Passive earth reinforcement of quay walls: numerical analysis and experimental framework

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Abstract. Deeper berth requirements due to increasing vessel sizes pose a significant challenge, rendering quay wall structures as critical infrastructure for the maritime logistics chain. This paper presents preliminary numerical analyses performed using two-dimensional finite element modelling to evaluate the global structural response of the quay wall for three passive soil-cement block configurations: Small, Wide, and Deep. The presented numerical analyses form the initial phase of a broader research programme focused on establishing a validated design framework for cement-treated soil reinforcement at the passive side of quay wall structures. This phase will be followed by 1g model-scale shaking table tests to verify the performance of the defined reinforcement configurations under dynamic loading conditions. The initial numerical results indicate that the Wide Block configuration provides superior reinforcement performance compared to the Deep Block arrangement. Increasing the improvement depth beyond a certain threshold was found to produce only marginal additional reductions in structural demand. Accordingly, the results are interpreted with reference to soil–structure interaction mechanisms controlling the quay wall response. These findings will guide the configuration of the planned shaking table experiments for dynamic soil–structure interaction assessment and provide insight into how mobilized lateral equilibrium conditions influence and govern overall wall deformation behaviour.

1 Introduction

Maritime transportation accounts for more than 70% of global trade. The continuous growth in international trade has encouraged the use of larger vessels to improve economic efficiency by transporting greater cargo volumes per voyage and reducing unit transportation costs. In parallel, increasingly stringent environmental regulations have further promoted the development of technologically advanced, large-scale vessels to enhance energy efficiency and reduce emissions.

The combined effect of these economic and regulatory drivers is leading to a continuous increase in overall vessel dimensions, particularly draft, thereby requiring port infrastructure to adapt accordingly [1]. Quay and berth structures capable of accommodating deeper drafts and higher berthing loads have therefore become critical components of modern maritime logistics systems (Fig. 1).

Fig. 1. A cross-sectional configuration of a port with quay berth.

In addition, the need to enable climate-resilient design in response to projected sea-level rise and increased wave action, together with the requirement to ensure adequate performance against geo-hazard exposure, presents significant challenges for these critical infrastructures. These evolving environmental and operational demands impose additional constraints on quay berth structures, highlighting the need for alternative and optimised design solutions for both existing facilities and newly planned developments.

Higher dredging level requirements for larger vessel berths reveal a significant challenge for sizing the wall structures according to bending actions within reasonable costs and due to urgencies in operational commencement. Furthermore, offshore soil conditions often reveal soft sedimentary deposits of significant thickness under the seabed which increases the bending length of the wall due to weak passive earth resistance.

Passive earth reinforcement in quay walls refers to ground improvement applied on the passive side of the structure, commonly through jet grouting, to enhance mobilized passive earth pressure [2-4]. By increasing passive resistance, the lateral force equilibrium is improved, leading to reduced bending moments and more efficient wall sizing. This approach is particularly advantageous in counteracting the structural demands associated with increased retained heights. The proposed design solution has been increasingly adopted

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in engineering practice to address these challenges, while its implementation is mostly guided by case-by-case judgements. In particular, the influence of reinforcement geometry and its role in governing soil–structure interaction mechanisms remain insufficiently defined, pointing the need for further investigation of a systematic framework [3-5].

This research is conducted within the framework of the QRDI–TÜBİTAK, Joint Academia–Industry Cooperation Funding Program investigates the soil–structure interaction mechanisms governing the performance of passively reinforced quay wall systems in soft soil conditions and aims to develop performance-based optimisation strategies for design. From a design perspective, the performance of quay wall systems found on soft soils must be evaluated across multiple limit states, including serviceability performance, ultimate capacity, and response under dynamic loading conditions.

Within this framework, the objective and specific contribution of this paper is to present preliminary numerical results on the influence of passive reinforcement geometry on mobilized lateral earth pressures and wall response, and to provide insight into the resistance mechanisms of the reinforced zone under seismic loading based on two-dimensional finite element analyses, thereby informing the design of subsequent physical modelling investigations.

2 Background

2.1 Quay wall systems in current practice

There are limited types of marine structural system selections for quay berths [5], [6]. The most conventional and widely applicable types can be addressed as caisson walls, block walls, sheet pile walls, RC diaphragm walls, bored pile walls and conventional semi-open piled (mostly steel tubular piles) platform structures. Among listed structural systems, caisson walls often have a depth limit due to constructive feasibility. Block walls possess similar restraints at higher water depths in addition to stability challenges, especially in the case of high earth pressures (due to increasing free length) and potential considerations of seismic action. Practically conventional semi-open piled platforms enable much higher water depths within the range of constructability, however, have the disadvantage of increasing quay width requirements due to underlaying slope coverage requirements, and corresponding high investment costs mainly governed by relatively expensive steel prices and offshore craftsmanship. In this regard, structural systems that constitute retained wall behaviour are often considered as viable and efficient solutions at relatively high-water depths or dredging depths arising from associated vessel draft requirements.

2.2 Concept of passive earth reinforcement in quay walls

The concept of passive-side reinforcement in quay wall systems is based on enhancing the contribution of the soil mass mobilised on the passive side of the wall to improve overall lateral equilibrium. Rather than increasing wall stiffness, the approach seeks to improve the soil–structure interaction mechanism by strengthening the passive zone, thereby promoting a more efficient mobilisation of passive earth resistance within the wall-soil system.

The mobilisation of passive earth pressure plays a governing role in the lateral performance of quay wall structures and is strongly dependent on deformation compatibility between the wall and the surrounding soil. The introduction of passive-side reinforcement alters this response by modifying the stiffness distribution within the passive zone, thereby influencing the deformation-controlled mobilisation of passive earth resistance in soft soil conditions.

Design observations indicate that the structural response is primarily governed by the free height H of the quay wall, which represents the dominant geometric parameter controlling lateral demand. The configuration of the passive reinforcement zone—particularly its width B—influences how this demand is mobilized and redistributed within the reinforced soil mass. This suggests that optimal H-B combinations may exist for achieving efficient passive resistance and minimizing the bending response of the wall.In parallel, under plane strain conditions, the bending stiffness of the quay wall, EI, together with the relative stiffness interaction between the wall, the reinforced soil mass—represented through an equivalent elastic modulus—and the surrounding untreated soil, governs deformation compatibility, load transfer mechanisms, and the development and redistribution of lateral earth pressures within the combined system of "wall - soil improvement - surrounding soil" thereby controlling the bending response of the wall.

The response of passively reinforced quay wall systems, as reflected in wall deformations and failure loads, provides a basis for interpreting soil–structure interaction mechanisms and the mobilization of lateral earth pressures.

2.3 Performance states of passive earth reinforcement in quay walls

The research programme aims at the rational optimization of passive-side reinforcement, particularly for quay walls with large, retained heights, where cost efficiency and constructability become critical considerations. Accordingly, the overall research framework addresses the performance of passively reinforced quay wall systems under serviceability, ultimate, and dynamic loading conditions.

Service loads and corresponding serviceability-level analyses are intended to represent in situ loading conditions, establish initial stress states, and quantify mobilized field earth pressures by monitoring construction-stage loading and associated quay wall deformations.

Ultimate or failure-level performance represents the limiting condition for passively reinforced quay wall systems and is associated with excessive wall deformations, global or local instability, or inadequate mobilization of passive earth resistance. For quay walls founded in soft soils, failure behaviour is closely related to the capacity of the reinforced passive zone to accommodate large deformations while maintaining effective load transfer to the wall.

In addition to serviceability and ultimate performance considerations, the seismic behaviour of the system also requires verification. Under seismic loading, the resistance behaviour of the reinforced passive zone must be assessed, as inertial forces within the reinforced block may induce internal strain incompatibility and interface contact degradation, potentially reducing the mobilized passive resistance depending on the level of seismic demand.

Understanding the response of passively reinforced quay wall systems across these performance states is therefore essential for developing reliable design guidance, particularly where existing literature and design codes provide limited recommendations for this type of application.

3 Numerical modelling framework

The numerical analyses were performed using a two-dimensional plane strain condition using 2D finite element Plaxis model. Key model components for analysis and evaluation as type of soil, structural materials, jet grout material, geometry and loading conditions are detailed in this section.

3.1 Problem idealisation

The model geometry represents a typical quay wall configuration founded in soft soil conditions, consisting of a reinforced concrete bored pile wall (Fig.2). The wall was modelled as structural plate element with an equivalent bending stiffness. The quay wall is characterised by its free height, H, which governs the retained soil height and the extent of wall deformation.

The jet-grout reinforced passive zone was idealised as a soil–cement mixture block, allowing its contribution to passive earth resistance and stiffness interaction with the wall and surrounding soil to be captured within the numerical framework. The passive reinforcement zone is defined by its geometric dimensions, including reinforcement width, B, and length, L. The soil domain was extended sufficiently in both horizontal and vertical directions to minimise boundary effects on the predicted wall response and earth pressure distribution. Boundary conditions were applied to restrain rigid body movements of the model while allowing realistic deformation patterns to develop within the wall–reinforcement–soil system.

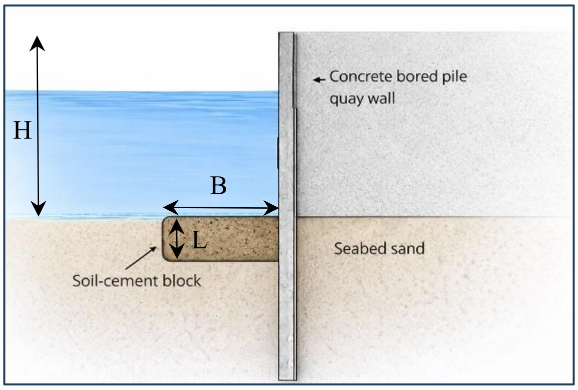

Fig. 2. The geometrical configuration of the passive side reinforcement under service condition.

3.2 Constitutive model parameters

The Hardening Soil (HS) constitutive model was adopted to investigate the nonlinear stress–strain response of the soil–cement reinforced zone under lateral earth pressure, while allowing proper control of stiffness compatibility between the quay wall, the soil–cement block, and the surrounding soil. Using the jet grout parameters and seabed properties given in Table 1, the parameters of the jet grout–improved soil block were calculated using the equivalent block method (composite soil model). For the analysis, the Hardening Soil constitutive model parameters were derived based on a 0.20 area ratio, and the corresponding equivalent stiffness and strength parameters are presented in the table. In the problem considered, a strain-based approach is required to capture changes in mobilized earth pressures under increasing shear demand, making the Hardening Soil model appropriate for evaluating block continuity without reaching ultimate failure.

The behaviour examined in this study is governed by the mobilisation of shear stress, the development of plastic strains, and the redistribution of stresses within the reinforced block under service and pseudostatic seismic loading conditions. In the Hardening Soil model, soil stiffness behaviour is governed by the parameters E_{50}^{ref}, E_{oed}^{ref}, and E_{ur}^{ref}, where E_{50}^{ref} and E_{oed}^{ref} were taken as equal and the unloading–reloading stiffness was assumed as $E_{ur}^{ref} = 3E_{50}^{ref}$. The HS-Small model was also considered through the inclusion of the small-strain parameters G_0^{ref} and $\gamma_{0.7}$, which define the initial stiffness behaviour at low strain levels.

3.2.1 Geometry and material properties

The conceptual geometrical model configurations are shown in Fig. 3, while the corresponding input parameters adopted in the PLAXIS 2D numerical analyses are summarized in Table 1. All soils, including the backfill, were modelled as loose marine sand deposits likely to be encountered at seabed levels, in order to represent a conservative scenario.

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3.3 Analysis cases and loading conditions

The numerical analyses were conducted through a series of static and pseudostatic cases to evaluate the influence of soil–cement block geometry on quay wall response. Static analyses were used to evaluate deformation response, internal force demand, and global stability verifications through strength reduction procedures.

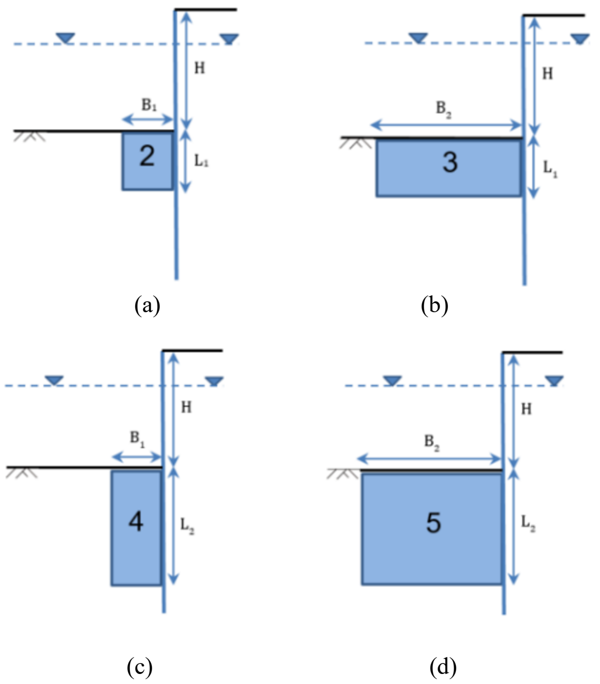


Fig. 3. Conceptual geometry of soil–cement reinforcement zone on the passive side of the quay wall. (a) Small Block, (b) Wide Block, (c) Deep Block, (d) Large Block.

Pseudostatic analyses were performed to represent earthquake-equivalent inertial forces acting on the quay wall–soil–cement block system and to assess the additional displacement demand induced by seismic loading. It is noted that pseudostatic analysis does not aim to capture dynamic failure mechanisms, instead it provides an indication of system performance and block integrity under increased magnitudes of the lateral loading.

For consistency, the static analysis models were coded as MS0 representing the unreinforced reference case and MS1–MS7 corresponding to reinforced configurations with varying block dimensions while maintaining identical boundary conditions, soil properties, and quay wall characteristics. In all reference cases, the free height (H) and embedment depth of the wall were both taken as 20 m. MS1 for small block approach, MS2&MS3 for Deep Block approach, MS4&MS5 for Wide Block approach and MS6 & MS7 for Large Block approach as figured in Fig. 4. Pseudostatic analyses were conducted for the selected configuration under system response in terms of deformation and internal force development.

Table 1. Reference material parameters used in numerical modelling.

Material	Parameter	Value	Comments
Loose-Sand Seabed	Secant stiffness, E_{50}^{ref} (MPa)	20	Typical marine sand
	Cohesion, c (kPa)	0	Cohesionless assumption
	Friction angle, ϕ' (°)	30–31	Marine sand range
	Unit weight, γ (kN/m³)	18	Submerged sand
Jet Grout	Column diameter, d (m)	0.8	Design geometry
	Column spacing, s (m)	1.6	Design geometry
	UCS, q_u (MPa)	5.0	Conservative design value
	Elastic modulus, E_{jg} (MPa)	1000	$E \approx 200 \cdot q_u$
Equivalent Block	Secant stiffness, E_{50}^{ref} (MPa)	212	Composite model
	Cohesion, c_{eq} (kPa)	490	Area-weighted
	Friction angle, ϕ_{eq} (°)	31.5	Weighted tanϕ
Quay Wall	Pile diameter, D (m)	1.5	Design assumption
	Pile spacing, s (m)	1.2	Design assumption
	Elastic modulus, E(MPa)	32	C30/37 concrete
	Bending stiffness, EI (kNm²/m)	2.17×10^6	Section property
	Axial stiffness, EA	2.41×10^7	Section property
	Unit weight, γ (kN/m³)	25	Self-weight
	Poisson's ratio, ν	0.20	Concrete assumption

4 Numerical results and discussion

The numerical analysis results are evaluated in terms of total horizontal displacement of the quay wall, bending moment distribution, and global safety factor. These outputs are used to assess the influence of soil–cement block geometry on deformation control, internal force demand, and overall system stability under static (service) and pseudostatic loading conditions for the context of the presented study.

4.1 Static analysis (Service condition)

The static analyses are discussed comparatively to evaluate the effect of reinforcement geometry on wall performance and load transfer mechanisms as given in Table 2.

4.1.1 Lateral displacements

The numerical study demonstrates that the introduction of a soil–cement block significantly improves the lateral performance and stability of the quay wall system. Compared to the reference case (MS0), all reinforced configurations exhibit substantial reductions in horizontal displacement and bending moment, together with increased safety factors against overall stability. The results indicate that increasing block dimensions enhances displacement control and global stability, with configurations MS6 and MS7 providing the most effective response. Lateral displacement ratios of approximately up to 1.0%H are generally regarded as acceptable serviceability-level deformations for flexible quay wall systems. The MS0 configuration results in substantially high deformations reaching 2.7% whereas for the MS6 configuration this ratio reduces to 0.63%, which falls within reasonable serviceability levels.

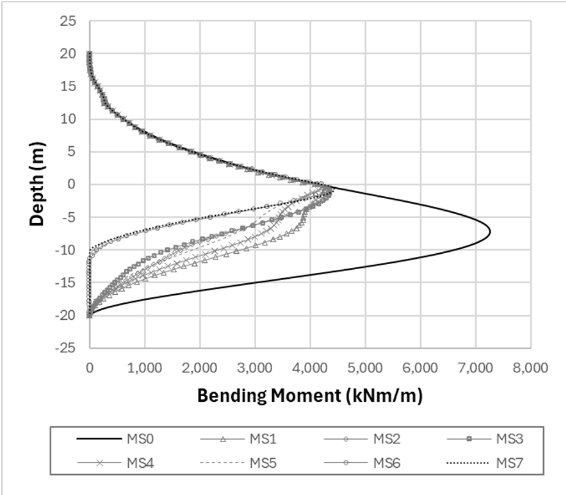
Table 2. Summary of block configuration geometry models and structural response.

ID	Case	B (m)	L (m)	u_y (cm)	M_{max} (kNm/m)	FS
No Block	MS0	0	0	53.9	7259	1.22
Small Block	MS1	5	5	25.8	4256	1.37
Deep Block	MS2	5	10	22.0	4346	1.44
	MS3	5	15	21.5	4355	1.44
Wide Block	MS4	10	5	23.5	4188	1.42
	MS5	15	5	21.1	4261	1.40
Large Block	MS6	10	10	13.7	4364	1.71
	MS7	15	15	12.61	4432	2.11

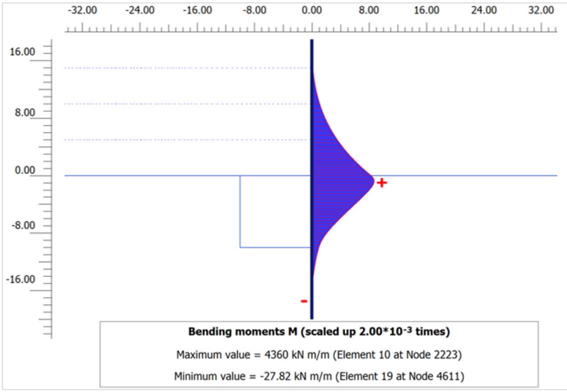
4.1.2 Bending moment distribution

The bending moment–depth distributions for the unreinforced and reinforced configurations are presented in Fig. 4. The unreinforced case (MS0) exhibits the largest bending moment envelope, with the peak occurring at a relatively greater depth below the seabed. In contrast, the reinforced configurations show reduced moment magnitudes and a shallower peak location, closer to the seabed level. This upward shift of the max bending region indicates that the reinforced passive zone enhances lateral resistance, improves load redistribution, and reduces the overall structural demand on the wall, where the maximum bending demand decreases by approximately 35–40% compared to MS0 in all reinforced configurations (MS1–MS7).

It is also observed that, beyond a certain reinforcement geometry, the bending moment envelopes remain within a relatively narrow range. While incremental increases in block dimensions improve lateral displacement control and global stability, they do not result in proportional reductions in peak bending moment. This behaviour suggests that once an effective reinforcement threshold is achieved, the internal force distribution stabilises. Overall, bending moments are notably reduced once the reinforced zone is introduced and remain within a relatively narrow range across different block geometries, suggesting a redistribution of lateral earth pressures rather than a purely stiffness-driven response.



(a)



(b)

Fig. 4. (a) Bending moment–depth distribution plots for the unreinforced wall (MS0) and different passive side reinforcement configurations (MS1–MS7) under service loading conditions, (b) Finite element bending moment diagram for the representative case (MS6).

4.1.3 Global factor of safety

The global factor of safety (FS) increases with the introduction and enlargement of the soil–cement block. While the unreinforced case exhibits the lowest stability level, progressive increases in block dimensions lead to consistent improvements in FS. MS6 and MS7 demonstrate a significant enhancement in global stability compared to intermediate configurations.

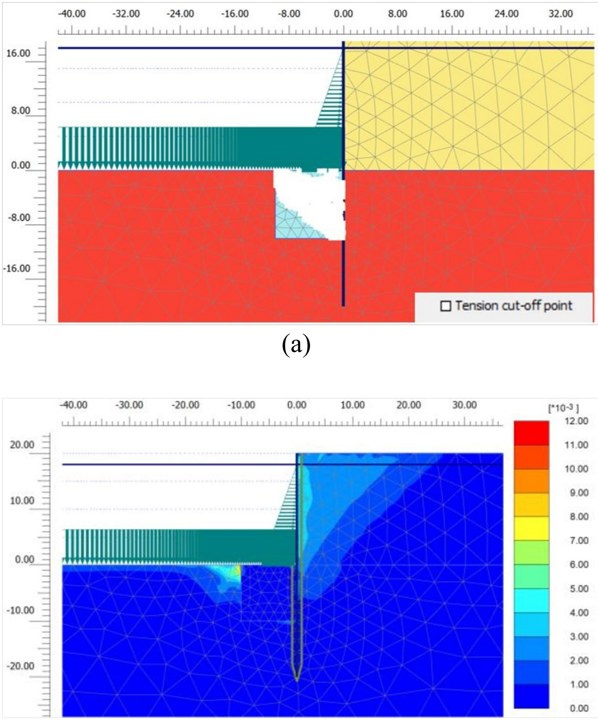
Notably, although bending moment reduction stabilises beyond a certain reinforcement size, the factor of safety continues to increase. This indicates that reinforcement geometry has a stronger influence on overall system stability than peak bending once an effective load redistribution mechanism is established.

4.1.4 Interface behaviour and block Integrity

The numerical analyses provide important insight into the interface behaviour between the quay wall and the idealised soil–cement block. The results indicate that load transfer within the reinforced zone is governed primarily by compressive stress paths and shear mobilisation as shown in Fig. 5a and 5b. Tensile stresses within the soil–cement block is not mobilised, consistent with the assumed no-tension behaviour adopted for the reinforcement material.

This observation highlights that the integrity of the reinforced block primarily depends on the availability of sufficient shear capacity.

Adequate shear resistance is therefore essential to maintain block continuity under lateral earth pressure and to ensure effective interaction between the wall and the surrounding soil.



(a)

(b)

Fig. 5. Finite element results (a) tension cut-off points and (b) shear strain distribution in the soil mass.

4.2 Pseudostatic seismic analysis

Pseudostatic analyses conducted for the optimal configuration (MS6) and were performed by applying increasing horizontal acceleration coefficients, k_h following completion of the excavation phase. The resulting displacements should therefore be interpreted as additional increments superimposed on the static displacement values. Horizontal seismic coefficients $k_h = 0.04, 0.08, 0.12$, corresponding to 4%, 8%, and 12% of gravitational acceleration (0.04g, 0.08g, 0.12g) were imposed as additional horizontal body forces within the model equivalent to the expected seismic loading. For the MS6 configuration lateral displacement increased by 21.2 cm at 0.04g to 33.2 cm at 0.08g and 65.4 cm at 0.12g, indicating progressive amplification of deformations with increasing seismic coefficient.

Numerical convergence was not achieved beyond $k_h = 0.15$, indicating loss of stability (failure) under higher equivalent seismic demand.

As expected, pseudostatic analysis results in increased lateral earth pressures and associated shear demand. The combined numerical outcomes indicate that the soil–cement block remains intact under both service and pseudostatic seismic loading conditions, which represent the range of anticipated design shear forces. These results hence verify the integrity of the reinforced zone under static and equivalent seismic loading assumptions.

While behaviour under static (and pseudostatic conditions) are identified, the study also highlights the need to investigate the response under cyclic dynamic loading. Ongoing and future experimental work will therefore focus on assessing whether cyclic loading may potentially lead to contact loss between the wall and the soil–cement block, denying validity of equivalent pseudostatic modelling of seismic action.

5 Physical modelling framework

The key objective of the planned experimental modelling study is to test, verify, and define the performance of jet-grouted passive-side reinforcement for quay walls under static and dynamic loading conditions. The programme aims to provide clear design recommendations for such reinforcement solution by performing a series of laboratory tests within a structured and comprehensive research framework.

5.1 Scaled-down experimental setup

The modeling tests will be performed in the Hydrodynamic Research Laboratory and Geotechnical Laboratory at Yıldız Technical University. They provide advanced capabilities for physical modelling studies related to coastal and offshore engineering systems. The physical modelling system consists of a rigid model container, soil and structural model components, and an integrated instrumentation system. The entire setup is installed on the shaking table, allowing controlled dynamic loading condition. Instrumentation will include pressure transducers for contact pressure, strain gauges for wall deformations, accelerometers on the wall, shaking table, and soil-cement block. A digital recording system will capture overall system displacements. Load cells will measure applied loads, and Particle Image Velocimetry (PIV) cameras will monitor system displacements, including possible arching on the wall. Pressure transducers will measure lateral pressures between the wall, backfill soil, and reinforced zone. The experimental setup features are presented in Fig. 6 and detailed descriptions of the experimental setup and instrumentation are provided in [8-10].

The physical test model -1g model will be constructed based on the free height (H) of the quay wall, with a Prototype: Model ratio of 25 based on the key dimensions and material properties detailed in Table 1 and Table 2 reference to the similitude relations provided in [7], [8]. All three testing phases will be conducted within a test tank measuring 4.5 m long x 1.0 m width x 1.0 m high. The main soil material will be loose sand with an effective friction angle of up to 35°. The aim is to simulate site conditions effectively, including sea and groundwater levels. For the model walls, aluminum alloy is preferred due to its ease of

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machining and fabrication and suitability for strain gauge instrumentation to measure bending moments.

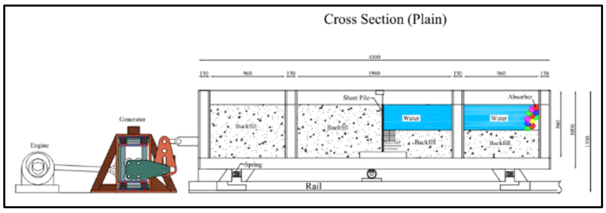

Fig. 6. Side view of the experimental set-up. Test tank cross-sectional view with the shaking table details [8-10].

5.2 Performing the serviceability tests and failure tests

Serviceability level studies cover monitoring the construction phase loads and corresponding deformations of the quay wall. Based on the outcomes of the preliminary numerical analyses presented in this study, various geometrical configurations of the soil-cement block (width B and length L) will be prepared. The benchmark test (MS0) will be conducted without passive reinforcement, serving as the control setup. Subsequent tests will involve four distinct geometrical configurations of passive side reinforcement (MS1, MS2, MS4 and MS6). A total of five models are planned for testing. During each experiment, earth pressures will be generated under 1g laboratory conditions to simulate soft sedimentary soil. The model geometry and loading conditions are designed in accordance with established scaling principles

After in-situ loading and deformation values are measured, the wall will be forced to fail in the next step under laterally applied monotonic loading from the top of the wall using a force-controlled actuator to also demonstrate and observe the capacity of the wall under failure conditions. These configurations along with the instrumentation, will result in a comprehensive understanding of the complete wall behavior under the in-service and the failure condition.

5.3 Performing the dynamic tests

Dynamic loading tests will be conducted to assess the resistance behaviour of the cemented block (reinforcement zone) under simulated seismic action. It is anticipated that the effective resistance may decrease due to potential interface separation between the wall and the reinforced block, arising from differential dynamic responses associated with their distinct natural frequencies and phase characteristics under seismic excitation. The experimental programme therefore seeks to quantify strength reduction in relation to seismic intensity (i.e., resistance degradation as a function of g-level).

To investigate the performance of passively reinforced quay walls under dynamic loading, two physical models are planned for testing: (i) a baseline dynamic test on the benchmark configuration, and (ii) a dynamic test on the optimized reinforced configuration.

The experimental programme will be conducted in a shaking tank capable of operating within amplitude and frequency ranges of 1–5 mm and 1–9 Hz, respectively. A series of calibration tests will be performed to determine the optimum amplitude–frequency combination required to achieve a stable and representative dynamic response.

6 Conclusion

This study presents a preliminary numerical investigation of the performance of passively reinforced quay wall systems, focusing on the influence of soil–cement block geometry on deformation behaviour, internal force demand, and global stability under static and pseudo-static loading conditions.

The introduction of passive-side soil–cement reinforcement significantly improved the lateral behaviour of the quay wall system. Compared to the unreinforced configuration (MS0), all reinforced cases exhibited substantial reductions in horizontal displacement and bending moment, together with notable increases in global factor of safety. The results confirmed that reinforcement modifies the soil–structure interaction mechanism by enhancing deformation compatibility and promoting more effective mobilisation of passive earth resistance.

The analysis demonstrated that increasing reinforcement width provides greater performance improvement than increasing reinforcement depth beyond a certain threshold. While bending moment reductions stabilised once an effective reinforcement configuration was achieved, global stability continued to improve with increasing block dimensions. This indicates that overall system performance is driven by reinforcement geometry primarily through modification of load redistribution and failure mechanisms rather than reductions in peak bending actions proportional to the adopted reinforcement geometry.

Pseudostatic analyses showed progressive amplification of lateral displacements with increasing horizontal seismic coefficient. Although the reinforced configuration (MS6) maintained block integrity under equivalent seismic loading up to approximately 0.15g, deformation demand increased significantly, highlighting the importance of considering displacement-based performance criteria in seismic design.

Overall, the findings provide insight to role of reinforcement geometry in controlling deformation and stability of quay walls founded in soft soils. The study establishes a rational framework linking reinforcement configuration to soil–structure interaction behaviour and offers preliminary geometric guidance for optimising passive-side improvement. The results form the basis for the subsequent physical modelling programme, which will further validate the observed performance mechanisms under static and dynamic loading conditions and contribute to the development of improved design recommendations for passively reinforced quay wall systems.

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References

1. Paulauskas, V., Wijffels, J., Quay walls mooring capacity increasing. Mechanika, Vol. 18(2), pp. 214-219, (2012) https://doi.org/10.5755/j01.mech.18.2.1569
2. T. Solomon Teshome, Z. N. Kutlu, İ. E. Kılıç, A. Şenol, Lateral equilibrium optimisation in deep excavations : the role of passive earth reinforcement. International Journal of Sustainable Engineering, **17**(1), 760–777, (2024)
   https://doi.org/10.1080/19397038.2024.2404559
3. S. Li, A. Yao, Y. Ma, Failure Mechanism and Passive Earth Pressure on Foundation Pits with Skirt Reinforcement. Soil Mech Found Eng **58**, 25–33 (2021). https://doi.org/10.1007/s11204-021-09711-5
4. P. Chen, X. Gong, Influence of skirt reinforcement in passive zone on deformation of excavation, E3S Web of Conferences **198** 02012 *ISCEG 2020* (2020) https://doi.org/10.1051/e3sconf/202019802012
5. V. Paulauskas, D. Paulauskas, B. Placiene, R. Barzdziukas, Quay wall stability and strength evaluation., Mechanika, Vol. **23**(2): 298-304. (2017) https://doi.org/10.5755/j01.mech.23.2.13776
6. J.F. Lu, B. Ye, J. Nagaya, Seismic Analysis of Geosynthetic-Reinforced Quay-Wall Structure. In: Huang, Y., Wu, F., Shi, Z., Ye, B. (eds) New Frontiers in Engineering Geology and the Environment. Springer Geology. Springer, Berlin, Heidelberg. (2013). https://doi.org/10.1007/978-3-642-31671-5_43
7. Muir Wood, D. (2004). Geotechnical Modelling (1st ed.). CRC Press. https://doi.org/10.1201/9781315273556
8. Z. T. Yuksel, N. Gerolymos, Y. Yuksel, On the seismic performance of block type quay walls: Numerical analyses against 1g shaking tank tests, Ocean Engineering, **281**, 114942. (2023). https://doi.org/10.1016/j.oceaneng.2023.114942
9. Y. Yuksel, Z.T. Yuksel, E. Cevik, K. Orhan, M. Berilgen, Evaluation of the seismic performance of a caisson and an L-type quay wall, Soil Dynamics and Earthquake Engineering, **92**, (2017). https://doi.org/10.1016/j.soildyn.2016.10.013
10. Z. T. Yuksel, Y. Yuksel, K. O.Cetin, E. Cevik, Seismic response of hunchbacked block type gravity quay walls, Soil Dynamics and Earthquake Engineering, **101**, (2017).
    https://doi.org/10.1016/j.soildyn.2017.08.002.