Study the feasibility of considering the deep mixing soil in a quaywall design

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Abstract: This study presents the improvement of clay soil properties in East Port-Said by the Deep Mixing Soil method (DSM) and its effect on a quay wall design and displacement behavior. First, the different kinds of soil improvement and their applications were discussed. Then, the first focus is on The Deep Soil Mixing method (DSM) particularly as the most common soil improvement technique around the world. After that, the clay soil strata of East Port-Said will be introduced showing every layer's geotechnical properties. Three proposals of quay wall will be presented and a three-dimensional finite element (Plaxis 3D version 2020) was used to simulate them. The first one is a combi wall with one anchor row, in this case, the king pile is a steel tubular pile filled with concrete and with a closed toe. The second proposal is similar to the first one, but the toe of the pile is opened, and the lower quarter of the pile is plugged with soil. Finally, in the third proposal, the application of DSM is presented; this one includes nine cases, the DSM block dimensions differ from one case to another. The effect of DSM block dimensions variety was shown in terms of bending moments, shear forces, horizontal and vertical displacements, and axial force for both front and back walls and the corresponding cross-sections and geometry dimensions. Also, the axial force in the anchor rod was checked. After that total cost estimation for each case and a comparison between them was made to get the most economic case, and to find out how applying DSM does affect the quay wall system displacement behavior, internal interactions, and total cost.

Keywords: Deep Soil Mixing (DSM), Sheet Pile Wall, Plaxis 3D, Hardening soil model, Quay wall Cost Estimation.

1. Introduction

Most areas all over the world have been built up and many countries are now being faced with the problem of the absence of stable ground for construction purposes and other engineering activities. As a result, soil stabilization has attracted much attention for improving ground properties to fit most engineering requirements. Soil stabilization is a technique to improve the engineering characteristics of the soil or mechanical properties such as shear strength, stiffness, density, and cohesion for soft soils. Many techniques of soil stabilization have been studied by many authors such as the Vibro-replacement method by Mansour Jadid, (2013), surcharge load by Adedokun, S. I. and Oluremi, J. R., (2013) and Hatami and Richard, (2006), grouting by Sina Kazemian, (2009), Geotextile by Arifuzzaman, (2016) and chemical agents such as cement, sawdust ash, fly ash, nano-silica, Lime by Kumar et al., (2015); Kazemian et al., (2010); Haeri et al., (2015) and Raghuwanshi et al., (2016).

During recent years, the stabilization of soft ground by the deep soil mixing (DSM) method has become increasingly strongly developed in many areas. It is a technique in which the unstable soil is blended with cementitious and other additives to form a soil binder column to improve strength parameters and reduce the compressibility of the weak soil. This method mainly depends on increasing the stiffness of the native soil by adding a strengthening admixture material such as cement, lime, gypsum, and fly ash (Abbey et al., 2015). To understand the performance of soil stabilized with DSM, it has been studied by many authors all over the world like Abbey et al. (2015); Md. Islam and Hashim; Bitir and Muşat (2014); Asturias and Lorenzo, (2015); Frikha et al. (2016); Rutherford et al. (2007); Rashid et al. (2015); Tuan and Thang (2019).

Although the effect of DSM on the mechanical properties of soil was demonstrated over a few years ago, little attention has been paid to its effect on quay wall structure systems design. Tolba et al (2016) studied the effect of applying DSM blocks in a diaphragm quay wall in Port Said East Port in case of increasing the dredging level of the existing quay wall from (-18.00m) to (-22.00m), as well as increasing the crane load from 80 tons/m to 120 tons/m. They made optimization of the DSM block dimension that gives the best results.

The main objective of this study is to illustrate the effect of DSM on the structural system design of a quay wall and the corresponding internal interactions, displacement behavior, and economic considerations. To understand the effect of applying DSM on the design of the quay wall, a quay wall of passenger berth was proposed to be studied in East Port Said, and then three proposals were introduced, the first one is a combi wall in which the king pile is a steel tubular pile filled with plain concrete with closed-toe, while the second one is the same as the first one but with open toe. In the third proposal, we apply DSM, both front and back walls are sheet piles with one anchor row. Nine cases were investigated, they represented nine DSM blocks with different dimensions on both sides - active and passive sides - and their corresponding cross-sections, geometry, interactions, and displacement behavior for quay wall elements. A general description of the quay wall structure elements for the three proposals with all cases, soil layer properties, surcharge, mooring loads, and finally the aimed dredged level was represented in detail. The modeling was simulated with three-dimensional software "Plaxis 3D version 2020" that depends on finite element analysis in which the behavior of soil and structure are integrated. The results were summarized and discussed. Finally, cost estimation of the three proposals was made and then the most economic one was chosen to be the optimized proposal.

2. Classification of ground improvement techniques

The problem of the absence of stable ground for construction purposes and other engineering activities is very common. This led to much attention was paid to ground improvement to improve soil's engineering characteristics. Ground improvements technologies are classified, depending on their working principles, to densification, replacement, drainage, soil stabilization, lightweight material. Some descriptions of ground improvement techniques are presented in the following.

2.1 Replacement

Replacement is the most simple and easy technique used as a ground improvement. Soft soil that is mostly soft clay with organic matters under the expected structure foundation is removed and replaced with high-quality soil material up to the desired level to achieve stability and prevent unfavorable settlement. Most of the time, natural sand and granulated gravel are used due to their good performance compared to soft clays. Because of the shortage of proper granular materials and because of dynamic problems, engineered soil became popular last years, typical examples are cement stabilized soils such as Deep Soil Mixing (DSM) and lightweight soil like Super Goe- Material (SGM).

2.2 Densification

Densification is a technique used for loose granular soil, municipal waste, heterogeneous soil, and liquefiable soil. Densification aims to reduce the settlement of loose granular soil, increase strength, and prevent liquefaction. There are many techniques of densification such as dynamic compaction, Vibro- stone column, Vibro-flotation, Vibro-rod, sand compaction pile (Kitazume, 2005), heavy tamping, and compaction grouting that are used in recent days.

2.3 Consolidation/Dewatering/Drainage

This technique is used for improving cohesive soil with low strength and low permeability; it reduces the long-term unfavorable settlement. These kinds of soils increase the strength and improve their compressibility with time under loading; therefore an external loading is applied to increase total stress in the ground. This increase of total stress is firstly sustained by the excess pore water when the soil is saturated, after that, the excess pore water pressure dissipates with time, which leads to increased strength and effective stress. This mechanism is called consolidation. Preloading by embankment fill is considered one of the oldest techniques to improve these kinds of soils. However, there are recent effective techniques that depend on the concept of drainage like Prefabricated Vertical Drains (PVD) and sand/gravel drains.

2.4 Admixture stabilization

Admixture stabilization is an engineering technique of mixing the chemical binder with soil to improve its strength, deformation behavior, consistency, and permeability of the soil. This technique is called Deep Soil Mixing (DSM) various agents are used in the mixing process like cement, lime, sawdust ash, fly ash, nano-silica, and even air foamed as lightweight materials. These materials are widely used in marine works by recycling dredged soil and mixing them with seawater, cement, and air foam, this mix is called Super Geo- Material (SGM). Many other techniques are used to improve soft soils such as grouting, thermal stabilization (heating and freezing), and reinforcement. This paper will focus on studying the effect of deep mixing soil with cement on a quay wall design, internal interactions, and displacement behavior of its structural elements, then its effect on the total cost of the construction system.

3. Normalized soil model of East Port Said Port

Soft clay is considered one of the most problematic soils due to its high compressibility, low strength, and time dependency of deformation. For East of Port-Said which is known as El-Tina Plain, soft clays extend to more than fifty meters below the natural ground surface. Many geological studies had focused on the history of deposition of the Northern Nile Delta in general and El-Tina Plain in particular. These studies suggested that the soft clays in this region were all deposited in similar geological conditions. Hence, it is believed that their engineering properties are also similar. To understand the effect of (DSM) on the quay wall structural internal interactions and displacement behavior, a Hardening Soil Model (HSM) was simulated for each case. The deformations are roled in the (HSM) by three stiffness parameters which simulate loading, these parameters are (E_{50}), (E_{ur}) and (E_{oed}). Hamed et al. concluded that the unloading- reloading modulus (Eur) can be considered 7 times the value of undrained (E_{u50}) for Port-Said soil, whereas (E_{ur}) can be taken as 2 to 3 times (E_{50}) for cohesionless soils (after Tolba et al., 2020). (El-Nahhas et al., 2017) described the variations of (E_{oed}) and (E_{u50}) as shown in Figure 1, The expressions used to compute E_{ur}, E_{50} and E_{oed} are shown in equations as follows:

$$E_{ur} = E_{ur}^{ref}\left[\frac{\sigma'_3 + c\cot\varphi}{p^{ref} + c\cot\varphi}\right]^m \quad (1)$$

$$E_{50} = E_{50}^{ref}\left[\frac{\sigma'_3 + c\cot\varphi}{p^{ref} + c\cot\varphi}\right]^m \quad (2)$$

$$E_{oed} = E_{oed}^{ref}\left[\frac{\sigma'_1 + c\cot\varphi}{p^{ref} + c\cot\varphi}\right]^m \quad (3)$$

Where:
E_{ur}: The unloading-reloading deformation modulus.
E_{ur}^{ref}: The reference unloading-reloading deformation modulus corresponding to a reference confining stress, p^{ref}, of 100kPa.
E_{50}: The elastic deformation modulus for a mobilization of 50% of the maximum deviator stress (qf).
E_{50}^{ref}: The reference stiffness modulus corresponding to a reference confining stress, p^{ref}, of 100kPa.
E_{oed}: The tangent deformation modulus for primary loading.
E_{oed}^{ref}: The reference tangent deformation modulus for primary loading corresponding to a reference confining stress, p^{ref}, of 100kPa.
σ'_3: The effective confining pressure.
σ'_1: The effective vertical pressure.
c: The drained shear strength parameter (cohesion) of Mohr-Coulomb failure criterion.
φ: The drained shear strength parameter (friction angle) of Mohr-Coulomb failure criterion.
m: Power for stress-level dependency of stiffness.

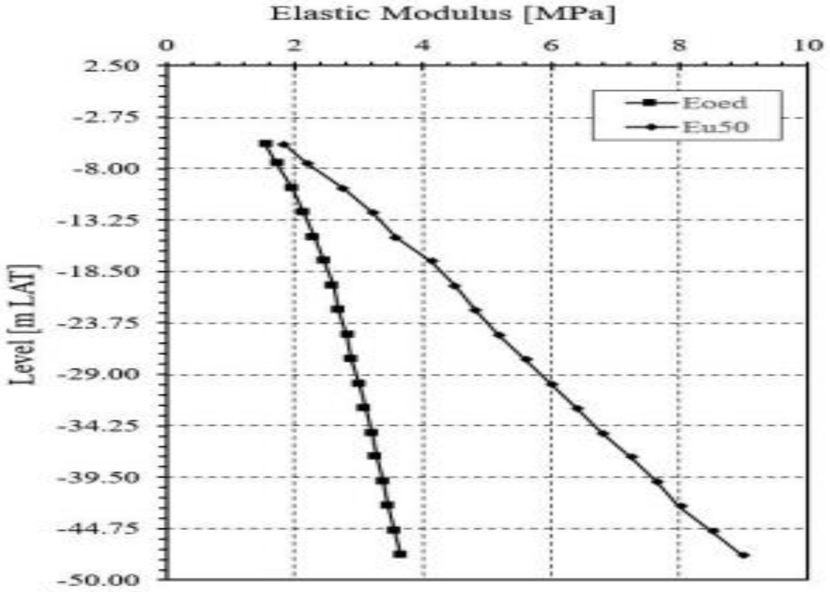


Figure 1 Variations of E_{u50} and E_{oed} with depth for Port-Said clay (after Tolba et al., 2020)

Tolba et al., 2020 made a sensitivity analysis of the soft clay of the east of Port Said parameters; this research was carried out to reach the critical soil model for the east of Port Said. This model was presented to be able to control the future analysis for the east of Port Said. To reach this normalized soil model, Tolba et al., 2020 made a parametric study for three different soil profiles Figure 2. These profiles were based on three previous field investigations Figure 3 to estimate the properties of soil in the east of Port Said. Seven boreholes were performed by Egypt Company (Geo Groups) in 2018 in the north region to a depth of 80m; another additional soil investigation was performed in 2017 by the soil mechanics team at the Suez Canal Authority Research Center which covered the industrial zone area. It consisted of drilling six boreholes to depths ranging from 42m to 63m. Also, Hamza and Hamed (2000) and Hight et al. (2001) reported the geotechnical site investigations which were carried out for different projects at the east of Port Said. The site characterization was performed by the Norwegian geotechnical Institute (NGI) that presented the geotechnical properties of thick deposit clay that extended from about 20m to 60m below ground level (Tolba et al., 2020).

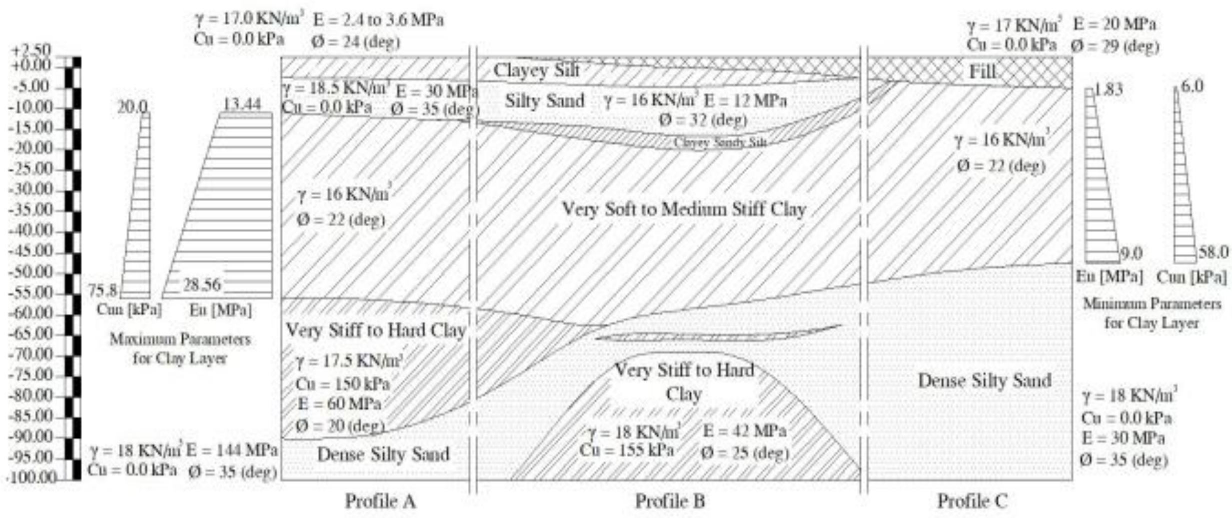


Figure 2 Interpreted geotechnical profile for east of Port Said soil (after Tolba et al., 2020)

The results from the six modeled case studies were compared for each model with the three soil profiles, and as a result Tolba et al. 2020 could conclude that profile C was mostly critical than the other profile A and B, so they presented a constitutive soil model for the optimization analysis with hardening soil parameters based on profile C as shown in Figure 4. This model was presented to control the future analysis for the east Port said, on which our optimization analysis was based.

Figure 3 Location's map showing the executed boreholes at East Port-Said (after Tolba et al., 2020)

Table 1 parametric study cases for east Port Said soft clay (after Tolba et al., 2020)

Study Case	Eu [MPa]	Cu [KPa]
Case 1	6.00	30
Case 2	9.00	32
Case 3	11.50	34
Case 4	14.00	36
Case 5	17.00	38
Case 6	20.00	40

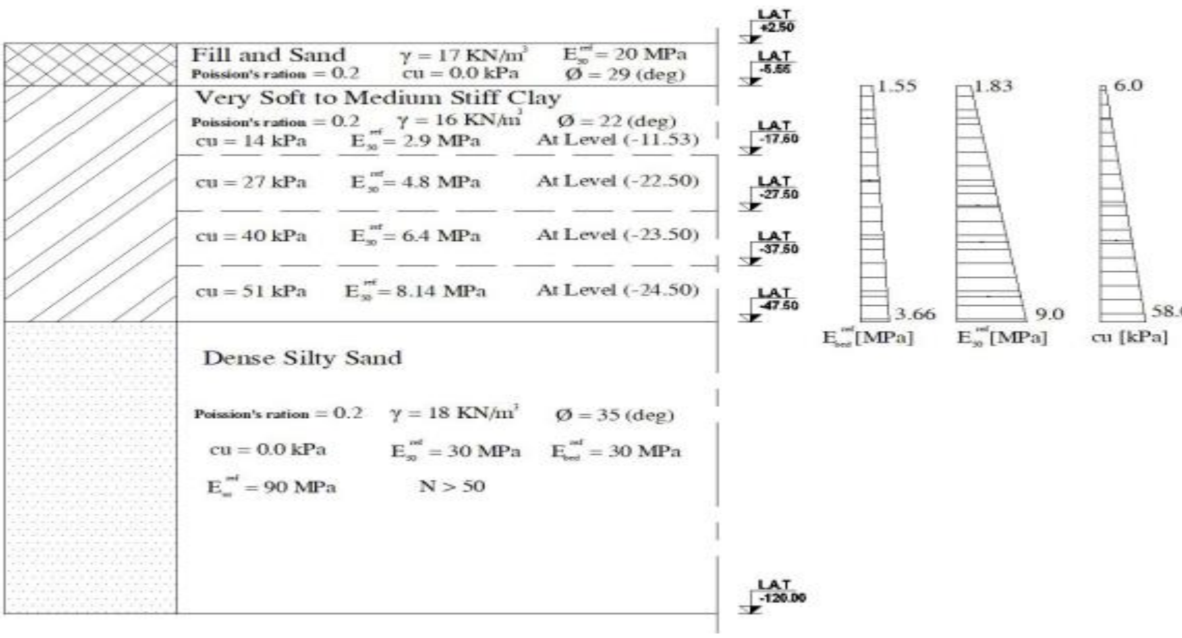


Figure 4 East Port Said Port normalized soil model (Tolba et al., 2020)

4. Modeling with the 3D finite element method

The finite element method has become more popular as a soil simulation and modeling tool. This has led to increased pressure on researchers and Geotechnical engineers to develop more comprehensive descriptions of soil behavior, which in turn leads to a more complex constitutive relationship Tolba et al (2016). A Hardening Soil Model (HSM) was simulated for our study. The deformations are ruled in the (HSM) by three stiffness parameters which simulate loading, which gives a more accurate and conservative description for soil properties, also three-dimensional numerical modeling gives a good opportunity to provide an interpretation of the model with reality. The quay wall structural elements, soil parameters, and external applied forces were defined in the software input data. The commercial finite element software Plaxis 3D 2020 was used in the present.

4.1 Definition of soil geotechnical data

As previously mentioned, the normalized soil model that was presented by Tolba et al., (2020), Figure 4, is adopted in the present study to assign soil stratigraphy input data. However, to define the parameters of improved soil, two samples were picked during the excavation works at the naval quay wall in the east Port-Said. One of them was at depths 36m and the other one was at 50m, the two samples of soil were specified as very soft to medium stiff clay. The machine used in excavation works was a bucket machine, Figure 5, that keeps the soil with its original physical and chemical properties. The samples were taken from a pit lies between BH-2 and BH-3, specifically lies 60m from BH-2 and 80m from BH-3 as shown in Figure 6.An experimental test namely Unconfined Compression Strength Test (UCS) Figure 7 was performed based on previous researches Li et al (2016); Pathivada (2005); Kitazume & Terashi (2012); Hwang (2006); Ramirez (2009) and industry design standards to characterize the clayey soil properties after treating with cement dosages 150kg/m3, 200kg/m3 and 250kg/m3. The readings obtained from the experiment were simulated by curves in terms of compression stress versus axial strain to get maximum ultimate compression strength (q_u).

Figure 5 Excavation bucket machine

Figure 6 General location of the project site and picked samples position from original boreholes

Figure 7 Experimental test stages

By applying equations of the soil-cementmixture and recommended range for value in FE analysis after (Jianguo Fan et al, 2018) Table 2, we could get corresponding cohesion (C) kPa, internal friction angle of soil (φ°), dilatancy angle (Ψ°) and elastic modulus of elasticity (E) kN/m2, for economic considerations, soil treated with 150kg/m3 cement was presented as improved soil block model.

Table 3 concludes the east Port said soil parameters normalized by Tolba et al., 2020 and shows data of treated soil. The nonlinear elastoplastic hardening soil model HSM for the soil layers in the drained and undrained condition was applied, as mentioned before, El-Nahhas et al., 2017 reported the variations of (E_{oed}) and (E_{u50}) in east of Port Said generally Figure 1 in east of port Said, but for improved soil, the corresponding properties of soil are changed due to the improvement, as a result, we used value of E_{oed} equals to E_{u50} as used in general (Vendel Józsa, 2011). For all soil layers, the default value of (0.2) is adopted for Poisson's ratio (ν) in the unloading reloading condition

Table 2 Summary of soil–cement mixture and recommended range for vault arch in FE analysi (after Jianguo Fan et al, 2018).

Parameter	Range of interpretation method	Remarks
Cohesion, C	$C = 48.265 + 0.22q_u$	q_u and c are in kPa
Internal friction angle, ϕ	32°- 36° for fine-grained soil-cement mixture and 38°- 43° for coarse-grained soil-cement mixture	Higher cement content, admixing of sodium silica may help to use higher ϕ value
Elastic modulus, E	Use a value between $E_{soil-cement} = 12900q_u^{0.41}$ and $E_{soil-cement} = 30000\sqrt{q_u}$	Higher cement content, admixing of sodium silica may have higher E values. The unit of $E_{soil-cement}$ is in kPa
Dilatancy angle, Ψ	$\Psi = \phi - 30°$ when $\phi > 30°$, otherwise $\Psi = 0°$	It is also applicable to native soil, but effective internal friction angle shall be used
Initial earth pressure coefficient, K_0	$K_0 = v/(1-v)$ or $K_0 = 1 - \sin\phi$	It is also applicable to native soil, but effective internal friction angle shall be used

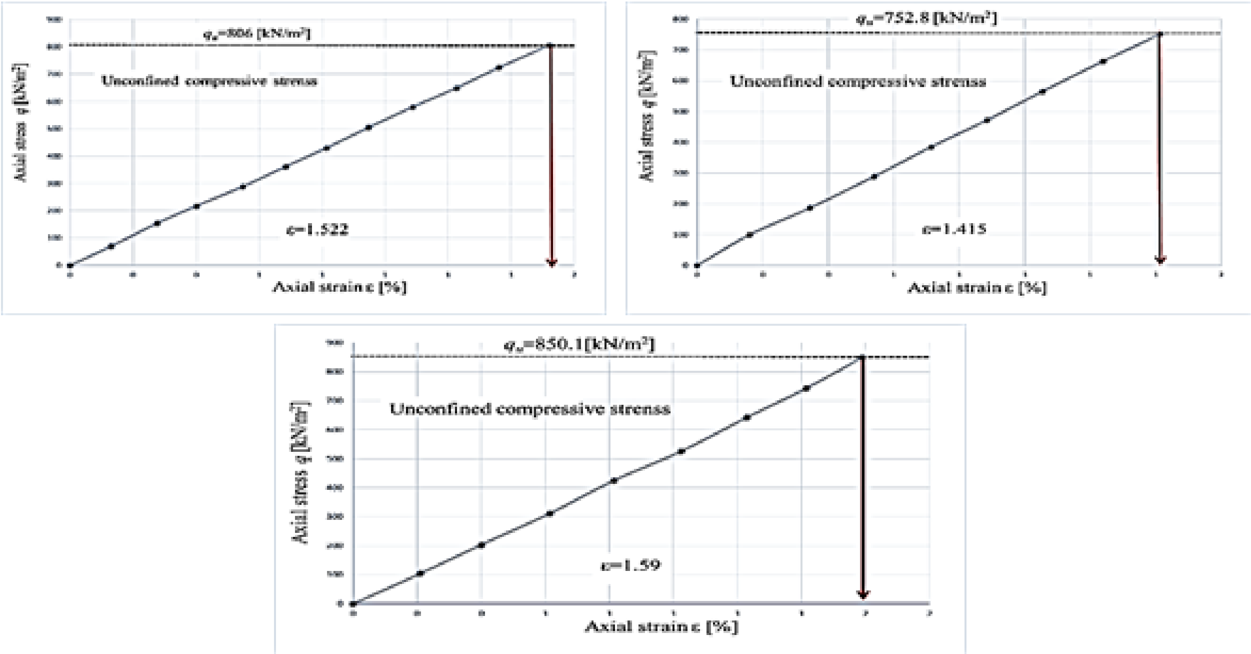


Figure 9 Stress strain curves for three samples treated with 150kg/m3 of cement and curing time 28 days at depth 36 m

Table 3 Geotechnical data for East Port-Said Hardening Soil model HSM

Layer	Type	Level		Unit weight		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]	Rinter [-]	m
		Top	Botto	γuns	γsat										
Fill (Crushed stone)	Drained	+3.00	-6.00	15	17	1	1	20	40	10	50000	50000	150000	0.7	0.7
Very soft to medium clay (A)	undrained (A)	-6.00	-17.50	16	17.5	0.001	0.001	14	22	0	2900	1850	20300	0.5	1
Very soft to medium clay (B)	undrained (A)	-17.50	-27.00	16	17.5	0.001	0.001	27	22	0	4800	2400	33600	0.5	1
Very soft to medium clay (C)	undrained (A)	-27.50	-37.50	16	17.5	0.001	0.001	40	22	0	6400	2900	44800	0.5	1
Very soft to medium clay (D)	undrained (A)	-37.50	-47.50	16	17.5	0.001	0.001	51	22	0	8140	3400	46980	0.5	1
Dense silty sand	Drained	-47.50	-120.00	18	20	1	0.1	1	35	5	30000	30000	90000	0.7	0.7
Improved soil	Drained	-11.00	-45.00	15	16	0.001	0.001	255	35	5	1850000	1850000	12950000	0.5	1

3.2 Structural elements properties

In this proposal Figure 11, the same as the previous one,the front In the present study, three proposals were introduced, in each proposal, the structural system of the front wall was presented in detail, also the corresponding internal interactions and displacement behavior were reported. The geometry data, cross-sections, and structural arrangement are introduced as follows:

A) Combined wall with Steel Tubular Closed shoe king pile filled with concrete

wall is a combi-wall consists of steel tubular king pile 2997mm diameter and 25mm skin thickness filled with non-shrinkage In this proposal, Figure 10 the front wall is a combi-wall consists of steel tubular king pile 2997mm diameter and 25mm skin thickness filled with non-shrinkage concrete without reinforcement with a closed shoe, and double intermediate sheet piles AZ 36, the top level of the wall is at (+3.00m), while the bottom level of the king pile is at (-60.00m) and (-30.00m) for intermediate sheet pile with a total length of 63.0m for king pile and 33.0m for intermediate sheet piles. The front wall system is tied to a back wall of steel sheet pile AZ50, its top-level is at (+2.500m) and (-20.00m) for the bottom level to be 22.5 m for overall length, the anchorage system consists of one row of anchors 108 Dia. at level (-2.00m) spaced at 5.797m the distance between the centers of two successive king piles. The back wall lies at a distance of 23.00m from the front wall. Table 4 summarizes this proposal's geometry.

Table 4 Proposal 1 structural system content

Quay wall components	
Front wall: King Pile (Tubular Steel Pile)	
Diameter (mm)	2997
Skin Thickness (mm)	25
Top level (m)	(+3.00)
Bottom level (m) / Closed ended	(-60.00)
Concrete Bottom level (m)	(-60.00)
Front wall: Double intermediate sheet pile	
Section Type	AZ36
Top level (m)	(+3.00)
Bottom level (m)	(-30.00)
Back wall:	
Section Type	AZ50
Top level (m)	(+2.50)
Bottom level (m)	(-20.00)
Length (m)	22.50m
Tie rods:	
Diameter (mm)/ Length (m)	108mm/23.0m
Tie rod level (m)	(-2.00)
Spaced at (m)	5.797m

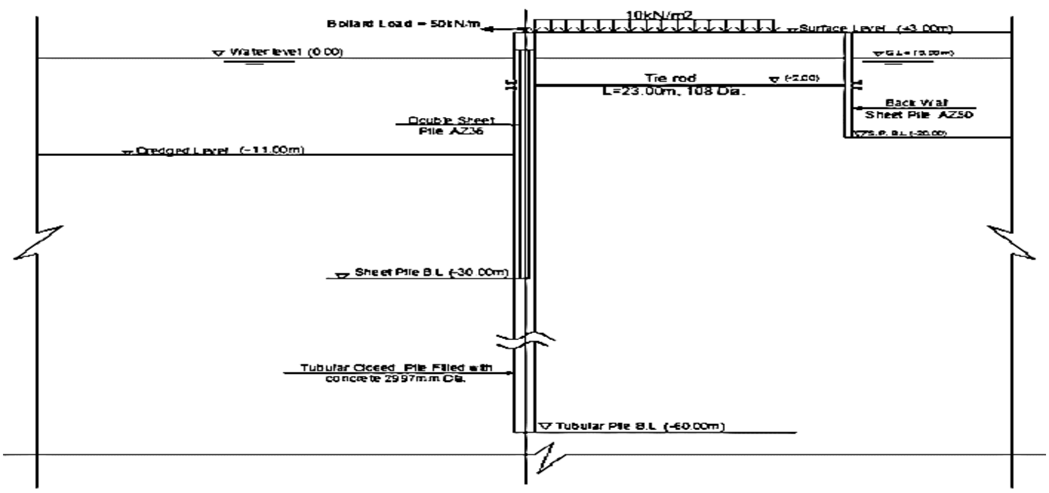


Figure 10 Proposed compiened wall with closed ended king pile

B) Combined wall with Steel Tubular Opened shoe king pile filled with concrete and blogged soil
concrete without reinforcement but with an opened shoe, and double intermediate sheet piles AZ 36, the top level of the wall is at (+3.00m), while the bottom level of the king pile is at (-60.00m) and (-30.00m) for intermediate sheet pile, the concrete-filled in the piles stops at level (-45.00m), while the balance lower length of soil is blogged with the soil from level (-45.00m) to (-60.00m). The front wall system is tied to a back wall of steel sheet pile AZ50, its top-level is at (+2.500m) and (-20.00m) for the bottom level, the anchorage system consists of one row of anchors 108 Dia. at level (-2.00m) spaced at 5.797m the distance between the centers of two successive king piles. The back wall lies at a distance of 23.00m from the front wall. Table 5 summarizes this proposal geometry.

Table 5 Proposal 2 structural system content

Quay wall components	
Front wall: King Pile (Tubular Steel Pile)	
Diameter (mm)	2997
Skin Thickness (mm)	25
Top level (m)	(+3.00)
Bottom level (m)/ Opened ended	(-60.00)
Length (m)	63.00m
Concrete Bottom level (m)	(-45.00)
Front wall: Double intermediate sheet pile	
Section Type	AZ36
Top level (m)	(+3.00)
Bottom level (m)	(-30.00)
Back wall:	
Section Type	AZ50
Top level (m)	(+2.50)
Bottom level (m)	(-20.00)
Tie rods:	
Diameter (mm)/ Length (m)	108mm/23.0m
Tie rod level (m)	(-2.00)
Spaced at (m)	5.797m

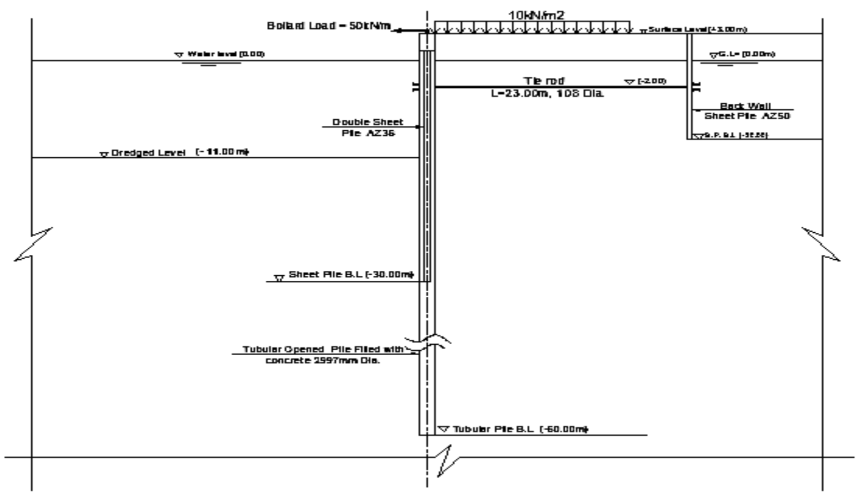


Figure 11 Proposed compiened wall with opened ended king pile

Table 6 Proposal 3 structural system content

Case 1		Case 2		Case 3	
Quay wall components		**Quay wall components**		**Quay wall components**	
Front wall:		**Front wall:**		**Front wall:**	
Section Type	AZ46	Section Type	AZ46	Section Type	AZ46
Top level (m)	(+3.00m)	Top level (m)	(+3.00m)	Top level (m)	(+3.00m)
Bottom level (m)	(-40.00m)	Bottom level (m)	(-40.00m)	Bottom level (m)	(-40.00m)
Back wall:		**Back wall:**		**Back wall:**	
Section Type	AZ25	Section Type	AZ28	Section Type	AZ28
Top level (m)	(+2.50m)	Top level (m)	(+2.50m)	Top level (m)	(+2.50m)
Bottom level (m)	(-20.00m)	Bottom level (m)	(-15.00m)	Bottom level (m)	(-17.00m)
Tie rods:		**Tie rods:**		**Tie rods:**	
Diameter (mm)/ Length (m)	52mm/23.00m	Diameter (mm)/ Length (m)	64mm/23.00m	Diameter (mm)/ Length (m)	52mm/23.00m
Tie rod level (m)	(-2.00m)	Tie rod level (m)	(-2.00m)	Tie rod level (m)	(-2.00m)
Spaced at (m)	1.16m	Spaced at (m)	1.16m	Spaced at (m)	1.16m
DSM block width (m):		**DSM block width (m):**		**DSM block width (m):**	
Active / Paasive	10.0m/10.0m	Active / Paasive	20.0m/10.0m	Active / Paasive	30.0m/10.0m
Case 4		**Case 5**		**Case 6**	
Quay wall components		**Quay wall components**		**Quay wall components**	
Front wall:		**Front wall:**		**Front wall:**	
Section Type	AZ46	Section Type	AZ46	Section Type	AZ46
Top level (m)	(+3.00m)	Top level (m)	(+3.00m)	Top level (m)	(+3.00m)
Bottom level (m)	(-40.00m)	Bottom level (m)	(-40.00m)	Bottom level (m)	(-40.00m)
Back wall:		**Back wall:**		**Back wall:**	
Section Type	AZ28	Section Type	AZ25	Section Type	AZ28
Top level (m)	(+2.50m)	Top level (m)	(+2.50m)	Top level (m)	(+2.50m)
Bottom level (m)	(-10.00m)	Bottom level (m)	(-12.50m)	Bottom level (m)	(-15.00m)
Tie rods:		**Tie rods:**		**Tie rods:**	
Diameter (mm)/ Length (m)	52mm/23.00m	Diameter (mm)/ Length (m)	52mm/23.00m	Diameter (mm)/ Length (m)	52mm/23.00m
Tie rod level (m)	(-2.00m)	Tie rod level (m)	(-2.00m)	Tie rod level (m)	(-2.00m)
Spaced at (m)	1.16m	Spaced at (m)	1.16m	Spaced at (m)	1.16m
DSM block width (m):		**DSM block width (m):**		**DSM block width (m):**	
Active / Paasive	40.0m/10.0m	Active / Paasive	50.0m/10.0m	Active / Paasive	10.0m/20.0m
Case 7		**Case 8**		**Case 9**	
Quay wall components		**Quay wall components**		**Quay wall components**	
Front wall:		**Front wall:**		**Front wall:**	
Section Type	AZ46	Section Type	AZ46	Section Type	AZ46
Top level (m)	(+3.00m)	Top level (m)	(+3.00m)	Top level (m)	(+3.00m)
Bottom level (m)	(-40.00m)	Bottom level (m)	(-40.00m)	Bottom level (m)	(-40.00m)
Back wall:		**Back wall:**		**Back wall:**	
Section Type	AZ18	Section Type	AZ18	Section Type	AZ18
Top level (m)	(+2.50m)	Top level (m)	(+2.50m)	Top level (m)	(+2.50m)
Bottom level (m)	(-17.50m)	Bottom level (m)	(-17.50m)	Bottom level (m)	(-17.50m)
Tie rods:		**Tie rods:**		**Tie rods:**	
Diameter (mm)/ Length (m)	48mm/23.0m	Diameter (mm)/ Length (m)	48mm/23.0m	Diameter (mm)/ Length (m)	48mm/23.0m

Tie rod level (m)	(-2.00m)	Tie rod level (m)	(-2.00m)	Tie rod level (m)	(-2.00m)
Spaced at (m)	1.16m	Spaced at (m)	1.16m	Spaced at (m)	1.16m
DSM block width (m):		**DSM block width (m):**		**DSM block width (m):**	
Active / Paasive	10.0m/30.0m	Active / Paasive	10.0m/40.0m	Active / Paasive	10.0m/50.0m

C) Applying Deep Soil Mixing (DSM)

In this proposal Figure 12, a soil improvement is applied by Deep Soil Mixing method DSM, this action leads to reduction of front and back walls cross-sections and bottom levels, also the cross-section of anchor rod was reduced, in this proposal, nine cases were studied, in each case, the dimension of DSM block was increased by 10m wide in one side active or passive, and then the corresponding internal reactions and displacement were investigated. Generally, the top-level for the front wall was (+3.00m), while its bottom level was (-45.00m), the top-level for the back wall was (+2.50m), while the bottom level varied according to DSM size and design requirements, also the cross-sections of both front and back wall differ from case to another to fit resistance requirements. The anchor rod lied at level (-2.00m), and its cross-section and prestressing force were changed in each case. Table 6 summarizes this proposal's properties.

In the present study, the cross-section of the sheet pile for both the quay wall and anchor plate was changed when the dimensions of the treated soil were modified according to resistance requirements.Ninecaseswere modeled, in each one of them, the treated soil block dimensions were changed. Then,the effects on internal reactions and displacement were studied, as a result, the structural element cross-sections, geometry, and arrangement were adopted to be fitted with the induced interactions. So, in each case of them, the structural element properties and its geometry will be presented.

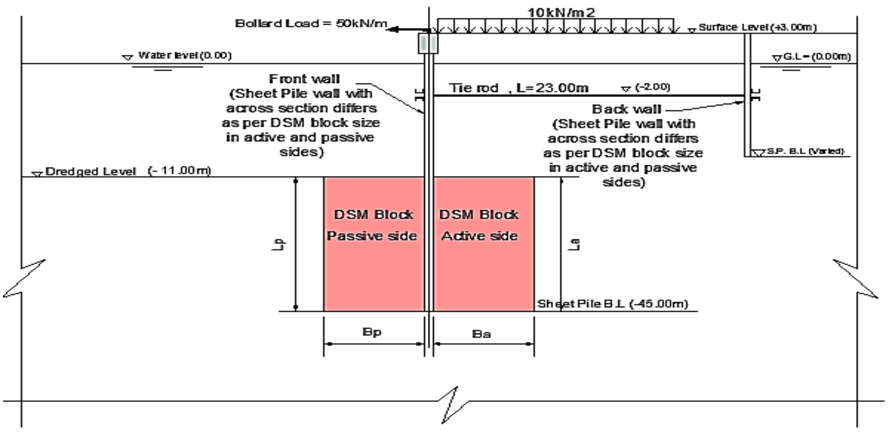


Figure 12 Proposed Sheet pile wall with applied (DSM)

3.2.1 Sheet Pile cross sections properties

Five steel cross-sections were used for the quay wall and anchor plate sheet pile for all cases. The five different sheet pile wall sections were modeled in Plaxis as plate elements. Equivalent plate element properties were used based on equations provided by the software material model manual. Poisson's ratio for sheet pile walls is assumed zero according to software manual recommendation. The basic properties of each sheet pile wall were extracted from the material data sheets presented in Table 7 as per (ArcelorMittal Commercial RPS Sheet Piling (Steel Sheet Piling) General Catalogue).

As per PLAXIS 3D 2020 software manual, the model is simulated by assigning the following parameters (after Tolba et al., 2020):

E_1 : Young's modulus in first axial direction
E_2 : Young's modulus in second axial direction
I_1 : Moment of inertia against bending over the first axis
I_2 : Moment of inertia against bending over the second axis
I_{12} : Moment of inertia against torsion
G_1 : In-plane shear modulus
G_{13} : Out-of-plane shear modulus related to shear deformation over first direction
G_{23} : Out-of-plane shear modulus related to shear deformation over second direction
υ_{12} : Poisson's ratio ($\upsilon_{12} < \sqrt{E_1/E_2}$)
A_{23} : Effective material cross section area for shear forces Q_{23}

$$E_1 = \frac{12\, E_{steel} I_1}{d_3} \quad (1)$$

$$E_2 = \frac{12\, E_{steel} I_2}{d_3} \approx \frac{E_1}{20} \quad (2)$$

$$G_{12} = \frac{6\, E_{steel} I_{12}}{(1+\upsilon_{steel})d^3} \approx \frac{6\, E_{steel} I_1}{10\, d^3} \quad (3)$$

$$G_{13} = \frac{E_{steel} A_{13}}{2(1+\upsilon_{steel})\, d} \approx E_{steel} \frac{A}{3} \times \frac{1}{2d} \approx E_{steel} \frac{A}{6d} \quad (4)$$

$$G_{23} = \frac{E_{steel} A_{23}}{2\,(1+\upsilon_{steel})\, d} \approx E_{steel} \frac{A}{10} \times \frac{1}{2d} \approx E_{steel} \frac{A}{20d} \quad (5)$$

$$\gamma = \frac{A\, \gamma_{steel}}{d} \quad (6)$$

3.3 Applied loads on touristic berth quay wall

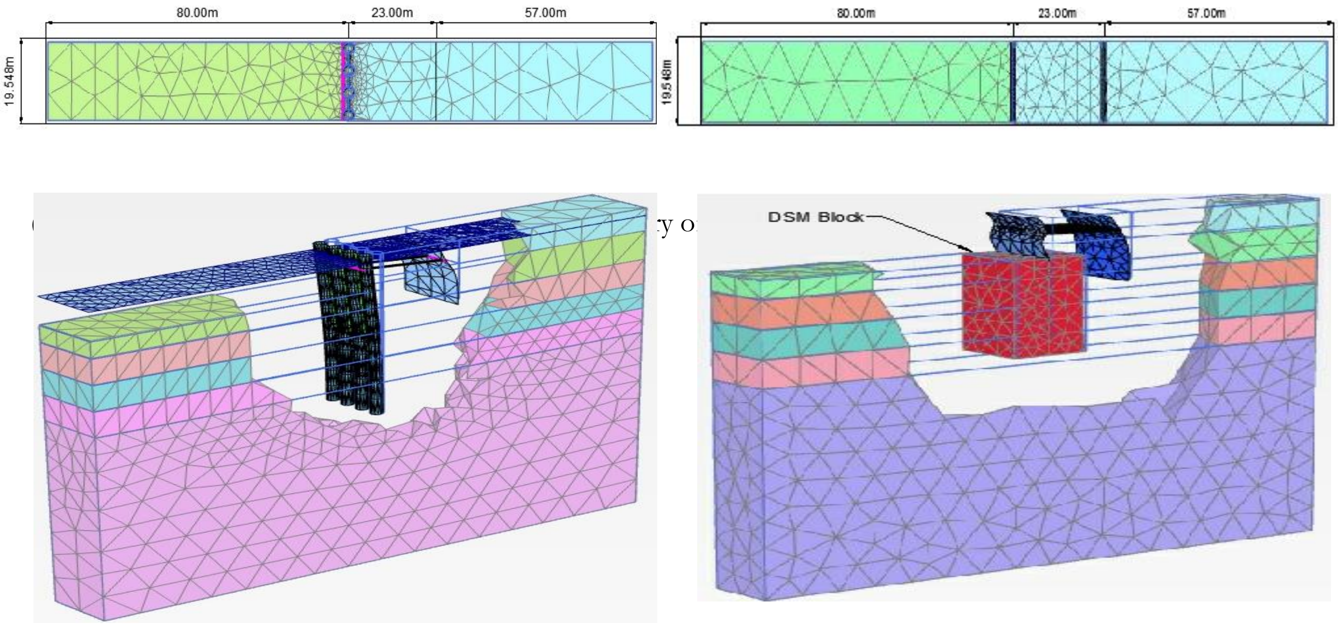
As per (IS 4651(Part III)-1974), a surcharge load of 10 kN/m2 was considered in the 3D model which was extracted from the data presented in Table 7 at 16.50 m from the front quay wall sheet pile. For mooring force, a linear force of 50 kN/m was applied on the top of the sheet pile due to the design ship.

Table 7. The function of berth related to Truck loading according to (IS 4651(Part III)-1974)

Function of Berth	Truck Loading	Uniform Vertical L.L(kN/m2)
Passenger Berth	B	10
Bulk unloading & loading berth	A	10 to 15
Container berths	A or AA or 70 R	30 to 50
Cargo berth	A or AA or 70 R	25 to 35
Heavy Cargo berth	A or AA or 70 R	50 to 60
Small boat berth	B	5
Fishing berth	B	10

3.4 Generated mesh for passenger quay wall model

A finite element mesh was created for both the soil and the quay wall structural system before Plaxis 3D software can perform calculations. The steel tubular piles system was completely repeated every 5.797m, where the outer diameter of the pile is 2.997m, and between every two consecutive pile there are double AZ36 sheet pile each of them is 1.40m width, the numerical model was built by only four panels for this quay wall to have an overall width of 19.548m in Y-direction to represent four (4) tubular piles and six (6) intermediate sheet piles, while it is 160.00m for X-direction where the front quay wall lies at the middle of the model to be both right and left boundaries are of 80.00 from the front wall. The lower boundary of the model is at level (-120.00m), while the top one is at (+3.00m) to be with an overall depth of 123.00m. For simplicity and accurate comparison, the same model width was assigned for the model with applying DSM block although the homogeneity of the front wall cross-section as a sheet pile wall. Besides the front wall structure system, the model included anchorage system components which were anchor plate represented by the back wall and anchor tie rods.



(b) The 3D model without DSM (d) The 3D model with DSM

Figure 13 Plaxis 3D generated mesh of the models

3.5 Modelling of study cases construction stages

To simulate construction stages in our models, seven (7) phases were assigned for both proposals 1 and 2, while eight (8) phases were assigned for the third one. In each phase objects, soil layers, forces, and DSM blocks were activated or deactivated as per construction stage action. For all proposals, the first phase represents the initial phase when no construction action is performed in our quay wall, hence the ground level on both sides of the quay wall is the same which is (-6.00m).

Table 8 Description of the construction phases for proposals 1 & 2

	Phase name	Phases Description
0	Initial phase	Initial phasecalculation basedonthe definedat rest pressurecoefficient value(Ko)for each soil layer, wherethequay wall and anchor plate systems werenot activated yet, ground level at both sides of the wall are (-60.00m).
1	Installing front wall	Installing the front combi wall (king steel tubular pile 2.997m diameter from leve (+3.00m) to (-60.00m), and intermediate double sheet pile AZ36 from level (+3.00m) to (-30.00m)
2	Installing back wall	Installing back wall sheet pile AZ50 from level (+2.50m) to level (-20.00m) at 23.00m from front wall
3	Filling	Filing with crushed rocks from level (-6.00m) to (-2.50m)
4	Installing tie rods	Installing tie rods M 108 between front and back wall spaced at 5.797m the distance between the center lines of the king piles at level (-2.00m) and applying prestress 1000 kN
5	Refilling	Refilling with crushed stone from level (-2.50m) to (+3.00m)

6	Dredging	Dredging in front of the front wall from level (-6.00m) to design dredged level (-11.00m).
7	Applying loads	Applyingof designloads (10 kN/m for uniform load+ 50kN/m for mooring force).

Only the soil layers are activated in this phase, where the initial effective stresses and pore pressures are calculated. Construction phases are presented for all proposals in the following tables, where proposals 1 and 2 had the same construction stages, while proposal 3 had an additional stage that presented applying of DSM blocks phase.

Table 9 Description of the construction phases for proposal 3 for all cases

	Phase name	Phases Description
0	Initial phase	Initial phasecalculation basedonthe definedat rest pressurecoefficient value(Ko)for each soil layer, wherethequay wall and anchor plate systems werenot activated yet, ground level at both sides of the wall are (-60.00m).
1	Applying DSM block	Improving the ground soil by applying the deep soil mixing method with cement of 150kg/m3 on both sides active and passive from level (-11.00m) to (-45.00m), and the width increases by 10m for one side in each case from 10m to 50m.
2	Installing front wall	Installing the front sheet pile wall AZ46 from level (+3.00m) to (-40.00m).
3	Installing back wall	Installing back wall sheet pile from level at 23.00m from front wall, its top level is (+2.50m) , while the bottom level differs in each case.
4	Filling	Filing with crushed rocks from level (-6.00m) to (-2.50m)
5	Installing tie rods	Installing tie rods between front and back wall sapced at 1.16m at level (-2.00m) and applying prestress as following: Case (1) : 52M , Prestress force: 200 kN Case (2) : 64M , Prestress force: 200 kN Case (3) : 52M , Prestress force: 250 kN Case (4) : 52M , Prestress force: 250 kN Case (5) : 52M , Prestress force: 250 kN Case (6) : 52M , Prestress force: 200 kN Case (7) : 48M , Prestress force: 150 kN Case (8) : 48M , Prestress force: 150 kN Case (9) : 48M , Prestress force: 150 kN
6	Refilling	Refilling with crushed stone from level (-2.50m) to (+3.00m)
	Phase name	Phases Description
7	Dredging	Dredging in front of the front wall from level (-6.00m) to design dredged level (-11.00m).
8	Applying loads	Applyingof designloads (10 kN/m for unifrom load+ 50kN/m for mooring force).

4. Finite element analysis results

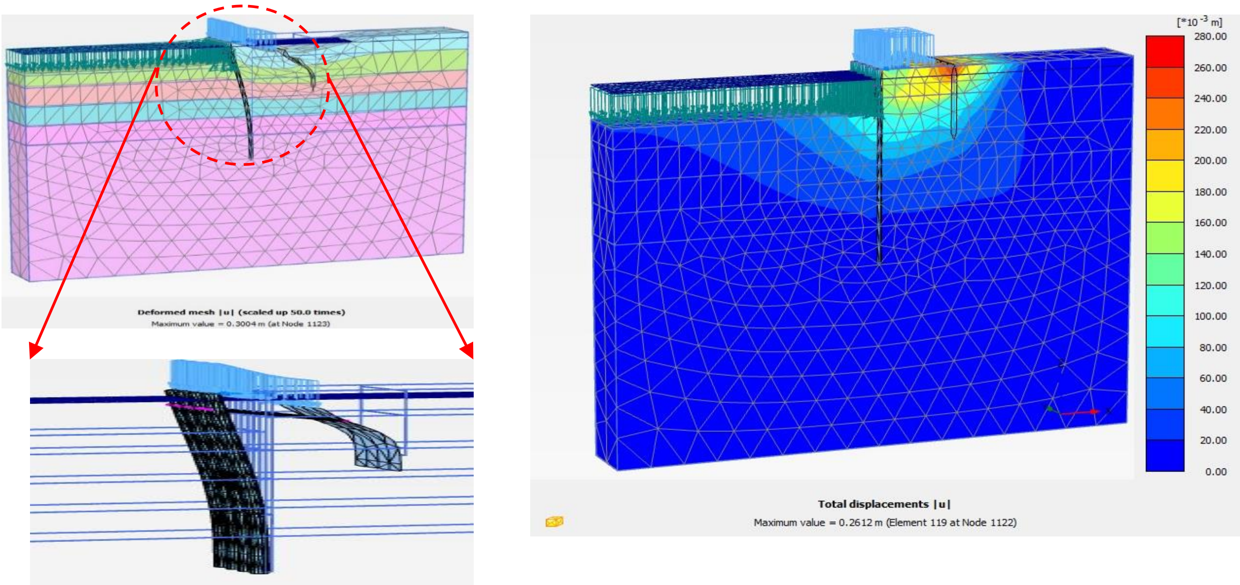
To understand the effect of improving soil properties on the designing of structural elements of the quay wall three-dimensional finite element models were set up. These models simulate a passenger berth in East of Port Said, which presents simple quay wall structure systems to study the effect of soil improvement without complications. Three quay wall systems were investigated, and for one of them we applied soil improvement in nine cases, the DSM block was assumed to be on both sides active and passive for the front wall, and in each case, the width of the DSM block was increased by 10.00m for one side. As an expected result, applying DSM affected the quay wall design where the front wall combi wall turned to be a sheet pile wall with lower sectional stiffness and linear mass along the wall. Also, the anchor rod diameter was reduced to be within 42mm and 64mm instead of 108mm. As well, the back wall's cross-section was reduced in all cases compared to the models without DSM.

4.1 Results of Proposal 1

The model outputs were based on the modeling scheming described before. Figure 14 shows deformed mesh and displacement behavior for both soil and quay wall structure elements for the last construction phase. The maximum displacement $|U|$ for soil is equal to 261.2mm around the top of the backwall, while it is 300.4mm forthe back wall, 172.8mm for the king pile of the front wall, and finally, 177.1mm for the intermediate sheet pile as shown in Table 10. The maximum horizontal displacement U_x for the front wall is equal to 176.6mm within the allowable limit (1.5% of thewall height or < 300mm) after Tolba et al., 2020 which is 210mm for the present quay wall.

Table 10. Results of PLAXIS 3D modeling for proposal 1

Internal reactions	Front wall		Back wall	Tie rod
	King Pile	Intermediate sheet pile		
Compined wall filled with concrete and closed ended, Umax for soil = 261.2mm				
Cross section	2997x25mm	AZ36	AZ50	108mm
Length (m)	63	33	22.5	23
Moment (kN.m)	1.139	85.86	305.4	-
Shear (kN)	120.7	158.7	477.1	-
Axial force (kN)	1794	85.82	48.31	2345.81
Displacement max (mm)	172.8	177.1	300.4	
Displacement (H) (mm)	172.3	176.6	277.3	-
Displacement (Z) (mm)	19.25	13.24	115.6	-
Stress (kN/m2)	0.25	27.83	62.40	256.07



(a) Deformed mesh of proposal 1 last phase
(c) Total soil displacement of proposal
(b) Structure deformation of proposal 1

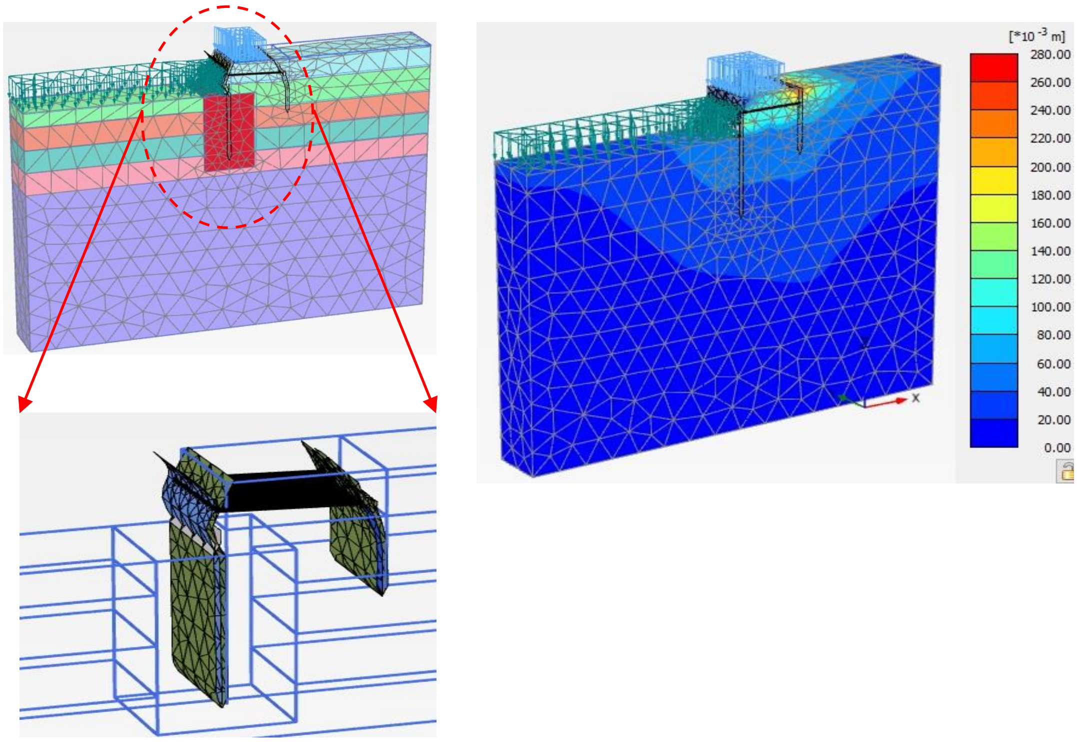
Figure 14 Displacement behavior for both soil and structure elements for proposal 1

4.2 Results of Proposal 2

Figure 15 shows deformed mesh and displacement behavior for both soil and quay wall structure elements for the last construction phase. The maximum displacement $|U|$ for soil is equal to 261.2mm around the top of the back wall, while it is 300.9mm for the back wall, 170.5mm for the king pile of the front wall, and finally,173.1mm for the intermediate sheet pile as shown in Table 11. The maximum horizontal displacement U_x for the front wall is equal to 172.7mm within the allowable limit which is 210mm as mentioned before.

Table 11. Results of PLAXIS 3D modeling for proposal 2

Internal reactions	Front wall		Back wall	Tie rod
	King Pile	Intermediate sheet pile		
Combined wall filled with concrete and opened ended, Umax for soil = 261.7mm				
Cross section	2997x25mm	AZ36	AZ50	108mm
Length (m)	63	33	22.5	23
Moment (kN.m)	1.199	94.49	309.8	-
Shear (kN)	222.5	149.7	361.6	-
Axial force (kN)	2029	91.06	48.96	2431.56
Displacement max (mm)	170.5	173.1	300.9	
Displacement (H) (mm)	170	172.7	278.2	-
Displacement (Z) (mm)	18.65	12.67	114.6	-
Stress (kN/m2)	0.29	30.47	63.29	265.43



(a) Deformed mesh of proposal 3 last phase
(b) Structure deformation of proposal 3
(c) Total soil displacement of porposal 3

Figure 15 General displacement behavior for both soil and structure elements for all cases of proposal 3

4.3 Results of Proposal 3

As mentioned before, this proposal was studied in nine cases, in each case, we increased the DSM block width by 10.00m on one side passive or active. Table 12 presents the output results for all these proposal cases, also Figure 16 shows a general deformed mesh and displacement behavior for all cases.

Table 12. Results of PLAXIS 3D modeling for proposal 3

Internal reactions	Front wall	Back wall	Tie rod
Block 1 (10mx34m) for both active and passive Umax for soil= 270mm			
Cross section	AZ46	AZ25	52mm
Length (m)	43	23	23
Moment (kN.m)	362.6	237.3	-
Shear (kN)	681.6	353	-
Axial force (kN)	48.41	27.17	463.606
Displacement max (mm)	202	270	
Displacement (H) (mm)	202	269.9	-
Displacement (Z) (mm)	3.4	51.88	-
Stress (kN/m2)	80.57	98.12	218.30
Block 2 (10mx 34m) passive, (20mx 34m) active Umax for soil= 266mm			
Cross section	AZ46	AZ28	64mm
Length (m)	43	18	23
Moment (kN.m)	357	239.2	-
Shear (kN)	662.7	358.1	-
Axial force (kN)	39.54	52.98	494.799
Displacement max (mm)	121.8	266	
Displacement (H) (mm)	120.2	265.9	-
Displacement (Z) (mm)	5.2	32.48	-
Stress (kN/m2)	78.98	89.33	153.81

Internal reactions	Front wall	Back wall	Tie rod
Block 3 (10mx 34m) passive, (30mx 34m) active Umax for soil= 327.7mm			
Cross section	AZ46	AZ28	52mm
Length (m)	43	18	23
Moment (kN.m)	392.4	270.8	-
Shear (kN)	615.6	371	-
Axial force (kN)	51.6	38.61	466.647
Displacement max (mm)	193.3	366.7	
Displacement (H) (mm)	193.3	366.7	-
Displacement (Z) (mm)	3.981	6.483	-
Stress (kN/m2)	87.08	100.12	219.73
Block 4 (10mx 34m) passive, (40mx34m) active Umax for soil= 334.5mm			
Cross section	AZ46	AZ28	52mm
Length (m)	43	13	23
Moment (kN.m)	391.2	277.5	-
Shear (kN)	591.2	372.2	-
Axial force (kN)	25.42	81.09	477.547
Displacement max (mm)	194.2	381.2	
Displacement (H) (mm)	194.2	380.4	-
Displacement (Z) (mm)	1.8	25.6	-
Stress (kN/m2)	86.01	104.57	224.87
Block 5 (10mx 34m) passive, (50mx 34m) active Umax for soil= 332.4mm			
Cross section	AZ46	AZ25	52mm
Length (m)	43	15.5	23

Moment (kN.m)	390.1	268.1	-
Shear (kN)	617.5	369.8	-
Axial force (kN)	40.97	50.95	471.885
Displacement max (mm)	182.7	374.7	
Displacement (H) (mm)	182.7	374.7	-
Displacement (Z) (mm)	7.13	3.826	-
Stress (kN/m2)	86.30	111.95	222.20
Block 6 (20mx 34m) passive, (10mx 34m) active Umax for soil= 262.8mm			
Cross section	AZ46	AZ28	52mm
Length (m)	43	18	23
Moment (kN.m)	357	249.1	-
Shear (kN)	701.1	379.5	-
Axial force (kN)	33.46	23.57	447.547
Displacement max (mm)	198.1	171.3	
Displacement (H) (mm)	198.1	162.5	-
Displacement (Z) (mm)	2.7	63.87	-
Stress (kN/m2)	78.84	102.74	210.74
Block 7 (30mx 34m) passive, (10mx 34m) active Umax for soil= 214.4mm			
Cross section	AZ46	AZ18	48mm
Length (m)	43	20.5	23
Moment (kN.m)	333.4	184.6	-
Shear (kN)	751.5	307.1	-
Axial force (kN)	30.64	27.93	419.72
Displacement max (mm)	204.8	241.5	
Displacement (H) (mm)	194.6	236.6	-
Displacement (Z) (mm)	5.628	56.87	-
Stress (kN/m2)	73.61	104.41	231.95

Internal reactions	Front wall	Back wall	Tie rod
Block 8 (40mx 34m) passive, (10mx 34m) active Umax for soil= 211.3mm			
Cross section	AZ46	AZ18	48mm
Length (m)	43	20.5	23
Moment (kN.m)	331.7	183.7	-
Shear (kN)	755.1	305.2	-
Axial force (kN)	30.21	25.32	416.172
Displacement max (mm)	201.5	237.7	
Displacement (H) (mm)	191.4	233.8	-
Displacement (Z) (mm)	7.44	52.3	-
Stress (kN/m2)	73.22	103.74	229.99
Block 9 (50mx 34m) passive, (10mx 34m) active Umax for soil= 209.2mm			
Cross section	AZ46	AZ18	48mm
Length (m)	43	20.5	23
Moment (kN.m)	333	183.6	-
Shear (kN)	759.5	304.5	-
Axial force (kN)	32.21	25.37	413.891
Displacement max (mm)	201.8	235.6	
Displacement (H) (mm)	191.7	232.4	-
Displacement (Z) (mm)	8.494	48.35	-
Stress (kN/m2)	73.58	103.69	228.73

5.1 Discussion of finite element results

To understand the effect of applying DSM, three proposals were studied; two of them before applying soil improvement, and the third one was with applying it in nine cases. The first proposal which is a closed-ended king pile had a maximum soil displacement of 261.2mm around the top of the back wall, while for the second proposal it was 261.7mm which is very close to the value of the previous proposal. Not just values of soil displacement were too close, but also the values of total displacement for the front wall and back wall were close. They were 172.8mm, 177.1mm, and 300.4mm for king pile, intermediate sheet piles, and back wall respectively for proposal 1 while they were 170.5mm, 173.1mm, and 300.9mm for proposals 2. Also, the moment of the king pile was too close where it is 1.139 kN.m for proposal 1 and 1.199 kN.m for proposal 2 with an increment of 5.27%, so it can be seen that the values of interactions of the two proposals are nearly similar. It can be noticed also that the horizontal displacement of the front wall for both proposals increases from the bottom to reach its maximum value at the top of the wall in the last construction phase where surface and mooring loads were applied.

For proposal 3, nine cases (9) were simulated to be studied, as can be seen, the maximum soil displacement was observed in case 4 with a value of 334.5mm, while the minimum value was for case (9) where it was 209.2mm. Also, it can be seen that mostly when the width of the DSM block was increased on the active side, the total displacement of soil increased gradually except for case 5 the value of soil displacement was 332.4mm while it was 334.5mm for the previous case with difference only 2.1mm, unlike increasing DSM block width in the passive side, it led to reducing the value of soil displacement gradually.

Besides, increasing DSM block width in the passive side led to reducing cross-sections of both anchor tie rod and back wall where for cases 7, 8, and 9 the cross-section for the tie rod was 48mm and AZ18 profile was assigned for the back wall, while it was 52mm for anchor rod for cases 1,3,4 and 5 and AZ28 profile was assigned for back wall for cases 2,3 and 4 and AZ 25 for cases 1 and 5 with the difference of back wall length for all cases. For stresses of the front wall, we can see that the large width values in the active side gave higher stress values compared to the values resulted from large block width on the passive side with the same cross-section profile for the front wall. For shear forces for the front wall, large blocks on the active side gave lower results compared to those on the passive side, unlike the back wall, which gave higher results than on passive sides. In addition, the horizontal displacement for the front wall for all cases was too close to each other except for case 2 where a 62mm anchor rod was used which led to reducing the horizontal displacement value to 120.2mm, but in general horizontal displacement for the front wall in all cases within the allowable limit (1.5% of the wall height or < 300mm) after Tolba et al., 2020 which is 210mm for the present quay wall. So, it can be generally concluded that increasing DSM block size on the passive side gives best results than increasing it on the active side. Moreover, it can be seen that the displacement for front wall for proposals without applying DSM increased gradually from bottom to the top of the wall, while for applying DSM the displacement of the front wall was nearly zero within the DSM block and started to increase gradually from dredged level to the top of the wall outside DSM block.

6. Cost estimation

In this part of the research, the costs of the seven cases of the quay wall were estimated. It is important to mention that cost estimating is a very vital part of the overall decision-making process to choose a quay wall design system. The cost estimation of a project is affected by market situation, commercial consideration, and site requirements. The final cost of a project consists of two kinds of costs, direct costs (civil works, foundations, earthworks, transportation, installation, demolishing works), indirect costs (site preparation, storage, etc.), and additional costs (risk, profit, etc.). In our research, the costs are estimated only for civil works (namely earthworks, steel, and concrete). In the cost estimation process, the price of each element was introduced individually.

6.1 Element price

6.1.1 Steel

a) Sheet pile

Delivery steel elements	1120 U$/ton
Installation sheet pile element	480 U$/m
Coating	53.30 U$/ton

b) Anchor rod

The same as the steel sheet piles per ton.

6.1.2 Concrete

The price of a concrete structure depends on the concrete, reinforcement, and formwork. prices per cubic meter in each country are used to have an indicator to identify trends and support selections in alternatives. The price of concrete, including casting, reinforcement, and formwork is set to 320 U$/m3.

6.1.3 Earth works

The price of earthworks depends on the kind of the soil, location of soil, the used machinery, and transportation of soil removed or refilled. According to the archive of Port-Said marines an average value of 6 U$/m3 was given for excavation and 10 U$/m3 for both refill with rocks and dredging.

6.1.4 Deep Soil mixing (DSM)

Deep Soil Mixing (DSM) price depends on the kind of soil treated, amount of binder (cement) used per meter, kind of the machine, the diameter of columns, typical improvement patterns of treated soil mass (block type, wall type, gride type) and the way of execution (dry way or wet way), in our study a value of 48 U$/m3 was given for (DSM) according to a Japanese company.

6.2 Quantity survey and total cost per meter wall

In this section we determined the total quantity for each term and then with the knowledge of the price of each element we got the total price for each proposal, a price analysis was made for quay wall elements, and then a total cost was estimated for each case to optimize the most economic case of them.

Table 13. Quantityof quay wall elements for all proposals

Element	Quantity per meter wall										
	Proposal 1	Proposal 2	Proposal 3								
			Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Front wall king pile delivery and Installation (ton)/m	22.88	22.61	-	-	-	-	-	-	-	-	-
Front wall sheet pile delivery and installation (ton)/m	5.59	5.59	9.83	9.83	9.83	9.83	9.83	9.83	9.83	9.83	9.83
Back wall sheet pile delivery and installation (ton)/m	5.69	5.69	3.34	2.98	2.98	2.15	2.25	2.98	2.42	2.42	2.42
Coating (ton)/m	34.16	33.89	13.17	12.81	12.81	11.98	12.08	12.81	12.25	12.25	12.25
Anchor rod delivery and installation (ton)/m	1.66	1.66	0.38	0.58	0.38	0.38	0.38	0.38	0.33	0.33	0.33
Concrete for capping beam (m3)/m	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50	7.50
Dredging (m3)/m	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Excavation (m3)/m	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Refill (m3)/m	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Concrete in king pile (m3)/m	84.30	64.23	-	-	-	-	-	-	-	-	-

Table 14. Cost estimation for quay wall elements for all proposals

Element	Price per unit element	Quantity per meter wall										
		Proposal 1	Proposal 2	Proposal 3								
				Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
Front wall king pile delivery and Installation $/ton	1600	36606.23	36171.9	-	-	-	-	-	-	-	-	-
Front wall sheet pile delivery and installation $/ton	1600	8939.04	8939.04	15727.68	15727.68	15727.68	15727.68	15727.68	15727.68	15727.68	15727.68	15727.68
Back wall sheet pile delivery and installation $/ton	1600	9104.4	9104.4	5343.36	4772.16	4772.16	3446.56	3600.96	4772.16	3873.68	3873.68	3873.68
Coating $/ton	53.3	1820.52	1806.05	701.93	682.9	682.9	638.74	643.89	682.9	652.97	652.97	652.97
Anchor rod delivery and installation $/ton	1600	2657.7	2657.7	606.65	927.3	606.65	606.65	606.65	606.65	522.87	522.87	522.87
Concrete for capping beam $/m³	320	2400.0	2400.0	1600.0	1600.0	1600.0	1600.0	1600.0	1600.0	1600.0	1600.0	1600.0
Dredging $/m³	10	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Excavation $/m³	6.0	900.0	900.0	900.0	900.0	900.0	900.0	900.0	900.0	900.0	900.0	900.0
Refill $/m³	10	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0
Concrete in king pile $/m³	320	26974.93	20552.32	-	-	-	-	-	-	-	-	-
DSM $/m³	48	-	-	32640.0	48960.0	65280.0	81600.0	97920.0	48960.0	65280.0	81600.0	97920.0
Total cost in $/meter of wall	-	93402.81	85731.42	61519.62	77570	93569.4	108519.6	124999	77249.4	92557.2	108877.2	125197.2
Total cost in EGP/meter of wall	-	**1401042**	**1285971**	**922794**	**1163551**	**1403541**	**1627794**	**1874988**	**1158741**	**1388358**	**1633158**	**1877958**

Table 15. Summary of costs per meter wall for all proposals cases.

Proposal NO.	Cost per meter wall
Proposal (1)	1401042.0 EGP/m
Proposal (2)	1285971.0 EGP/m
Proposal (3):	
Case (1)	922794.0 EGP/m
Case (2)	1163551.0 EGP/m
Case (3)	1403541.0 EGP/m
Case (4)	1627794.0 EGP/m
Case (5)	1874988.0 EGP/m
Case (6)	1158741.0 EGP/m
Case (7)	1388358.0 EGP/m
Case (8)	1633158.0 EGP/m
Case (9)	1877958.0 EGP/m

he cost of all proposals is summarized in Table 16 and Figure 16, from cost results it can be seen that large DSM block sizes on each side gave very close values for the same sizes. In more detail, for example, both cases 2 and 6 had the same block sizes, but the first one on the active side while the other one on the passive side, case 2 gave a cost value of (1163551 EGP/m), while cost 6 gave (1158741 EGP/m), and they are very close values with a difference of (48010 EGP/m) for case 2, so for the same DSM block size, large block on the passive side gave more economic result compared to the same block size on the active side. The same thing goes for cases 3 and 7, the difference in cost results between them was (15183 EGP/m) for the active side, which is a higher difference than the previous comparison. Unlike cases 4 and 8, the difference between them was (5364 EGP/m), but this time the difference was for case 8, this means that for case 4 and 8, large DSM block on the active side gave more economic result compared to the same block size on the passive side, the same thing goes for cases 5 and 9, where the difference was (2970 EGP/m) for passive side, this leads to there is no certain rule to decide which side gives best economic results, and both sides must be analyzed to determine the optimized DSM block position. Another thing that can be observed from Figure 16, the relationship between the cost per meter wall and DSM block size is almost linear; also both active side and passive side curves are almost typical with a slight difference. From all results, it can be finally concluded that case 1 with a block size of (10m x 34m) for both sides is the most economic case among all cases. In addition, it gave acceptable output results for displacement and internal stresses, so case 1 can be considered as our optimized construction system.

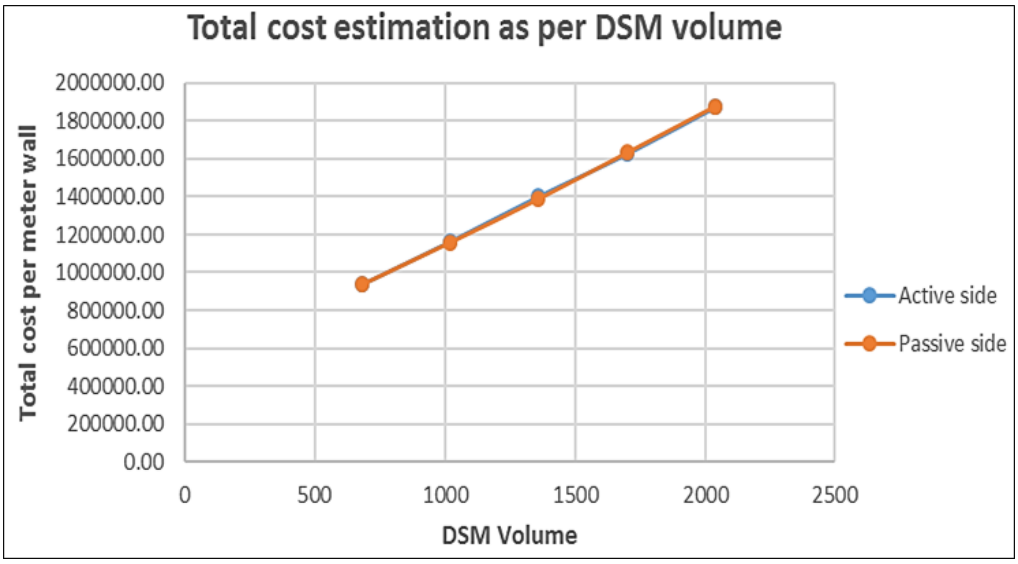


Figure 16 Total cost estimation as per DSM volume

7. Conclusions

The present research studied the effect of applying the deep soil mixing method DSM on designing structural element cross-sections, geometry dimension of them, and the corresponding total cost of the quay wall. To do that the passenger type was chosen as a case study. Also, soil profile normalized by Tolba et al., 2020 for East of Port Said was used to assign the geotechnical data. Three proposals were introduced to be studied, the first and the second were without applying soil treatment DSM, while the third one was with applying DSM with several dimensions on both sides active and passive, the corresponding results of each case were investigated and also the resulted cost of each of them to conclude the economically optimized case. From finite element analysis results and cost estimation for each case of the following conclusions can be drawn:

- Using the DSM method could have a very notable and direct effect on induced interactions in structural elements and displacement behavior of the quay wall, and as a result, it affects the corresponding cross-sections and geometry dimensions.
- In the present study, not all cases with applied DSM gave cost values less than cases without it, where cases with large DSM block sizes gave high values of cost exceeded cases that without applying DSM.
- There is an approximate proportional linear relationship between DSM block volume and the total cost of the quay wall per meter, we could say it is almost a linear relationship.
- In most cases, the DSM block on the passive side gave better output results for displacement behavior for soil and internal interactions than that on the active side, but it does not mean that it gives the best economic results for the same compared cases.

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