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Geotechnical engineering for harbour structures in the Port of Barcelona since the 15th century

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ABSTRACT: The Port of Barcelona has been continuously expanding towards the sea since the 15th century, adapting to maritime transport demands and accommodating ever larger ships and cargo. Until 1965, harbour structures were constructed mostly on sandy soils using rubble mounds and simple foundations. However, in 1966, the expansion of the eastern breakwater encountered soft soils from the Llobregat prodelta requiring the development of novel geotechnical solutions. Subsequently, a significant seawards expansion of the port was undertaken in the late 20th and early 21st centuries, involving the construction of new breakwaters and quays, mainly using concrete caissons founded on soft silty clay material. Advanced soil characterization and enhanced designs were required to overcome stability and settlements challenges during construction and operation. In addition, during this period, old quays founded on sandy soils were repurposed and remodelled to support larger loads and deeper draughts. Various construction solutions were implemented, including sheet piles, anchors, piles and different types of soil improvement. Based on a better understanding of soil behaviour, it has been possible to optimize solutions using appropriate computational tools. The paper provides an overview of how the interplay between foundation ground and harbour structures has evolved over centuries.

KEYWORDS: Port structures, soft soils, soil improvement, stability, challenges

1 INTRODUCTION

The Port of Barcelona has undergone a continuous expansion towards the sea since 15h century, adapting to increasing maritime transport demands and the necessity of accommodating larger ships and cargo.

This progressive development has posed various geotechnical challenges, requiring innovative solutions in foundation and infrastructure design. The Port's historical evolution highlights the interplay between maritime structures and geotechnical engineering, particularly concerning soil stability, settlement control, and ground improvement. This paper explores the foundation techniques employed over different periods (Figure 1) and analyses the impact of advanced soil characterization and enhanced designs on the stability and functionality of Barcelona port infrastructures.

Figure 1. Structures build from origin to present. The red dashed triangle (la Barceloneta quarter) is a reference for the following figures.

Throughout the various development phases of the port, construction activities have been influenced by the geological setting of the Barcelona coastline. Figure 2 illustrates results of marine geological surveys of the port area.

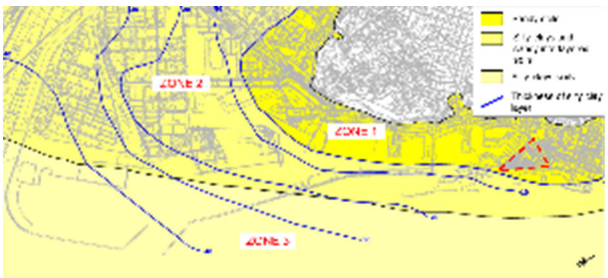

Figure 2. Marine geological survey of the Port of Barcelona seabed, Ventayol (2016).

In the bright yellow strip adjacent to the urban coastline (Zone 1), the upper 30 meters of the soil column consist of sandy and gravelly soils. Further south lies an intermediate zone (Zone 2), where alternating layers of sands and silty-clays outcrop along the seabed. In the south-eastern portion of the port, there is soft soil of the prodelta of Llobregat river, zone 3. The soil of Zone 3 is characterized by silty-clays with a continuous deposit thickness ranging from 20 to over 40 meters (Figure 3).

The total thickness of the silty-clay layer is variable in Zone 2 and Zone 3; it increases progressively toward the southern sector. For this reason, geotechnical properties of these materials vary significantly depending on the location within the port, posing considerable challenges to the design of port structures

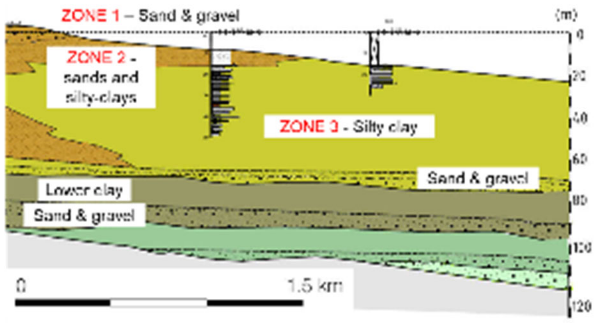

Figure 3. Representative soil profile of Barcelona Port (modified from Gámez 2007).

2 HISTORICAL EVOLUTION

2.1 *Origins to 1965*

The original port, documented in 1447, known as the Port of Alfonso V, was located within 1km inland from the present coastline (Figure 4). It was sheltered by two islands, which were connected to the mainland via berms constructed with land-based dumped fill, placed over sandy deposits adjacent to the urban coastline.

The first major expansion occurred during the 18th century, marked by the construction of the first breakwaters and the initiation of land reclamation from the sea. These breakwaters were built using stone masonry, founded directly on the marine sandy seabed through the deposition of rubble fill and riprap, Tatjer (1972).

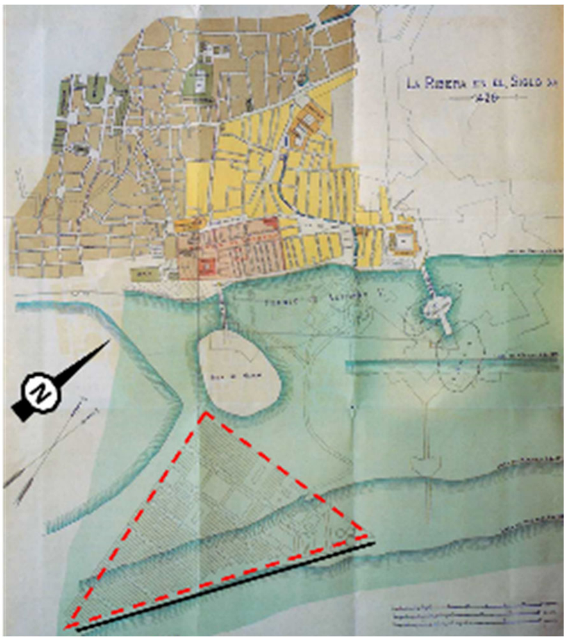

Figure 4. Artistic recreation based on historical cartography "La Ribera en el siglo XV (1439)", Sanpere (1890).

A subsequent and significant enlargement took place in the 19th and early 20th centuries, involving the development of transverse wharves, main and counter-breakwaters, and cargo handling zones designed for steam-powered vessels. Massive dredging operations were executed to increase the depth of the harbour (to -8m) and facilitate the navigation of ships with greater draught (Figure 5).

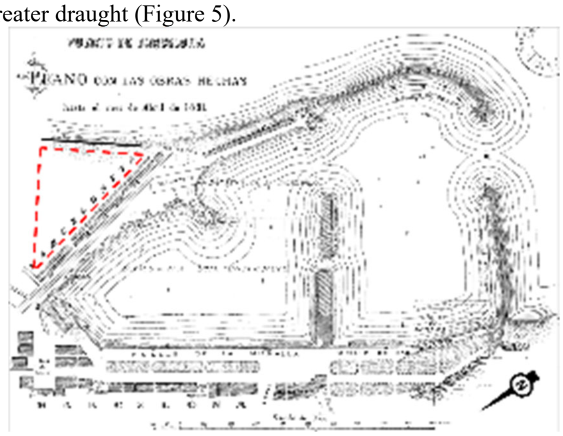

Figure 5. Barcelona Port enlargement April 1881, Junta del Puerto de Barcelona (1881).

The structural elements of this enlargement included: (i) traditional and ashlar masonry for quay walls and vertical structures, (ii) timber caissons filled with stone as foundation units, (iii) large cut stone blocks and riprap revetments for dikes. During this phase of development, while the majority of foundations were laid on sandy soils (Zone 1), the Eastern breakwater was founded over the intermediate zone with sandy and silty clays soils (Zone 2).

In addition to expansion works, the port's breakwaters underwent numerous repair interventions, mainly due to storm damage, but sometimes resulting from military conflicts or construction-related instabilities. Nevertheless, over time, a marked improvement was achieved owing to increased experience and enhanced understanding of soil behaviour, alongside significant technological advancements in construction equipment and execution methods.

Until 1965, the port's expansion was carried out using conventional construction techniques and geotechnical stability was achieved primarily through empirical methodologies - based on accumulated field experience and the technological resources available at the time- within the constraints imposed by the geomechanical behaviour of the seabed.

2.2 *1965 to present*

Between 1965 and 1990, the Eastern breakwater was extended and an inner basin was excavated inland, red contours in Figure 6.

Figure 6. Barcelona Port in 1993, Autoritat Portuaria de Barcelona APB (1993). Unpublished image. Reproduced with permission.

These works were markedly distinct due to differing geotechnical conditions. The extension of the eastern breakwater in 1965 encountered large thickness layers of silty clays (Zone 3) whereas the inner basin was excavated in Zone 2 soils. The challenge posed by the Eastern breakwater necessitated advanced geotechnical strategies to ensure geotechnical stability and limit excessive settlements using rubble-mound, rockfill and blocks.

Subsequently, the late 20th and early 21st centuries saw a significant seaward expansion of the port, primarily characterized by the construction of East and South breakwaters (located on the left-hand side of Figure 1) and quays founded on Zone 3. These conditions required comprehensive soil characterization methods and optimized designs to overcome geotechnical constraints during construction. Furthermore, various older quays originally supported by sand foundations were remodelled and reinforced to withstand greater loads and accommodate larger draught vessels. Various construction solutions were deployed to enhance stability and durability.

3 GEOTECHNICAL METHODS APPLIED IN PORT EXPANSIONS

3.1 *Soil characterization and modelling*

Extensive offshore site investigations and laboratory testing provided insights into soil composition, strength, and deformation characteristics. Geotechnical tests have been conducted using the latest version of available methodologies implemented by leading international and national companies and laboratories. These investigations have yielded highly valuable results, enabling the execution of laboratory tests and the proposal of innovative advancements, as reported by NGI (1998, 2002 and 2009), Gens and Alonso (2001), Madrid (2021), Tarragó (2021) and Deu et al. (2021) and (2024). Furthermore, these findings have revealed the presence of gassy soils, which are currently under investigation to assess their potential impact on future port structures, Tarrago et al. (2018 and 2024).

In these site investigations, two primary types of materials are essentially distinguished: granular soils and fine-grained soils, although intermediate forms and a wide variety of particle size distribution exist -characteristic of deltaic deposits.

Characteristic properties of both soils have been determined, its values are presented in Table 1 according a parameters compilation from Gens and Alonso (2001), Alonso et al. (2009), Madrid et al. (2013), Madrid (2021) and Tarragó (2021).

Table 1. Characteristic properties of granular and fine-grained soils.

Symbol & Units	Fine-grained	Granular	Hydraulic fill
γ_{nat} [kN/m^3]	18.5	21	18.0
e [-]	0.8	0.8	1
FC [%]	95	5	90
IP	15	NP	13
C_C	0.20	0.06	0.23
C_S	0.01	0.009	0.07
$C\alpha$	0.005	0.002	-
k [m/s]	10^{-8}	10^{-6}	$5 \cdot 10^{-8}$
$c_{u\ peak}$ / σ'_v	0.25	-	0.25
$c_{u\ SS}$ / σ'_v	-	-	0.06
φ [°]	-	32	-

The characterization of undrained shear strength of fine-grained soils from Zone 3 represented a milestone in the understanding and assessment of these materials because it influences the stability of many embankment and quay foundations. Direct simple shear tests and unconsolidated triaxial tests under anisotropic consolidation in compression and extension were conducted to characterize these fine-grained. Examples of DSS tests results from South breakwater and Prat quay are presented in Figure 7.

Geotechnical modelling and simulations helped predict settlement and stability issues before construction using coherent constitutive models for presented properties. Thus, the appropriate calibration of constitutive models using representative geotechnical parameters remains fundamental to obtaining realistic and robust predictive results.

3.2 *Foundation designs and ground improvement techniques*

Traditional shallow foundations have been proved suitable for new structures on fine-grained soils; however, the proper design of new foundations using concrete caissons and rubble-mound required thorough analyses to simulate realistically the geomechanical behaviour, to ensure adequate safety factors and to limit displacements during both the construction phase and service of breakwaters and quays. Although rubble-mound and large concrete caissons foundations are commonly chosen as the construction solution (Figure 8), alternative systems such as pile-supported wharves or sheet pile walls have also been implemented on occasion.

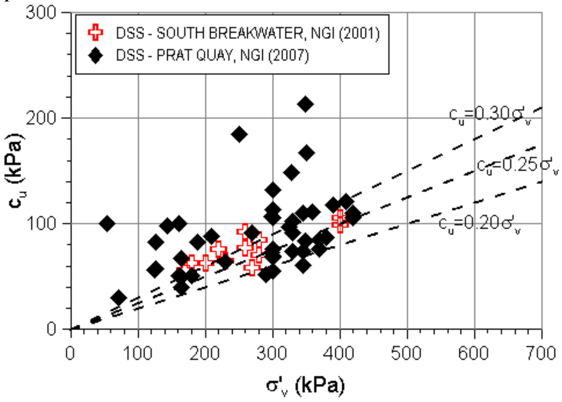

Figure 7. DSS tests results from South breakwater and Prat quay foundation, Gens and Alonso (2001).

Various soil improvement strategies have been applied. These techniques aimed to accelerate soil consolidation, to enhance bearing capacity, and to mitigate excessive settlements. The APB has consistently implemented a range of geotechnical and structural strategies to accommodate increased loading demands, deeper berths, and expand quay areas. The typical intervention in the port for quay expansions during the period from 1965 to present has primarily involved the construction of concrete caisson-type quay walls and ground improvement through preloading. Although in the expansion area the use of caisson technology remains predominant, and preloading continues to be the standard method for soil improvement, the port has also explored alternative solutions. These alternatives have been implemented in other projects and include techniques such as stone columns, gravel pile, piling, sheet piling, the use of gravity-based structures -quay block with or without passive toe dead weights-, anchoring systems, vertical strip drains (Figure 9), soil impregnation techniques and jet grouting in localized interventions on existing quays.

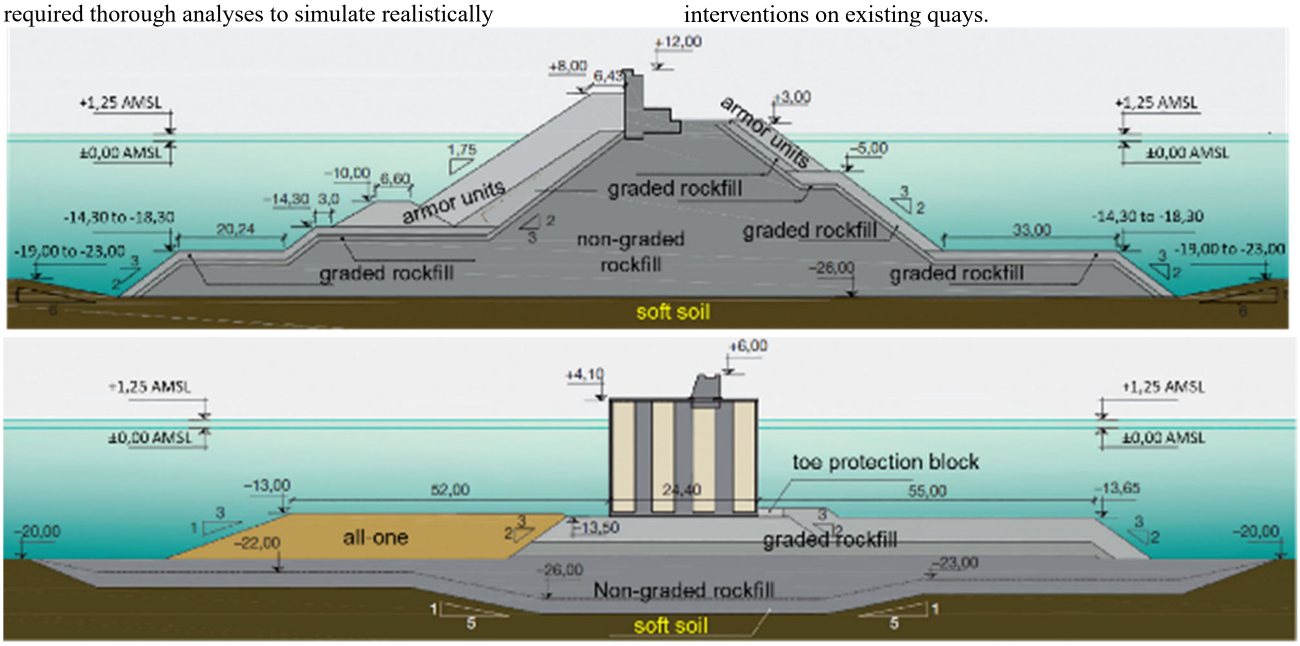

Figure 8. East breakwater cross section (up), South breakwater cross section (down) modified from Gutiérrez and Grassa (2015).

These interventions were carried out in areas where the operational use of the quay had changed, requiring structural upgrades. All of these techniques have undergone testing and validation to ensure their technical suitability and correct application.

Figure 9. Strip vertical drains and preloading in new quay esplanade of Barcelona Port.

These combined strategies reflect the port's commitment to balancing robust engineering solutions with adaptability to local ground conditions. While jet grouting remains a versatile method, concerns regarding its reliability underline the need for rigorous site-specific assessment because it has occasionally failed. In contrast, traditional structural techniques -such as concrete caissons, stone columns, piles, sheet piles or anchors- continue to provide dependable performance in both load enhancement and quay development projects. Moreover, improvement through preloading has proven highly effective on quays and esplanades for increasing the undrained shear strength of clayey silts and for reducing long-term settlements, as reported in Alonso et al. (2000).

This integrated approach ensures the long-term serviceability and structural resilience of the port infrastructure.

3.3 *Numerical simulations for predictive analysis*

Computational tools are used to simulate soil-structure interactions, to optimize design parameters and to ensure long-term stability and operational efficiency.

Despite the advancement of computational tools -now offering increased power and the capability to simulations-, combined with the development of advanced constitutive models, two-dimensional or pseudo-2D analyses (Tarrago and Gens, 2024) are often sufficient for addressing geotechnical challenges typically associated with linear infrastructure in port environments. Nevertheless, in cases involving complex geometric or loading asymmetries, three-dimensional simulations have proven beneficial in enhancing design accuracy and reliability, as for instance in the simulation of jetty with mooring dolphin structures (Figure 10).

To achieve accurate predictive modelling, an accurate simulation and the observational method during construction is essential (Peck, 1969). Advanced monitoring systems have been progressively implemented in the Port of Barcelona since 1999, beginning with the construction of the extension of East and the new South breakwaters. An example is presented in Figure 11 where inclinometers, settlement gauges, vertical extensometer, vibrating wire piezometers, clinometers and topographic survey were installed.

Very often, measured pore water pressures are lower than the simulation results, which would suggest a reduction in the undrained nature of the material; however, the reliability of pore pressure readings obtained from vibrating wire piezometers can never be fully guaranteed.

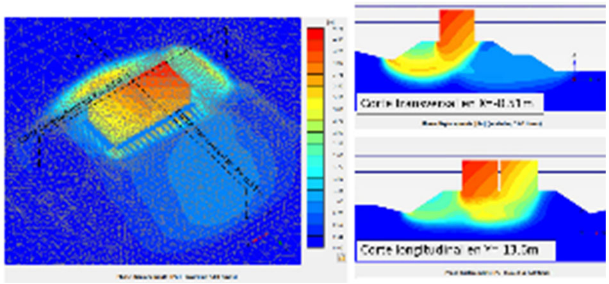

Figure 10. 3D Simulation of jetty with mooring dolphin structures in Barcelona Port Dolphin, APB (2023). Unpublished image. Reproduced with permission.

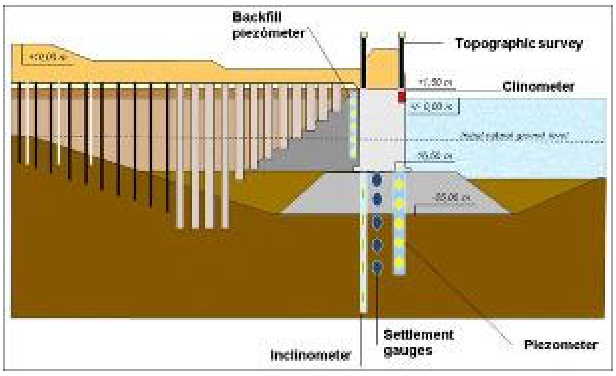

Figure 11. Complete monitored cross-section during Prat quay construction.

As an example, the comparison between observed (blue lines) and computed (red line) settlements of caissons quay founded on a rubble mound and silty clays during construction are presented in Figure 12. The agreement is quite good (Tarragó, 2021).

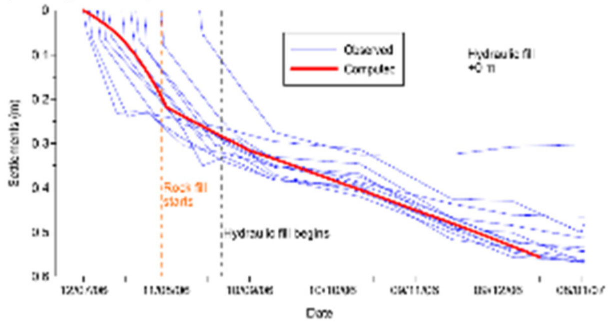

Figure 12. Caissons settlements along the quay wall during construction.

The data collected over the years has provided valuable insight into stress-strain behaviour, enabling a deeper understanding and refinement of constitutive models. These adjustments have significantly contributed to the development of more realistic and reliable simulations for geotechnical applications within the Barcelona port environment.

4 ENVIRONMENTAL IMPACT AND SUSTAINABILITY CONSIDERATIONS

The Port’s expansion has not only presented engineering challenges but also raised concerns regarding environmental sustainability. Large-scale dredging and land reclamation altered coastal sediment dynamics and potentially impact marine ecosystems. Efforts have been undertaken to incorporate environmentally conscious engineering solutions: (i) by reducing dredging volumes through the integration of construction and demolition waste (CDW) materials (Figure 13), and (ii) by using dredged materials that are low in biodiversity but possess poor geotechnical properties, which -after ground improvement techniques-, can adequately ensure geotechnical stability.

Indeed, the need to reduce dredging operations, combined with the increasing focus on circular economy and material sustainability has spurred interest in the reuse of CDW. Although their use has not yet been standardized, the geomechanical behaviour of CDW under load has been evaluated at the Port. Following large scale laboratory and field testing -including oedometer and triaxial tests- and its application in backfilling operations, its strength and compressibility properties have been characterized (Tarragó et al., 2011 and 2023).

Figure 13. CDW aggregate (750.000m^3) backfilling Adossat quay wall. APB (2019). Unpublished image. Reproduced with permission.

5 GEOTECHNICAL CHALLENGES OVERCOME

During geotechnical projects carried out in the Port of Barcelona since the year 2000, some events have occurred beyond the scope of standard geotechnical control. These challenges, though varying in severity, have contributed meaningfully to the advance of geotechnical knowledge and practice within the port infrastructure. Different studies of these events concluded with the proposal of redesigned, suitable solutions integrating lessons learned.

5.1 *Caisson failure induced by wave action*

In 2001, a storm triggered the failure of four newly constructed caissons at the entrance of Barcelona harbour (Figure 14).

Figure 14. Affected caissons, Alonso et al. (2015).

The failure was attributed to cyclic mobility of silty clay foundation. Investigations included laboratory and field data analysis, followed by a detailed back-analysis using both analytical and numerical methods. The analytical approach addressed pore pressure evolution and undrained shear strength variation, while finite difference modelling validated and refined the assessment. The undrained shear strength reduction was identified as the primary cause of collapse (Alonso et al., 2015).

5.2 *Local quay failure induced by static liquefaction*

The failure of a section 600m of caisson quay wall during construction event occurred in 2007 (Figure 15).

Figure 15. Affected caissons, APB (2007). Unpublished image. Reproduced with permission.

Design, construction, and monitoring records -along with post-failure site investigations-, identified flow liquefaction of the hydraulic fill -silty clay from Zone 3-, as the primary cause. The foundation material was not involved in the failure.

An elastoplastic constitutive model -CASM, Yu (1998)-, was employed to simulate undrained brittleness, supported by finite element analyses that reproduced the failure scenario (Gens, 2019 and Tarragó, 2021). Afterwards, soil improvement and continuous monitoring were implemented for subsequent construction using hydraulically-deposited fills. In addition, an operational framework was developed to evaluate, mitigate, and monitor liquefaction potential in hydraulic fill used in quay structures. As a result, no further static liquefaction events have occurred in the Barcelona Port.

5.3 *Time-dependent settlements in CDW aggregate*

Instrumented preloading was applied over reclaimed land, consisting of a 12 m thick CDW aggregate layer -aggregates ranging from 20 to 300 mm-, placed on the underlying soft soil of Zone 3 (Figure 16).

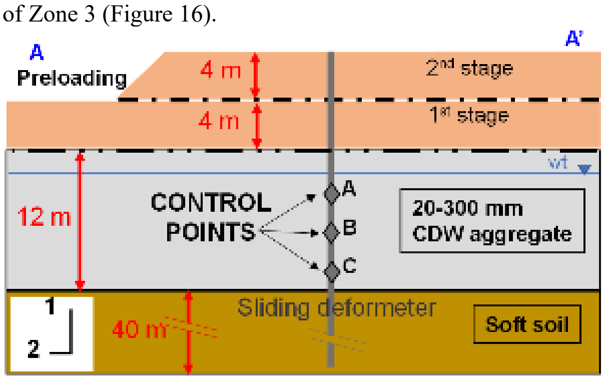

Figure 16. Instrumentation plan cross-section, Tarragó et al. (2023).

Vertical strains were monitored using sliding deformeters and settlement plates. Large scale oedometer tests (300mm diameter) were conducted under saturated conditions. Both field and lab results revealed high and time-dependent compressibility (Figure 17) of CDW material (Tarragó et al., 2023). Despite these properties, the material can be made suitable for use in port platform construction by means of an appropriate preloading.

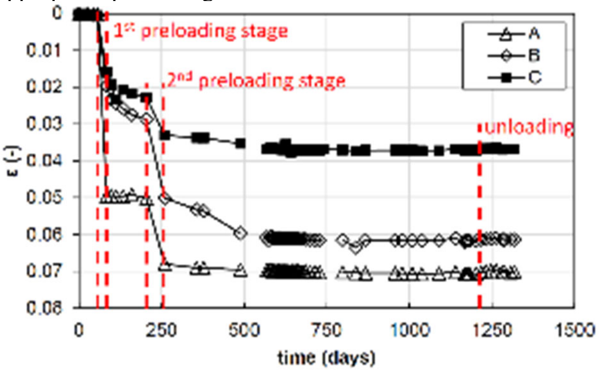

Figure 17. Evolution of vertical strains, ε – t, in A, B and C, Tarragó et al. (2023).

6 CONCLUSIONS

The continuous evolution of the Port of Barcelona underscores the essential role of geotechnical engineering in maritime infrastructure development.

The transition from rudimentary rubble mound foundations to sophisticated breakwater and quay designs - based on geotechnical criteria-, reflects advances in soil mechanics, foundation technologies, computational modelling and monitoring systems.

Lessons learned from past geotechnical challenges provide valuable insights for future expansion projects, particularly in integrating resilient design practices and optimizing material sustainability.

The level of understanding achieved regarding the behaviour of the port soils is high, with good agreement obtained between numerical models and monitoring records. Despite some unavoidable uncertainties, the geotechnical insight into soil behaviour enables design adjustments to enhance stability and limit deformation to be made with a high degree of reliability.

As port operations intensify, further innovations in geotechnical monitoring, predictive analysis, and adaptive foundation systems will shape the next phase of infrastructure development, to ensure stability and efficiency.

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8 REFERENCES

Alonso, E. E., Gens, A., Lloret, A. (2000). Precompression design for secondary settlement reduction. *Géotechnique, 50(6), 645-656.*

Alonso, E. E., Gens, A., Tarrago, D., Madrid, R. (2009). Liquefaction potential of hydraulic fills. *In Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (Volumes 1, 2, 3 and 4) (pp. 957-960). IOS Press.*

Alonso, E. E., Pinyol, N. P., Fernández, P. (2015). Caisson Failure Induced by Wave Action. *In Forensic Geotechnical Engineering (pp. 45-93). New Delhi: Springer India.*

Deu, A., Tarragó, D., Martí, X., Peña, S., Devincenzi, M. (2021). DMT, CPTU and laboratory tests comparison for soil classification and strength parameters of deltaic soft soils in Barcelona Port. *In Proceedings of the 6th International Conference on Site Characterization (ISC6).*

Deu, A., Gens, A., Da Fonseca, A. V., Devincenzi, M., & Tarragó, D. (2024). Offshore shear wave velocity measurements for the assessment of soil sampling quality. *In Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization (Vol. 18, p. 21).*

Gàmez, D. (2007). Sequence Stratigraphy as a tool for water resources management in alluvial coastal aquifers: application to the Llobregat delta (Barcelona, Spain). *PhD thesis. Technical University of Catalunya.*

Gens, A., Alonso, E. E. (2001). Barcelona Port Authority. New dykes simple shear tests on shelby samples (NGI and CEDEX laboratories). *UPC report. internal document Barcelona Port Authority.*

Gens, A. (2019). Hydraulic fills with special focus on liquefaction. *In Proceedings of the XVII ECSMGE-2019: Geotechnical Engineering foundation of the future (pp. 1-31). International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE).*

Gutiérrez, R., Grassa, J. M. (2015). Diseño, construcción y explotación de diques de abrigo portuario en España desde finales del siglo XX. *Ribagua, 2(2), 80-96.*

Junta del Puerto de Barcelona (1881). Memoria sobre los actos más importantes de la Junta del Puerto de Barcelona desde su instalación, con una reseña muy general de las obras ejecutadas. *Autoritat Portuaria de Barcelona (APB). https://www.portdebarcelona.cat/ca/coneix-el-port/autoritat-portuaria/arxiu-de-lapb/memories-historiques*

Madrid, R., Gens, A., Alonso, E., Tarrago, D. (2013). A simplified procedure to assess the dynamic stability of a caisson breakwater. *In Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering (pp. 2367-2370).*

Madrid, R. (2021). Construction and post-construction performance of vertical breakwaters on soft soils. The Port of Barcelona case. *PhD dissertation.*

NGI (1998). MAST III - PROVERBS, Effect of cyclic loading on capacity and stiffness, design diagrams. *NGI report No. 524094-2, December 1998.*

NGI (2002). Port de Barcelona. Laboratory testing. *Geotechnical Testing Report. March, 2002.*

NGI (2009). Laboratory testing Muelle Prat. Port de Barcelona. 2008 *Laboratory test result. January 2009.*

Peck, R. B. (1969). Ninth Rankine Lecture: 'Advantages and limitations of the observational method in applied soil mechanics'. *Géotechnique 19. 171-187.*

Sanpere, M. (1890). La Ribera en el siglo XV (1439). *Lm. IV, entre p. 60-61, col. pleg. - Lit. Henrich y Com. en Com.ta (Suc. N. Ramirez y Com.). Institut Cartografic de Catalunya*

Tarragó, D., Gens, A., Alonso, E.E., Romero, E. E., Griell, R., Estrada, J. L., Uzcanga, J. (2011). The sustainability of the Barcelona port enlargement works. *In 6th International Congress on Environmental Geotechnics (pp. 1228-1233). McGraw Hill.*

Tarrago, D., Deu, A., Gens, A., Alonso, E. E., Griell, R. Madrid (2012). Preload improvement and monitoring in a newly reclaimed area. *In International Conference on Ground Improvement and Ground Control: transport infrastructure development and natural hazards mitigation, ICGI 2012: Wollongong, Australia: 30 October-2 November, 2012: proceedings (pp. 389-394). Research Publishing.*

Tarragó, D., Gens, A. (2018). Gas effect on CPTu and dissipation test carried out on natural soft-soil of Barcelona Port. *In Cone Penetration Testing 2018 (pp. 605-609). CRC Press.*

Tarragó, D. (2021). Hydraulic fills liquefaction: effect on quay stability. *PhD dissertation.*

Tarragó, D., Gens, A., Deu, A. (2024). Gassy soils of the Llobregat delta: Impact on geomechanical characterization. *In ISC'7: 7th International Conference on Geotechnical and Geophysical Site Characterization (pp. 1050-1055). International Centre for Numerical Methods in Engineering (CIMNE).*

Tatjer, M. (1972). El impacto de la industrialización en la morfología de un barrio del siglo XVIII. La evolución de la Barceloneta. *Revista de geografia, 55-104.*

Ventayol, A. (2016). Geología y Geotecnia del Puerto de Barcelona. Geología urbana. *Universitat Politècnica de Catalunya – BarcelonaTech, research seminar.*

Yu, H.S. (1998). CASM: A unified state parameter model for clay and sand. *International Journal for Numerical and Analytical Methods in Geomechanics 22, 621-653.*