MODELING BY ADVANCED CALCULATION METHODS OF THE INTERACTION OF GRAVITY QUAY WALLS

ABSTRACT OF THE DOCTORAL THESIS

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Table of Contents

The doctoral thesis includes: ‣229 pages, of which 48 pages Current state of knowledge ‣ 90 figures, of which 49 in Current state of knowledge ‣ 21 tables, of which 9 in Current state of knowledge ‣ 48 bibliographical references

RESEARCH MOTIVATION

The Port of Constanta has experienced a significant evolution in recent years, consolidating its position as the main logistics hub of the Black Sea region and Eastern Europe. In 2023, a record traffic of over 92.5 million tons of goods was recorded, up 22.5% compared to 2022. This expansion was driven in particular by the regional geopolitical context, marked by the conflict in Ukraine, which required the reconfiguration of trade routes.

Of the total traffic, 71 million tons represented maritime traffic, and 22 million tons river traffic, up by 18% and 40%, respectively, compared to the previous year. A major component was the transit of grain, which exceeded 36 million tons, of which over 14 million came from Ukraine

To sustain this volume of activity, the port has benefited from major investments in infrastructure, including the expansion of the internal road network and the modernization of utilities. Projects worth more than €476 million are also planned for the coming years. One of these investments will be the construction of new port quays.

The calculation of the quays is carried out based on the regulations and technical design guides. Until the advent and accessibility of calculation programs based on the finite element method (FEM), sizing was carried out through a simplified calculation, but sufficient to ensure structural stability. These checks were aimed in particular: sliding on the foundation, overturning and pressures transmitted to the ground.

The advantages of using MEF-based computing programs are as follows:

- Adaptability to complex shapes – MEF allows the analysis of structures with arbitrary geometries, variable loads and various support conditions, being suitable for a wide range of applications.
- High versatility – the method is applicable in almost all fields of engineering: structural mechanics, heat transfer, fluid mechanics, electromagnetism, biomechanics, etc.
- Compatibility between different types of elements – the computing network (mesh) can simultaneously contain finite elements of various types and sizes, facilitating the faithful modeling of complex geometries.
- Integration into a single program – MEF can be fully implemented in a single software package, allowing the automation of the analysis steps and streamlining the simulation process.
- Approximation to physical reality – the mathematical model obtained faithfully reflects the real structural behavior, leading to accurate and relevant results for the design.

Challenges and limitations of the method

Improper application of the MEF can generate errors, the most common being: incorrect choice of the limits of the computing domain, inadequate definition of the finite network, improper use of interFigure elements or adoption of oversimplified terrain models.

Given the non-linear and time-dependent nature of soil behavior, it is essential that the modeling of geotechnical designs is carried out with a high degree of detail. The sequence of construction stages must be strictly observed, as the order of execution can significantly influence the final distribution of stresses and deformations. Critical events can occur not only in the final stage, but also during the intermediate phases.

Modern MEF-based programs include functionalities for phased construction modeling and stability analysis. In this context, the determination of safety factors is recommended to be done by progressively reducing the resistance of the soil, rather than by amplifying the applied loads (except in situations involving predetermined undrained resistance).

Eurocode 7 compliant methods are currently being developed, which introduce partial factors for material parameters, actions and strengths, ensuring a more realistic and reliable assessment of geotechnical behaviour.

Although MEF is a powerful tool, the accuracy of the results depends crucially on understanding the physical phenomena involved and rigorously applying the principles of geotechnical engineering. Incorrect modeling and ignoring a preliminary analytical analysis can lead to sizing errors and, implicitly, compromising the safety of the structure. In the current context, analytical computing is often neglected in favor of automated numerical simulations, which can generate structural problems and risks to project safety.

Following the exposition of this problem, the motivation of the doctoral thesis appears:

The main goal of this thesis is to carry out an advanced analysis of the structural behavior of port elements, using the finite element method (FEM) as a tool for design evaluation and optimization, in the context of the development of modern maritime infrastructure.

In order to achieve this general objective, the following specific directions are pursued:

1. Investigating the limitations of classical structural calculation methods applied to port constructions and highlighting the associated risks (e.g. undersizing and non-compliance with structural conformity criteria).
2. Application of the finite element method in the analysis of a realistic gravitational quay model, using a specialized program (e.g. Plaxis), to simulate the behavior under various types of stresses.
3. Comparison of the results obtained by traditional analytical calculation with those from numerical simulations, in order to assess the accuracy and relevance of each method.
4. Formulation of technical recommendations for advanced modeling and safe design of port structures, based on the conclusions of the analysis.

KEYWORDS: Gravity quay walls, port infrastructure, finite element modeling

I. THE CURRENT STATE OF KNOWLEDGE

1.1. Quay wall structures

Port constructions intended for berthing – such as quays, berths and duc-d'albii – are essential elements of maritime infrastructure. Their fundamental role is to facilitate the conduct of port operations by ensuring optimal conditions for the safe anchoring, securing and operation of ships, both for cargo handling and for the transfer of passengers.

These structures perform the vital function of physical link between the ship and the port platform, constituting the point where the maritime logistics flow intersects with the land infrastructure. In certain situations, they also take on the role of supporting the ground behind the platform, helping to stabilize the site and prevent landslides or settlements

The quay is defined as a construction that provides a continuous mooring line for ships. The segment where the ship is tied is called the mooring front. When the mooring line is not continuous, the structure is called pointing, and if it is intended for passenger transport, it becomes a pier.

To anchor ships at independent points in the port area, duc-d'albi are used, isolated constructions that serve as additional attachment points. They are strategically placed to protect ships from mechanical shocks produced during mooring maneuvers. In addition, in certain modern port configurations, floating quays are also used, made in the form of pontoons connected to the shore by articulated walkways, providing a flexible and efficient solution for mooring smaller ships.

In the case of seaports where the annual volume of goods handled exceeds 500 t/ml of berth front, it is necessary to adopt robust construction solutions, such as vertical profile quays. Although they involve high material consumption and high costs, their major advantage lies in facilitating mooring maneuvers and optimizing logistics flows

1.2. Main types of quays

The typology of mooring constructions is varied and depends on factors such as:

- the type of goods handled (dry, liquid, containers, etc.);
- the geotechnical characteristics of the foundation land;
- hydrodynamic regime (currents, waves, tides);
- the level of structural stress;
- the estimated volume of traffic;
- available economic and technical resources.

Among the most used types of quays are:

1. **Gravity quays** – massive structures that provide stability through their own weight, supporting the filling behind the quay (Figure I.1).
2. **Quays made of caissons** – based on the same self-weight principle, but executed by a different technology, using prefabricated elements, (Figure I.2).
3. **Open berth quay** – where the port platform is supported by piles that transmit the loads to more resistant layers of the land, (Figure I.3).
4. **Sheet pile walls** – made of sheet piles, frequently used for medium-sized ports or as temporary solutions (Figure I.4).

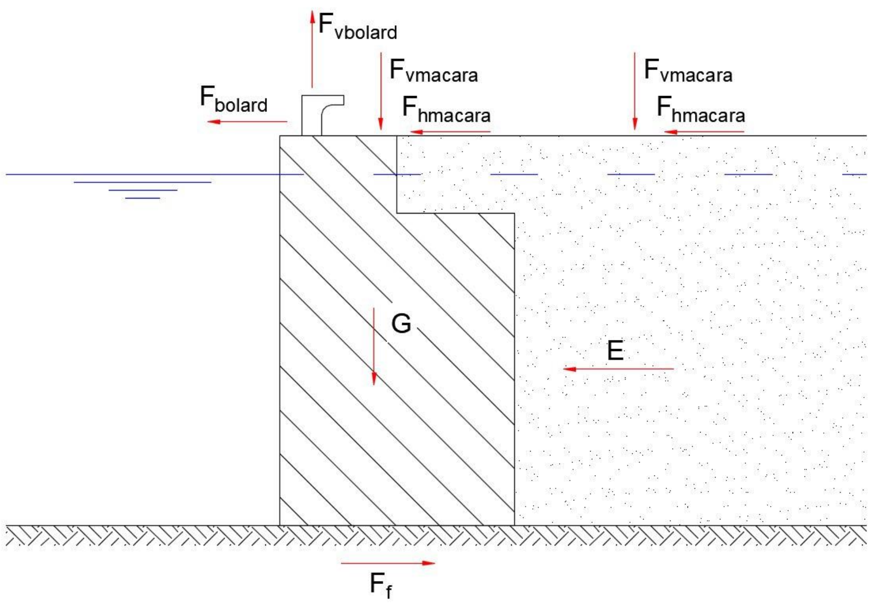

Figure I.1: Gravity Quay wall

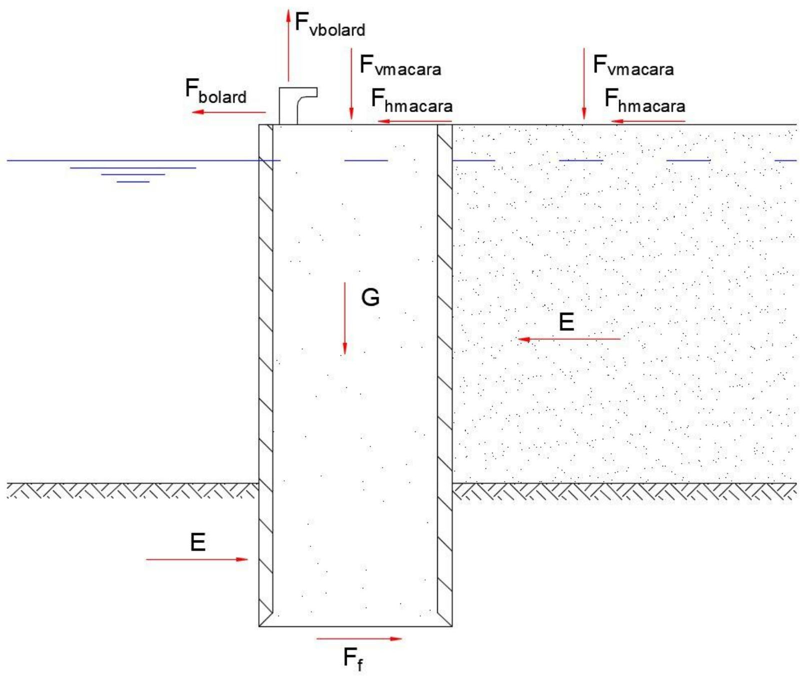

Figure I.2: Quay made of caissons

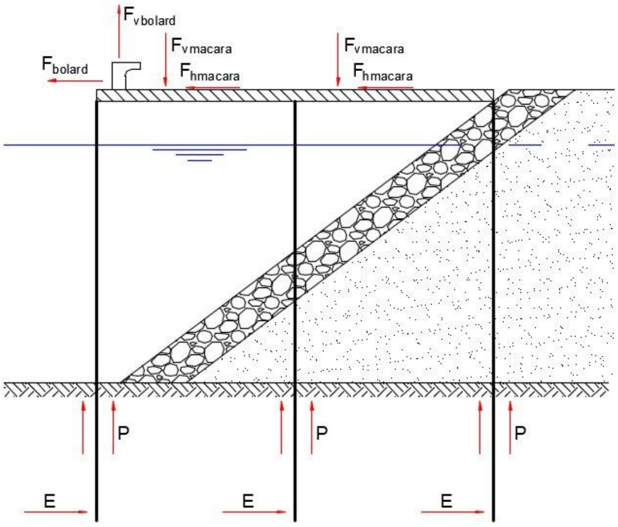

Figure I.3: Open berth quay wall

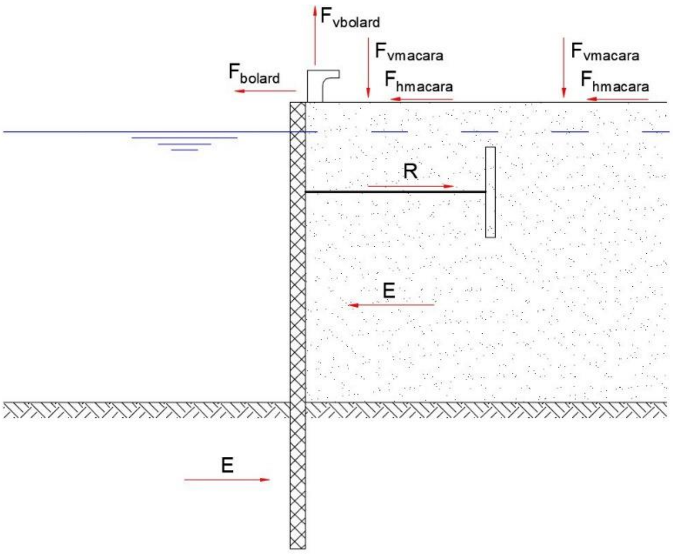

Figure I.4: Sheet pile quay wall.

1.3. Advantages and disadvantages

Each type of quay has both advantages and limitations. There is no one-size-fits-all solution, and the choice of the optimal type depends on local terrain conditions, berthing depths, port traffic type, and available economic resources**.**

For example, gravity blocks offer durability and robustness, but involve high costs and high material consumption. Open berth quays are more economical in areas with great depths, but they require a good knowledge of the foundation ground to avoid stability problems. Sheet pile wharfs can be installed quickly and are flexible, but have a shorter service life and limited structural strength.

1.4. Standardization and adaptation to local conditions

In the European Union, the design and execution of port structures is carried out according to **Eurocodes** and international standards developed by organizations such as **PIANC** or **CIRIA.** The market for building materials is harmonised, ensuring access to common processing and distribution standards in most Member States.

However, implementing a solution used in a reference port, such as Rotterdam, in another context – for example, in the Port of Constanta – is not simple. Although the ports serve ships similar in size and berths, the differences in experience in the execution, together with the **geotechnical particularities of the site**, make it difficult to replicate an identical construction solution.

Thus, **adapting to local conditions** becomes an essential criterion in the design of a quay. Choosing the optimal solution involves a complex analysis of the technical, economic and operational factors, which will be detailed in the next chapter: *The factors underlying the sizing of a quay*.

In designing for ultimate limit states, partial factors are applied to representative actions. In the case of standing actions, these factors take into account whether they are either favourable (stabilising) or unfavourable (destabilising).

When several variable actions occur simultaneously alongside the permanent actions, combination factors (with subunit values) are applied to the additional ones, thus reducing cumulative effects. In this approach, one of the variable actions is considered the main action and the others are treated as companion actions, reflecting the low probability that all maximum effects will occur simultaneously. In the case of shares originating from the same source, they are analysed together – either as main actions or as accompanying actions – and can be considered favourable or unfavourable, depending on the situation.

Eurocode 7, dedicated to geotechnical design, raises a conceptual problem regarding the classification of permanent actions. For example, the upward hydrostatic pressure exerted by groundwater under the base of a wall can be interpreted in two ways:

- favorable, when it reduces the contact pressure on the foundation;
- unfavorable, when the slip or tipping resistance decreases.

Similarly, the lateral pressure exerted by groundwater on the wall is generally considered unfavourable. To manage these ambiguous situations, the Code allows for the classification of both pressures as either favourable or unfavourable, with the design subsequently based on the worst-case condition.

The actions to be considered depend on the specifics of each project, but generally include:

- wave action;
- the pressures exerted by the earth;
- actions on the platform (including overloads and loads from cranes);
- berthing actions;
- mooring actions;
- seismic action;

II. PERSONAL CONTRIBUTION

The personal contribution in the addressed field of ‘advanced modeling’ of berthing structures (gravity wharves) consisted in the finite element method (FEM) modeling of an existing structure from the Port of Constanța, which was subject to a major rehabilitation project and to the deepening of the existing basin.

2.1. Research methodology

Following a complex project to deepen an existing quay in the Port of Constanta, it was necessary to carry out a detailed analysis using the finite element method (FEM). The characteristic section of the construction is illustrated in

The technical solution adopted consisted of making a wall of dry piles, with a total depth of 10 m. The piles have a diameter of 1.20 m and were executed using recoverable tubing technology. Their role is to compensate for the effects of the additional depth of 2 m, a measure requested by the beneficiary to allow the docking of ships of greater capacity.

In a first stage, a simplified calculation of the pilots was carried out, intended to obtain preliminary dimensions. However, the correct sizing of these elements is a complex problem, related to the land-structure interaction.

By deepening the port basin by 2 m, from -11.50 m to -13.50 m, the balance of the existing quay is significantly affected. In order to avoid disturbing its functionality and to limit vertical settlements to acceptable values, additional stabilisation and structural control measures have been imposed.

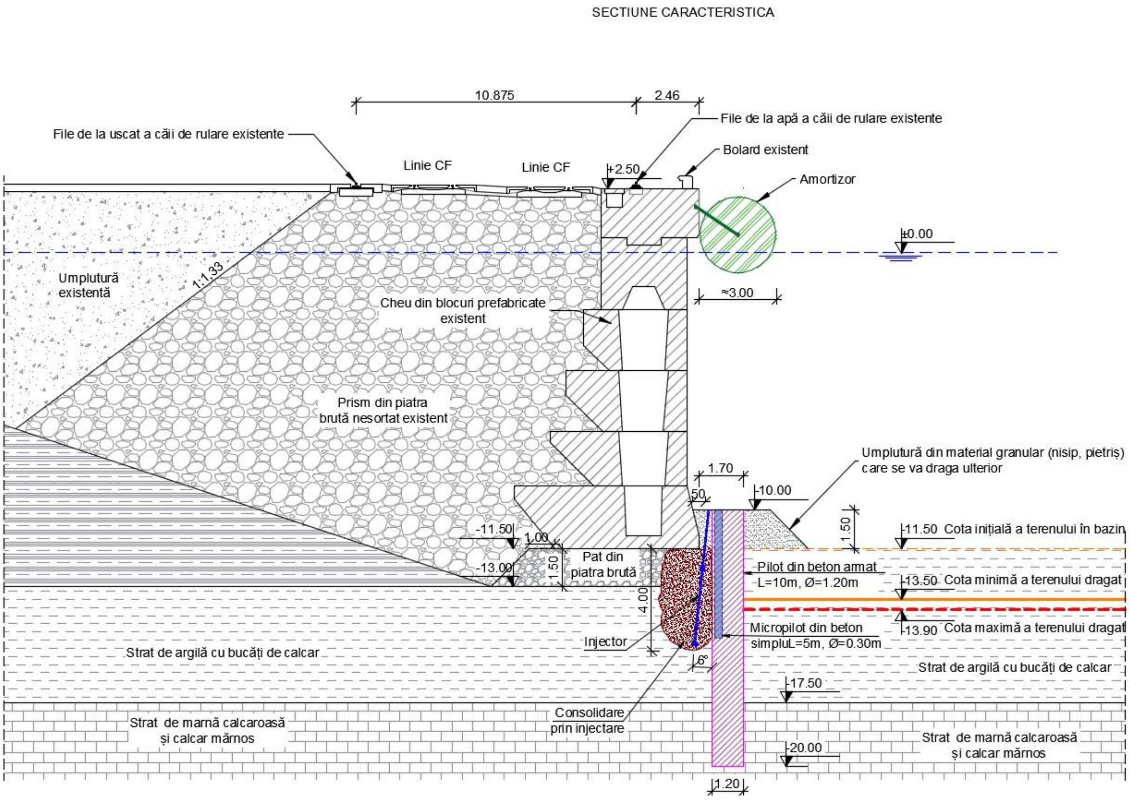

Figure II.1: Case study analyzed.

The research consisted of modeling this quay using the finite element method and its calibration and validation.

2.2. Results and discussions

For the testing of the model, a uniformly distributed force of 40 kPa was applied on the ground, corresponding to the normal state of operation of the port construction. As a result of this loading, for the Service Limit State (SLS), the following deformation was obtained:

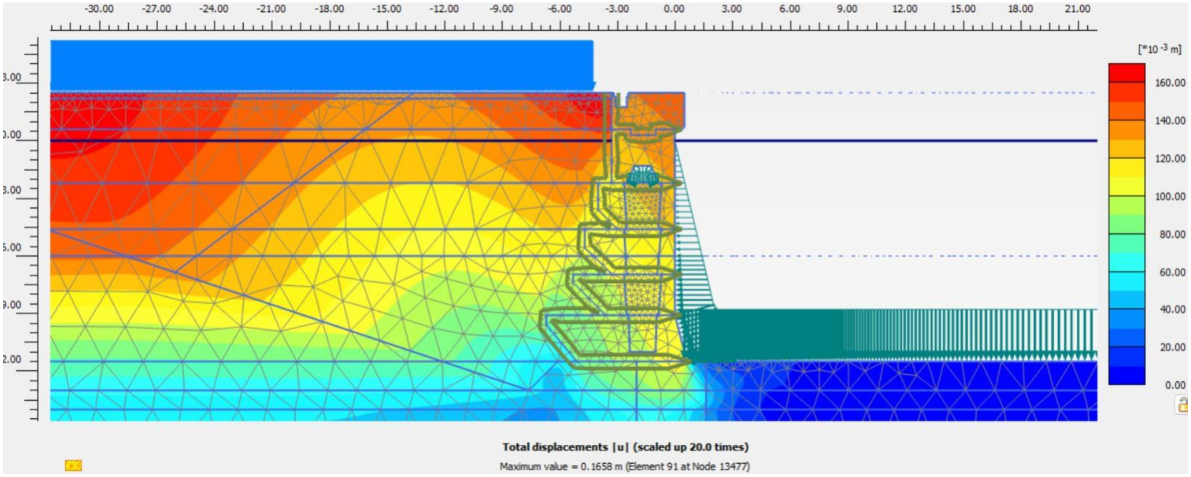

Figure II.2: Deformed quay

By running this analysis, you can determine your movements and efforts. By assigning a uniformly distributed load on the platform of 4 t/m², corresponding to the normal operating load of the quay, the results obtained can be read. An interesting aspect is the distribution of pressures on the foundation bed. This is not perfectly linear, as in the analytical calculation, but the maximum value on the water side is 325 kPa, and on the land side is 220 kPa. These values are very close to those indicated in the old calculation summaries. The pressure obtained is illustrated in Figure II.3:

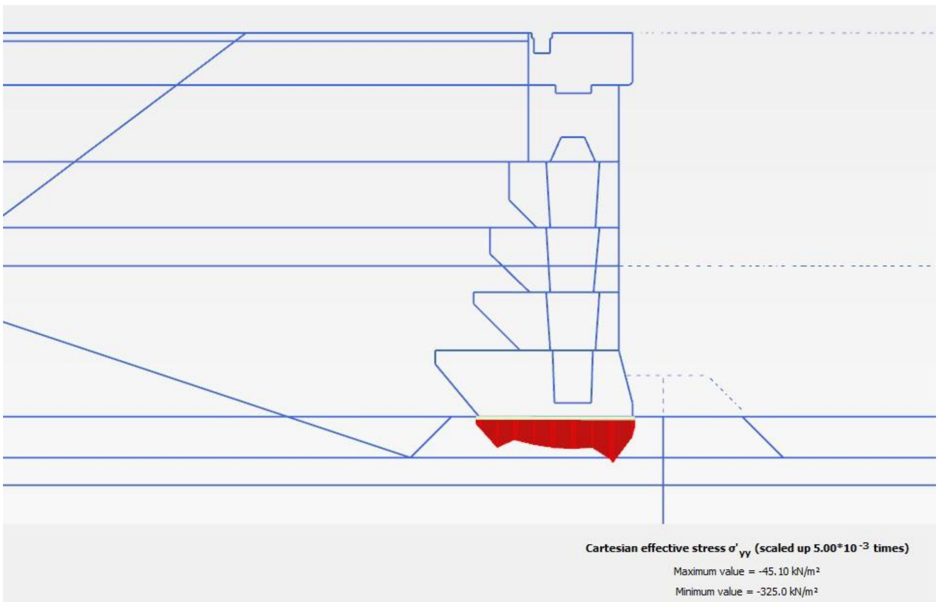

Figure II.3: Pressures on the quay bed.

Similar to the simplified case, the stages of pilot drilling, dredging and injection were introduced. From this model, the initial aim was to obtain the sliding plan. For comparison, an overall stability analysis was first carried out, which indicated a safety factor of around 1.20. Therefore, it was necessary to maintain this level of safety. After the introduction of the injection and the pilot, the final safety factor obtained was 1.18, a value that confirms that the structure is safe. The stability analysis aimed to highlight whether the depth of the pilot is sufficient to maintain the original slip plane. The two sliding planes obtained by the reduction method φ–c are shown in the following figures:

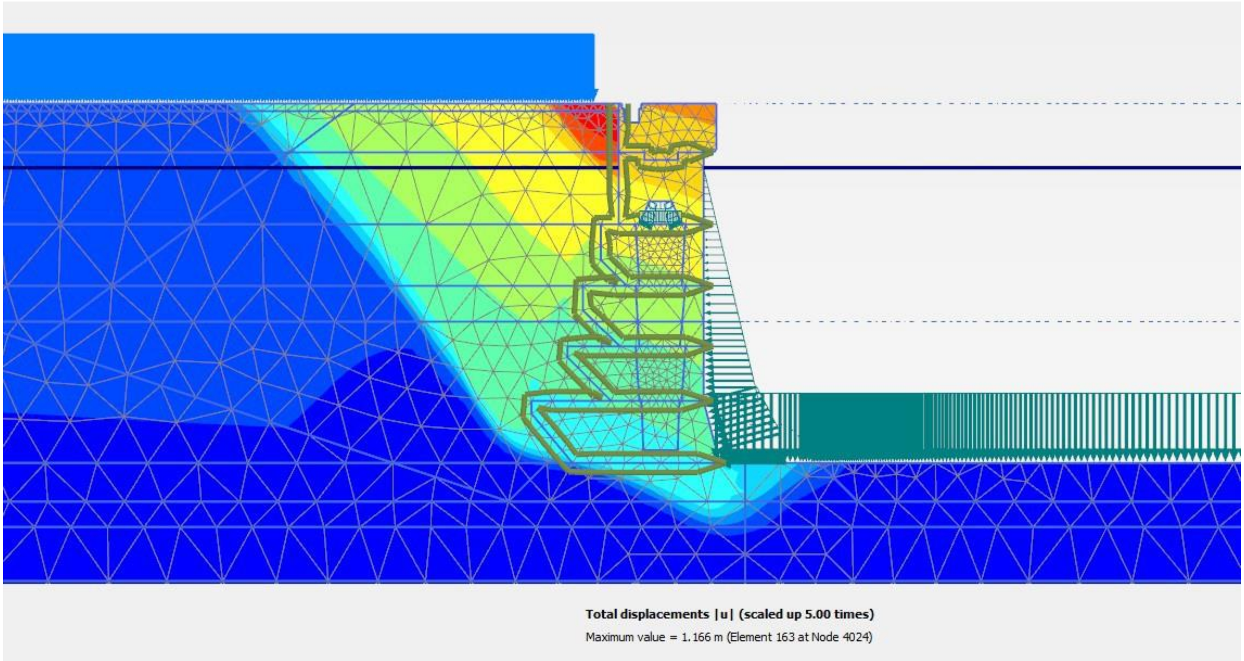

Figure II.4: Initial failure plan.

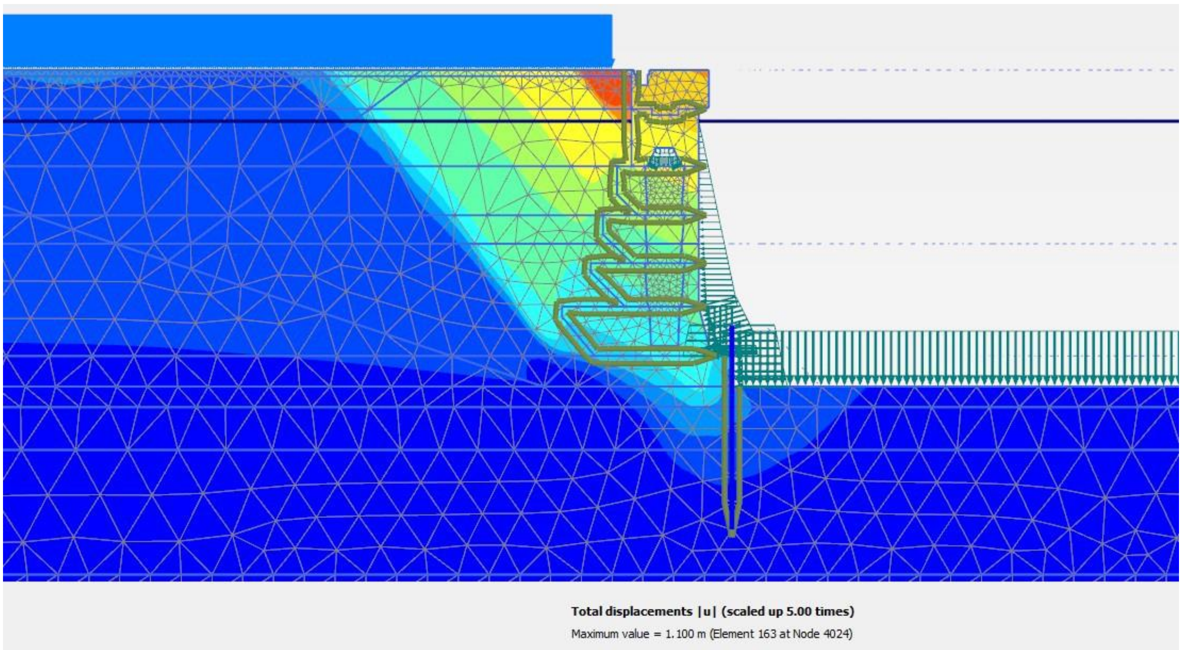

Figure II.5: The final failure plan.

Confirmation that the model is calibrated on the basis of the old calculation shortcuts and that the length of the pilot is sufficient allowed the transition to the design stage. For a new quay, the sizing was carried out in accordance with the principles set out in the Eurocode using the calculation approach 3.

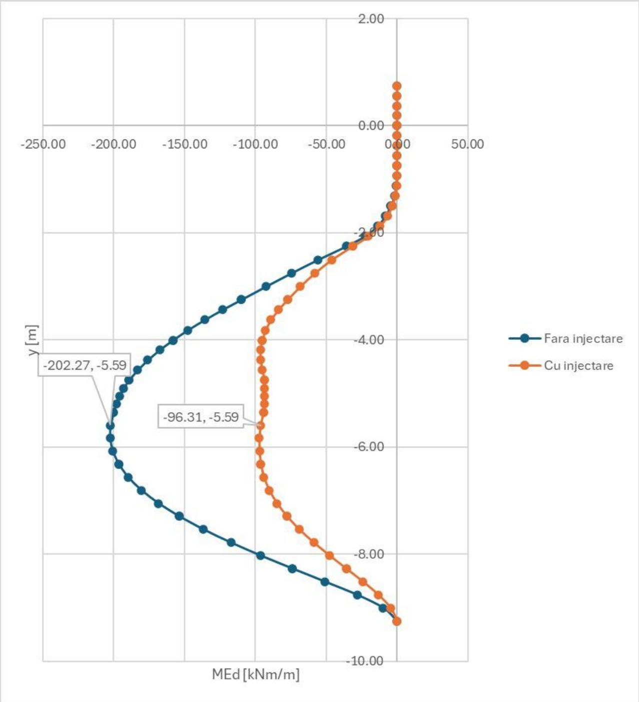

Figure II.6: Moments obtained in the pilot

The results obtained, both for the injection and non-injection models, confirm the values determined by the simplified calculation method. They clearly highlight the issues under consideration. Advanced modeling, together with the use of an appropriate constitutive model, demonstrates that the resulting values are closer to the actual behavior of the system, and the determined moments more accurately reflect the structural reality.

The deformation in SLS, with the operating load of 40 kPa, is illustrated for the pilot without injection into the Figure II.7 and Figure II.8.

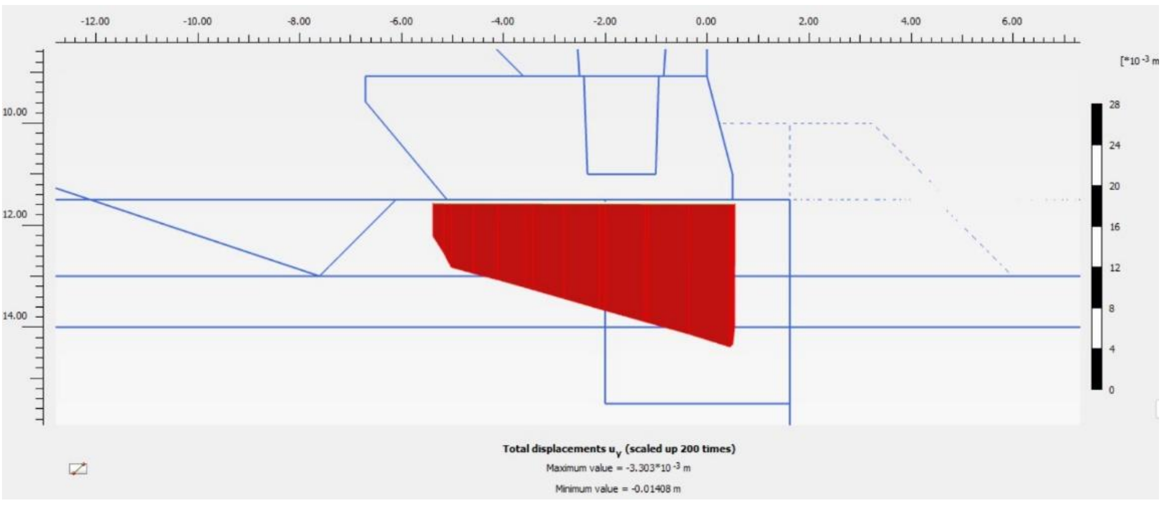

Figure II.7: Settlements without injection.

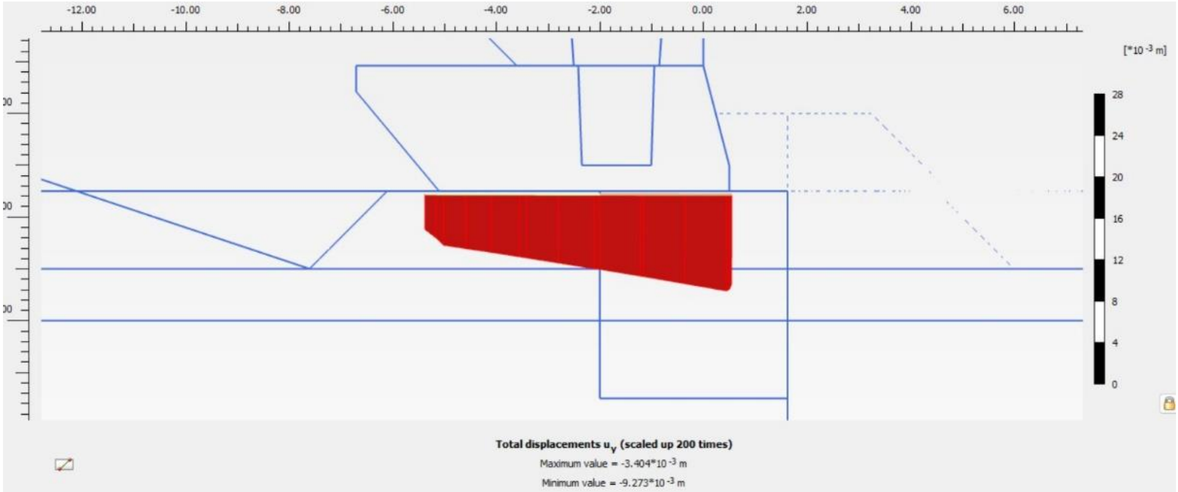

Figure II.8: Settlements with injection.

The final deformation reduction is about 5 mm. Although this value is not very high, it should be noted that the stone bed is already compacted and strengthened by repeated charge/discharge cycles. As for the pilot, the results are more obvious: the reduced moments allow the correct determination of the cocking. These very small displacements demonstrate that deepening the quay is possible without disturbing its functionality, and this innovative process ensures an extended construction life. The complete calculation of the finite element model is presented in the Support Annex of the thesis.

A key result of this analysis is the confirmation that the Finite Element Method (FEM) is a robust and reliable tool for the analysis of port mooring structures. While classical methods provide a useful basis for preliminary checks, they do not always capture the actual distribution of stresses, settlements and land-structure interactions. By contrast, numerical modeling allows the simultaneous integration of several factors (geotechnical, hydraulic and dynamic), leading to a more faithful understanding of structural behavior.

Several methods were addressed in this study. In a first stage, the pressures taken from the old calculation summaries were used, which were the basis of the initial sizing of the quay. Starting from these pressures, a simplified model was made, in which the soil was represented as an elastic material with the Mohr–Coulomb yield criterion. The results indicated relatively large pile moments of around 420.5 kNm/m.

For the model in which all execution steps were simulated and in which a more advanced terrain model was used, the moment was halved:This significant difference can lead to substantial savings in the project, especially in terms of reinforcement consumption. Subsequently, the pilot's cockpit was sized according to the minimum cocking criteria provided in the Romanian norms and standards.

The studies carried out on the analyzed gravitational quay model showed that MEF confirms the trends resulting from the analytical calculations, but also highlights additional aspects, such as the concentration of efforts in critical areas, the effect of execution staging and the nonlinear behavior of the terrain. These results demonstrate the robustness of the method and its ability to validate or correct the solutions obtained through simplified calculations.

3. General conclusions and future research directions

The doctoral thesis aimed at the advanced analysis of the behavior of port mooring structures, with a focus on the gravity quays in the Port of Constanta and how they meet the requirements of safety, stability and operation. The results obtained confirm the importance of combining classical calculation methods with modern numerical modeling tools in order to obtain technically viable and economically efficient solutions.

The main conclusions are:

1. Diversity of construction solutions – Gravity, sheet pile, boom or flexible wharfs each have advantages and limitations. The choice of the optimal solution must be adapted to local conditions, in particular geotechnical characteristics and port loads.
2. Limitations of analytical computing – Classical methods, although essential for validation, do not capture the real complexity of the terrain-structure interaction and can generate significant errors.
3. The added value of numerical modeling – The Finite Element Method (FEM) allows the realistic assessment of settlements, stresses and critical areas, highlighting the nonlinear behavior of the land and the influence of the execution stage.
4. Validation by calibration – Comparison of the modelling results with the data from the briefs and regulations showed a good match, which validates the use of MEF as a robust and reliable tool in port design.
5. Economic impact – The differences in moments obtained through modelling compared to the simplified calculation can lead to significant reductions in the consumption of reinforcement and materials, which translates into substantial savings for investment projects.

Practical recommendations:

- Mandatory integration of numerical modelling in parallel with analytical checks for all major port projects.
- Carrying out detailed geotechnical investigations, which reduce uncertainties and ensure the correct substantiation of the calculation models.
- Adapting the constructive solutions to the local specifics and the available resources, avoiding the direct takeover of external models (e.g. Rotterdam) without validation under the conditions of the Port of Constanta.
- Monitoring of existing structures for continuous calibration of calculation models and prevention of critical situations.
- Aligning port design with European strategies on sustainable transport and environmental protection, in the context of the increasing importance of the TEN-T network and international logistics corridors.

Overall, the general conclusion is that the modernization of the Romanian port infrastructure cannot be achieved without a rigorous scientific approach, based on the use of advanced calculation methods and an in-depth understanding of land-structure interactions. The paper demonstrates that MEF is not just an additional tool, but a necessity for the sustainable, safe and economically optimal design of the ports of the future.

4. Originality of the doctoral thesis

The originality of this thesis lies in the integrated and applicative approach to the problem of port mooring structures, with emphasis on the gravitational quays in the Port of Constanta. Unlike other established works, this research is not limited to the theoretical presentation of constructive solutions, but proposes a **direct correlation between analytical calculations, numerical modeling and real field conditions**.

Major original contributions:

1. **Critical analysis of the limits of classical methods** – The thesis demonstrates, by comparison, that the exclusive use of breviaries and simplified methods can lead to unreliable or economically inefficient solutions.
2. **Detailed modeling through MEF** – A complex simulation was carried out, which integrated the stratigraphy of the land, the geotechnical characteristics, the execution stages and the port actions, providing a realistic image of the structural behavior.
3. **Validation by calibration** – The results of the modeling were compared and correlated with the classical values in the regulations and abbreviations, confirming the robustness of the proposed method and its usefulness in engineering practice.
4. **Economic and technical impact** – The differences between the analytically calculated moments and those resulting from MEF showed the potential to optimize material consumption and reduce costs, without compromising structural safety.
5. **Applicative directions for the Port of Constanta** – The thesis is not limited to a general theoretical analysis, but provides concrete recommendations for the design and modernization of the Romanian port infrastructure, adapted to the geotechnical specificity and local resources.

Scientific and practical value:

- From a scientific point of view, the work contributes to the development of knowledge in the field of land-structure interaction for port constructions and provides a methodological framework applicable to other sea or river ports.
- From a practical point of view, the results can be used as a support for designers, port authorities and investors, in order to substantiate critical infrastructure modernization decisions.
- Through the published articles and papers, the thesis already has an impact in the academic and professional environment, confirming the relevance and applicability of the results obtained.

In conclusion, the originality of the research consists in the integration of classical and modern calculation methods in an applicative approach adapted to the conditions of the Port of Constanta, in demonstrating the advantages of using MEF for the design of port structures and in formulating practical recommendations, scientifically and technically validated, which can guide future investments in the strategic infrastructure of Romania and the Black Sea region.

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