

Extending the Lifespan and Increasing the Robustness of Port Quays: A Study on Anchor Tie Rods and Soil Settlements

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ABSTRACT: As maritime transportation grows larger, contemporary port basins are required to be deeper. This has proliferated quay constructions with sheet pile walls anchored by long anchor tie rods at one or more anchor levels. However, there are indications that various ports in Denmark have recently experienced problems with failing anchors. This paper aims to identify the knowledge gaps related to the anchor tie rods and suggest a research plan to produce sufficient knowledge to prevent future problems with failing anchors. The methodological approach in this paper is twofold. One part is a preliminary literature review that will identify the knowledge gaps in the literature. The second part consists of informal interviews with 18 relevant stakeholders, mainly from Denmark. The stakeholders report various experiences with broken anchors and present several hypotheses on the causes of the incidents. Based on the findings from the preliminary literature review and the informal interviews, it becomes clear that the design of anchor tie rods today is based on experience and not very well scientifically founded. This leaves three main knowledge gaps to be investigated. To fill out the knowledge gaps, a research plan is proposed. The research plan contains suggestions to do laboratory tests and field tests both supported by finite-element models that can in turn be calibrated based on the findings from the tests. Overall, the proposed research plan should enable science to better support the design recommendations that will be used to design anchor tie rods in the future and thereby prevent failing anchors.

KEYWORDS: Anchor tie rods, Sheet pile walls, Port infrastructure, Finite element modelling, Harbor engineering, Structural failures.

1 INTRODUCTION

Maritime transport and ports play a key role in the sustainable transportation system of the future (Fossilfrit Sverige, 2025). Ports act as terminals between roads and the ocean, which is supported by the EU infrastructure plan (European Commission, 2024). The development and maintenance of ports is therefore essential to promote maritime transport. However, port structures are challenged by larger ships, rising water levels, and complex transportation needs causing heavier loads on the surfaces of the quays due to increased and heavier cargo (Danmarks Statistik, 2024; Payne et al. 2023).

A common method for constructing quay walls in modern ports is to use anchored sheet pile walls (De Gijt, 2010). The anchors supporting the sheet pile walls are often constructed as dead-man anchors. The heavier loads and the increased water levels have led to increased anchor forces to be carried from the quay wall through the tie rod to the anchor block.

To accommodate these larger anchoring forces, new and stronger anchor tie rods have been introduced. However, there have recently been indications that sheet pile anchors in several

Danish ports have failed.

Experts have suggested that the tie rods are subjected to a transverse load that they are not designed for. The experts suggest that the transverse loads can be caused by settlements of the soil supporting the anchor tie rod and the anchor plate, see Figure 1. It has also been suggested that the ductility of the material of the tie rod decreases as the diameter of the tie rod increases. This could be due to the production techniques.

The main objective of this research is to identify the research and knowledge gaps regarding anchor tie rods used for sheet piles in harbours. The knowledge gaps will be identified through informal interviews detecting the problems and a literature study uncovering the state of the art in the field. Based on the discovered knowledge gaps in the literature and the suggested problems from the informal interviews a conceptual research plan will be suggested. The research plan should lead towards understanding the interaction between anchor tie rod, soil, and sheet pile wall. The proposed research should help prevent anchor failures in the future.

Section 2 presents the methodology, while Sections 3 and 4 present the results of the preliminary literature review and the informal interview, respectively. Next, the analysis of the results, resulting in a research plan, is presented in Section 5, while Section 6 presents the conclusion.

2 METHODOLOGY

The research for this paper is a combination of qualitative insights from industry stakeholders and a preliminary structured literature review. The informal interviews with the stakeholders help to explore the unwritten know-how and identify the problems that the anchor tie rods experience. The preliminary literature review reflects the state of the written works used for designing and constructing quay walls today. The two parts have been carried out in parallel and have been combined to create a filling platform for the research plan.

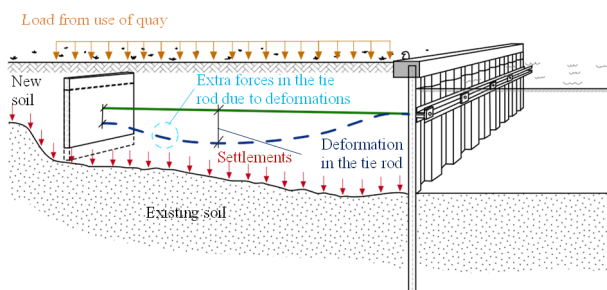


Figure 1. Insufficient knowledge of forces (light blue) makes the horizontal anchors (green) supporting the sheet pile wall (right) break. To the left the anchor plate is seen including its possible settlement. The forces are assumed to come from settlements (red) and overlying loads (orange) causing deformations in the tie rod (dark blue). The sketched deformation of the tie rod is only one of the possible scenarios and is not yet confirmed.

2.1 Approach of the preliminary literature review

The purpose of the literature review was to identify the knowledge gaps in relation to anchor tie rods in quay walls. To conduct the review, the following research questions were proposed:

- What knowledge of anchor tie rods and the surrounding construction parts exists today?
- How are anchor tie rods designed today, and which recommendations have been provided?
- What evidence of failing anchor tie rods exists today?

The resources include peer reviewed scientific papers, handbooks, design standards, design recommendations, and industrial presentations.

The languages of the research have been restricted to Danish and English as these are the languages understood by the first author. This naturally creates an orientation towards the common praxis in Denmark.

The search has been conducted through SDU Mimer which is a Primo interface based on CDI (Ex Libris, 2024) and therefore have access to over 5 billion records. Block searches combining keywords in different ways have been conducted in Mimer to ensure as broad a search as possible within the relevant field. See the keywords in Table 1.

In addition to manual block searches, the Mimer AI assistant has been used to conduct further searches. The AI assistant is trained only to search within Mimer and create block searches based on the prompts given. The AI search has been done to confirm the keywords in the block search. The AI search can be seen in Table 2.

To support the preliminary literature review informal interviews with relevant stakeholders were conducted.

Table 1. Keywords for the block search

Subject	English words	Danish words
Tie rod	Tie rod	Gevindankre*
	Tie rods	Gevindanker*
	Anchor rod	Ankerstang*
	Anchor rods	Ankerstænger*
	Anchor bar	Dødmansankre*
	Anchor bars	Ankerplade*
	Deadman anchors	Ankerspuns*
	Anchor plates	Jordankre*
	Anchor screens	Ankerpæle*
	Screw anchors	Injicerede ankre*
	Ground anchors	
	Anchor piles	
	Retaining wall	Retaining wall, Retaining walls
Settlements	Settlement* Consolidation*	Sætning*

Table 2. AI generated search

Prompt:	Jeg skal lave noget forskning omkring knækkede ankerstænger ved spunsvægge. Kan du finde nogle kilder som beskriver hvordan man dimensionerer ankerstænger og gerne også nogen hvor der er lavet forskning på sådanne stænger	
English part of search string	Danish Part of search string	
(broken anchor rods design) OR (anchor rod dimensioning spundwalls) OR (research on anchor rods in retaining walls) OR (spundwall anchor rod failure analysis) OR (engineering standards for anchor rods in construction)	(dimensionering af ankerstænger) OR (knækkede ankerstænger spunsvægge) OR (forskning om ankerstænger) OR (design af ankerstænger i spunsvægge) OR (stabilitet af ankerstænger ved spunsvægge)	

2.2 Informal interviews approach

The purpose of the informal interviews was to uncover the non-written know-how and qualify the experienced problems with the anchor tie rods. This should further underline and qualify the knowledge gaps identified in the preliminary literature review.

During the study, informal interviews were conducted with 18 stakeholders with the purpose of answering one or more of the overarching questions:

- How are the anchors installed in the field?
- What are the experiences with failing anchors?
- What is the general perception of the cause of anchor failure?

The stakeholders participating in the informal interviews were three consulting engineers, one Eurocode representative, four contractors, four anchor manufacturers, one researcher, one court-appointed construction expert, three port administrators, and one inventor. They were interviewed as part of a group discussion or in one-on-one conversations.

The stakeholders have been selected with the purpose of having representatives from a wide range of the field.

During the interviews, notes were taken, or the entire conversation was recorded. After each informal interview, the notes or recordings were analysed with the purpose of identifying themes.

All stakeholders have been willing to share their experiences, but almost all insist that they and their discussed cases are kept anonymous.

The informal interviews have been carried out without an interview guide and the questions asked during the sessions have evolved during the conversations.

3 PRELIMINARY LITERATURE REVIEW

3.1 Scientific work

The use of sheet pile walls with or without anchors is a well known technique (De Gijt, 2010) and has been considered in many textbooks (Das 2007; Hansen, 1978; Janbu et al 1956; Ovesen, 2012; Thoresen, 2014; Tuijtel et al., 2004). The design of the sheet pile wall has been a subject of many studies, e.g. (Bilgin, 2010, Geizen, 1973, Rowe, 1952), and several design approaches have been suggested, e.g. (Hansen, 1953).

The design of the anchor block supporting the sheet pile wall is also well described in the literature. See, for example, the early work by Ovesen (1964). However, studies on the tension in anchor tie rods are rarer, even though some studies have been carried out both on real retaining walls, e.g. (Sun, 2022), and by finite-element analysis, e.g. (Akan, 2021). The two examples of studies mentioned here were both done on cable anchors and only the tension force in the anchors have been considered since cables in general are not expected to resist transverse loads.

A finite element analysis of dead-man anchors supporting retaining walls created from concrete reports both shear forces and bending moments in the tie rods (Chauhan, 2024), but from the article it is not possible to determine the source of these internal forces. In the mentioned study, a gravity retaining wall was modelled by the finite element method and the optimal position of the anchor block was investigated. As a side note, the author described the shear and bending in the tie rods and the changes with the length of the tie rod. The distributions of the shear forces and bending moments in the tie rod are shown in figures in the article (Chauhan, 2024).

Studies on the interaction between underground tubes and soil have been carried out (Jung, 2016; Trautmann, 1985) describing the forces on the tubes from movement. To the

knowledge of the authors this field have not yet been extended to tie rod anchors. Moreover, only Chauhan (2024) seems to provide a description of bending and shear forces in a tie rod that it has been possible to find. As it was carried out with gravity walls, the deformations around the tie rods are not the same as for sheet pile walls. This leaves a gap in the scientifically supported knowledge on dead-man anchors.

3.2 Design codes and national recommendations

Sheet pile walls and the corresponding anchors are covered by the Eurocode EN 1993-5 (CEN, 2025) and the corresponding national annex for Denmark (CEN, 2017). Here Section 8.11 covers anchors and describes the tension resistance of the anchors. According to the Eurocode, the tensile strength of the anchor tie rod should be taken as the lesser of the tensile strength of the threaded area of the anchor, $R_{t,d}$, and the shaft area of the anchor tie rod, $R_{tg,d}$, (CEN, 2025, clause 8.11.2(1)).

The tensile strength for the shank is given as

$$R_{tg,d} = A_g f_{yd}, \quad (1)$$

where A_g is the cross-sectional area of the shank, f_{yd} is the design yield strength of the steel (CEN, 2025, clause 8.11.2(1)). The yield strength of a dead-man anchor without suitable corrosion protection should, according to the CEN norm, not be larger than 500 MPa (CEN, 2025, Clause 6.3(5)).

The tensile strength of the threaded area is given as

$$F_{t,Rd} = k_t A_s f_{ud}, \quad (2)$$

where A_s is the tensile stress area at the threads, f_{ud} is the design tensile strength of the steel anchor, and k_t accounts for the type of threads (CEN, 2025, clause 8.11.2(1)).

The design guide covers the appearance of bending in the connections by introducing an alternative to equation (2)

$$F_{t,Rd} = k_b A_s f_{ud}, \quad (3)$$

where k_b is a reduction factor to account for bending in the connection. However, this factor does only cover deformations in the connection with an angle less than 2° (CEN, 2025, clause 8.11.2(2)). This is in accordance with the Danish National annex. Here it is stated that k_t should be reduced by 2/3 if the detailing does not ensure that no bending occurs in the anchor (CEN, 2017). It is mentioned that k_b takes the settlements of the anchor into account. The factor of 2/3 and k_b are motivated by the British National Annex (BSI, 2012), where a similar passage can be found.

In the German recommendations, the question of bending in the tie rods is addressed as follows (Son, 2024):

“A prerequisite for proper design is a suitable detail for the anchor connection, which means anchors must be connected via a form of hinge. Anchors must be installed at a higher level so that any settlement or subsidence does not cause any additional stresses.” (Son, 2024)

The recommendations in EAU only refer to the Eurocode and do not mention any scientific work done within this area (SON, 2024).

Just as in the Eurocodes and the German recommendations, the settlements of the anchor and the extra stresses arising from them are described in several books along with recommendations on how to deal with them (Tuijtel et al., 2004; Thoresen, 2014). But in none of them, reference can be

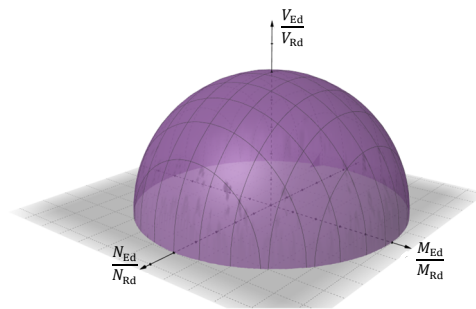


Figure 2. NMV-diagram of the anchor tie rod based on the equations given in the Eurocode for Bolts (CEN, 2024), see Equation 4.

found to research on the matter. At present it has not been possible to find any scientific material researching the influence of settlements on the anchor, thus marking a research gap.

If the anchor should be designed for a combination of a normal force and a transverse load causing bending and shear, one could use the design method of bolts described in the Eurocode (CEN, 2024). Here the equations for tension resistance of a bolt corresponds to equation (2) of this article. In table 5.9 of (CEN, 2024) the combination of normal and shear force in a bolt is given. If this is combined with the design criteria for pin connections with bending and shear given in table 5.6 of the Eurocode the total combination will be given as

$$\left(\frac{V_{Ed}}{V_{Rd}}\right)^2 + \left(\frac{N_{Ed}}{N_{Rd}}\right)^2 + \left(\frac{M_{Ed}}{M_{Rd}}\right)^2 \leq 1, \quad (4)$$

which correspond to the graph shown in Figure 2. However, this is not common practice today.

3.3 Recording of incidents

There have been indications that suggest that several Danish ports have issues with failing anchors (Lundbye, 2019; Rammegruppen, 2023) but it has not been possible to find any systematic recordings of the matter.

However, several stakeholders have in the informal interviews referred to various incidents, mainly in Denmark. This does not mean that broken anchors are only an issue in Denmark but simply reflects that most of the interviewed stakeholders are Danish.

4 RESULTS FROM THE INFORMAL INTERVIEWS

From the informal interviews, several challenges with the anchor tie rods were discussed. It should be noted that what is reported in this section is what the different stakeholders have said. It is not the absolute truth but rather an expression of the different opinions and experiences that exist in this field. In the following they have been categorized and described.

4.1 Settlements

Literature and stakeholders agree that settlements can be one of the main reasons for unwanted deformation of the anchors causing transverse loads. Several reasons for the settlements have been suggested. The first suggestion is settlements of the original soil due to the newly added load from the above sand. A design engineer explained that the propensity of intact soil to create settlements is usually assessed before a project is carried out but the impression is that sometimes the magnitude of the settlements is underestimated, and that the settlements cause larger deformations in the tie rods than expected, since they are moved downwards along with the surrounding soil. The same stakeholder referred to a case where this was observed as they dug up old anchors at a quay in Denmark. Here the anchors had an s-like deformation, and the stakeholder claimed that it was

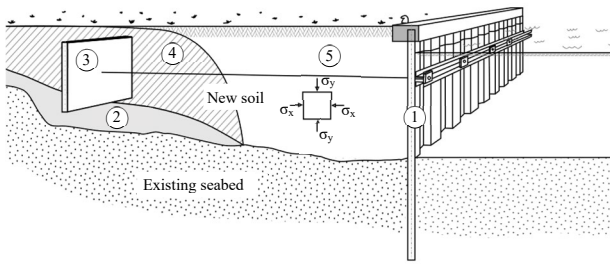


Figure 3. Illustration of the steps when constructing a new quay wall. (1) The sheet pile wall is installed into the seabed. (2) The sea area behind the sheet pile wall is filled with soil in such a way that the sheet pile walls do not experience a large force from it. (3) The anchor plates and anchor tie rods are installed. (4) The soil around the anchor plate are installed. (5) The soil next to the sheet pile wall can be installed.

due to settlements. Other stakeholders suggested that already the installation method could cause settlements.

4.2 Construction

The construction of a quay, as illustrated in Figure 3, was discussed during a group conversation with several stakeholders representing contractors, manufacturers, and researchers. The stakeholders mentioned additional possible sources of ground settlements, namely difficulties with installing the sand below the anchor tie rod after the tie rods have been installed. One stakeholder explained that the soil often consists of sand which is pumped into place as a jet of water and sand. The stakeholder argued that this method causes the large grains to settle close to the quay wall while the smaller grains travel farther away from the wall. This can have the unfortunate effect of creating an overly well-sorted soil that is harder to compact correctly.

If the sand is not pumped into place, it can be dozed from the land side. If this is the case, the sand is installed horizontally instead of vertically. The question is whether it creates a different ratio between the horizontal and vertical initial stress than expected. If that is the case, it could cause larger deformations under the tie rod than expected.

Regarding the installation of the sand underneath the tie rods, the stakeholders also pointed out that it sometimes could be hard to compact the sand sufficiently due to high water levels and the tie rods being in the way. If the sand is not compressed correctly, the overburden from the sand above the tie rod and the loads on the quay will cause settlements.

While discussing installation of anchor tie rods, other installation errors were mentioned such as the anchor rods hanging like a hammock before backfilling with soil around them, see Figure 4. This has often been documented by pictures of construction sites. If the anchors are installed in an s-shape, transverse loads will occur in the tie rods, even without settlements of any kind. The tie rod will try to straighten itself out as it experiences increasing tension. But as soil is installed above the tie rod, the soil will cause a downward force on the tie rod. Here it should be mentioned that the downwards force on the anchor might not be the entire weight of the above soil due to mechanisms described in the studies on underground tubes (Jung, 2016; Trautmann, 1985).

Since the installation has already caused large deformations in the tie rod, the transverse load now introduced will create an extra tensile force in the tie rod along with a shear force and a bending moment. Because the tie rod is not designed for these second-order effects in terms of shear forces, additional normal forces, or bending moments, the tie rod may break even though it is designed according to the Eurocode.

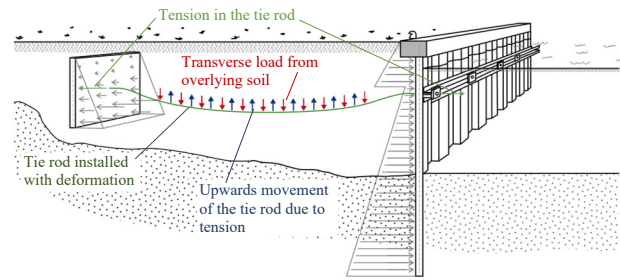


Figure 4. Anchor installed with a pre-deformation causing an upward movement (blue) when the tension in the tie rod (green) is activated. The overlying soil creates a downwards force (red) on the tie rod due to the upward motion.

4.3 Design of anchor tie rods

During an informal interview with an experienced engineer, it was suggested that the issue of transverse forces in tie rods is not relevant, as the preferred design strategy is to avoid such forces altogether. To neutralize this effect, the German recommendations suggest installing the tie rods with a precamber.

In two different informal interviews in the format of one-on-one-discussions, two design engineers mentioned installing the anchors in the lower half of a tube enabling the soil and the tube to settle without the tie rod being influenced. However, when asked if this method works, one of them answered: "I do not know" and afterwards explained that it had not been inspected afterwards. In a third informal interview, a contractor explained that after the incident at Kalundborg Harbour in 2019 (Lundbye, 2019) it has become much more common to install the tie rods in tubes. This reflects a tendency to focus on designing the construction to avoid the effects of transverse loads as in the German recommendations. But the common denominator for all these solutions appears to be that they are based on common sense and practical experience, and they lack scientific background. Hence, one question remains: Is it possible to create a design that avoids transverse load to be transferred into the tie rod?

4.4 Types of nuts

The tie rod is often connected to the sheet pile wall via a nut, see Figure 5. During several informal interviews, the shape of these nuts was discussed. One stakeholder claimed that the most used nut today is a spherical nut. This type of nut should create a hinge in the connection, thus minimising the bending moment in the connection. However, none of the stakeholders could document that they had any effect at all. On the other hand, one stakeholder reported an incident on a cofferdam with several anchor levels. Here there had been some broken anchors in the lower levels. The upper levels had spherical nuts while the lower levels had traditional flat nuts. The stakeholder suggested that the spherical nuts created a better connection to the sheet pile wall during installation.

Several stakeholders have raised questions about the effect of these spherical nuts. The question is if the spherical nut creates the expected hinge in the connection?

4.5 Types of anchors

In general, and slightly simplifying, there are two types of anchor bars being used for dead-man anchors. One type is a steel bar made of standard construction steel and with threaded areas at the ends. According to a manufacturer there has been a development of the steel strength of these types of bars from S235 to S355. These were the common types before the SAS anchors were introduced.

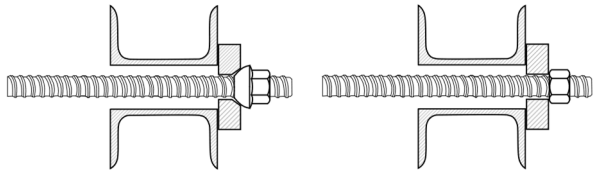


Figure 5. Illustration of a spherical nut (left) and a flat nut (right) each connecting the anchor tie rod to a stretch which is installed on the sheet pile wall.

The manufacturer claims that the SAS anchors became popular in Scandinavia in 2002–2005 and have been used widely since then. The bars are made of high-strength steel and have a larger thread stretching along the entire bar length which enables the contractor to shorten or lengthen the bars much more easily than with the lower-strength bars. The advantage of this type of bar is the higher strength necessitating smaller diameters.

Several stakeholders have reported concerns regarding the performance of the newer anchor type. In several cases, Danish ports have reverted to a more traditional anchor design, reportedly due to concerns about the reliability of newer systems. While these accounts are anecdotal and often shared informally, they point to a broader uncertainty in the field.

The uncertainty is shared by some consulting engineers. They find the newer high-strength anchors more convenient with the threaded area stretching throughout the entire tie rod leaving more room for instalment tolerances. However, as the uncertainty spreads, they lack arguments for using the newer anchor types and find themselves forced to go back to older low-strength steel solutions with threads only at the ends of the bars.

One of the uncertainties with the high-strength bars is the production method. It is suggested that the production method creates a soft core in the bar while the crust becomes much stronger but slightly brittle. This should not cause large problems if the tie rod is kept straight, but if any bending is introduced to the bar, the reduced ductility of the steel could be a cause of failure. Lab tests from the manufacturer suggests that a rotation of 10 degrees does not have any influence on the resistance of the tie rod. However, these tests are carried out on bars with smaller diameters where the issue of varying material properties through the cross section can be less significant.

In the beginning of the research period, the anecdotes of broken anchors were all with SAS anchors. However, later in the process, stories with broken anchors with rods of mild steel became known as well. This aligns with the impression of the problem being known far back in time. These cases with low-strength anchors indicate that the described conviction of the problem being a high-strength-steel-only issue is maybe not entirely true. However, it should still be tested to what extent the problem is more pronounced for high-strength steel than for low-strength steel.

4.6 Corrosion

From some of the cases discussed, it has been suggested that hydrogen embrittlement could be an explanation of the failures. This issue is well known in offshore high-strength steel constructions. The question is whether the environment behind the sheet pile walls in a quay wall is exposed sufficiently to sea water to cause these kinds of problems and if the steel is of high enough strength for hydrogen embrittlement to be an issue.

From the interviewed stakeholders there is no consensus about the influence of hydrogen embrittlement on the anchor tie rods. Some stakeholders refer to tests done on high-strength tie rods. From what the stakeholders report about the tests, there

should be indications that hydrogen embrittlement can be an issue. However, it has not yet been possible to get access to the reports from the tests.

Other stakeholders remain critical of the suggestion of hydrogen embrittlement being a significant factor of failure. They claim never to have seen any indications of this.

Based on the literature review and informal interviews with the stakeholders it is evident that most research has focused on the behaviour of the sheet pile wall and the anchor block, while the tie rod connecting the two has received limited attention. None of the stakeholders have been able to refer to any scientific research done in this area.

Reviewing the recommendations in several writings, it appears that practical experiences have been gathered over time (Son, 1996; Son, 2021; Son, 2024). This indicates that failing anchors are not a new issue and that many different solutions have been used.

5 ANALYSIS AND RESEARCH PLAN

When looking at the findings of the literature review and informal interviews, it becomes clear that many years' experiences form the basis of the knowledge we have about the anchor tie rods today. However, almost no scientific research has been done in this area.

Based on the presented literature review and the findings from the informal interviews, three overall research gaps have been identified:

1. The frequency of the problem of failing anchor tie rods is not known.
2. The influence of transverse loads on anchor tie rods and the magnitude of these loads are undocumented.
3. The forces to be included in the design recommendations and the way to include them are inadequately described.

Research gap 1 can be answered by conducting a mapping of the industrial ports in Denmark, the northern part of Germany, and the southern part of Sweden. These areas experience roughly the same climate and to some extent the same geological environment. There have been no indications that this is only a northern European issue, but as the challenges with anchors discovered so far are in Denmark, it is natural to further explore this area and similar neighbouring areas.

To investigate research gaps 2 and 3, a research framework with several steps and methods must be developed. The suggested first step in the research framework is to investigate the influence of the transverse loads on the stresses and resistance of a tie rod in regard to the N-M-V-diagram shown in Figure 2. The transverse load should be an extra load added after the axial load in the tie rod. From such tests it should be possible to determine what factors have a large influence on the stresses. This requires that all relevant factors are identified through literature studies and conversations with professionals before the test series is planned.

From the results of the research, a detailed plan for performing tests with tie rods surrounded by soil can be conducted. A combination of the above-mentioned tests and field tests where the behaviour of installed anchors is monitored should provide data that will make it possible to fill in the identified research gap 2.

In parallel with the above suggested experiments, the development of a conceptual model for finite-element analysis should be carried out. Here a multi-fidelity-approach can be used, combining a global low-fidelity model with a submodel in high fidelity for analysis of the soil–structure interaction of an anchor tie rod. The global model should cover the sheet pile wall, anchor block, anchor tie rods, and a soil domain of sufficient size to analyse the overall interaction between the soil

and the steel structures. This model should be established in low fidelity and provide the basis information to feed the submodel with relevant information. The submodel can then be used to explore the stresses in and deformations of the tie rod in relevant spots along the entire tie rod.

The finite-element models form the basis for the tests and after the tests have been carried out the models can be calibrated based on the tests. In this way, the models can provide us with even more information.

By analysing the answers of research gap 2, it should be possible to formulate a recommendation on how to design tie rods when taking the transverse loads into account.

6 CONCLUSIONS

Based on the research, the three identified research gaps are:

1. The frequency of the problem of failing anchor tie rods is not known.
2. The influence of transverse loads on anchor tie rods and the magnitude of these loads are undocumented.
3. The forces to be included in the design recommendations and the way to include them are inadequately described.

Based on the knowledge gaps, an outline of the steps in the proposed future research have been presented including laboratory tests investigating the transverse loads, field tests measuring installed anchors, and finite-element models supporting the real-life tests.

With onset in the presented findings, it has become clear that further research in the field is needed to ensure safe, durable and sustainable harbours in the future.

USE OF GENERATIVE AI

During the work with this paper the author has used a generative AI (Copilot) to explore and generate ideas for the structure of parts of the paper. No AI generated text has been used, and all analysis and other academic work have been done by the authors and not by generative AI.

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