 18 cm, while the value computed by PLAXIS is 23 cm, resulting in a discrepancy of nearly (27%).

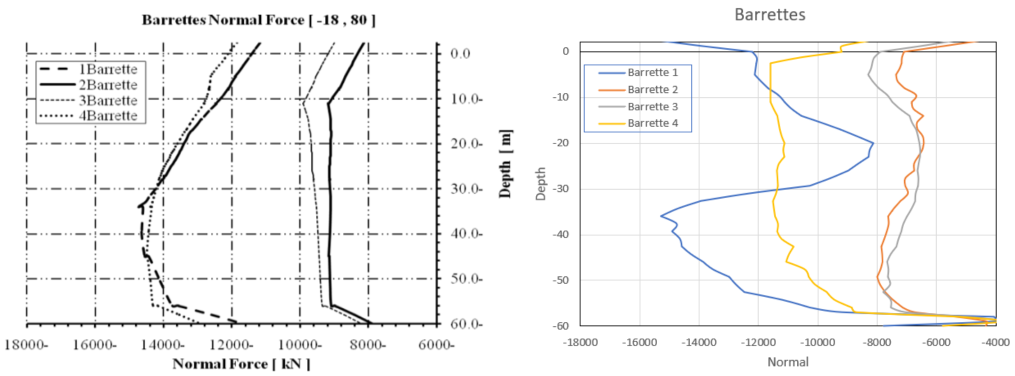

Figure 13 : Normal Force of Barrettes a) M. ElGendy et al. [18] b) F.E. study.

The above figure indicates that the reported maximum normal force is approximately 14600 kN, while the value computed by PLAXIS is 15200 kN, resulting in a discrepancy of around (4.1%).

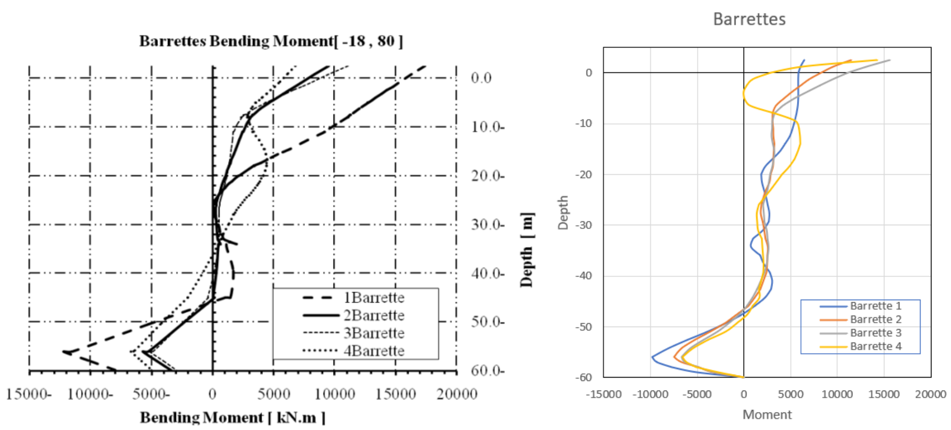

Figure 14 : Bending Moment of Barrettes (MC) a) M. ElGendy et al. [18] b) F.E. study.

The above graph indicates that the reported maximum bending moment is about 17000 kN·m, whereas the value computed by PLAXIS is 15600 kN·m, resulting in a variance of around (8%).

5.2.2. Verification result for soil profile (B)

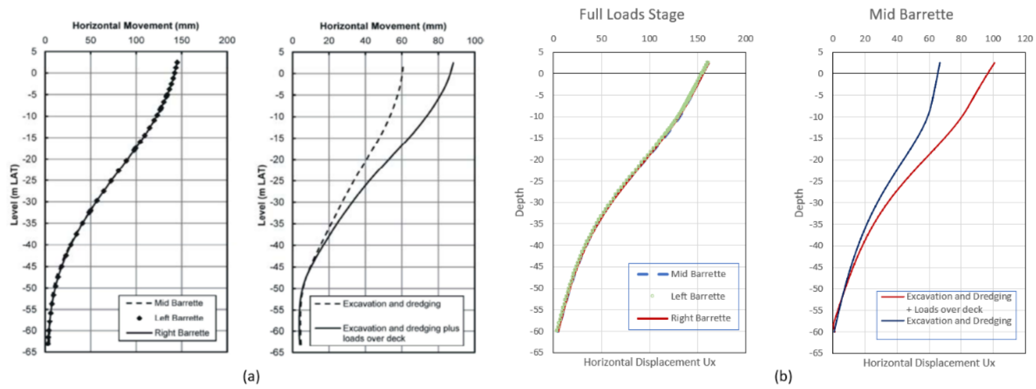

Figure 15 : *Horiz. Disp. of Barrettes (HSM-Undrained) a) O. M. Hamed et al. [19] b) F.E. study.*

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13
O.M. Hamed mm [19]	0	8	9	9	16	23	32	38	45	55	61	88	145
F.E. study mm	0	8.2	8.6	8.8	16.7	23.7	31.6	37.3	44.5	54.4	66.6	101	161
Error %	0	2.3	4.67	2.37	4.4	3.04	1.13	1.91	1.18	1.19	8.81	13.76	10.46

Table 7 : *Barrette Horizontal Displacement Error for all phases (HSM-Undrained).*

The above chart and table show that the majority of the result discrepancies are below (5%), which is an acceptable margin for horizontal displacement throughout all phases in undrained conditions with HSM. For the 7th stage, the computed horizontal displacement is 31.6 mm, while the reported value is 32 mm, resulting in a variance of around (1.1%).

Phase	1	2	3	4	5	6	7	8	9	10	11	12	1
O.M. Hamed mm [19]	0	12	13	14	14	17	25	35	51	77	107	151	1
F.E. study mm	0	13.6	15	15.8	14.9	17.5	23.1	31.9	45.2	67.3	100.3	158.2	2
Error %	0	12.28	14.35	11.95	6.43	2.73	7.94	9.24	12.01	13.39	6.46	4.66	5

Table 8 : *Barrette Horizontal Displacement Error for all phases (HSM-Drained).*

The preceding table indicates that the majority of the discrepancies in findings are below (10%), which is an acceptable percentage for horizontal displacement throughout all phases in the drained condition with HSM. For the 7th stage, the computed horizontal displacement is 23.1 mm, while the reported value is 25 mm, resulting in a variance of approximately (7.9%).

Phase	1	2	3	4	5	6	7	8	9	10	11	12
O.M. Hamed mm[19]	0	9	11	12	15	20	28	40	60	94	134	182
F.E. study mm	0	10.22	12.06	13.1	16.07	22.75	31.41	41.95	62.11	96.08	138.7	198.3
Error %	0	13.56	9.64	9.17	7.13	13.75	12.18	4.88	3.52	2.21	3.51	8.96

Table 9 : *Barrette Horizontal Displacement Error for all phases (SSC-Drained).*

The above table demonstrate that the majority of the differences in findings are below (10%), which is an acceptable percentage for horizontal displacement throughout all phases in the drained condition with SSC. For the 12th stage, the computed horizontal displacement is 198 mm, but the reported value is 182 mm, resulting in a discrepancy of around (8.9%).

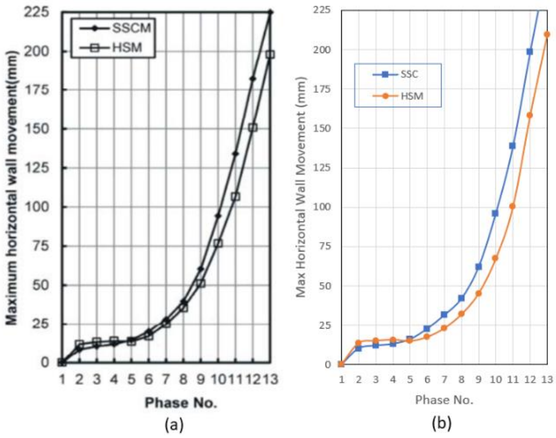

***Figure 16 :** Displacement comparison for HSM and SSC a) O. M. Hamed et al. [19] b) F.E. study.*

The preceding chart illustrate the comparisons between the drained condition for both HSM and SSC material models, as well as the comparison between the computed results and the published findings.

6. Comparitive Study

In the previous mentioned research, profile (A) was identified as the MC material model, while profile (B) was designated as HSM. In this section, profile (A) is redefined as HSM and profile (B) as MC to facilitate a comparative study of the distinct soil profiles alongwith the differing material models. For profile (A) the elastic modulus will be E_{50} = E while E_{oed} and E_{ur} will develop from imperical equations while for profile (B) will be E = E_{50}, to convert the profile from material model to another.

6.1. Soil profile (A) HSM results

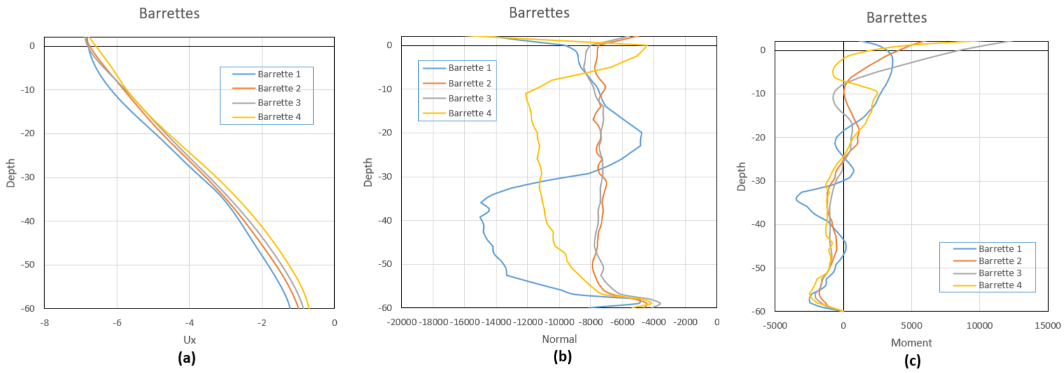

***Figure 17 :** Profile (A) HSM results a) Horizontal displacement b) Normal force c) Bending moment.*

The max horizontal displacement is about 6.9 cm from barrette 2, the max normal force is about 15000 kN from barrette 1 and the max bending moment is about 12500 kN.m from barrette 3.

6.2. Soil profile (B) MC results

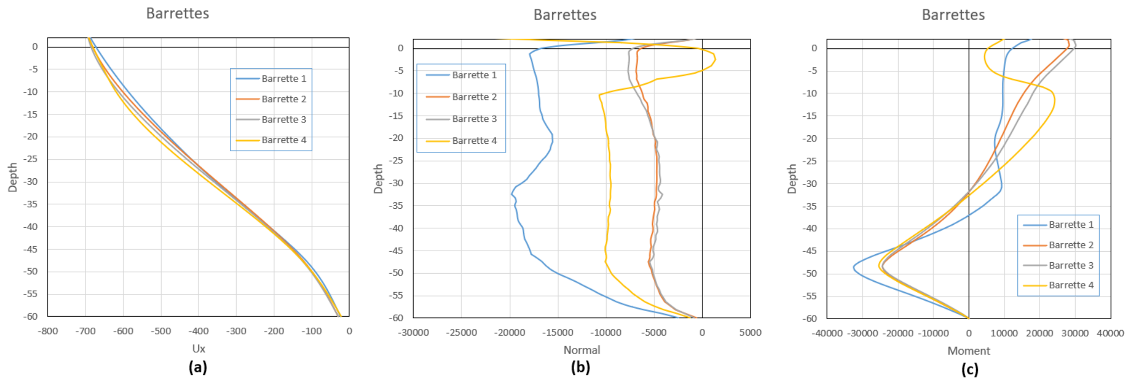

Figure 18 : Profile (B) MC results a) Horizontal displacement b) Normal force c) Bending moment.

The max horizontal displacement is about 695 mm from barrette 4, the max normal force is about 19500 kN from barrette 1 and the max bending moment is about 32000 kN.m from barrette 1.

6.3. Comparison results

Comparison between MC and HSM material models for both profiles (A) and (B) in horizontal displacement, normal force and bending moment.

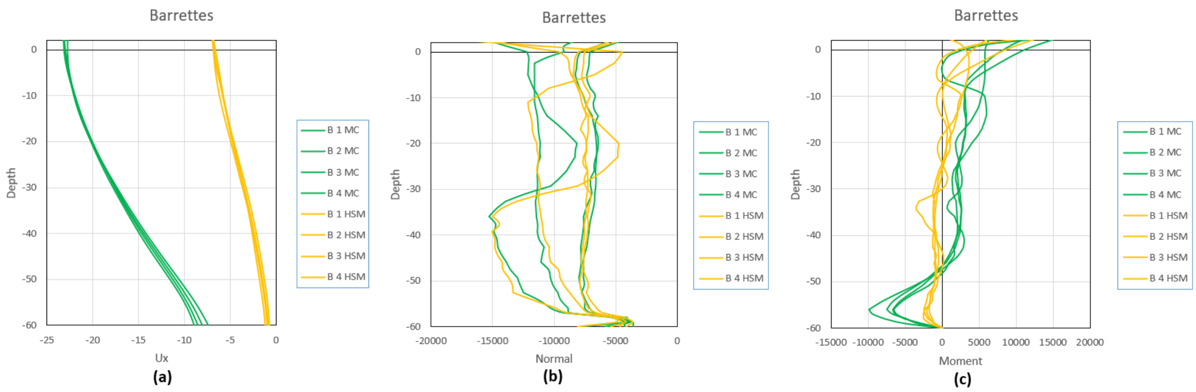

Figure 19 : Profile (A) comparison results a) Horizontal displacement b) Normal force c) Bending moment.

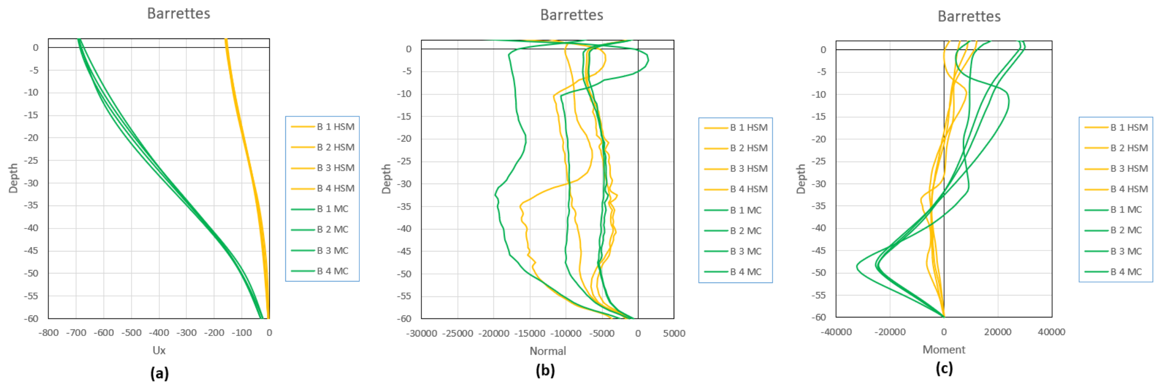

Figure 20 : Profile (B) comparison results a) Horizontal displacement b) Normal force c) Bending moment.

The prior comparison indicates that the MC material model exhibited a significant increase in horizontal displacement, averaging approximately (280%). In contrast, the increase in normal force averaged around (11%), while the bending moment increased by an average of about (80%) when compared to HSM.

Comparison between profiles (A) and (B) for both MC and HSM material models in horizontal displacement, normal force and bending moment.

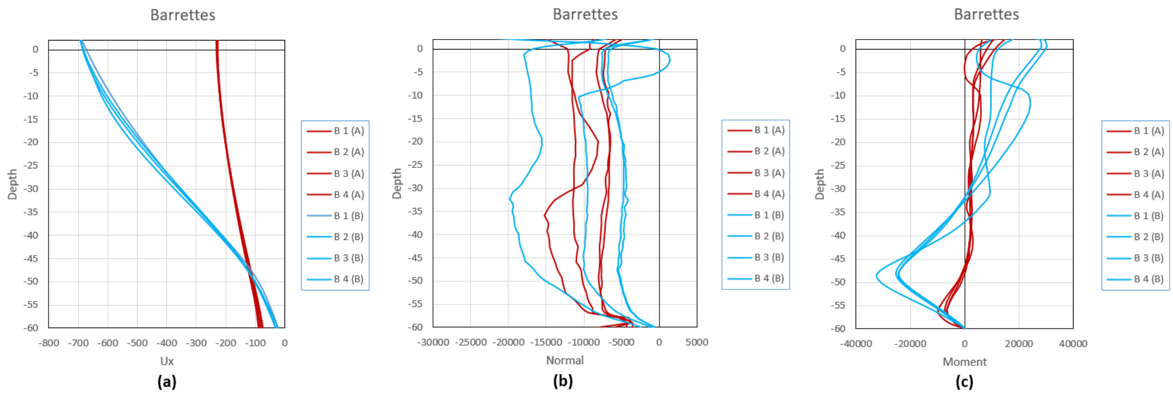

***Figure 21 :** Profile (A and B) comparison results for MC a) Horizontal displacement b) Normal force c) Bending moment.*

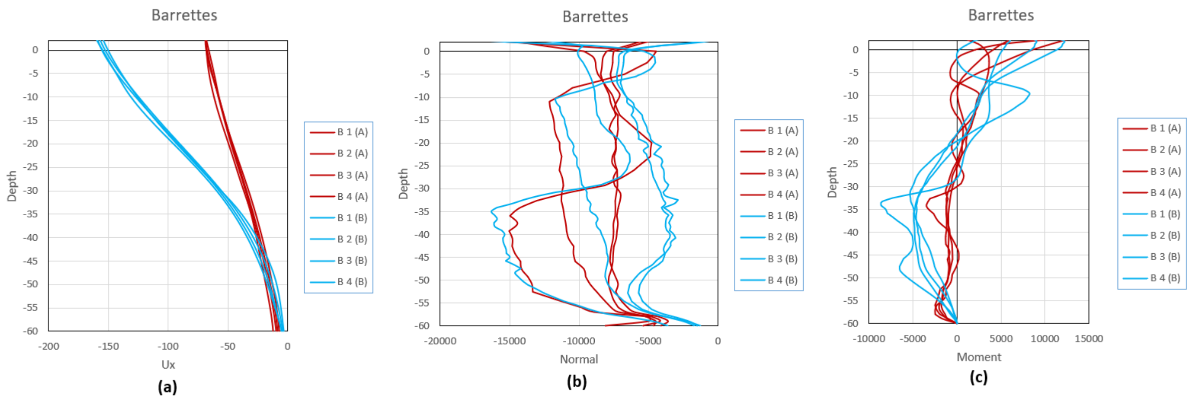

***Figure 22 :** Profile (A and B) comparison results for HSM a) Horizontal displacement b) Normal force c) Bending moment.*

The preceding comparison indicates that soil profile (A) exhibited minimal relatively horizontal displacement, averaging approximately (-65%). The normal force demonstrated a diminished value, averaging around (-15%), while the bending moment also showed a reduced value, averaging about (-30%). When comparing the soil profile (B) for both MC and HSM, it is evident that the changes for HSM are less pronounced than those for MC, as seen in the figures.

7. Parametric study

Based on prior studies, the Hardening Soil Model (HSM) was selected for the parametric study due to its suitability as a material model, as it characterizes soil with more precise parameters, yielding more specific outputs, particularly for clay soil, which is regarded as a very hard soil in treatment with the retaining structures, especially in Port Said, where the case study is situated. Moreover, the availability of the data offers by Omaima M. Hamed et al. in (2017) [19, 22].

A parametric study was conducted to assess the increase in crane loads by increments of 10% until a total increase of 100%, which is doubled the original loads. Additionally, the deepening of the quay wall was executed in 1 m increments until reaching a depth of -24 m, representing a 6 m increase from the original depth. All these instances have been conducted under drained and undrained situations. The resultant straining actions and displacements for the front diaphragm barrette wall from each scenario in the parametric analysis are computed and compiled in the subsequent tables and charts.

Table 10 : *Results for straining actions and displacement for the increment in the Crane loads.*

HSM - Undrained Condition											
Crane loads Increment	Original	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Max. Horiz. Disp. (mm)	155	159	162	166	170	175	179	182	187	191	195
Max. Norm. F. (kN)	16300	16840	17340	17850	18370	18900	19460	19930	20500	21000	21540
Corres. B. M. (kNm)	8000	8320	8540	8750	8970	9180	9390	9615	9800	10040	5700
Max. B. M. (kNm)	8600	8850	9000	9300	9530	9750	9960	10200	10400	10650	10890
Corres. Norm. F. (kN)	15900	16430	16920	17430	17940	18460	19000	19470	20040	20520	21000
HSM - Drained Condition											
Crane loads Increment	Original	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Max. Horiz. Disp. (mm)	204	209	215	220	225	231	236	242	248	254	259
Max Norm. F. (kN)	20580	21160	21750	22330	22900	23500	24090	24670	25250	25830	26400
Corres. B. M. (kNm)	13660	13900	14160	14400	14670	14920	15170	15430	15680	15930	16180
Max. B. M. (kNm)	13800	14000	14290	14540	14790	15040	15280	15530	15770	16000	16260
Corres. Norm. F. (kN)	20560	21150	21730	22315	22900	23490	24070	24650	25230	25800	26400

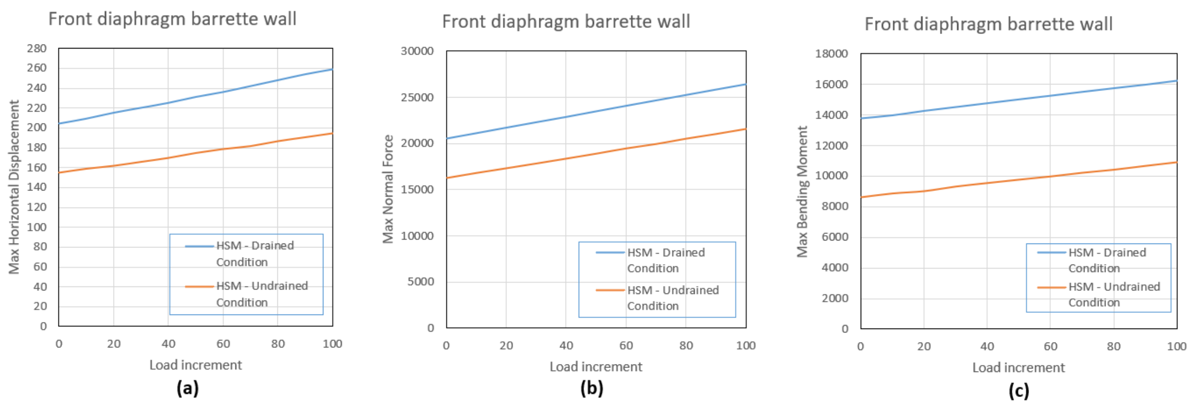

Figure 23 : *Crane load increment results a) Horizontal displacement b) Normal force c) Bending moment.*

The prior data indicate that raising the crane loads from 800 kN/m to 1600 kN/m, which is a doubling of the load, leads in an average increase in horizontal displacement of (26%), a (30%) increase in normal force, and a (22%) increase in bending moment.

Table 11 : *Results for straining actions and displacement for the increment in the Dredging level.*

HSM - Undrained Condition							
Dredging level Increment	Original	1 m	2 m	3 m	4 m	5 m	6 m
Max. Horiz. Disp. (mm)	155	169	184	199	216	234	253
Max. Norm. F. (kN)	16300	16800	17500	18190	18900	19600	20340
Corres. B. M. (kNm)	8000	8880	9280	9610	9950	10230	10400
Max. B. M. (kNm)	8600	9080	9380	9610	9950	11050	12340

Corres. Norm. F. (kN)	15900	16100	16750	18190	18900	17160	17840
HSM - Drained Condition							
Dredging level Increment	Original	1 m	2 m	3 m	4 m	5 m	6 m
Max. Horiz. Disp. (mm)	204	228	255	282	312	344	379
Max. Norm. F. (kN)	20580	20860	21400	21940	22500	23160	23820
Corres. B. M.(kNm)	13660	14000	13970	13630	12980	11950	10570
Max. B. M. (kNm)	13800	14300	15150	16500	18540	20970	23600
Corres. Norm. F. (kN)	20560	20740	21080	21400	21760	22160	22780

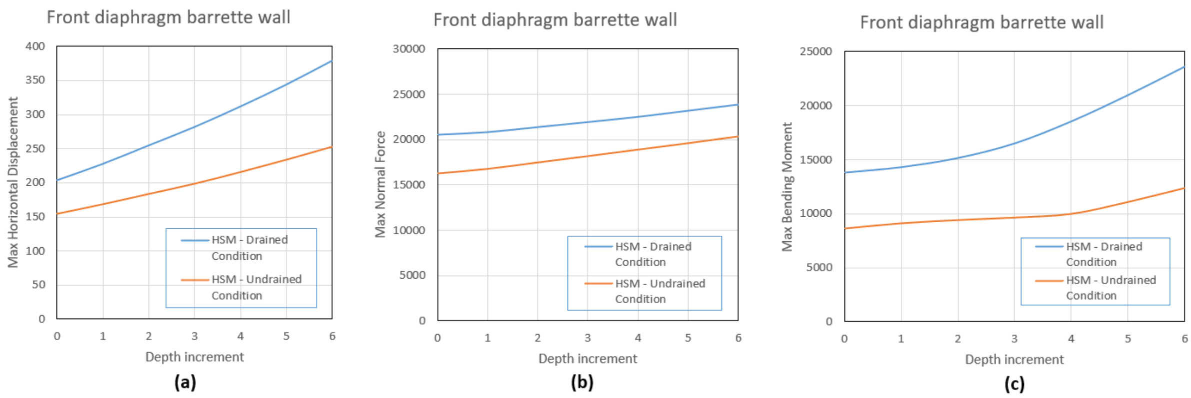

***Figure 24 :** Deepening results a) Horizontal displacement b) Normal force c) Bending moment.*

The preceding results demonstrate that increasing the depth in front of the wall from -18 m to -24 m, an increment of 6 m, results in an average percentage increase in horizontal displacement of (70%), in normal force of (20%), and in bending moment of (55%).

8. CONCLUSION

For Deep-Sea quay wall at Rotterdam case study verification, it is clear that most of the results are within the accepted difference with the calculated results and the field measurements published by M. A. Kamal, with average difference (10%), this difference is due to the different versions of the software used for the finite element model and related to the available data from the authors.

For the Port Said East Port the diaphragm quay wall container terminal case study verification, the soil profile (A), it is clear that the verification error is relatively accepted due to the lack of data while for the soil profile (B) with O. M. Hamed for HSM and SSC material models which are etablished based on the soil profile devoloped by the Suez Canal Authority Research Center (SCARC) in East portsaid, it is clear that most of the results are within the accepted difference with the calculated results published by O. M. Hamed, most of the results are less than (10%), this difference is due to the different versions of the software used for the finite element model and related to the available data from the authors. Due to this satisfactory of this verification and with the agreement that the HSM material model considered the most effective in dealing with clay soil, this soil profile then used for the parametric study on this existing quay wall.

A comparative study conducted by this research on two soil profiles (A and B) employed MC and HSM material models for each profile. The results indicate that the MC material model yields higher results than the HSM, particularly regarding horizontal displacement, showing that the MC model is more conservative due to its relative deficiency in soil definition parameters compared to HSM. Moreover, the soil profile (A) exhibits findings that are inferior to those of soil profile (B), due to the clay layer commencing at -11 m in profile (A) compared to -5.5 m in profile (B). Additionally, the elastic modulus of the strata in profile (A) is relatively elevated.

A Parametric study developed by this research for the crane load increment and the deepening in front of the quay wall for the existing diaphragm quay wall in east portsaid port along with the soil profile presented by O. M. Hamed using HSM material model in PLAXIS3D to calculate the resulted straining actions and displacement related to each case in the parametric study for drained and undrained conditions. The results demonstrate that the deepening in front of the quay wall has a larger impact than the increment in crane load; for instance, the bending moment escalates by 22% when the crane loads are doubled, but it grows by 55% when the deepening attains 6 meters beyond the initial depth. Furthermore, the most significantly impacted outcome from the increase in crane loads was the normal force, but for the deepening, the most affected outcome is the horizontal displacement which was highly influenced.

9. FUTURE WORK AND RECOMMENDATIONS

Future research will investigate the optimum FRP design details for strenghening the quay wall against the extra loads and after a ship hit, in addition to comparing FRP methods with traditional techniques in a feasibility study to demonstrate the advantages of FRP.

Extensive research has been conducted using machine learning techniques to predict FRP design for the strengthening of beams, columns, and slabs; as a result, we recommend employing these techniques to predict the FRP design required for upgrading quay wall capacity, as carrying out such a study is critical.

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11. REFERENCES

1. Sarhan, T. E. and H. A. Elosta. "Novel technique for the retrofitting and refurbishment of a damaged offshore quay a case study application." *Ships and Offshore Structures* (2021):
2. Ruggeri, P., V. M. E. Fruzzetti and G. Scarpelli. "Renovation of quay walls to meet more demanding requirements: Italian experiences." *Coastal Engineering* 147 (2019): 25-33. 10.1016/j.coastaleng.2019.01.003.
3. Bill Paparis, P. E., P. E. Michael Quadagno, P. E. Guy Buzzoni, P. E. James McQueen and P. E. John Lizzo. "Modernizing a three decade old wharf structure for the next generation of containerships." *Port Development in the Changing World* (2012):
4. Hutauruk, R. M. and P. Rengi. "Numerical simulation of ship collision to the quay." The 2016 International Conference on Science and Technology, 2017.
5. Rigueiro, C., J. Ribeiro and A. Santiago. "Numerical assessment of the behaviour of a fixed offshore platform subjected to ship collision." X International Conference on Structural Dynamics, EURODYN 2017, 2017.
6. Habets, C. J. W. "Performance-based seismic analysis of an anchored sheet pile quay wall." *TU Delft Research Repository* (2015):
7. Elgamal, A. "A numerical assessment of jetty side support system." 14th Baltic Sea Region Geotechnical Conference, 2021.
8. Edward H. Stehmeyer III, P. E. and P. E. Ralph Petereit. "Wharf improvements for new panamax size vessels." 15th Triennial International Conference, 2019.
9. Qasim, R. M. and A. Q. Hasan. "Investigating the behavior of offshore platform to ship impact." *Civil Engineering Journal* 6 (2020): 495-511. 10.28991/cej-2020-03091486.

10. Nathan Watson, P. E., P. E. Adam Bergman, P. E. John Klekotka and P. E. Steve Hager. "Unique wharf upgrade to diversify operations for larger roro shipments and new containerized cargo." 15th Triennial International Conference, 2019.
11. Arun Bhimani, S. E., S. E. Anna Dix and P. E. Claude Gentil. "Wharf upgrade considerations for large low profile cranes." 15th Triennial International Conference, 2019.
12. Mohamed, D., E. Tolba and E. Galal. "A study of sheet pile quay wall rehabilitation method." *Port-Said Engineering Research Journal* 0 (2022): 0-0. 10.21608/pserj.2022.131369.1174.
13. Muthukkumaran, K. and R. Sundaravadivelu. "Numerical modeling of dredging effect on berthing structure." *Acta Geotechnica* 2 (2007): 249-59. 10.1007/s11440-007-0040-1.
14. Galal, E. M. "A numerical study for upgrading the container terminal of port-said west port." *PORT SAID ENGINEERING RESEARCH JOURNAL* 21 (2017):
15. Joel Aguilar, P. E., S.E., M.ASCE, P. E. Cheng Lai, S.E., M.ASCE, P. E. Omar Jaradat, Ph.D., M.ASCE and P. D. Arul K. Arulmoli, G.E., F.ASCE. "Pier j, berths 245-247, landside rail girder upgrade project." 15th Triennial International Conference, 2019.
16. PREMALATHA, P. V., K. Muthukkumaran and P. JAYABALAN. "Effect of dredging and tie-rod anchor on the behavior of berthing structure." *International Journal of Engineering Science and Technology (IJEST)* (2011):
17. Zhu, L., W. Liu, H. Fang, J. Chen, Y. Zhuang and J. Han. "Design and simulation of innovative foam-filled lattice composite bumper system for bridge protection in ship collisions." *Composites Part B: Engineering* 157 (2019): 24-35. 10.1016/j.compositesb.2018.08.067.
18. ElGendy, M., E.Tolba, E.Galal and M.Mourad. "Effect of deepening in-front of port-said east port diaphragm quay wall." *PORT SAID ENGINEERING RESEARCH JOURNAL* 20 (2016): 54:63.
19. Hamed, O. M., M. F. Mansour, A. H. Abdel-Rahman and F. M. El-Nahhas. "Investigating the behavior of an existing quay wall using the characteristic parameters of port-said clay, egypt." *World Applied Sciences Journal* (2017): 10.5829/idosi.wasj.2017.483.499.
20. Kamal, M. A. *A study to select optimum quay wall structural system at port said east port*. Port Said University, 2021,
21. Hamza, M. and H. Hamed. "Three dimensional soil-structure analysis of portsaid east quay wall." *Maritime Engineering and Ports II* (2000):
22. Hamed, O. M., M. Mansour, A. H. Abdel-Rahman and F. M. El-Nahhas. "Geotechnical characterization of port-said clay." 19th International Conference on Soil Mechanics and Geotechnical Engineering, 2017.