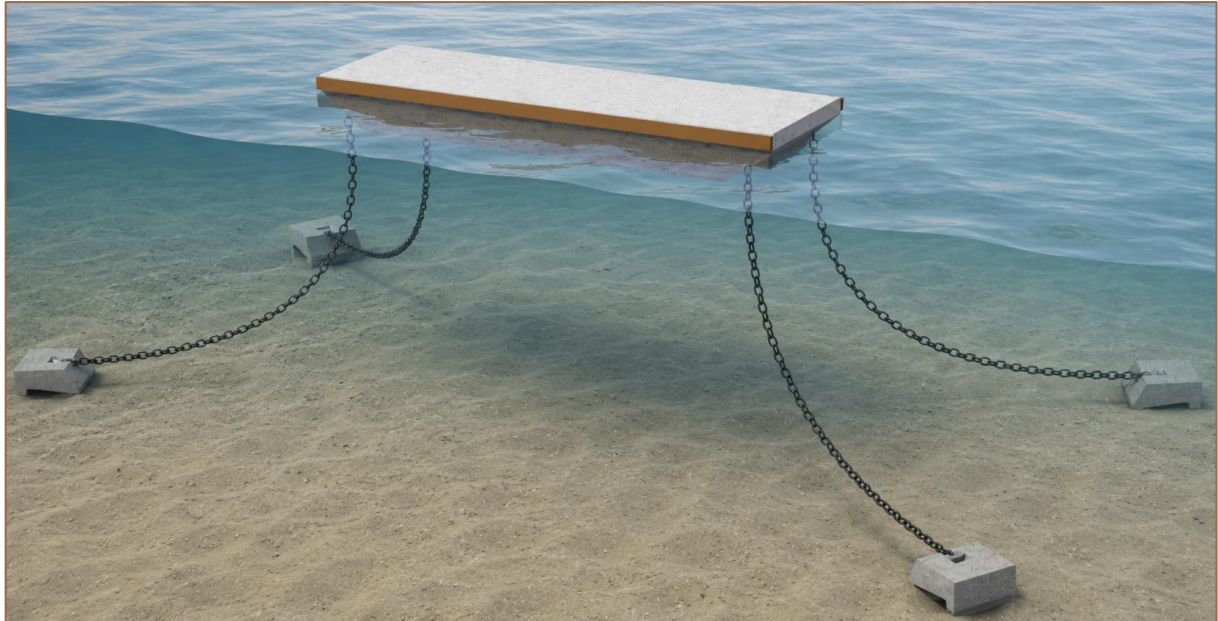




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Development of a Mooring Calculation Model for pontoons

Preliminary Dimensioning of Mooring Chains and
Concrete Anchors

Bachelor's thesis in Mechanical Engineering

Johannes Aliprantis
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DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
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Rendering of a SF1024 pontoon by SF Marina

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Abstract

Floating concrete pontoons require reliable mooring systems to limit movement and transfer environmental and operational loads to the seabed. In practice, anchoring solutions must also remain cost-effective, installable and compatible with available chain and anchor dimensions. The aim of this thesis was to develop a calculation prototype for preliminary dimensioning of mooring chains and concrete deadweight anchors for SF Marina's floating pontoon systems.

The prototype was developed in Python and combines analytical models for chain geometry, mooring loads and anchor capacity to evaluate feasible chain and anchor configurations under given environmental conditions. The chain model is based on static equilibrium and submerged chain weight, while the anchor capacity model uses capacity tables derived from a simplified Pearl Harbor type anchor formulation. The program evaluates discrete chain dimensions and anchor weights, allowing the selected solution to correspond to practical component alternatives rather than idealized continuous sizes.

The prototype was evaluated using a reference case and a comparison between analytical anchor capacity tables and PLAXIS 2D simulations. The results were consistent with SF Marina's proposed anchoring solution and showed that the chain strength margin was large, while the anchor capacity was more sensitive to seabed assumptions and anchor penetration depth.

The developed prototype is considered suitable as an internal early-stage design support tool. It can help compare mooring alternatives, identify governing parameters and document preliminary chain and anchor selections. However, the results should be interpreted with caution where seabed conditions, penetration depth or dynamic loading effects are uncertain.

Keywords: Mooring system, Catenary, Taut, Anchor holding capacity, Deadweight anchor, Pontoon

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Preface

This thesis project is carried out as a collaboration with SF Marina within the department of Mechanics and Maritime sciences. The thesis primarily focuses on the dimensioning of mooring systems for floating concrete pontoons. Mooring chains and concrete deadweight anchors are the foundation of the mooring system and is the primary focus.

We would like to express our gratitude to our examiner, Per Hogström, for valuable guidance and constructive feedback. We would also like to thank our supervisors at SF Marina, William Sigvardsson and Philip Lejon for their expertise, practical insight and continuous encouragement during this thesis project.

Finally, we would like to thank everyone at SF Marina for the opportunity to carry out this thesis project, and for their support throughout the project.

Gothenburg, May 2026

Johannes Aliprantis and Joel Jarlgren

Notations/Glossary

Marine Terminology

HAT	Highest astronomical tide
LAT	Lowest astronomical tide
Berth	Designated docking space
Freeboard	Height above water surface
Vessel	Ship
Pontoon	Floating concrete structure
Mooring	Securing a vessel
Fairlead	Attachment point for the mooring line
Storm surge	Abnormal sea level rise

Physics / mathematical

Quasi-static	Semi-static
Hydrodynamics	Motion of fluids
Catenary	Hanging chain/cable curve
Taut	Tightly stretched chain/cable

Chain notations

x	Horizontal axis
h	Vertical axis
T_0	Horizontal tension
l	Suspended arc length
P	Wet chain weight
h_s	Known vertical distance
x_s	Horizontal distance from touchdown point to fairlead
l_T	Total chain length
l_m	Chain length resting on seabed
l_s	Suspended chain length
X	Total horizontal distance from anchor to fairlead
α_a	Uplift angle at anchor
T	Tension suspended section
T_f	Maximum static tension in suspended section
A	Placeholder variable
B	Placeholder variable
u_a	Upper catenary parameter (fairlead)
u_f	Lower catenary parameter (anchor)
θ_f	Chain angle at the fairlead
T_a	Tension at the anchor
T_{\max}	Maximum static tension
$T_{0,pre}$	Horizontal pretension
H_{pre}	Horizontal pretension
T_{env}	Horizontal environmental load
$T_{0,load}$	Horizontal environmental load
x_i	Horizontal fairlead position
f_{cat}	Chain geometry
h_i	Vertical distance

$T_{0,i}$	Horizontal tension
$x_{HAT,pre}$	Horizontal fairlead position during HAT (only pretension applied)
$x_{LAT,pre}$	Horizontal fairlead position during LAT (only pretension applied)
$x_{HAT,load}$	Horizontal fairlead position during HAT (Maximum load applied)
$x_{LAT,load}$	Horizontal fairlead position during LAT (Maximum load applied)
S_x	Horizontal offset/span
r_{req}	Required envelope radius
r_{allow}	Maximum allowable horizontal displacement radius
$H_{pre,min}$	Minimum required pretension
$T_{chain,max}$	Maximum tension
T_i	Tension
MBL	Minimum breaking load
d	Nominal chain diameter
g	Chain grade
$FO S_{chain}$	Factor of safety on chain

Anchor notations

Q_0	Horizontal anchor capacity
F_b	Base resistance of anchor
F_f	Front resistance of anchor
F_s	Side resistance of anchor
W'	Submerged anchor weight
W_s	Weight of soil on top of anchor
μ	Friction coefficient
A_b	Base area of anchor
c_a	Adhesion between anchor and soil
A_f	Front projected area of anchor
K_p	Passive earth pressure coefficient
γ	Soil unit weight
D	Penetration depth
N_q	Bearing capacity factor
c_u	Undrained shear strength of soil
N_c	Bearing capacity factor
K_0	Earth pressure coefficient
A_s	Anchor side area
γ_c	Unit weight of concrete
γ_w	Unit weight of water
V	Anchor volume
p_a	Parametrization of anchor dimensions
A_{cs}	Cross-sectional area
Q_α	Reduced horizontal anchor capacity
η_α	Reduction factor
$FO S_{anchor}$	Factor of safety anchor

1. Introduction

In the introduction the aim of the project thesis is presented together with the necessary limitations and requirements defined by the commissioning party and other relevant factors. In addition, a short background to the project and the commissioning party is given.

1.1 Background

Concrete pontoons are widely used in harbours and marinas as stable floating structures for berthing small and medium sized vessels (SF Marina 2022). To ensure that these pontoons remain in place throughout their service life, a reliable anchoring system is required. These systems vary in terms of cost and complexity, but the most common setup consists of concrete anchors and chains (Tsinker, 1995). If the anchoring system is not properly dimensioned, there is a risk that the pontoon will move excessively or even break free resulting in catastrophic failure. Seeing as the operating environment of a lot of pontoon-installations are subject to harsh marine conditions such as strong winds, waves, currents and tidal variations these risks are very real (Tsinker, 1995).

At the same time, it's neither economically nor environmentally sustainable to significantly over-dimension anchors and chains. Unnecessarily large concrete anchors and oversized chains result in higher material and production costs, more demanding transport and installation and an increased climate impact due to higher material usage. In practice the anchor system is often dimensioned using rules of thumb, past experience and conservative safety margins rather than with a systematic engineering analysis tailored to the specific installation. (W. Sigvardsson, personal communication, January 25, 2026).

A consequence of this is that it's difficult to know whether a given solution is well balanced between safety and resource efficiency. At SF Marina, which design, supply and install concrete pontoons, there is a clear need for more structured guidance on how heavy a concrete anchor together with its chain need to be in order to safely and effectively anchor a concrete pontoon under harsh marine operating conditions (W. Sigvardsson, personal communication, January 25, 2026).

At SF Marina there are existing calculation models that describe the loads on the pontoon, these can be used as a basis for the analysis of the anchor and chain. The company also has early-stage models for dimensioning the anchor and chain however these models have known limitations but can however act as a starting point and a source of ideas. The company further has internal design rules and experience from numerous previous projects that can be used as support when different solutions are evaluated.

1.2 Commissioning party

The commissioning party for this thesis project is SF Marina which is a Swedish company located in Gothenburg that specializes in designing, manufacturing and installing floating marina systems. The company operates globally, with installations in over 50 countries (SF Marina, n.d.). The installations vary greatly in magnitude, climate- and environmental conditions.

SF Marina focuses on delivering floating structures, like pontoons and floating breakwaters, which are primarily used in harbours. Their products include standard floating pontoons, breakwaters, and customized pontoons that can support buildings and other structures. Their solutions are highly adaptable and can range from small-scale installations, such as recreational harbours, to large-scale marina installations such as harbours for superyachts. These systems are engineered to last, with low maintenance, long product life, even during extreme environmental conditions (SF Marina, n.d.).

To secure their floating structures, SF Marina uses several different anchoring and mooring methods. These include traditional piling, where piles are driven into the seabed and used to guide and stabilize the pontoon. The company also uses elastic mooring technologies like Seaflex, which can absorb the force from the waves and tides, improving stability (SF Marina, n.d.).

1.3 Problem description

Even though concrete pontoons are commonly used, SF Marina's dimensioning of their mooring system is based on simplified approaches, such as rule of thumb and prior experience. The lack of a scientific approach is compensated by using conservative safety margins, which in turn is suspected to result in overdimensioned systems. While these methods may ensure safety, they do not provide sufficient scientific and systematic basis (W. Sigvardsson, personal communication, January 25, 2026). This method also results in increased cost due to resource inefficiency.

1.4 Aim and objectives

The aim of this thesis is to develop a prototype calculation program, using a scientific approach for dimensioning the mooring system for SF Marina's concrete pontoons. The thesis focuses on determining a suitable combination of anchor weight and chain configuration, based on environmental load and site conditions.

- Which established equations and assumptions will be used for chain behaviour, seabed interaction, and anchor resistance?
- How will these be implemented in a modelling procedure that converts the first-link load and site parameters into chain and anchor dimensions?
- Do the results provide sufficient accuracy for dimensioning when compared with selected validation methods, reference cases and SF Marina's internal guidelines?
- What are the limitations of the method?
- Which assumptions and input parameters have the greatest influence on the output?

1.5 Scope and limitations

Due to the complexity of the system, many limitations and boundaries are required to simplify it, this is done partly due to SF Marina's request for a low-resolution calculator, with few inputs.

The study is limited to the force input taken as output from SF Marina's calculator which is assumed to be correct. The study disregards the pontoon's stability, buoyancy and hydrodynamics. It's also assumed that the pontoon is installed in sheltered and shallow waters. Moreover, the seabed is limited to sand, clay, silt, bedrock, and is assumed to be homogenous and flat. The study only treats SF Marina's standard equipment, which involves chain, anchor and pontoon type. The study will not evaluate any ecological, economic, environmental nor societal impact.

Some other limitations that are neglected due to low impact and unrealistically high resolution in the context of SF Marina's request include: Salt concentration of water, water pollution, animal impact, corrosion due to UV radiation, overgrowth of algae/seaweed/corals, material fatigue and wear due to currents.

2. Method

The method chapter highlights the chosen approach to the thesis project and how the thesis handles different sources. Moreover, a short description of how the model is developed, implemented and verified is presented.

2.1 Overall development approach

This thesis was carried out as a prototype development project supported by literature-based engineering modelling and computational implementation. The purpose of the work was not to perform a purely theoretical study, but to develop a calculation procedure that could be used to evaluate anchor and chain dimensions for floating concrete pontoons.

The work was divided into three main parts. First, relevant theory and existing calculation approaches were collected from literature, standards, technical reports and internal SF Marina documentation. Secondly, the selected models were adapted to the defined system boundary of the thesis. Third, the adapted models were implemented in a Python-based prototype and evaluated through numerical comparison, a detailed reference case, a broader comparison with previous SF Marina layouts and sensitivity studies.

The development was carried out iteratively. Individual parts of the calculation model were first treated separately, such as chain geometry, pretension, anchor capacity and strength checks. These parts were then connected into one calculation flow, where the program evaluates possible anchor and chain combinations based on user-defined input data and design criteria.

2.2 Requirements

The requirements for the prototype were defined from the intended use case at SF Marina. The tool was intended to support early-stage dimensioning of anchor and chain systems for concrete pontoons, where the user needs a practical estimate of suitable anchor weights and chain dimensions based on site-specific conditions.

The main requirement was that the prototype should be able to evaluate whether a selected mooring configuration satisfies the relevant design constraints. These constraints include allowable pontoon displacement, chain strength, anchor capacity and the capabilities of the installation team and their equipment. The program also needed to use standard chain dimensions and anchor weights rather than producing theoretical dimensions that are not practically available (W. Sigvardsson, personal communication, January 25, 2026).

The input data were kept limited to parameters that can realistically be estimated during early project planning. These include water levels, chain length, environmental force input, seabed type, allowable displacement (W. Sigvardsson, personal communication, January 25, 2026). This was done to keep the prototype useful as a practical engineering tool rather than a detailed numerical simulation model.

2.3 Literature and source selection

Scientific literature was used to establish the theoretical basis for the calculation model. The sources were selected based on their relevance to mooring systems, catenary chain behaviour, anchor holding capacity, seabed interaction and practical design criteria for marine structures.

The chain model was primarily based on the quasi-static catenary formulation presented by Ma et al. (2019). This source was given high priority because it provides a modern and comprehensive description of mooring line behaviour, including the relationship between horizontal tension, submerged line weight, suspended length, vertical drop and line angle. Tsinker (1995) was used as a complementary source, since it is more closely related to marine structures and is also reflected in existing SF Marina calculation procedures. However, the approach in Tsinker is more case-based and less suitable as the only basis for a flexible computational model. The formulation by Ma et al. (2019) was therefore used as the main theoretical basis for the chain geometry model, while Tsinker (1995) was used for comparison and practical context.

Anchor-related literature was evaluated in a similar way. General descriptions of deadweight anchors and soil-anchor interaction were taken from marine geotechnical and mooring literature, while the analytical structure used for the Pearl Harbor type anchor was mainly based on Lin and Nakamura (1993). This source was considered relevant because the anchor geometry used by SF Marina is closer to an embedded gravity anchor than to a simple concrete block. At the same time, the model was not used as a direct design rule without modification, since the anchor capacity depends strongly on seabed type, penetration depth and uplift angle. The analytical formulation was therefore used to generate capacity tables for different anchor weights, seabed assumptions and line angles, rather than to define a single constant anchor efficiency.

Internal SF Marina documents and existing calculation tools were also reviewed. These sources were not treated as independent scientific references, but as important practical references for current company practice, available chain dimensions, installation constraints and expected input data. This made it possible to align the prototype with existing workflows while still basing the main calculation models on external engineering literature.

The detailed chain equations and assumptions are presented in Chapter 4. The anchor capacity formulation and generation of capacity tables are described in Chapter 5. Implementation of model in the prototype is described in Chapter 6.

2.4 Model development procedure

The calculation model was developed by translating selected engineering theory into computational form. The first step was to define the physical system and calculation boundary. The model was limited to force transfer from pontoon fairlead, through the chain, to the anchor and seabed. The environmental load acting on the pontoon was treated as an external input. The physical system boundary is described in Chapter 3.

The model was then divided into separate calculation parts. The chain geometry model was used to calculate chain profile, horizontal reach, line tension and line angle for different water levels and load states. The pretension and displacement model was built around the chain model and used to determine whether the pontoon movement remained within the allowed

envelope radius. The chain strength model compared the resulting line tension with catalogue-based breaking loads. These calculation models are presented in Chapter 4.

The anchor capacity model was handled separately from the main design loop. Analytical anchor capacity models from literature were used to generate capacity data for different anchor weights, seabed types and uplift angles. These data were stored in tabulated form and later used by the prototype during the design search. This allowed the program to include seabed-dependent anchor capacity without recalculating the full analytical anchor model during each iteration. The anchor capacity model and the construction of the capacity tables are described in Chapter 5.

After the separate parts had been developed, they were combined into a single design procedure. The program evaluates possible combinations of chain dimensions and anchor weights, rejects alternatives that do not satisfy the design criteria and ranks the remaining alternatives according to the selected optimisation objective. The full program logic and candidate evaluation procedure are described in Chapter 6, while the verification and evaluation of the developed model are described in Chapter 7.

2.5 Software implementation

The calculation model was implemented in Python. The program was structured around separate calculation functions for chain geometry, pretension, anchor capacity lookup, strength checks and candidate selection. This modular structure made it possible to test and update individual parts of the model without rewriting the entire program.

Catalogue-based input data were used where possible. Chain properties were stored as selectable standard dimensions, including chain weight and breaking load. Anchor capacity data were read from external tables, allowing the capacity model to be updated without changing the main program code. This also made the input data easier to inspect and modify.

The prototype was developed with a graphical user interface to make the calculation flow accessible without requiring direct interaction with the code. The user enters the required site and design parameters, after which the program calculates feasible combinations and presents selected results such as required anchor weight, chain dimension, pretension, utilisation and chain geometry.

2.6 Verification and evaluation

The prototype was evaluated through several complementary steps. This was done because no full-scale measured load test of the complete pontoon, chain and anchor system was available. The evaluation therefore combined internal verification, numerical comparison, a detailed reference case and a broader comparison with previous SF Marina anchoring layouts.

The first step consisted of internal verification of the implemented calculation procedure. Selected equations, intermediate results and limiting cases were checked against hand calculations and expected physical behaviour. This included checks of the catenary geometry, pretension level, displacement envelope, suspended chain length, seabed contact, maximum chain tension, uplift angle and anchor utilisation. The purpose of this step was to ensure that the implemented calculation logic produced physically reasonable results before the model was compared with external cases.

The second step consisted of a numerical comparison of the anchor capacity model. A set of representative anchor cases was analysed in PLAXIS 2D and compared with the analytical anchor capacity tables used in the prototype. This comparison was focused on the anchor and seabed interaction rather than the complete mooring system. The purpose was to evaluate whether the simplified analytical capacity model produced capacities of the same order as a numerical soil-anchor model for the tested anchor geometries, seabed assumptions and uplift angles.

The third step consisted of a detailed reference case based on an existing SF Marina project. This case was given the highest validation weight in the thesis because the applied loads were provided directly by SF Marina. The prototype could therefore be evaluated using the same load basis as the original company calculation, instead of reconstructing the environmental load conditions from separate assumptions. This made it possible to compare the prototype output with an existing design proposal under controlled input conditions. The reference case also followed the same general type of load and anchoring workflow as SF Marina's existing anchoring documentation (Lundström, 2022).

In addition to the detailed reference case, a broader comparison was carried out using anchoring drawings from previous SF Marina projects. This comparison included a larger number of anchor legs from different installations and was used to evaluate whether the prototype selected chain and anchor dimensions within the same practical range as previous SF Marina solutions. For each installation, available drawing information such as pontoon layout, anchor-leg direction, chain length, chain dimension and anchor weight was extracted where possible. The information was then converted into the input format used by the prototype.

For the broader comparison, project-specific wind, wave and current loads were generally not available in the same form as in the detailed reference case. These environmental input values therefore had to be estimated separately by the authors. Wind input was based on climate-load information and reference wind-speed guidance for the evaluated locations. The reference wind speed was treated as a 10-minute mean wind speed at 10 m height and used as the design wind input in the load calculation (Boverket, 2023, 2025). Water-level input was based on extreme sea-level estimates for high sea water levels with different return periods along the Swedish coast (Andersson et al., 2023).

Wave input was estimated using a simplified fetch-based approach (SMHI, 2010). For each installation, the governing exposed directions were identified from the layout and surrounding geography. The available fetch was then estimated from map or chart information. Significant wave height and wave period were estimated from wind speed, wind duration and fetch. Wave growth is mainly governed by wind speed, wind duration, fetch and water depth (Sveriges meteorologiska och hydrologiska institut [SMHI], 2010). The fetch-based approach is also consistent with established coastal engineering methods for estimating wind-generated waves under fetch-limited conditions (U.S. Army Corps of Engineers, 2002). Current input was estimated from available oceanographic information and general descriptions of current conditions in Swedish waters (SMHI, 2011).

The broader installation comparison was therefore treated as an engineering reasonableness check rather than as a strict validation case. The main reason is that the environmental loads were reconstructed by the authors, while the corresponding original load assumptions used by SF Marina were not available. This means that deviations between the prototype and the existing drawings may be caused by differences in assumed wind, wave or current conditions,

rather than by the chain and anchor model itself. The comparison was therefore used mainly to assess trends, magnitudes and practical consistency across several installations.

Agreement in the broader comparison was evaluated qualitatively. The focus was not to reproduce each individual anchor leg exactly, but to determine whether the calculated chain dimensions and anchor weights were within a reasonable practical range compared with previous SF Marina layouts. This made the broader comparison useful as a complement to the detailed reference case, since it tested the prototype against a wider range of anchoring configurations, water depths and practical layout scales.

3. System description: physical system

An overview of the entire physical system is presented, with all of the key components described in detail, Such as Pontoon, anchor, chain, seabed, surrounding water and imposed load on pontoon. A description of how the anchors are installed is also given under this chapter.

3.1 Physical system boundary

The physical system considered in this thesis consists of the pontoon, the fairlead or chain attachment point, the mooring chain, the anchor, the seabed, and the surrounding water level conditions. These components define the load path from the floating pontoon to the seabed. The environmental load is transferred from the pontoon into the chain, through the anchor, and finally into the seabed.

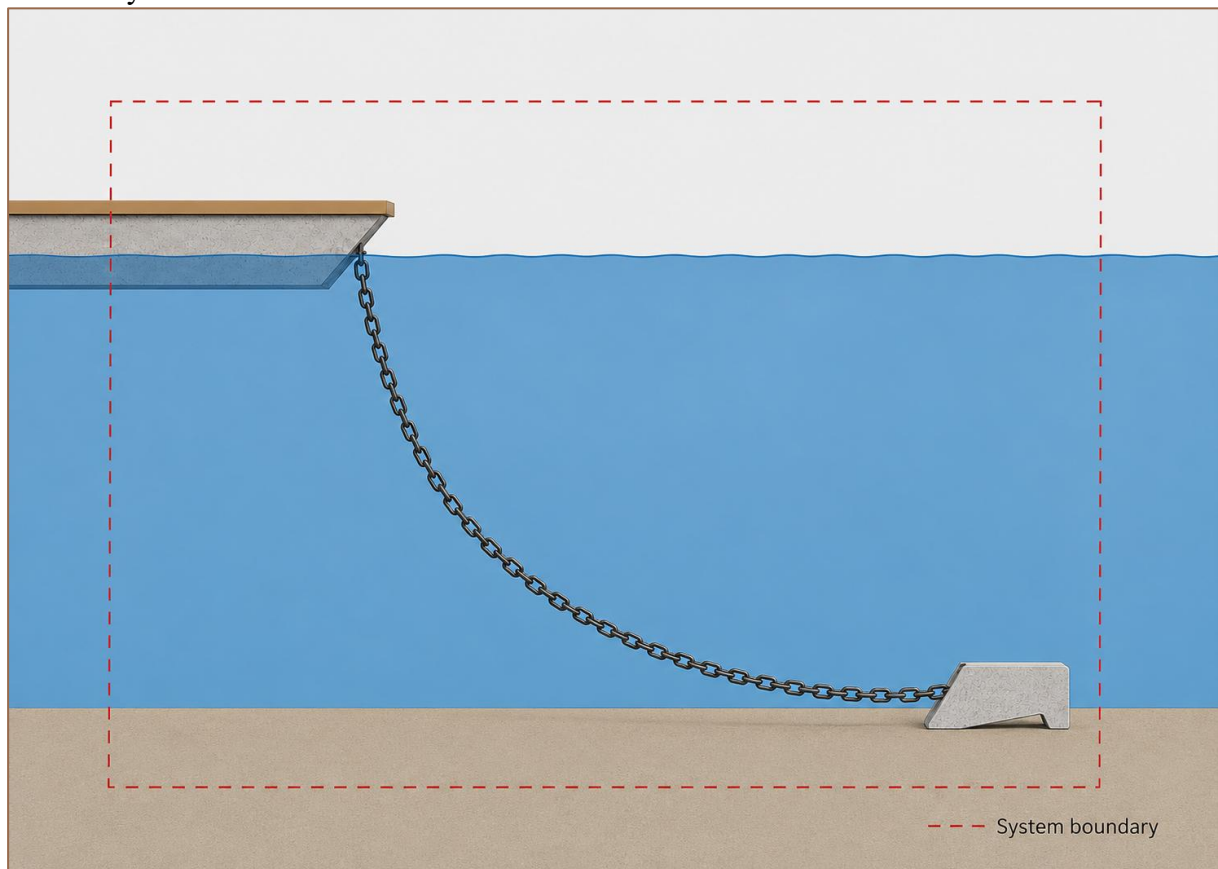


Figure 1, System boundary and load path used in the calculation model.

3.2 Pontoon and fairlead

This thesis considers SF Marina's standard concrete pontoons in the SF1000 to SF2000 range. These pontoons vary in size from approximately 2.40×10.00 m to 8.00×30.00 m, with a typical freeboard between 0.50 m and 0.75 m depending on pontoon type and intended use (SF Marina n.d).

The pontoons are made of reinforced concrete and contain plastic foam, which provides buoyancy and prevents loss of flotation if water enters the structure. The concrete grade is typically C40/50. Depending on the pontoon model, the total pontoon mass ranges from approximately 14 tonnes to 200 tonnes, and the buoyancy capacity ranges from approximately 500 kg/m^2 to 1000 kg/m^2 (SF Marina n.d).

For the anchoring system, the relevant part of the pontoon is the chain attachment point, here referred to as the fairlead. The fairlead defines the upper boundary of the mooring line and determines the vertical position from which the chain is suspended. Its position relative to the water level is therefore important for the chain geometry, the catenary shape, and the resulting line tension. In the calculation model, the pontoon itself is not structurally analysed. It is instead treated as the floating body to which the mooring load is applied (Ma et al., 2019).

3.3 Chain

The mooring chains used in the system are studless chains with nominal diameters ranging from 16 mm to 60 mm. The corresponding catalogue breaking loads range from 160 kN to 2260 kN, while the dry unit weight ranges from approximately 5.6 kg/m to 78.7 kg/m (Ma et al., 2019). Some chains are coated to improve corrosion resistance in marine environments.

The chain forms the connection between the pontoon fairlead and the anchor. Its self-weight is an important part of the physical system, since it determines the catenary shape, the horizontal restoring behaviour, and the uplift angle at the anchor. In the design model, the total chain length is defined from the selected length factor and the governing water depth (Ma et al., 2019). A common initial design assumption used by SF Marina is that the chain length is approximately four times the HAT water depth (W. Sigvardsson, personal communication, January 25, 2026).

3.4 Anchor

The anchor used in this thesis is often labelled as a Pearl Harbor type deadweight anchor (Tsinker 1995), see Figure 2. This anchor type differs from a simple deadweight block because its geometry makes it penetrate or dig into the seabed when loaded horizontally. This can increase the holding capacity compared with a regular concrete deadweight anchor (ONA Marine, 2021).

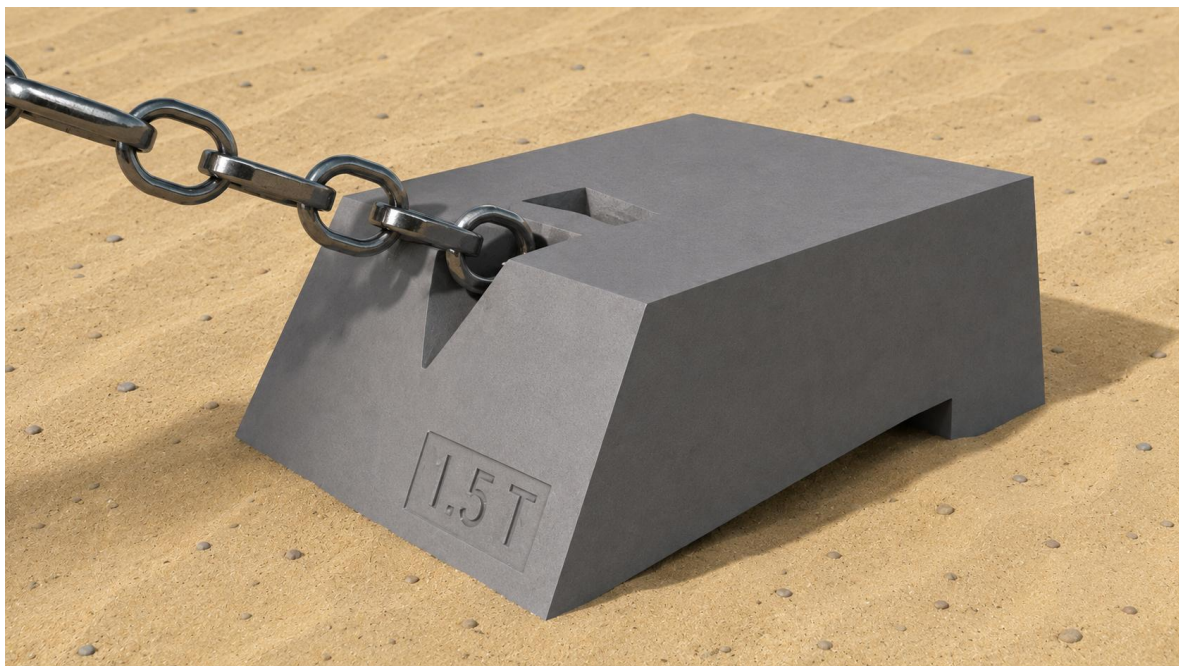


Figure 2, Standard 1.5 tonne SF Marina anchor (without anchor penetration).

However, the anchoring system is not designed to rely on continued anchor movement during service. Significant anchor displacement is considered an unwanted failure mode, since it would change the mooring geometry and increase pontoon movement. The capacity model therefore considers the anchor resistance at the assumed installed position and penetration depth, rather than relying on additional capacity from large drag distances.

The anchor is primarily manufactured from surplus concrete from pontoon production. The normal concrete grade is C40/50, although C20/30 may be used when surplus C40/50 concrete is not available (SF Marina n.d). Since the density difference between these concrete grades is small, the influence on the anchor mass and submerged weight is limited. For the anchoring model, the anchor mass and geometry are therefore more important than the specific concrete strength class.

3.5 Seabed

The seabed is a central part of the physical system because it is the load-bearing medium for the anchor and, in some cases, also interacts with the chain. Although the seabed is not a hardware component, it directly affects the performance of the anchoring system. The forces from the pontoon are transferred through the chain to the anchor, and finally into the seabed.

The mechanical behaviour of the seabed depends on material type, density, strength, friction angle, adhesion, and geometry. Typical seabed materials can range from solid bedrock to granular soils such as sand and gravel, or cohesive soils such as silt and clay. These materials interact with the anchor in different ways, which makes anchor capacity strongly dependent on local ground conditions (Thompson & Beasley, 2012).

For smaller-scale SF Marina installations, detailed geotechnical investigations are not always available before installation (W. Sigvardsson, personal communication, January 25, 2026). In such cases, the seabed type must be simplified into a limited number of representative material categories. This introduces uncertainty in the predicted anchor capacity. The calculation model therefore treats the seabed as homogeneous within the installation area and assumes a flat seabed without slopes, cavities, or local irregularities.

3.6 Water level

The water level is treated as a physical boundary condition rather than a hardware component. It defines the vertical distance between the seabed and the pontoon fairlead and therefore has a direct influence on the chain geometry.

Changes in water level affect the catenary shape, the suspended chain length, the horizontal reach of the mooring line, and the uplift angle at the anchor. A higher water level increases the vertical distance between the fairlead and seabed, while a lower water level reduces it. Both conditions must be considered because the governing chain tension, pontoon offset, and anchor loading may occur at different water levels.

In the calculation model, the relevant water levels are represented by highest astronomical tide (HAT) and lowest astronomical tide (LAT). These values are used to describe the maximum and minimum governing water depths for the analysed mooring case. The surrounding water also affects the submerged weight of both chain and anchor, which is included in the physical assumptions of the model.

3.7 Loads imposed on system

The mooring system is loaded by horizontal forces acting on the pontoon, see figure 3. These loads are mainly caused by wind, waves and current, but can also include operational loads from berthing or moored vessels. In mooring design, both the magnitude and direction of these loads are important, since they determine which mooring lines are loaded and how the force is transferred to the anchor and seabed (Ma et al., 2019).

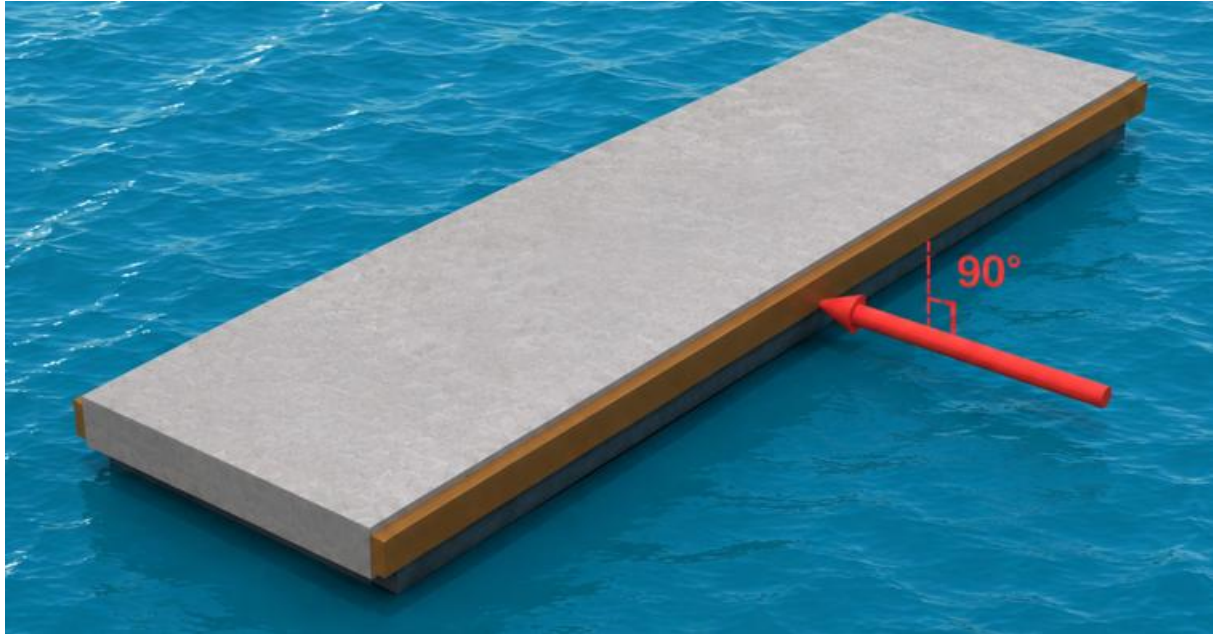


Figure 3, Load direction opposed on pontoon due to environmental- and operational loads.

In this thesis, the external load acting on the pontoon is not calculated inside the developed chain and anchor model. Instead, the resulting horizontal design load is treated as an input. This follows SF Marina's existing workflow, where wind, wave, current and berthing loads are first estimated in a separate load analysis and then used for chain and anchor dimensioning (Lundström, 2022).

For typical sheltered pontoon installations, the environmental load is often strongly influenced by wind acting on the projected area above the water surface. This includes the pontoon itself, but also vessels or other structures connected to it. SF Marina's existing load calculation method therefore includes windage areas for pontoons, vessels and additional structures connected to the pontoon (Lundström, 2022).

Waves and currents may have lower influence in many sheltered marina cases. However, low expected wave heights do not mean that wave loading can always be neglected. Wave loading is dynamic and may introduce both wave-frequency loads and low-frequency drift effects, which can increase pontoon motion and line tension. In some cases, wave-induced forces may therefore become larger than forces from wind or current alone, even if the site is relatively sheltered (Ma et al., 2019).

Berthing loads are treated as separate operational loads. These may govern in cases where a vessel applies a large force to the pontoon during docking or when a vessel is held against the pontoon by thrusters. In the developed model, such loads are treated as equivalent static horizontal design loads, since the prototype does not include time-dependent impact behaviour or dynamic hydrodynamic response.

The load direction also affects how many anchor lines are active. A load acting perpendicular to the pontoon is treated as the governing case, since this normally loads only the anchors on the loaded side of the pontoon. If the load acts at an angle, the force can be distributed between more anchor lines, which is generally less critical (Ma et al., 2019). The model therefore uses the perpendicular load case as a conservative design assumption.

The anchor layout angle, see figure 4, describes the plan-view angle between the pontoon and the anchor position. This should not be confused with the chain uplift angle at the seabed, which is calculated later from the chain geometry.

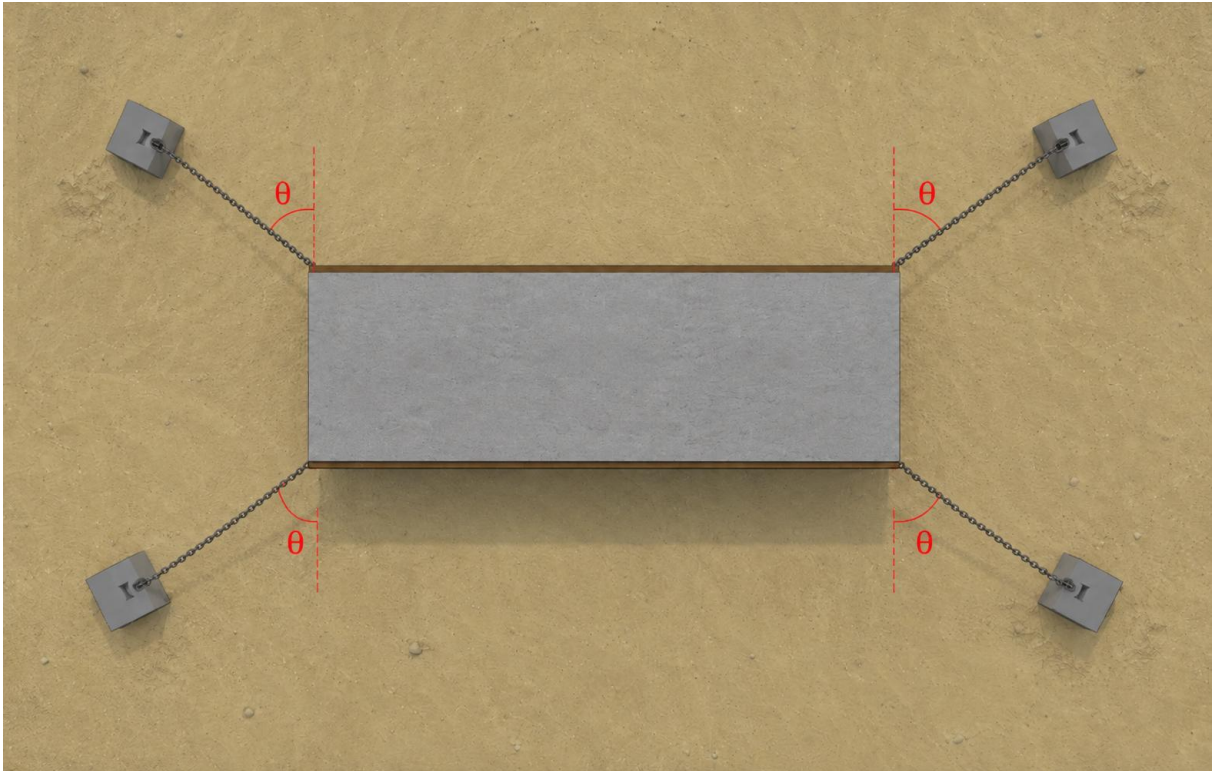


Figure 4, Example of typical SF Marina anchor chain layout.

3.8 Installation constraints

The installation method is an important practical constraint for the anchoring system. It affects which anchor sizes can realistically be used and therefore influences the range of feasible design solutions.

For smaller installations, SF Marina commonly prefers anchors with a mass of approximately three tonnes or less (W. Sigvardsson, personal communication, April 2, 2026). Anchors in this size range can be handled with relatively simple equipment, without requiring large crane vessels. The installation is typically carried out using a small floating raft with an outboard motor. The raft has an opening in the centre, allowing the anchor to be positioned and lowered through the raft.

The installation process normally starts at the dock. A small mobile crane lifts the anchor from land onto the raft, see figure 5, where it is secured with ropes so that it remains suspended in the water during transport. This reduces the load carried directly by the raft and improves manoeuvrability. The intended anchor position is then set by using a pre-measured rope or reference distance from a fixed point, such as the dock or another known reference point.

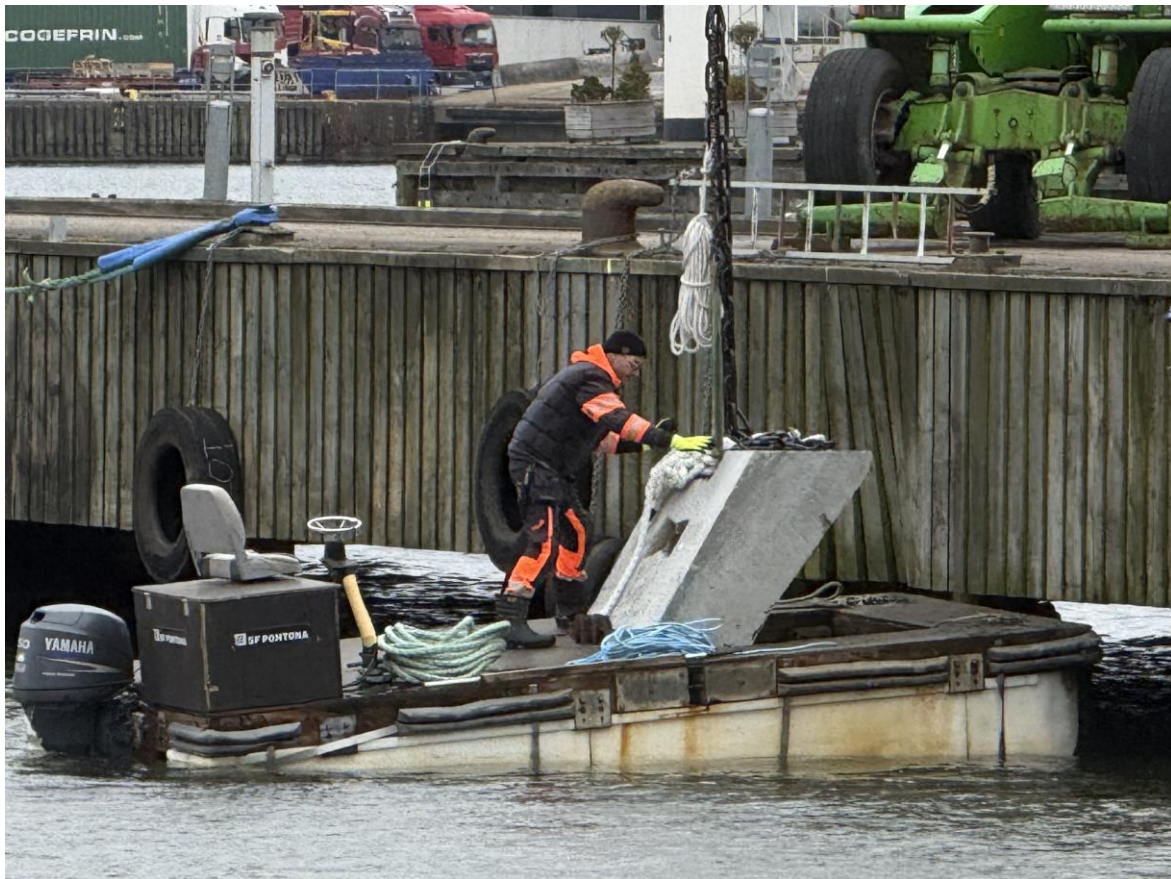


Figure 5, Picture of SF Marina's installation-raft.

The anchor is lowered in a controlled manner by gradually paying out the rope under tension. This reduces the risk of uncontrolled impact with the seabed and gives the operator better control of the anchor position and orientation during deployment. The method is mainly limited by the anchor size and weight. Anchors exceeding three tonnes requires more robust handling equipment (A. Neumeyer, personal communication, April 2, 2026).

For this reason, it is preferable to use several smaller anchors rather than one larger anchor. For example, two three-tonne anchors may be easier to install than one six-tonne anchor. However, the combined holding capacity is not necessarily identical to that of one larger anchor, since load sharing, anchor spacing, and seabed interaction affect the final resistance.

For larger installations, heavier anchors are transported and installed using larger vessels and crane equipment. This allows larger anchor masses to be handled but increases both cost and logistical complexity. Such methods are therefore mainly used when smaller installation methods are not feasible (W. Sigvardsson, personal communication, April 2, 2026).

When seabed conditions allow it, SF Marina attempts to improve anchor penetration during installation (P. Degerman, personal communication, April 2, 2026). This can be done by air jetting around or beneath the anchor, which loosens the surrounding seabed material and allows the anchor to settle further into the soil. The exact penetration depth is normally not measured after installation. Instead, the penetration is estimated from installation experience, often as approximately one third of the anchor height (P. Degerman, personal communication, April 2, 2026).

4. Theory and calculation models

In chapter 4 necessary theory is given to support the calculation behind the model. The calculation model primarily covers equations used for the geometry and behaviour of the chain.

4.1 Mooring system boundary and load path

The calculation model considers the load path from the pontoon fairlead to the seabed anchor, as illustrated in figure 6. The pontoon is treated as the loaded floating body, the chain as the force-transferring element, and the anchor together with the seabed as the resisting part of the system. This follows the general purpose of mooring systems, where the mooring arrangement provides station keeping by resisting environmental and operational loads acting on the floating structure (Ma et al., 2019).

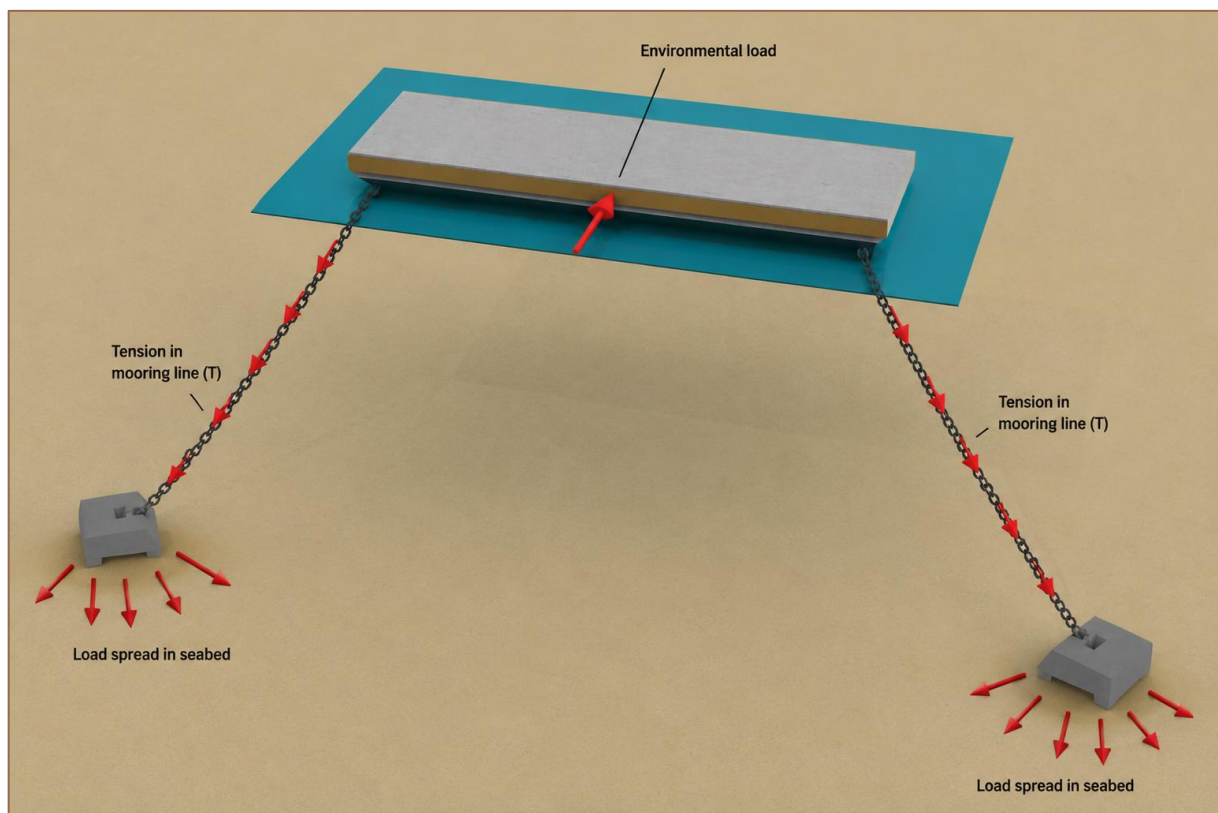


Figure 6, Load path from the pontoon through the mooring lines to the anchors and into the seabed.

The environmental load acting on the pontoon is treated as an external input. The existing SF Anchoring tool separates load analysis from the chain and anchor calculation, where wind, wave, current and berthing loads are first estimated and then used for anchoring dimensioning (Lundström, 2022). The developed model therefore starts from a resulting horizontal design force at the pontoon and evaluates how this force is transferred through the chain to the anchor.

The resulting line tension, chain geometry and uplift angle at the anchor form the basis for the following calculation models. These values are later used to evaluate pontoon displacement, chain strength and anchor capacity.

4.2 Quasi-Static mooring analysis

The chain model is based on a quasi-static mooring analysis. In this approach, the chain is assumed to be in static equilibrium for each evaluated load level, and the line geometry and tension are determined from the position of the fairlead. This is a common simplification for catenary mooring analysis when the focus is on mean load response, line geometry and restoring force rather than time-dependent motion of the floating body (Ma et al., 2019).

The difference between the quasi-static response and a dynamic response is illustrated in figure 7. The quasi-static model represents the equilibrium position caused by the applied horizontal load. A dynamic analysis would also include time-dependent effects such as inertia, damping and wave-frequency motion, which may increase the maximum offset and line tension. Such effects are not solved directly in the chain geometry model, but the selected design load is used as the governing input for the quasi-static calculation.

This approach is suitable for the prototype because the main purpose is to compare feasible anchor and chain combinations using a practical engineering model. The resulting equilibrium position, chain tension and uplift angle are then used in the following sections for displacement checks, chain strength checks and anchor capacity evaluation.

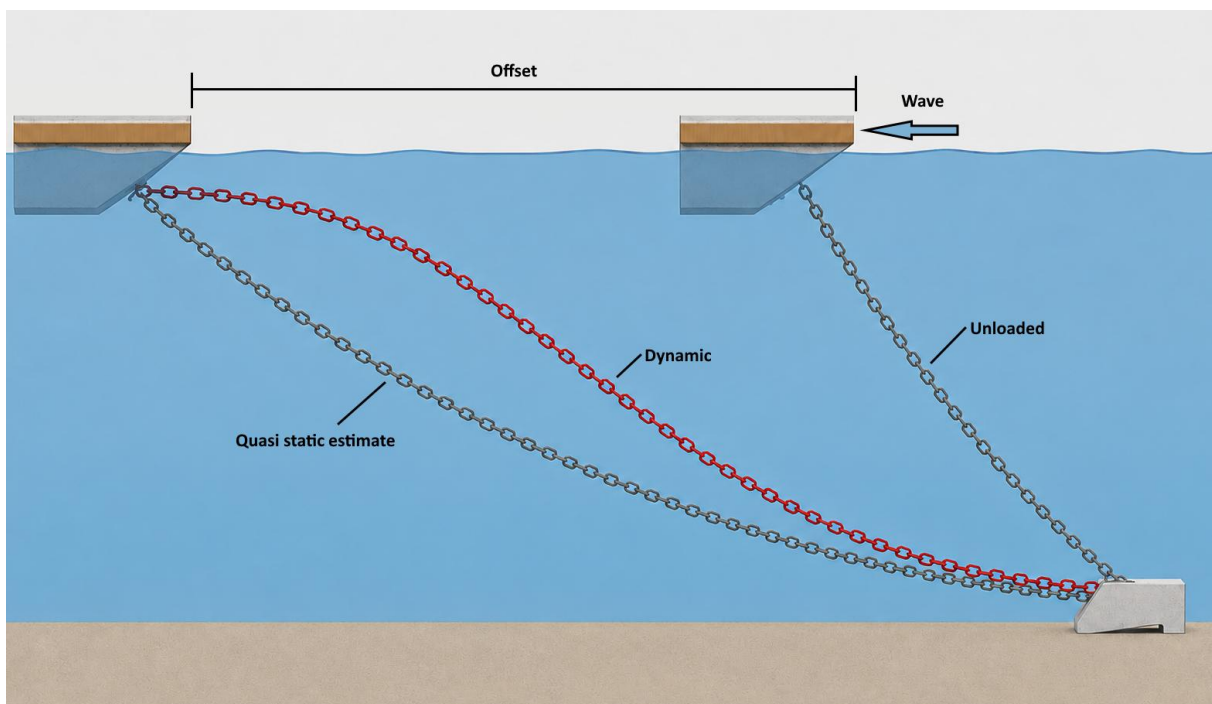


Figure 7, Conceptual difference between quasi-static and dynamic mooring response. Note, chain lengths are not to scale in order to illustrate the differences, Own illustration, concept based on Ma et al. (2019) and Tsinker (1997).

4.3 Chain geometry model

The chain geometry model is based on the static catenary formulation presented by Ma et al. (2019). The chain is treated as a single-material, inelastic mooring line with constant wet weight per unit length. The line bending stiffness and torsional stiffness are neglected, which Ma et al. describe as a reasonable assumption for chains when the radius of curvature is large compared with the chain link size. The coordinate system and the main geometric parameters are shown in figure 8.

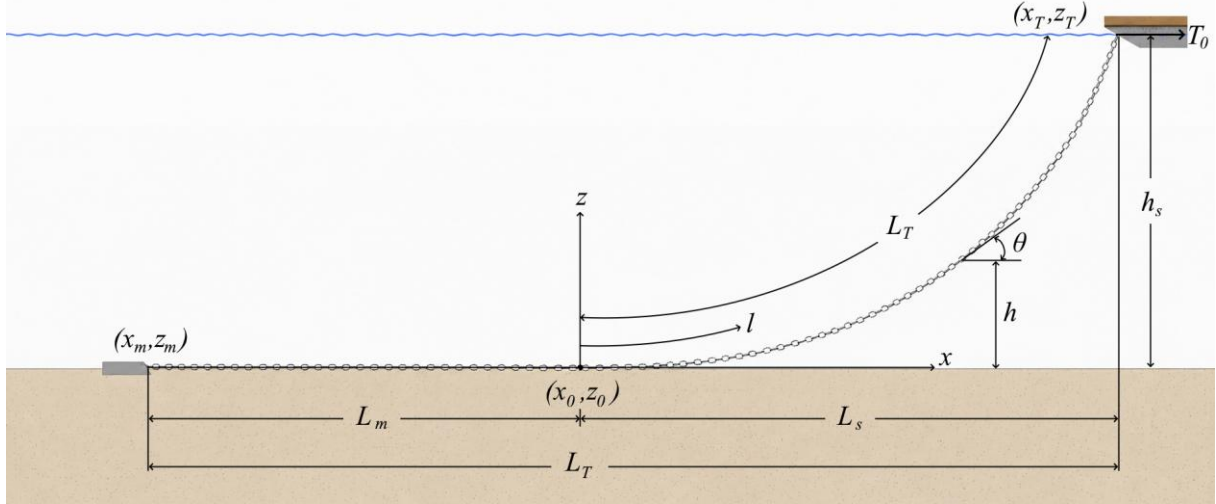


Figure 8, Static catenary geometry and notation used for the chain model. Inspired by Ma et al. (2019).

The origin of the coordinate system is placed at the touchdown point, where the suspended part of the chain first contacts the seabed and the chain angle is zero. The horizontal coordinate is denoted x , the vertical coordinate is denoted h , the suspended arc length is denoted l , the horizontal tension component is denoted T_0 , and the wet chain weight per unit length is denoted P .

The suspended arc length from the touchdown point to a horizontal position x is calculated as:

$$l(x) = \frac{T_0}{P} \sinh \left(\frac{P}{T_0} x \right) \quad (1)$$

The ratio T_0/P corresponds to the catenary parameter commonly denoted a in the classical mathematical catenary equation. In this thesis, the notation from Ma et al. (2019) is kept in the equations to maintain consistency with the mooring theory source.

The corresponding vertical coordinate is calculated as:

$$h(x) = \frac{T_0}{P} \cosh \left(\frac{P}{T_0} x \right) - \frac{T_0}{P} \quad (2)$$

For a known vertical distance h_s between the seabed and the fairlead, the suspended chain length required to form a touchdown point is calculated as:

$$l_s = \sqrt{h_s \left(h_s + 2 \frac{T_0}{P} \right)} \quad (3)$$

Equations (1), (2), and (3) correspond to equations 5.11, 5.12, and 5.13 in Ma et al. (2019). These equations describe the static catenary shape of a single-material inelastic mooring line when dynamic effects and elastic elongation are neglected.

The horizontal distance from the touchdown point to the fairlead is obtained by rearranging equation (2):

$$x_s = \frac{T_0}{P} \cosh^{-1} \left(1 + \frac{Ph_s}{T_0} \right) \quad (4)$$

The total chain length is denoted l_T . If the available chain length is larger than the required suspended length, the remaining chain length is assumed to lie on the seabed:

$$l_m = l_T - l_s \quad (5)$$

where l_m is the chain length resting on the seabed. The total horizontal distance between the anchor and the fairlead is then calculated as:

$$X = l_m + x_s \quad (6)$$

For this case, the chain has a touchdown point and the uplift angle at the anchor is taken as zero:

$$\alpha_a = 0 \quad (7)$$

The tension along the suspended chain section increases with height due to the wet chain weight. The static line tension at height h is calculated as:

$$T(h) = T_0 + Ph \quad (8)$$

At the fairlead, where $h = h_s$, the maximum static tension in the suspended section becomes:

$$T_f = T_0 + Ph_s \quad (9)$$

Ma et al. (2019) describe this relation as the horizontal force plus the suspended submerged chain weight for a chain-only catenary mooring line.

If the total chain length is shorter than the suspended length required to form a touchdown point, no part of the chain is assumed to rest on the seabed:

$$l_T < l_s \quad (10)$$

In this case, the chain is treated as fully suspended between the anchor and the fairlead. The same catenary formulation is used, but the lower end of the suspended chain is now located at the anchor instead of at a touchdown point. Two placeholder variables are introduced:

$$A = \tanh^{-1} \left(\frac{h_s}{l_T} \right) \quad (11)$$

$$B = \sinh^{-1} \left(\frac{Pl_T}{2T_0 \cosh(A)} \right) \quad (12)$$

The lower and upper catenary parameters are then defined as:

$$u_a = A - B \quad (13)$$

$$u_f = A + B \quad (14)$$

Where u_a corresponds to the anchor end and u_f corresponds to the fairlead end. The horizontal distance between the anchor and the fairlead is then calculated as:

$$X = 2 \frac{T_0}{P} B \quad (15)$$

The uplift angle at the anchor is calculated from the local slope of the catenary:

$$\alpha_a = | \tan^{-1}(\sinh(u_a)) | \quad (16)$$

The chain angle at the fairlead is calculated as:

$$\theta_f = \tan^{-1}(\sinh(u_f)) \quad (17)$$

The corresponding line tension at the anchor is:

$$T_a = T_0 \cosh(u_a) \quad (18)$$

and the line tension at the fairlead is:

$$T_f = T_0 \cosh(u_f) \quad (19)$$

The governing chain tension is taken as the maximum static tension in the line:

$$T_{\max} = \max(T_a, T_f) \quad (20)$$

For cases with a touchdown point, the anchor is loaded horizontally, and the fairlead tension is calculated using equation (9). For fully suspended cases, the anchor uplift angle and the end tensions are calculated using equations (16), (18), and (19). The calculated horizontal reach, suspended chain length, anchor uplift angle and maximum chain tension are used in the following sections to evaluate pontoon displacement, chain strength and anchor capacity.

4.4 Pretension and displacement model

The pretension and displacement model uses the catenary equations from Section 4.3 to calculate how the horizontal fairlead position changes between unloaded and loaded conditions. In a catenary mooring system, the mooring line provides a restoring force as the floating body moves away from its initial position. The relationship between line tension, geometry and offset is therefore central to station-keeping analysis (Ma et al., 2019).

The allowed horizontal movement is represented by an envelope radius around the initial pontoon position, as illustrated in figure 9. The model evaluates whether the calculated pontoon displacement remains within this allowable envelope for the considered water levels and load states.

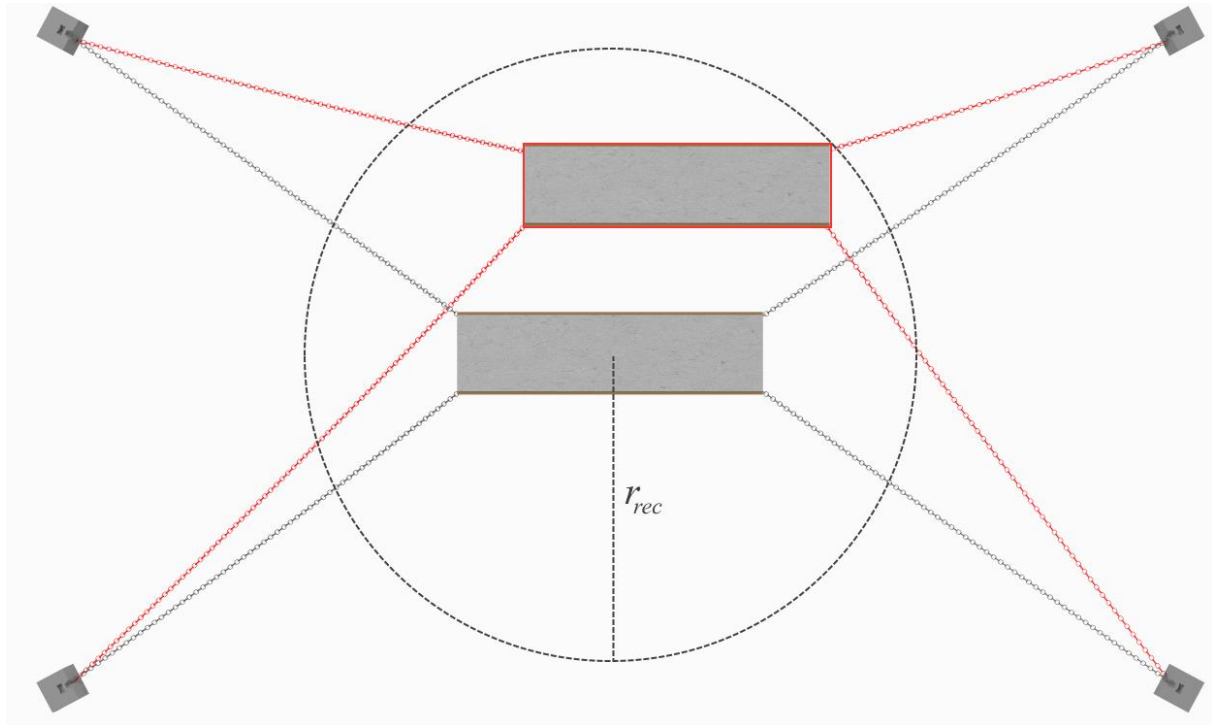


Figure 9, Horizontal displacement envelope used for the pontoon movement criterion.

Pretension is represented as an initial horizontal chain tension:

$$T_{0,pre} = H_{pre} \quad (21)$$

When the external design load is applied, the horizontal chain tension becomes:

$$\frac{T_{0,load}}{\cos \theta} = H_{pre} + T_{env} \quad (22)$$

where H_{pre} is the pretension, T_{env} is the horizontal environmental or operational design load acting on the mooring line and θ is the anchor layout angle discussed in chapter 3.7.

For a given water level, chain length, wet chain weight and horizontal tension, the catenary model gives the horizontal fairlead position as:

$$x_i = f_{cat}(h_i, l_T, P, T_{0,i}) \quad (23)$$

where f_{cat} represents the chain geometry model described in Section 4.3.

The model evaluates the fairlead position for both pretension and loaded conditions at high and low water levels:

$$x_{HAT,pre} = f_{cat}(h_{HAT}, l_T, P, T_{0,pre}) \quad (24)$$

$$x_{LAT,pre} = f_{cat}(h_{LAT}, l_T, P, T_{0,pre}) \quad (25)$$

$$x_{HAT,load} = f_{cat}(h_{HAT}, l_T, P, T_{0,load}) \quad (26)$$

$$x_{LAT,load} = f_{cat}(h_{LAT}, l_T, P, T_{0,load}) \quad (27)$$

The total horizontal span between the governing positions is calculated as:

$$S_x = \max(x_i) - \min(x_i) \quad (28)$$

The required envelope radius is then:

$$r_{req} = \frac{S_x}{2} \quad (29)$$

The displacement criterion is fulfilled when:

$$r_{req} \leq r_{allow} \quad (30)$$

where r_{allow} is the maximum allowable horizontal displacement radius. The minimum required pretension is defined as the lowest value of H_{pre} that satisfies Equation (30) for all evaluated water levels and load states:

$$H_{pre,min} = \min(H_{pre}) \quad \text{such that} \quad r_{req} \leq r_{allow} \quad (31)$$

This formulation allows the pretension to be treated as a design variable. A higher pretension reduces the movement between unloaded and loaded conditions, but it also increases the static load in the chain and anchor. The calculated pretension is therefore carried forward to the chain strength and anchor capacity checks.

4.5 Chain strength model

The chain strength check is performed by comparing the maximum calculated line tension with the minimum breaking load of the selected chain. The minimum breaking load is taken from catalogue values based on the nominal chain diameter and chain grade. Chain grade and diameter are commonly used to define the strength class of offshore mooring chain (Ma et al., 2019).

The governing chain tension is defined as the maximum line tension from all evaluated load cases:

$$T_{chain,max} = \max(T_i) \quad (32)$$

where T_i is the maximum line tension for load case i .

The selected chain has a catalogue minimum breaking load:

$$MBL = MBL(d, g) \quad (33)$$

where d is the nominal chain diameter and g is the chain grade.

The chain is accepted if:

$$T_{chain,max} \leq MBL \quad (34)$$

A simple chain factor of safety is calculated as:

$$FoS_{chain} = \frac{MBL}{T_{chain,max}} \quad (35)$$

This value is used as an output measure to show the margin between the calculated maximum chain tension and the catalogue breaking load.

5. Anchor Capacity Model

In this chapter, the calculations and reasoning behind the Anchor holding capacity is presented. The model estimates the anchor resistance based on geometry, penetration and interaction with the seabed.

5.1 Analytical holding capacity formulation

The anchor capacity model is based on the analytical holding-capacity model for the Pearl Harbor Anchor presented by Lin and Nakamura (1993). The model describes the horizontal holding capacity as the sum of three resistance components, these are the base resistance, the front resistance and the side resistance. The SF anchor is treated as a Pearl Harbor style concrete anchor, but its geometry is represented using the scaled anchor drawing shown in figure 10.

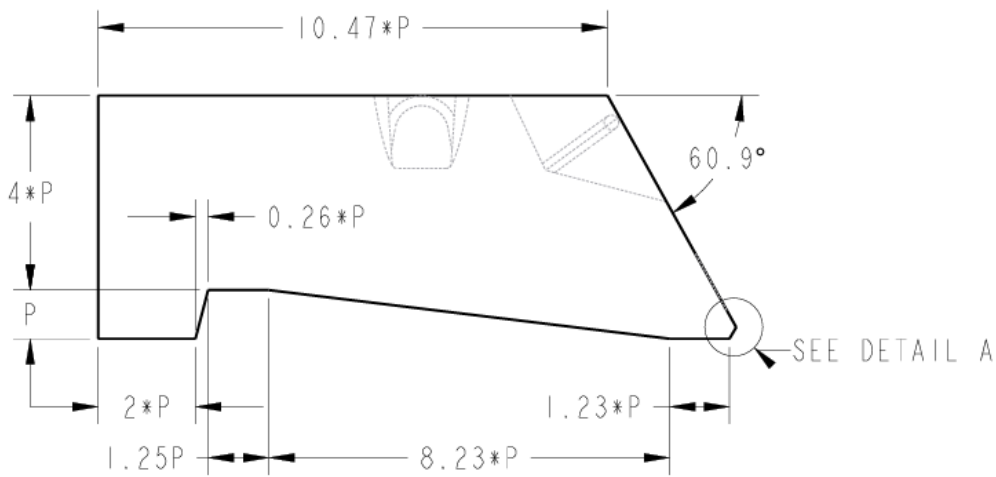


Figure 10, Parametrization of anchor, to support different anchor sizes.

For zero uplift angle, the horizontal anchor capacity is calculated as:

$$Q_0 = F_b + F_f + F_s \quad (36)$$

where Q_0 is the horizontal anchor capacity, F_b is the base resistance, F_f is the front resistance and F_s is the side resistance.

The base resistance is calculated as:

$$F_b = (W' + W_s)\mu + A_b c_a \quad (37)$$

where W' is the submerged anchor weight, W_s is the weight of soil on top of the anchor, μ is the coefficient of friction, A_b is the base contact area and c_a is the adhesion between the anchor and the soil.

The front resistance is calculated as:

$$F_f = A_f (0.5K_p \gamma D N_q + c_u N_c) \quad (38)$$

where A_f is the front projected area, K_p is the passive earth pressure coefficient, γ is the soil unit weight, D is the penetration depth, N_q and N_c are bearing capacity factors and c_u is the undrained shear strength of the soil.

The side resistance is calculated as:

$$F_s = 0.5 \cdot \gamma \cdot D \cdot K_0 \cdot \mu \cdot A_s + 2A_s \cdot c_a \quad (39)$$

where K_0 is the coefficient of earth pressure at rest and A_s is the anchor side area in contact with the soil. Equations (36) to (39) follow the resistance-component structure used by Lin and Nakamura (1993).

The submerged anchor weight is calculated as:

$$W' = (\gamma_c - \gamma_w)V \quad (40)$$

where γ_c is the unit weight of concrete, γ_w is the unit weight of water and V is the concrete volume of the anchor. In the present model, the anchor is not assumed to be covered by soil. The soil weight on top of the anchor is therefore set to:

$$W_s = 0 \quad (41)$$

The anchor drawing uses the scale parameter P . In this notation however, the same parameter is denoted p_a to avoid confusion with the wet chain weight P used in Section 4.3. The drawing defines the anchor volume as:

$$V = 645.2712p_a^3 \quad (42)$$

and the cross-sectional area as:

$$A_{cs} = 53.7726p_a^2 \quad (43)$$

where p_a is given in metres.

The base contact area is taken from the plan dimensions in the drawing:

$$A_b = 10.47p_a \cdot 12p_a \quad (44)$$

$$A_b = 125.64p_a^2 \quad (45)$$

The front projected area is taken as:

$$A_f = 2p_a \cdot 12p_a \quad (46)$$

$$A_f = 24p_a^2 \quad (47)$$

The side area used in the simplified resistance model is represented as:

$$A_s = 5p_a^2 \quad (48)$$

where A_s represents one side surface. The side-resistance expression in Equation (39) includes both side surfaces through the adhesion term.

The small heel at the lower back edge of the anchor is not modelled as a separate resistance component. It is expected to influence penetration and initial engagement with the seabed but assigning it an independent passive front resistance for example would require assumptions about local soil failure that are not included in the analytical model. The toe is therefore included only through the scaled anchor geometry and not through an additional projected resistance area.

The model from Lin and Nakamura (1993) is used as a horizontal-capacity model. For cases where the chain applies an uplift angle at the anchor, the horizontal capacity is reduced using an angle-dependent reduction factor:

$$Q_{\alpha} = \eta_{\alpha} Q_0 \quad (49)$$

where Q_{α} is the available anchor capacity at uplift angle α_a , and η_{α} is the reduction factor for the calculated uplift angle. The uplift angle α_a is obtained from the chain geometry model in Section 4.3.

The anchor is accepted if the available capacity is greater than or equal to the calculated anchor line load:

$$T_a \leq Q_{\alpha} \quad (50)$$

A simple anchor factor of safety is calculated as:

$$FoS_{anchor} = \frac{Q_{\alpha}}{T_a} \quad (51)$$

where T_a is the calculated line tension at the anchor. The soil parameters used in Equations (37) to (39) are described in Section 5.2, while the generated capacity tables are described in Section 5.3.

5.2 Seabed parameters

The anchor capacity depends strongly on the seabed material. In detailed anchor design, soil parameters should normally be based on geotechnical investigation, laboratory testing or in-situ testing. However, smaller marina installations are often planned with limited seabed information. The available site information may only describe the general seabed type, such as clay, sand, gravel or rock. For this reason, the model uses simplified seabed categories rather than site-specific soil profiles.

Each seabed type is represented by a single set of soil parameters. This means that the seabed is assumed to be homogeneous within the installation area. The model also assumes a horizontal seabed without local slopes, cavities or large irregularities. These assumptions simplify the calculation, but they also introduce uncertainty because the actual seabed may vary locally. This uncertainty is important because the seabed properties directly affect friction, adhesion, passive soil resistance and therefore the required anchor weight.

For cohesionless seabeds, such as sand and gravel, the main parameters are soil unit weight, friction angle and interface friction. For cohesive seabeds, such as clay and silt, the main parameters are undrained shear strength, adhesion and soil unit weight. This follows the general distinction between sandy soils, where resistance is mainly governed by submerged

unit weight and internal friction, and clayey soils, where undrained shear strength is an important parameter (Ma et al., 2019).

The seabed categories used in the model are based on the level of information that is normally available during preliminary design basis (W. Sigvardsson, personal communication, January 25, 2026). The purpose is therefore not to describe the exact geotechnical behaviour of a specific site, but to provide a practical estimate of how different seabed assumptions influence anchor capacity. If reliable site-specific soil data are available, the tabulated parameters should be replaced by project-specific values.

Bedrock is treated separately from soil-based seabeds. The analytical resistance terms in the Pearl Harbor anchor model are based on soil interaction and are therefore not directly valid for exposed rock. For rock seabeds, anchor capacity depends more on installation method, surface roughness, anchor seating and any additional reinforcement such as drilling or dowelling. Rock cases should therefore be interpreted with greater caution than soil cases.

5.3 Anchor capacity tables

The anchor capacity model is evaluated outside the main mooring solver and stored in capacity tables. The tables contain pre-calculated anchor capacities for different anchor weights, seabed types, penetration depths and uplift angles. This allows the main program to use the anchor model through a lookup procedure rather than recalculating the full analytical model during every design iteration.

The use of capacity tables has two main advantages. First, it makes the program faster and easier to inspect, since the calculated capacities can be reviewed separately from the chain solver. Second, it makes the anchor model easier to update. If new soil parameters, anchor dimensions or penetration assumptions are introduced, the capacity tables can be regenerated without changing the main calculation logic.

For each anchor size and seabed type, the zero-angle holding capacity is first calculated from the base, front and side resistance components. The capacity is then reduced for increasing uplift angle using the angle-dependent reduction factor described in Section 5.1. This gives a tabulated capacity Q_α for each evaluated uplift angle.

During the design calculation, the chain model provides the line tension and uplift angle at the anchor. The program then selects the corresponding capacity from the table for the chosen seabed type and anchor weight. If the calculated uplift angle falls between two tabulated values, the nearest conservative table value should be used. The anchor is considered acceptable if the tabulated capacity is greater than or equal to the calculated line tension.

The capacity tables are therefore the link between the analytical anchor theory and the practical component selection in the prototype. They allow the program to compare available anchor weights in a discrete and transparent way, while still accounting for the influence of seabed type and uplift angle.

6. System description: Program logic

This chapter describes how the calculation models are connected in the developed prototype. The purpose is not to repeat the theoretical background of the chain model, pretension model, strength check or anchor capacity model, but to describe how these parts are combined into one calculation sequence. The program is structured to evaluate practical combinations of chain dimensions and anchor weights for a defined mooring case.

The calculation is performed as an iterative candidate evaluation, see figure 11. Each available chain dimension is tested using the same site conditions, load input and design criteria. For each chain candidate, the program calculates the required pretension, evaluates the resulting chain states, applies the relevant design checks and determines the required anchor weight from the capacity tables. The accepted alternatives are then compared according to the selected optimisation objective.

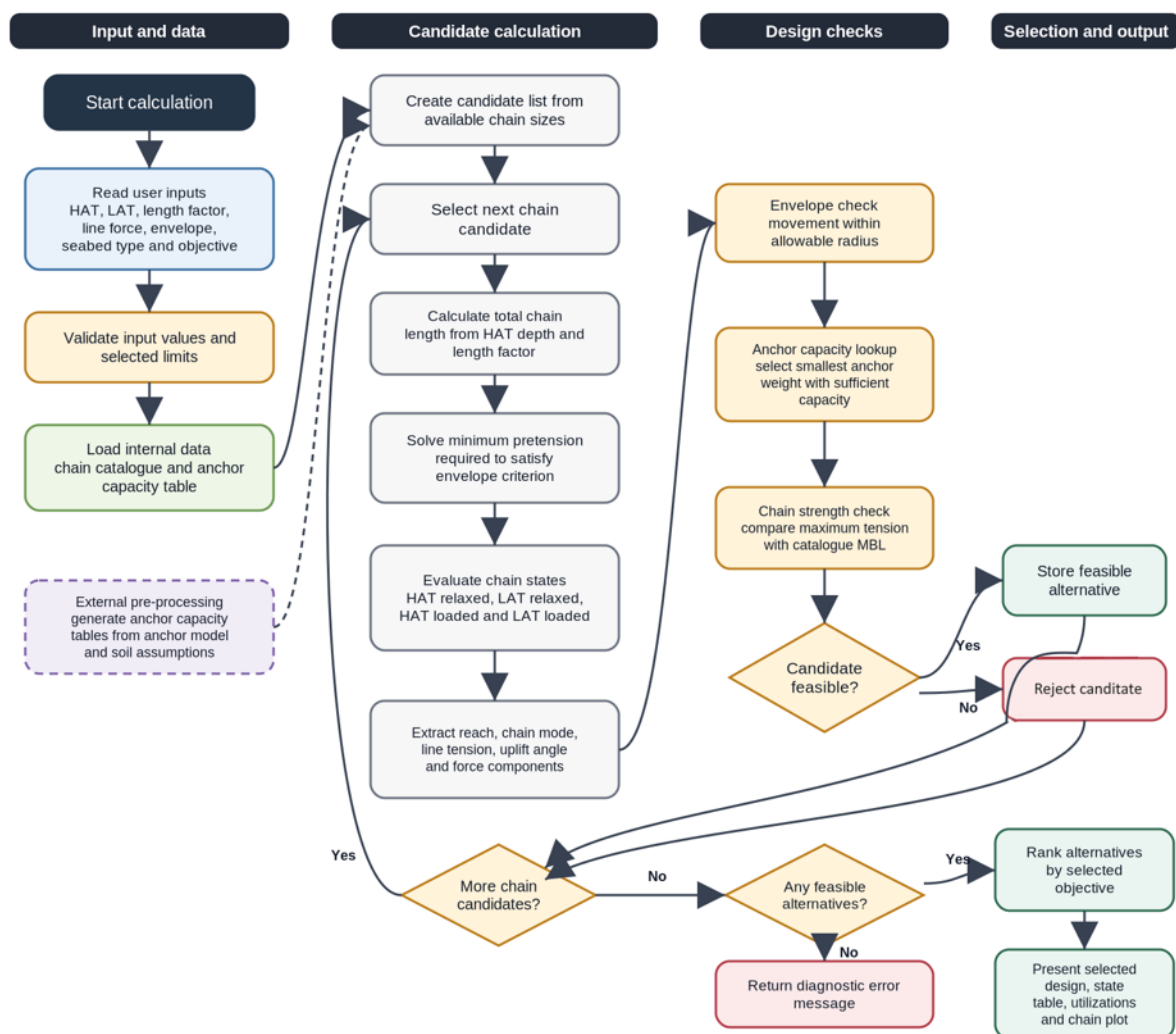


Figure 11, Block diagram of program logic.

6.1 Program structure and data flow

The program starts by reading the user-defined input values and the internal data required for the calculation. The user input defines the specific design case, while the internal data defines the available component alternatives and the tabulated anchor capacities. Before the calculation starts, the input values are checked so that the selected water levels, load values, chain length factor, displacement envelope and seabed option can be used in the following calculation steps.

The internal data is kept separate from the main calculation routine. Chain properties are stored as catalogue values, and anchor capacities are stored in pre-generated lookup tables. This separation makes the program easier to update because available chain sizes, anchor weights or capacity tables can be changed without changing the overall calculation sequence. The main solver therefore acts as a coordinating routine, where previously defined models and data sources are called in a fixed order.

After the input and internal data have been loaded, the program creates a list of chain candidates. Each candidate contains the chain properties needed for the following calculations. The anchor weight is not fixed at this stage. Instead, it is determined later by comparing the calculated anchor load with the available capacity values.

6.2 Candidate evaluation loop

Each chain candidate is evaluated independently. The program first calculates the total chain length for the candidate using the selected chain length factor and the governing water depth. This gives one fixed installed chain length, which is then used for all evaluated water levels and load states.

The next step is to determine the minimum pretension required for the candidate. The program increases the pretension until the calculated movement satisfies the displacement envelope requirement. This makes the pretension part of the design solution rather than a fixed input value. If the required pretension cannot be found within the allowed calculation range, the candidate is rejected and the program continues with the next chain size.

When a pretension value has been found, the program evaluates the chain response for the defined calculation states. These states represent the relevant combinations of water level and loading condition used in the design check. For each state, the program stores the calculated chain configuration, horizontal reach, line tension and uplift angle at the anchor. These values are then passed on to the feasibility checks.

The candidate loop is important because the effect of changing chain size is not limited to chain strength. A heavier or lighter chain also changes the geometry, the required pretension and the resulting load angle at the anchor. The program therefore evaluates each chain size through the full calculation sequence rather than checking chain strength alone.

6.3 Feasibility checks and anchor selection

After the chain states have been calculated, the program checks whether the candidate satisfies the design requirements. The displacement envelope is checked first. If the calculated movement is larger than the allowable value, the candidate is not accepted.

The anchor check is then performed using the calculated line tension and uplift angle from the chain evaluation. For each state, the program searches the relevant capacity table and

identifies the smallest anchor weight with sufficient capacity. Since several states are evaluated, the required anchor weight for the candidate is taken as the largest anchor weight required by any of the states. This ensures that the selected anchor is sufficient for the governing condition.

The chain strength check is performed using the maximum line tension obtained from the evaluated states. This value is compared with the catalogue strength of the selected chain. If the calculated tension exceeds the accepted strength criterion, the candidate is rejected. Only candidates that pass the displacement, anchor capacity and chain strength checks are stored as feasible alternatives. For each feasible candidate, the program stores the selected chain dimension, required anchor weight, required pretension and the governing calculated values. This makes it possible to compare complete chain-anchor combinations rather than treating the chain and anchor as separate design choices.

6.4 Ranking, output and diagnostic feedback

When all chain candidates have been evaluated, the program ranks the feasible alternatives according to the selected objective. If the objective is to minimize anchor weight, the program selects the feasible alternative with the lowest required anchor weight. If the objective is to minimize chain weight, the program instead selects the lightest feasible chain alternative. Secondary values are used to separate alternatives when several candidates give the same primary result.

The selected design is presented together with the values needed to interpret the result. The summary output includes the selected chain dimension, required anchor weight, pretension, maximum line tension, anchor utilisation, chain utilisation and governing state. A more detailed state-by-state output is also generated so that the user can see how the selected solution behaves in each evaluated condition.

The program also generates a chain profile plot. This is used as a visual check of the calculated chain geometry and makes it easier to identify whether the selected solution is mainly governed by a slack-chain condition, a partially lifted chain or a fully suspended chain.

If no feasible alternative is found, the program returns a diagnostic message instead of a selected design. The message is intended to indicate which part of the calculation prevented a solution, for example an overly strict displacement envelope, insufficient available anchor capacity, an uplift angle outside the available table range or a chain strength limitation. This feedback is important because it helps the user identify whether the input case should be adjusted or whether additional component alternatives are required.

7. Results

This chapter presents the results from the developed mooring design model and its implementation as a calculation prototype. The purpose of the results chapter is to show how the calculation model behaves when applied to representative input data. The chapter therefore focuses on the output generated by the prototype, rather than repeating the theoretical background.

7.1 Developed prototype

A functional Python-based prototype was developed to evaluate mooring chain and anchor combinations for floating concrete pontoons. The prototype combines the catenary chain model, pretension calculation, displacement envelope check, chain strength check and anchor capacity lookup into one calculation workflow.

The program evaluates available chain dimensions and anchor weights as discrete component alternatives. This means that the output is based on practical catalogue values rather than idealized continuous dimensions. The selected design is therefore directly connected to available chain sizes and predefined anchor weight intervals.

The graphical user interface is divided into three main areas, see figure 12. The input panel contains the main design parameters, including HAT depth, LAT depth, chain length factor, horizontal environmental force, allowable envelope radius, seabed type and optimisation objective. The graph area presents the calculated chain profiles for the evaluated load states. The output area presents the selected design and detailed results for each evaluated state.

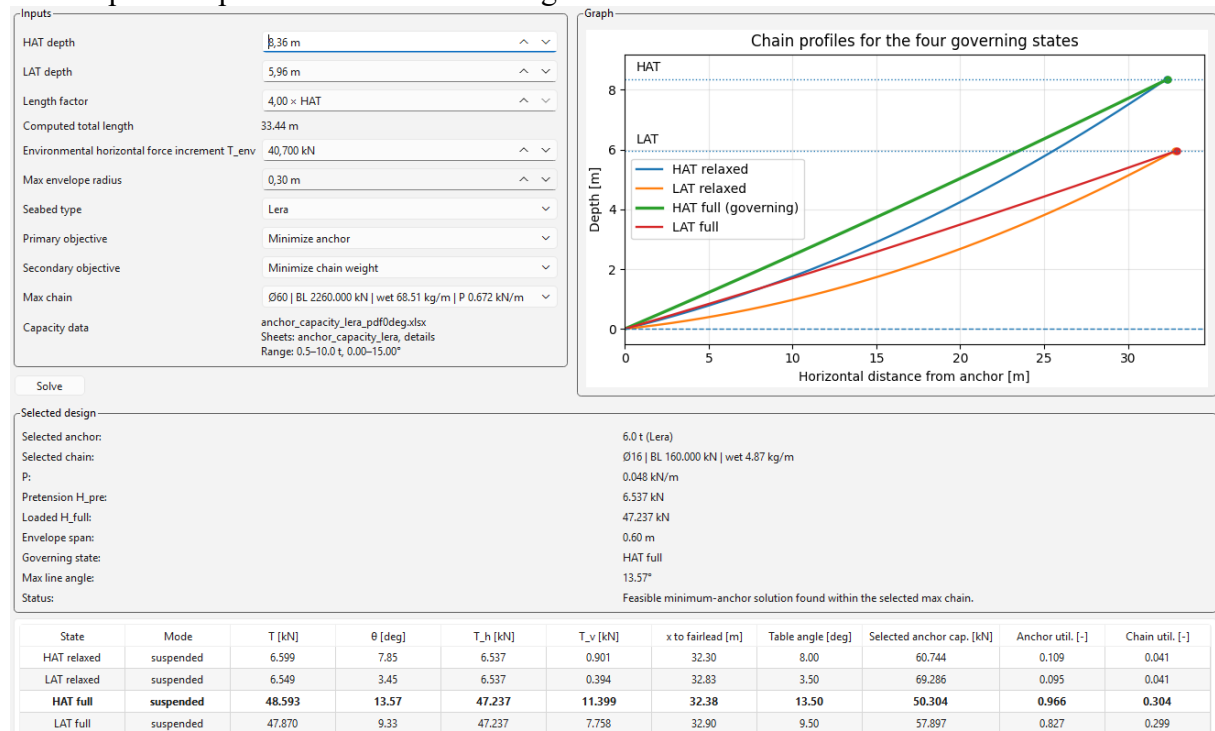


Figure 12, Prototype of user interface and how the result could be presented.

The prototype returns both a summary of the selected design and a detailed state-by-state output. The summary includes selected anchor weight, selected chain dimension, submerged chain weight per meter, required pretension, loaded horizontal force, envelope span, governing load state and maximum line angle. The detailed output includes chain mode, line tension, uplift angle, horizontal and vertical force components, horizontal reach, selected anchor capacity, anchor utilisation and chain utilisation.

The result of the development work is therefore a prototype that can compare feasible mooring alternatives automatically. Instead of manually checking one chain and anchor combination at a time, the program scans the available component alternatives and selects a feasible solution according to the chosen optimisation objective.

7.2 Numerical validation anchor capacity model

The generated anchor capacity tables were validated by comparison with numerical simulations in PLAXIS 2D. PLAXIS 2D is a finite element program used for two-dimensional geotechnical analysis, including soil deformation, stability, and soil-structure interaction problems (Seequent n.d). The purpose of the comparison was to evaluate whether the analytically generated capacity values were within the same range as a more detailed numerical model.

The validation was carried out for clay, sand, and gravel, corresponding to seabed material types found in the Gothenburg archipelago. Ten values were randomly selected from the generated anchor capacity tables. For each selected case, an equivalent model was created in PLAXIS 2D using the same anchor geometry, anchor weight, soil parameters, penetration depth, load angle, and interface assumptions as in the analytical model. The anchor was modelled as a concrete body embedded in the selected seabed material, and the holding capacity was evaluated using displacement-controlled pullout simulations, see figure 13. The capacity from PLAXIS 2D was taken from the plateau region of the resulting force-displacement curve.

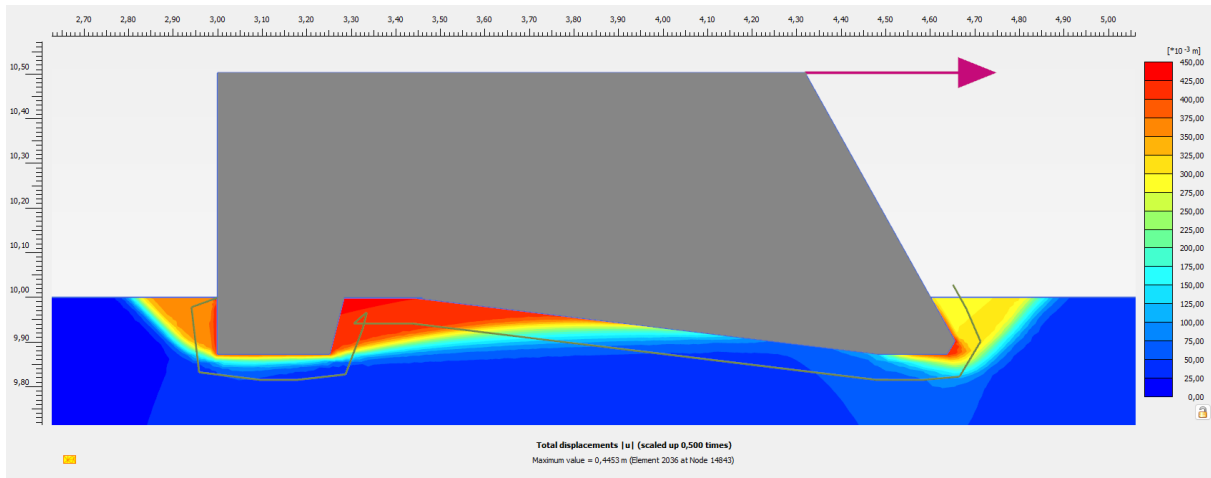


Figure 13, PLAXIS 2D simulation of anchor holding capacity. Note. Figure created by the author using PLAXIS 2D.

Since PLAXIS 2D gives results per meter out-of-plane width, see figure 14, the numerical results were converted to total anchor capacity using the corresponding anchor width from the anchor geometry. The converted PLAXIS 2D capacities were then compared with the corresponding values from the generated capacity tables.

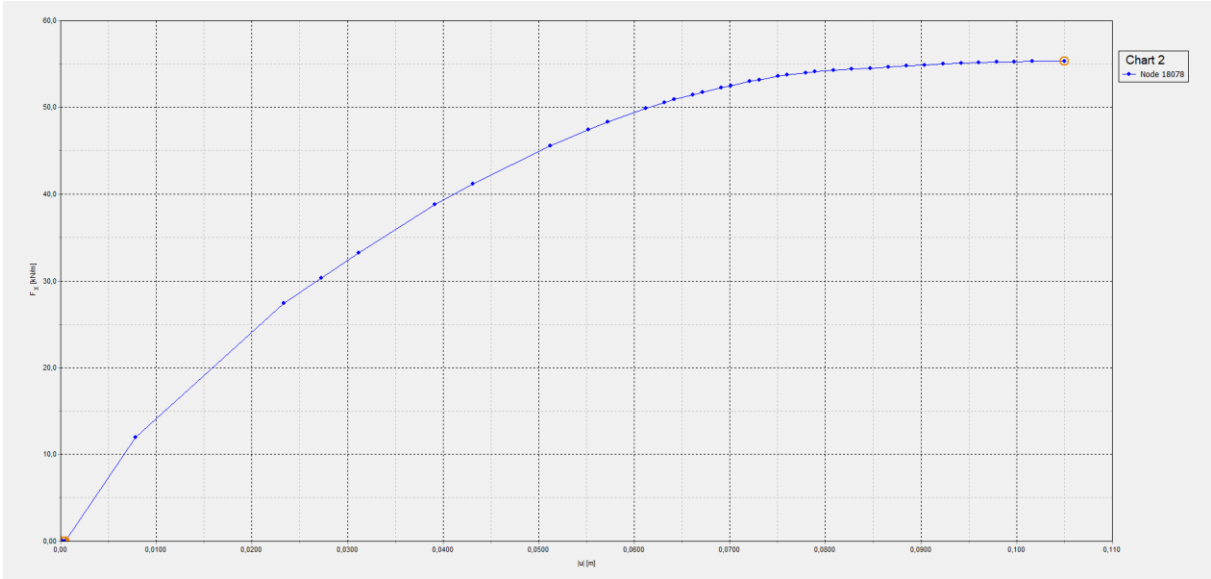


Figure 14, example output of PLAXIS 2D showing relation between holding capacity and seabed penetration.

The comparison showed good agreement between the two methods. During the PLAXIS 2D simulations, the anchor displayed the expected behaviour described by Lin and Nakamura (1993), where the nose of the Pearl Harbor Anchor rotates downward and digs into the seabed during loading, see figure 15. For the ten evaluated cases, the PLAXIS 2D simulations gave capacities that were on average 6.7% lower than the values obtained from the analytical capacity model. This indicates that the generated anchor capacity tables are consistent with the numerical model for the evaluated cases. The lower capacities obtained from PLAXIS 2D also suggest that the analytical model gives slightly higher, but still comparable, capacity estimates under the tested conditions.

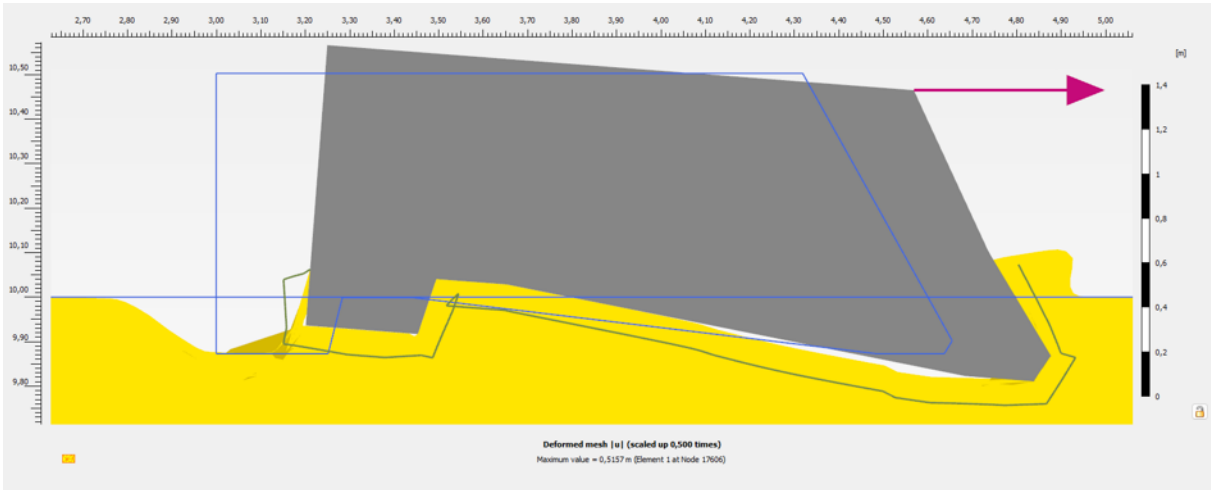


Figure 15, displacement output plot from PLAXIS 2D showing the anchor digging into the seabed.

7.3 Reference case

The reference case used in this chapter is based on the proposed anchoring solution for the ferry berth at Sjumansholmen in the Gothenburg archipelago. The case was selected because it represents a real installation scenario with defined external load requirements, water levels, seabed assumptions and proposed anchoring layout.

The proposed installation layout is shown in figure 16. The pontoon is positioned adjacent to the existing berth structure and restrained by several mooring chains connected to 3-tonne deadweight anchors placed around the pontoon. The proposed solution uses 30 mm mooring chain for the anchor lines. The dashed lines represent the mooring chains, while the red squares indicate the proposed 3-tonne anchor positions. The governing anchor legs are arranged with a plan-view angle of 12° and are intended to counteract the berthing loads from the Styröbolaget ferry.

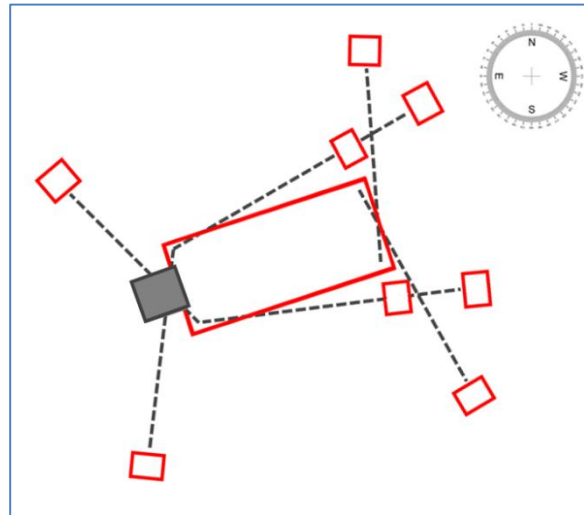


Figure 16, Proposed anchoring layout for the Sjumansholmen reference case.

The studied pontoon was analysed for a constant horizontal load of 200 kN. This load represents the specified berthing load from a Styröbolaget ferry approaching and mooring at the berth (S. Jansson, personal communication, April 15, 2026). Since no time history, duration or detailed dynamic load description was available, the load was treated as an equivalent static design load. This is consistent with the quasi-static modelling approach used in the prototype.

The load direction was defined relative to the pontoon geometry and the anchor layout. In the reference case, the governing load was applied perpendicular to the pontoon, while the selected anchor legs were arranged with a plan-view angle of 12° . This angle was included directly as an input in the prototype and used when distributing the applied load to the governing anchor lines.

The water depth at normal water level was taken as 3.00 m. A high-water addition of 1.45 m was then applied, giving a maximum analysed water depth of 4.45 m (SMHI. 2023). In the prototype, these values were entered as the lower and upper governing water levels.

7.4 Chain geometry results

Four chain states were evaluated: relaxed and loaded conditions at the lower analysed water level, and relaxed and loaded conditions at the upper analysed water level. This makes it possible to study both the effect of the applied load and the effect of water level variation on the chain profile.

The calculated chain profiles are shown in figure 17. The upper water level with full applied load was found to be the governing chain geometry case. This state produced the largest line tension and the largest uplift angle at the anchor. The result is expected, since the upper water level increases the vertical distance between the seabed and the pontoon fairlead, while the applied horizontal load stretches the chain and reduces the amount of chain resting on the seabed.

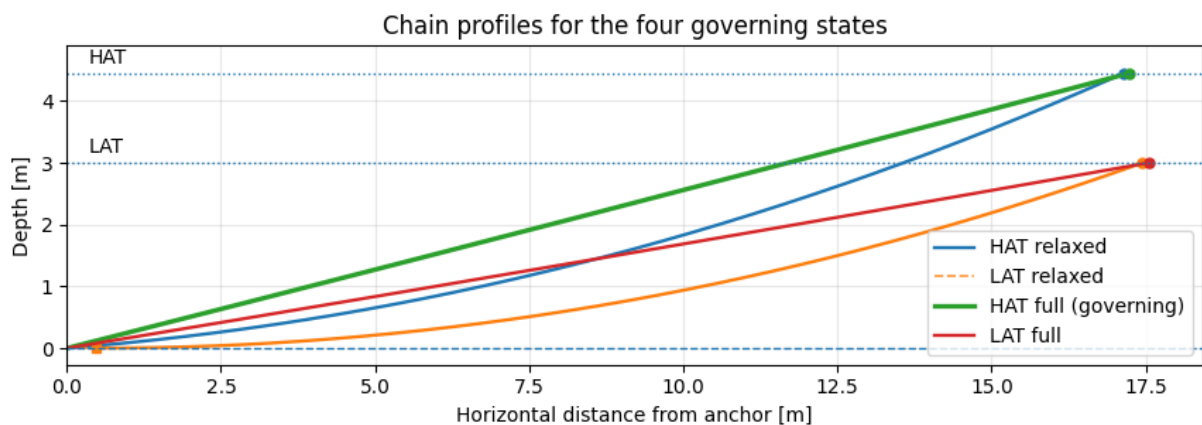


Figure 17 Chain profiles for the four governing states in the Sjumansholmen reference case.

The required pretension in the analysed anchor leg was calculated to be 3.2 kN. This pretension was sufficient to keep the calculated pontoon movement within the specified displacement envelope. The maximum line tension in the chain was 108.7 kN, occurring in the loaded upper-water state. The corresponding maximum uplift angle at the anchor was 14.18° , and the maximum horizontal force component at the anchor was 105.46 kN.

The main chain geometry results are summarized in table 1.

Result parameter	Value
Chain dimension	30 mm
Required pretension	3.2 kN
Maximum chain tension	108.7 kN
Maximum horizontal force at anchor	105.46 kN
Maximum uplift angle at anchor	14.18°
Governing chain state	Upper water level, full load

Table 1, Chain geometry results from Sjumansholmen reference case.

The chain strength check shows that the proposed 30 mm chain is not governing for the reference case. Assuming chain grade R3, the safety factor against chain breakage is approximately 7.7. This is significantly higher than the required safety level for the studied load case, which indicates that the proposed chain is conservative with respect to breaking load.

7.5 Anchor capacity results

The governing chain state resulted in a maximum horizontal force component of 105.46 kN and an uplift angle of 14.18° at the anchor. These values were therefore used as the design load for the anchor capacity check.

The prototype selected a 3-tonne Pearl Harbor type deadweight anchor for the governing anchor leg. The selected anchor size was evaluated against the calculated horizontal force component and the corresponding uplift angle from the chain analysis. The result shows that the required anchor capacity is governed by the loaded upper-water state, which also produced the highest chain tension and the largest uplift angle.

The calculated anchor capacity was strongly dependent on the assumed penetration depth. At low penetration depths, the available anchor resistance was below the required holding force. As the penetration depth increased, the resistance from soil contact, front bearing and side adhesion increased, which improved the calculated safety factor.

The resulting safety factor against anchor sliding is shown in figure 18. The safety factor reached 1.00 at approximately 0.17 m penetration. This indicates that the selected 3-tonne anchor reaches equilibrium with the governing horizontal anchor load at this penetration depth. Higher safety levels require larger penetration depths. A safety factor of 1.25 was reached at approximately 0.23 m, a safety factor of 1.67 at approximately 0.32 m, and a safety factor of 2.00 at approximately 0.40 m.

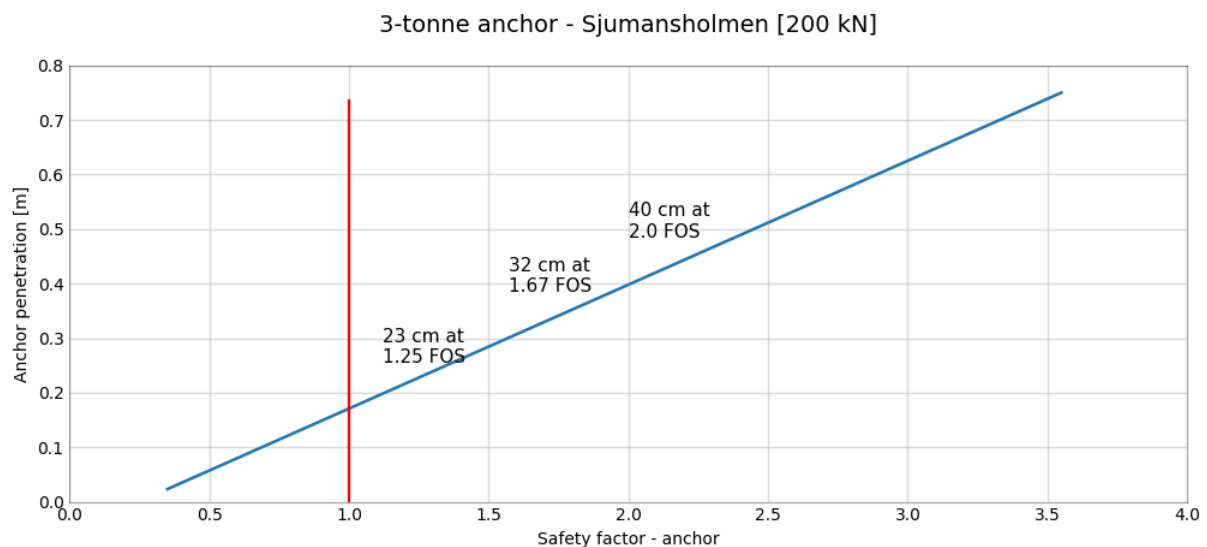


Figure 18, Calculated safety factor against anchor sliding as a function of penetration depth for the selected 3-tonne anchor.

The results show that the selected 3-tonne anchor is feasible if sufficient penetration is achieved during installation. However, the capacity margin is highly sensitive to penetration depth. This means that the installation procedure is important for the final performance of the anchoring system. If the anchor is placed directly on the seabed without meaningful penetration, the calculated holding capacity may be insufficient for the governing reference load.

7.6 Broad comparison with previous SF Marina anchoring layouts

A broader comparison was carried out to evaluate whether the prototype produced chain and anchor selections within the same practical range as previous SF Marina anchoring layouts. In total, 174 individual anchor legs from five previous SF Marina projects were analysed. The broader comparison included anchoring layouts from several previous SF Marina projects located in different Swedish coastal environments. The evaluated layouts included Malagakajen in Skärhamn, Mor Annas brygga in Trolldalen on Lidingö, Rävsnäs harbour in Norrtälje municipality, Donsö Djuphamn in the Gothenburg archipelago and a project in Karlskrona. Together, these layouts covered a wide range of anchoring configurations, including different pontoon arrangements, anchor-leg directions, chain dimensions and anchor weights. An example of the drawing type used in the comparison is shown in Figure 19, where the Rävsnäs layout specifies Ø38 mm chain and 3 tonne anchors (SF Pontona Sverige AB, 2020).

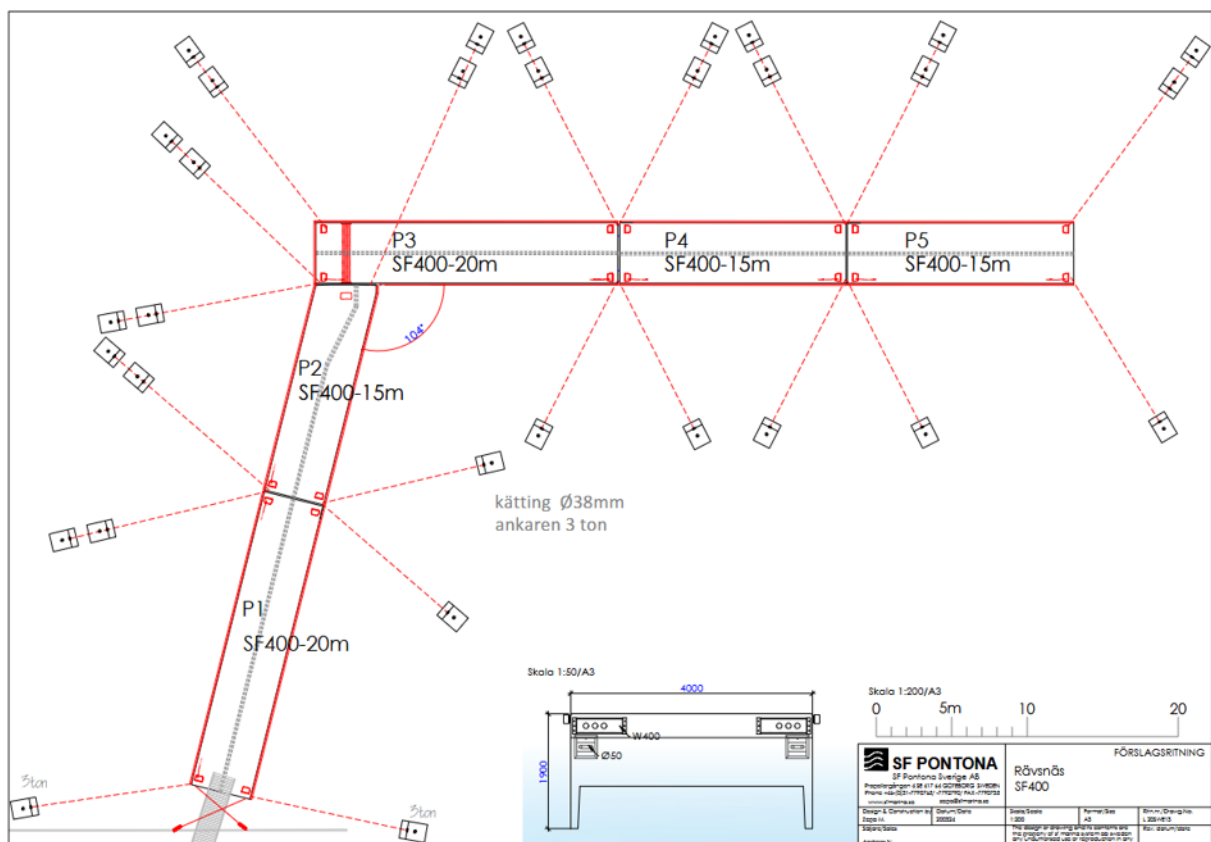


Figure 19 One out of five previous SF Marina installations, where anchor sizes were analysed and compared to prototype calculator. Note. Reproduced from internal drawing provided by SF Marina (2020). Internal company material, not publicly available.

The purpose of this comparison was not to reproduce each previous installation identically. Instead, it was used to evaluate whether the prototype produced results that were consistent with the general sizing level used in practice. This distinction is important because the original environmental load assumptions for these installations were not available in the same way as for the detailed reference case. The comparison was therefore interpreted as a broad engineering plausibility check rather than a direct validation of each individual anchor leg.

Figure 20 shows the comparison between anchor weights selected by the prototype and the anchor weights specified in the SF Marina drawings. The anchor weights in the evaluated drawings were 2, 3, 6 and 10 tonnes. The results show good overall agreement between the prototype and the drawing-based anchor selections. The same anchor weight was selected in 72.4% of the evaluated anchor legs. In 23.6% of the cases, the prototype selected a lower anchor weight than the drawing, while a higher anchor weight was selected in 4.0% of the cases. The mean ratio between drawing-based anchor weight and prototype-selected anchor weight was 1.155. This indicates that the prototype generally selected slightly lower anchor weights, while still following the same overall sizing trend.

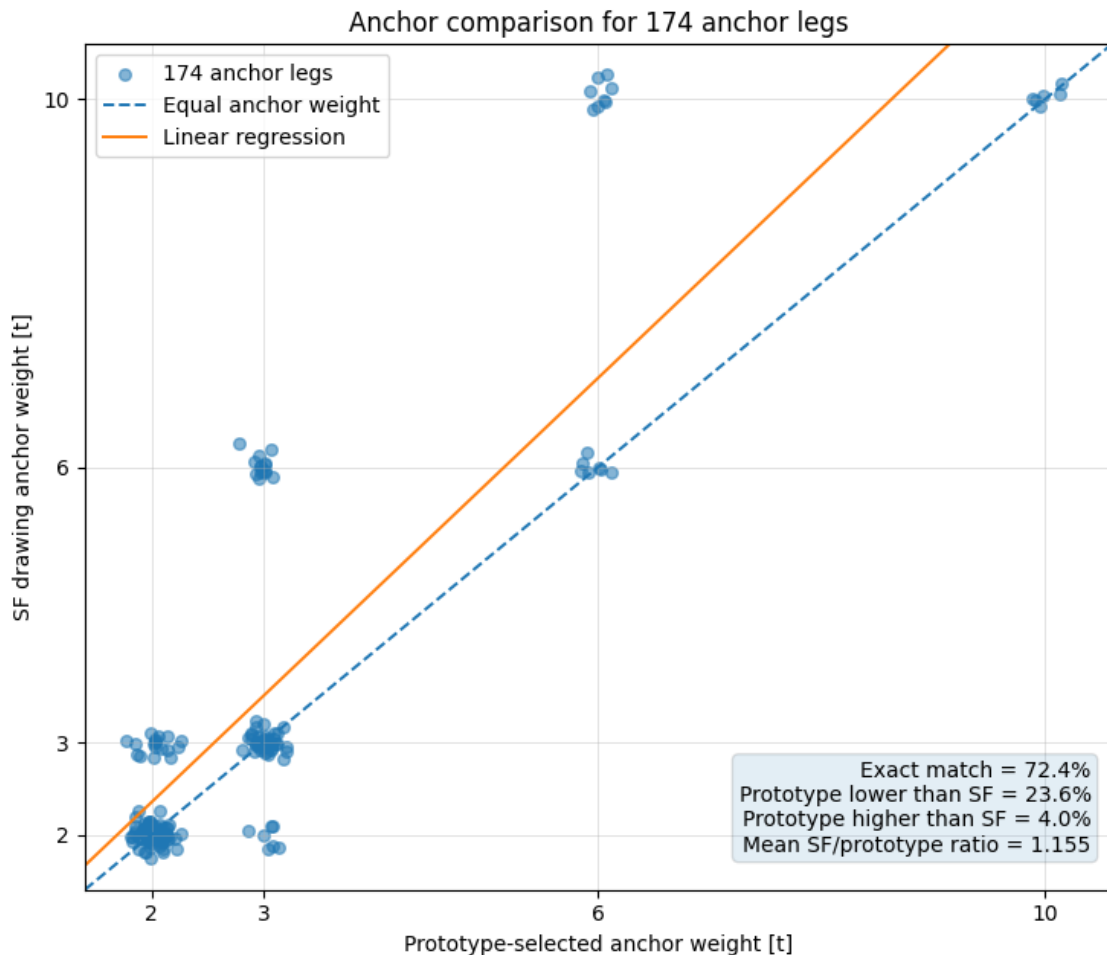


Figure 20, Comparison of anchor weights from five previous SF Marina installations to prototype-selected anchor weights.

The anchor comparison shows that the prototype captures the general anchor-weight level used in previous SF Marina layouts. Most points are located close to the equal-weight line, especially for the common 2 and 3 tonne anchor cases. Larger deviations occur mainly where the prototype moves one anchor class below the drawing-based selection, for example from 6 tonnes to 3 tonnes or from 10 tonnes to 6 tonnes. This is expected because the prototype selects from discrete anchor sizes, meaning that relatively small differences in calculated utilisation can result in a step change in selected anchor weight.

Figure 21 shows the corresponding comparison for chain dimensions. In contrast to the anchor-weight comparison, the chain comparison shows a clearer trend where the SF Marina drawings use larger chain dimensions than the prototype. The mean ratio between drawing-based chain dimension and prototype-selected chain dimension was 1.484. This means that the chain dimensions in the previous SF Marina layouts were, on average, approximately 48% larger than the dimensions selected by the prototype.

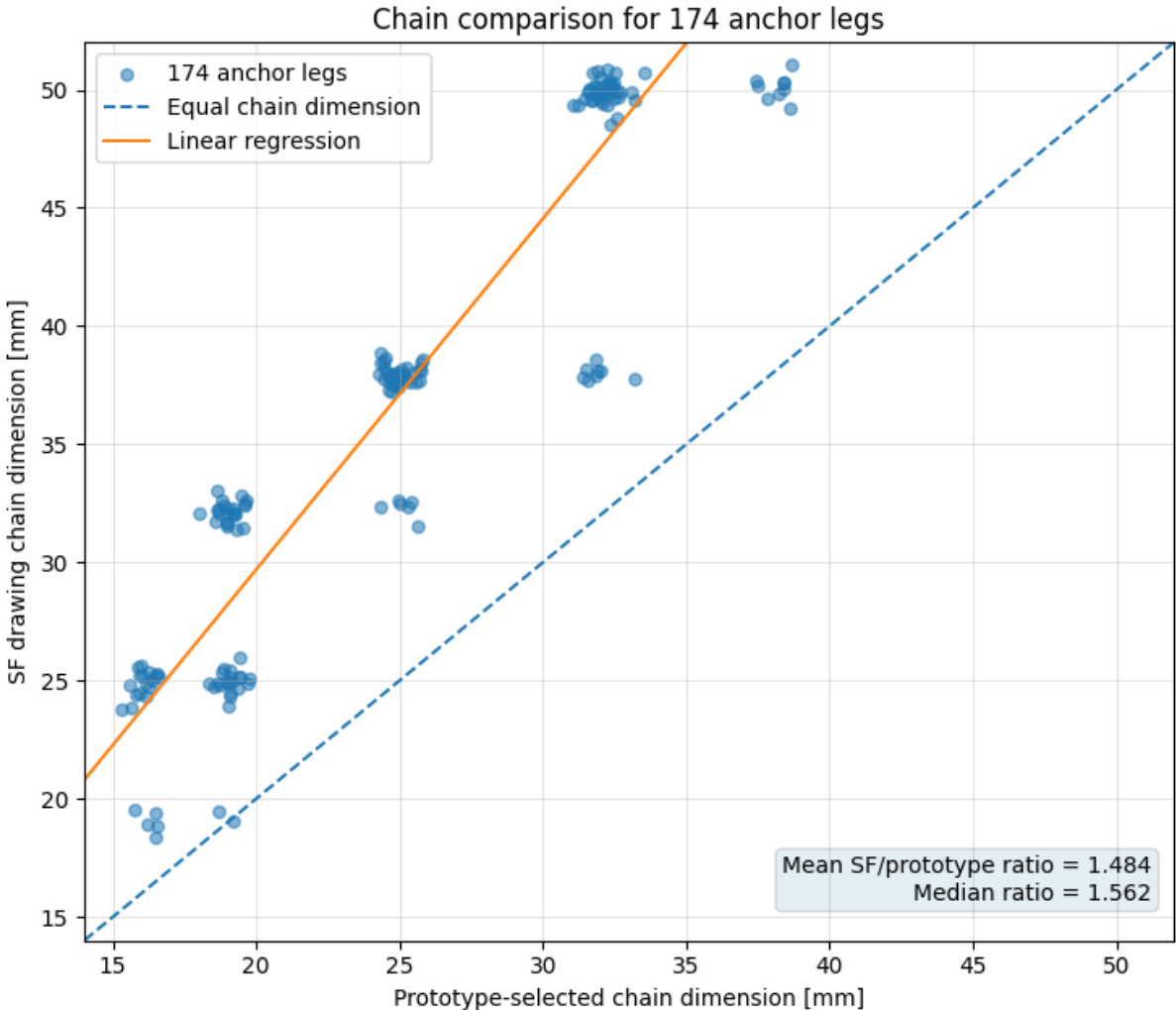


Figure 21 Comparison of chain dimension from five previous SF Marina installations to prototype-selected chain dimensions.

This difference is mainly explained by the difference between practical anchoring design and the simplified chain criterion used in the prototype. In practice, a larger chain dimension does not only increase the minimum breaking load. It also increases the submerged chain weight, which contributes to the catenary effect and provides additional damping in the mooring system. This effect is considered in SF Marina's practical design approach, but it is not included as a separate dynamic criterion in the prototype. The prototype only checks the selected chain against minimum breaking load with an applied safety factor (W. Sigvardsson, personal communication, March 2, 2026).

The chain comparison should therefore not be interpreted as showing that the previous SF Marina chain dimensions are incorrect. Instead, it shows that the prototype selects smaller chain dimensions when the selection is governed mainly by strength. The larger chain dimensions used in previous layouts can be understood as a result of practical robustness, dynamic damping, handling margins and standardisation of available chain sizes. The result also highlights a limitation of the prototype: it can evaluate whether a chain has sufficient strength, but it does not fully evaluate the dynamic benefit of using a heavier chain.

Overall, the broad comparison supports the use of the prototype as an early-stage design tool. The anchor-weight comparison showed good agreement with previous SF Marina layouts, while the chain comparison indicated that the prototype generally selected smaller chain dimensions than those used in the evaluated drawings. The results therefore suggest that the prototype is able to reproduce the general anchoring scale used in practice, while also identifying cases where existing design practice includes additional conservatism that is not fully represented in the current calculation model.

7.7 Summary of key results

The results show that the developed prototype can evaluate a complete mooring design case by combining chain geometry, pretension, displacement envelope, chain strength and anchor capacity in one workflow. The prototype produces practical output values such as selected chain dimension, selected anchor weight, required pretension, line tension, uplift angle, anchor utilisation and chain utilisation. This makes it possible to compare complete chain-anchor combinations instead of evaluating the chain and anchor separately.

The numerical validation of the anchor capacity model showed good agreement between the analytical capacity tables and the PLAXIS 2D simulations. For the ten evaluated cases, the PLAXIS 2D simulations gave capacities that were on average 6.7% lower than the analytically generated capacity values. This indicates that the generated anchor capacity tables are consistent with the numerical soil-anchor model for the evaluated cases, although the analytical model gave slightly higher capacity estimates.

The Sjumansholmen reference case showed that the prototype produced a result that was consistent with the proposed SF Marina anchoring solution. The proposed design used 30 mm mooring chain and 3-tonne deadweight anchors, which corresponded well with the prototype result. The required pretension was calculated to 3.2 kN, and the maximum chain tension was 108.7 kN. The governing chain state occurred at the upper water level with full applied load, where the maximum uplift angle at the anchor was 14.18° and the maximum horizontal force component at the anchor was 105.46 kN.

The chain strength check showed that the chain was not the governing component in the reference case. For the proposed 30 mm chain, the calculated safety factor against chain breakage was approximately 7.7 when using R3 chain quality. This indicates that the chain had a large strength margin for the studied load case. The anchor capacity was more sensitive to the assumed seabed penetration. The selected 3-tonne anchor reached a safety factor of 1.00 at approximately 0.17 m penetration, 1.25 at approximately 0.23 m, 1.67 at approximately 0.32 m and 2.00 at approximately 0.40 m. This shows that the anchor capacity result depends strongly on the achieved penetration depth during installation.

The broader comparison with previous SF Marina layouts included 174 individual anchor legs from five projects. The anchor-weight comparison showed good overall agreement between the prototype and the drawing-based anchor selections. The same anchor weight was selected in 72.4% of the evaluated anchor legs. In 23.6% of the cases, the prototype selected a lower anchor weight than the drawing, while a higher anchor weight was selected in 4.0% of the cases. The mean ratio between drawing-based anchor weight and prototype-selected anchor weight was 1.155. This indicates that the prototype generally selected slightly lower anchor weights, while still following the same overall sizing trend as the previous SF Marina layouts.

The chain comparison showed a clearer difference between the prototype and the drawing-based selections. The mean ratio between drawing-based chain dimension and prototype-selected chain dimension was 1.484, meaning that the chain dimensions used in the previous SF Marina layouts were approximately 48% larger than the dimensions selected by the prototype. This result is mainly explained by the fact that the prototype only checks the chain against minimum breaking load with an applied safety factor. In practical SF Marina design, a larger chain dimension also increases submerged chain weight, which contributes to the catenary effect and provides additional damping in the mooring system (W. Sigvardsson, personal communication, March 2, 2026).

Overall, the results support the use of the prototype as an early-stage design support tool. The PLAXIS 2D comparison supports the generated anchor capacity tables, the reference case shows agreement with an existing SF Marina anchoring proposal, and the broader comparison shows that the prototype produces anchor and chain selections within the same practical range as previous SF Marina layouts. At the same time, the results show that the prototype should not be interpreted as a complete replacement for detailed design. The main remaining uncertainties are related to seabed conditions, anchor penetration, installation quality and dynamic damping effects that are not fully represented in the current quasi-static model.

8. Discussion

This chapter discusses results, model and uncertainties in the thesis are discussed. The primary goal of the discussion chapter is to reflect on whether the result and thesis are believable or not. The parts of the thesis that makes it less believable are mainly presented under uncertainties.

8.1 Interpretation of results

The results from the reference case indicate that the developed prototype can produce a feasible mooring solution that is broadly consistent with the proposed design for the Sjumansholmen installation. The prototype selected a 3.0-tonne anchor and a 30 mm mooring chain, which agrees reasonably well with the proposed anchoring solution used as reference input. This indicates that the calculation model gives results that are in line with existing engineering judgement at SF Marina.

However, this agreement should not be interpreted as a complete validation of the model. The proposed design is itself based on practical experience, assumptions and available project information, rather than on full-scale measured anchor loads or verified anchor capacity tests. The comparison therefore mainly shows that the model produces results within a realistic practical range. It does not prove that the calculated safety margins are exact.

The results should therefore be interpreted as a qualitative validation rather than a quantitative validation. The model appears suitable for early-stage design support and comparison of alternative mooring configurations. For final design, especially in projects with high consequence of failure or strict documentation requirements, additional verification is still required.

A key result from the reference case is that the chain was not the governing component. The selected 30 mm chain had a large safety margin against breakage. Instead, the governing uncertainty was related to the anchor capacity and the assumed penetration depth in the seabed. This shows the importance of including seabed-dependent anchor capacity in the design process, rather than relying only on simplified deadweight efficiency factors.

8.2 Reliability of the chain model

The chain model is considered the most reliable part of the developed calculation procedure. The catenary behaviour of a mooring chain is well established, and the governing equations are based on force equilibrium and chain self-weight. Compared with the anchor capacity model, the chain model contains fewer uncertain empirical assumptions.

The main input parameters affecting the chain result are water depth, total chain length, submerged chain weight, applied horizontal load and pretension. These parameters can normally be defined with reasonable accuracy. The chain breaking load is also available from chain catalogues, which makes the strength check more straightforward than the anchor capacity check.

The largest uncertainty in the chain model is not the catenary formulation itself, but how accurately the real installation corresponds to the model input. The actual anchor position, fairlead height, chain length, seabed level and pretension may deviate from the assumed values. These deviations can affect the calculated pontoon movement and uplift angle at the anchor.

The model also assumes a simplified two-dimensional chain profile for each evaluated line. This is appropriate for the intended use of the prototype, but it does not capture all possible three-dimensional effects in a full mooring layout. For example, interaction between several mooring lines, oblique loading, seabed irregularities and installation tolerances may affect the actual response of the system.

Despite these limitations, the chain model is considered suitable for the intended level of analysis. It provides a consistent method for calculating chain geometry, line tension, uplift angle and displacement envelope. These results are also useful as input to the anchor capacity check, where the uplift angle and horizontal anchor load are important design parameters.

8.3 Anchor, Seabed and Penetration Uncertainty

The largest source of uncertainty in the developed model is the prediction of anchor holding capacity. Anchor capacity depends strongly on the interaction between the anchor and the seabed. This interaction is affected by soil type, soil strength, anchor geometry, penetration depth, line angle, anchor orientation and installation method.

Accurate prediction of anchor capacity requires reliable geotechnical data. In many small or medium-sized marina projects, detailed geotechnical investigations are not available at the early design stage. Instead, the seabed is often estimated from nautical charts, geological maps, local experience or simple site observations. This is practical, but it introduces uncertainty into the design process.

Natural seabeds are rarely uniform. A site may contain mixtures of clay, silt, sand, gravel, stones and local rock outcrops. The model simplifies this by using a limited number of seabed categories. This makes the model easier to use, but it also means that the selected seabed type may not fully represent the actual conditions at the installation site.

The seabed is also assumed to be flat and homogeneous. In reality, the seabed may slope, contain depressions or vary locally in elevation, see figure 22. A sloping seabed can affect both the effective water depth and the anchor resistance. If the anchor is placed on a slope, gravity may either assist or reduce the holding capacity depending on the direction of loading. Local depressions or uneven seabed geometry may also affect how the anchor settles and how the load is transferred into the soil.

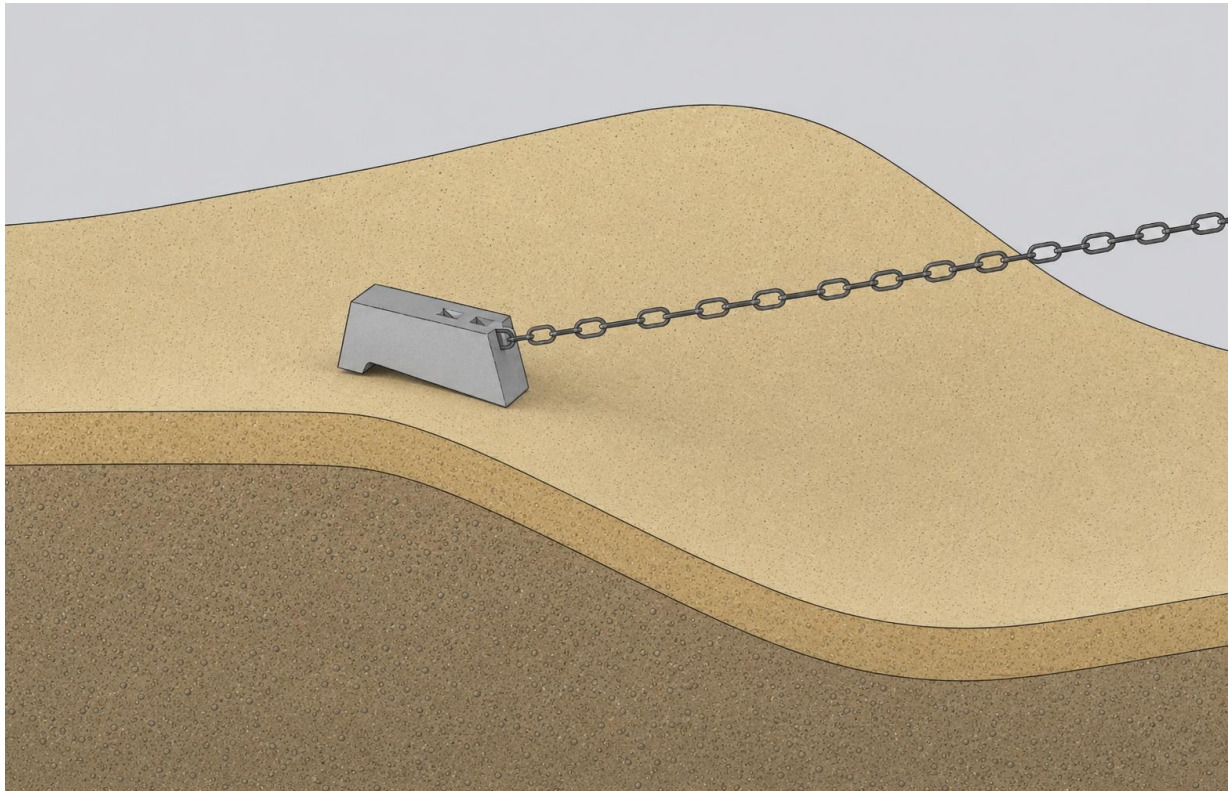


Figure 22, Anchor placed in a disadvantageous location such as slope or local seabed depression.

Anchor penetration is especially important. In the reference case, the calculated anchor safety factor was highly sensitive to the assumed penetration depth. Small changes in penetration produced large changes in calculated holding capacity. This means that the final performance of the anchor depends not only on anchor mass, but also on how well the anchor becomes embedded in the seabed.

The actual penetration depth after installation is normally not known unless it is measured or inspected. Penetration may occur during lowering, from impact with the seabed, by gradual settlement over time, or by installation methods such as air jetting. In soft seabeds, the anchor may continue to settle after installation. This can improve capacity over time, but it cannot be relied upon for design because the governing load may occur shortly after installation.

Because of these uncertainties, the anchor capacity results should be used with caution. The model can indicate whether a proposed anchor is likely to be feasible, but the result depends on the validity of the seabed and penetration assumptions. A conservative safety margin should therefore be used when seabed data or installation control is limited.

8.4 Installation uncertainty

The installation process has a direct influence on the final performance of the mooring system. Even if the calculated design is feasible, the real system may behave differently if the anchor position, orientation, penetration or pretension differs from the assumed values.

Anchor placement is important because it affects chain length, chain angle and pretension. In the calculation model, the anchor position is treated as known. In practice, the position is determined during installation and may deviate from the intended layout. Small deviations may be acceptable, but larger deviations can change the chain geometry and reduce the ability of the system to satisfy the displacement envelope requirement.

Pretension is another important installation parameter. The calculated pretension is required to keep the pontoon movement within the specified envelope. If the pretension is too low, the pontoon may move more than predicted. If the pretension is too high, the chain tension and anchor load may increase. Pretension can be influenced by anchor placement, chain length, seabed slope and how the chain is tensioned during installation.

The installation method used by SF Marina is practical and suitable for many smaller projects, but it relies partly on operator experience. The lowering speed of the anchor, the final anchor orientation and the achieved penetration depth are not always measured directly. This means that the installed system may not exactly match the assumptions used in the calculation model.

Anchor orientation may also affect the holding capacity, see figure 23. The capacity model assumes that the anchor is loaded in a favourable and intended direction. If the anchor rotates during lowering or lands with an unintended orientation, the effective resistance may be reduced. This is especially relevant for anchors where geometry contributes to holding capacity, rather than pure submerged weight alone.

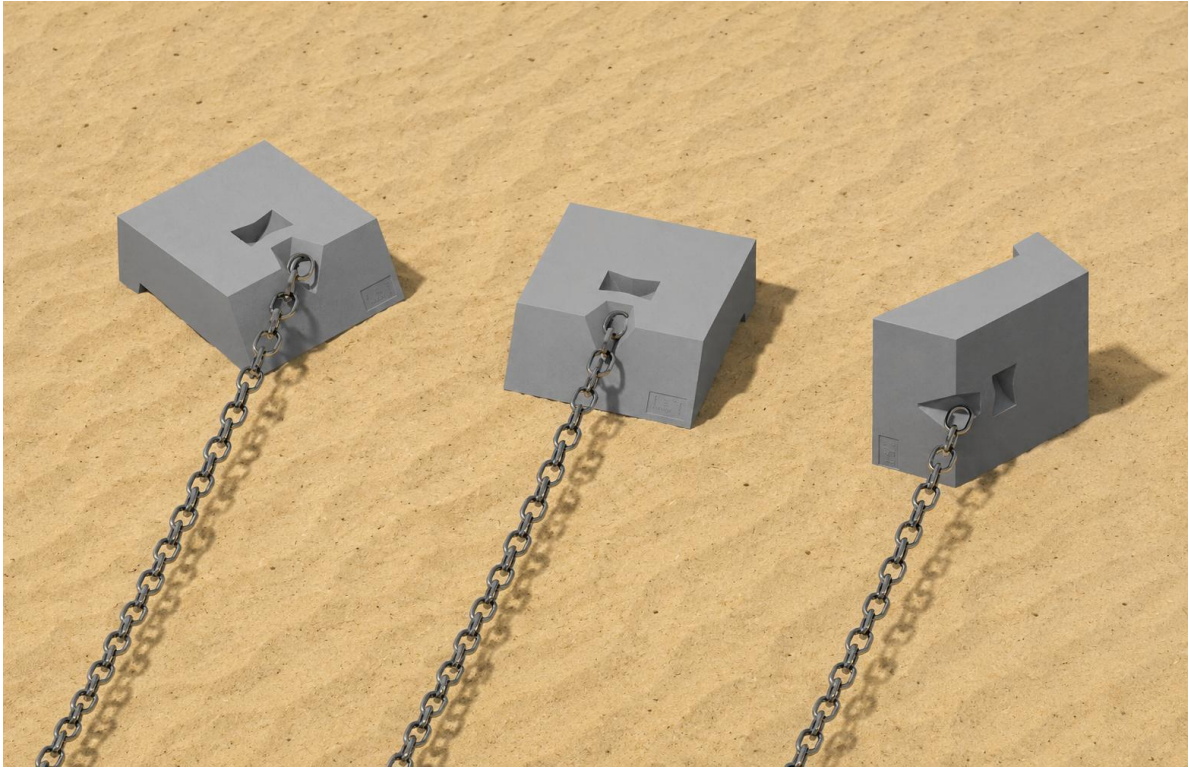


Figure 23, Examples of faulty installations that may negatively impact anchor holding capacity.

Another practical uncertainty is the use of multiple anchors on the same chain, see figure 24. In some installations, several smaller anchors may be used instead of one larger anchor. This can be practical from a handling and installation perspective, but it changes the load distribution and interaction between anchors. The combined capacity of several anchors is not necessarily equal to the capacity of one larger anchor with the same total mass. This should be considered when using the model for non-standard anchor arrangements.

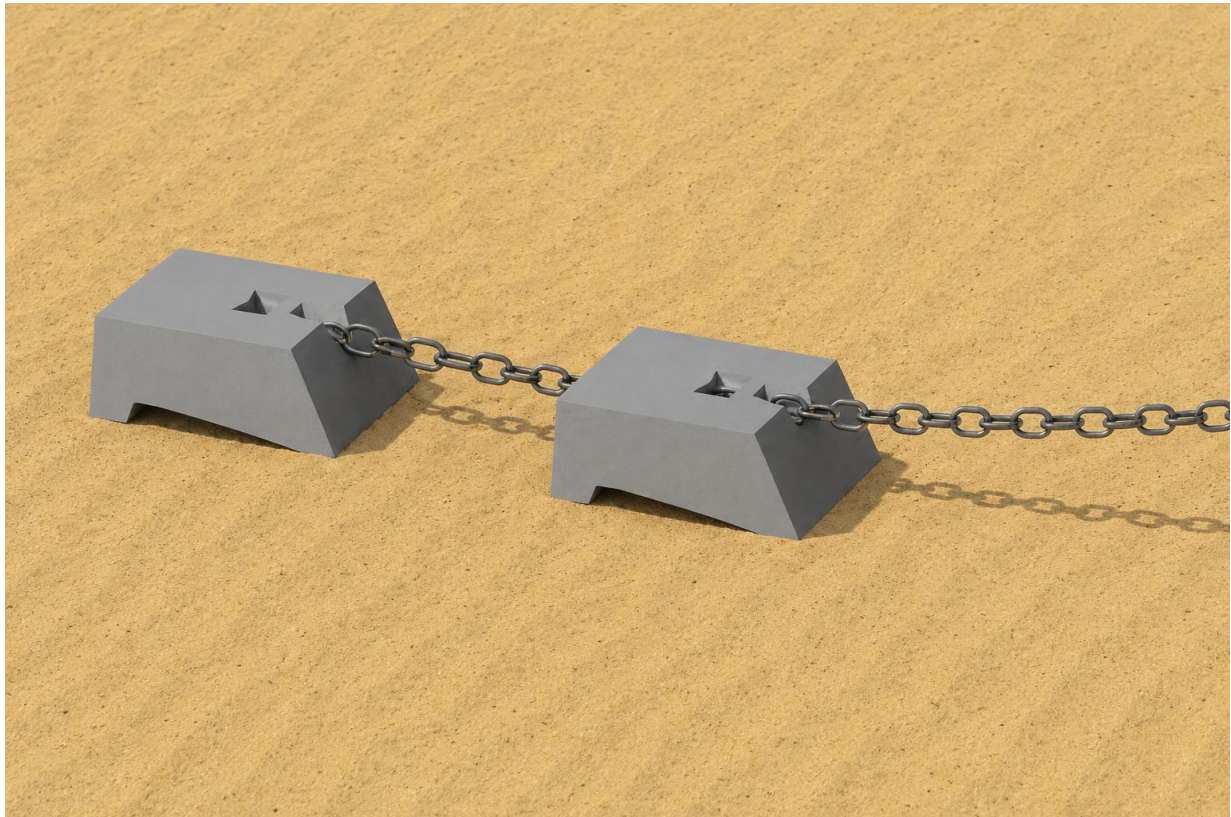


Figure 24, Two interconnected anchors which are meant to substitute one larger anchor.

The chain profile close to the pontoon is also relevant from a practical perspective. If the chain rises too close to the pontoon, there may be a risk of interference with vessel keels or other marine operations. This was not included as a governing constraint in the current prototype. For installations with larger vessels or limited clearance, this should be checked separately.

8.5 Limitations of the quasi-static approach

The developed model is based on a quasi-static approach. This means that the mooring system is analysed under static equilibrium conditions, without explicitly modelling dynamic effects such as wave-frequency motion, transient berthing impact, damping or time-dependent load variation.

This simplification is appropriate for early-stage design and for sheltered marina environments where the dynamic response is expected to be limited. It also keeps the model simple enough for practical use without requiring advanced hydrodynamic input data. However, simplification introduces limitations.

A real berthing event is dynamic. The load varies with time and depends on vessel mass, velocity, fender behaviour, contact stiffness and energy dissipation. In the reference case, the 200 kN berthing load was treated as an equivalent static design load. This allows the load to be included in the quasi-static model, but it does not describe the time-dependent behaviour of the berthing event.

The model also does not include cyclic loading, fatigue or long-term degradation. Chain wear, corrosion, repeated vessel motions and repeated loading may affect the long-term performance of the mooring system. These effects should be considered separately for final design if they are expected to be governing.

Another limitation is that uncertainties may combine. Individually, a small error in water depth, chain length, anchor position or seabed strength may not be critical. However, if several assumptions are unconservative at the same time, the total error may become significant. This is one reason why suitable safety factors and engineering judgement are still required.

The quasi-static model should therefore not be interpreted as a complete replacement for detailed mooring analysis. It is best understood as a simplified engineering tool for comparing design alternatives and identifying governing parameters.

8.6 Practical use for SF Marina

The intended use of the developed prototype is quick estimation of anchor and chain dimensions for SF Marina's floating concrete pontoon installations. The model can support early design decisions by giving a structured estimate of chain geometry, required pretension, chain strength and anchor capacity.

The main advantage of the model is that it combines several design checks in one workflow. Instead of relying only on experience or simplified anchor efficiency values, the user can compare different chain and anchor combinations and see which part of the system governs the design. This can make early design decisions more transparent and easier to document.

The model is especially useful when comparing alternatives. For example, it can be used to study how the selected anchor weight changes with seabed type, water depth, allowable pontoon movement, or chain dimension. It can also indicate when increasing chain size does not solve the governing problem because the limitation is instead anchor capacity.

However, the model should not be used as a complete replacement for specialist consultant work in demanding projects. If a client requires a formal design report, project-specific geotechnical assessment or advanced dynamic mooring analysis, the prototype is not sufficient by itself. In such cases, the model can still be used as a preliminary tool, but the final design should be verified using more detailed methods.

The model is therefore most suitable as an internal engineering support tool for early-stage design, quotation work and preliminary technical discussions. Its results should be combined with site knowledge, installation experience and appropriate safety margins.

8.7 Recommendations

The most important recommendation is to improve the verification of anchor capacity. Since the anchor capacity model is the largest source of uncertainty, physical testing of SF Marina's anchor geometry would provide valuable validation data. Full-scale testing would be preferable, but scaled model tests could also be useful if the soil conditions and scaling effects are handled carefully.

A suitable test programme should investigate how anchor capacity varies with penetration depth, line angle, soil type and anchor orientation. Similar testing principles have previously been used for Pearl Harbor type anchors by Lin and Nakamura (1993), but the test setup would need to be adapted to SF Marina's anchor geometry and installation conditions. The second recommendation is to improve installation control. The calculated results depend on anchor position, orientation, penetration and pretension. If these parameters are not controlled during installation, the model result becomes less reliable. Improved installation documentation would therefore increase the practical value of the prototype.

Anchor position could be improved by using two independent reference measurements instead of relying on one distance measurement. This would reduce the risk of placing the anchor at an unintended angle or distance from the pontoon. Anchor orientation could be improved by controlling the anchor rotation during lowering, for example by using the available lifting points to guide the anchor into the intended direction.

Pretension should also be verified more consistently. This could be done by using a simple tensioning method, such as a lashing lever or another controlled procedure, combined with documentation of the achieved pretension. This would help ensure that the installed system corresponds to the calculated model assumptions.

For soft seabeds, anchor penetration should be improved and documented where possible. Air jetting beneath or around the anchor may be used to increase penetration. Underwater inspection or camera documentation could then be used to confirm that the anchor has achieved a reasonable installation condition.

Finally, the model should be used with conservative assumptions when seabed data is limited. If the seabed type, penetration depth or installation quality is uncertain, the selected anchor should include sufficient margin to account for these uncertainties.

9. Conclusions

The aim of this thesis was to develop a calculation prototype for preliminary dimensioning of mooring chains and concrete deadweight anchors for SF Marina's floating pontoon systems. The developed prototype combines chain geometry, pretension, displacement control, chain strength and anchor capacity into one calculation workflow. This makes it possible to evaluate complete chain-anchor combinations rather than treating the chain and anchor as separate design choices.

The work shows that a quasi-static catenary model can be used to describe the chain behaviour at the intended level of detail. The model provides the horizontal reach, line tension and uplift angle needed for the following strength and anchor capacity checks. The chain part of the model is considered relatively reliable because it is based on established static equilibrium equations and catalogue-based chain data.

The anchor capacity model was found to be the most uncertain part of the calculation procedure. Anchor resistance depends strongly on seabed type, penetration depth, uplift angle, anchor orientation and installation quality. The generated capacity tables make it possible to include these effects in a practical way, but the result still depends on simplified soil assumptions and should therefore be interpreted with caution.

The reference case showed that the prototype can produce results that are consistent with an existing SF Marina anchoring proposal. The selected 30 mm chain and 3-tonne anchor were in line with the proposed solution for the studied installation. The chain strength check showed a large margin, indicating that the chain was not the governing component in the reference case. Instead, the governing uncertainty was the anchor capacity and the penetration achieved during installation.

The comparison between the analytical anchor capacity tables and PLAXIS 2D simulations showed reasonable agreement for the evaluated cases. This supports the use of the generated capacity tables as a preliminary design tool. However, the comparison was limited in scope and does not replace physical testing or project-specific geotechnical verification.

The developed prototype is therefore considered suitable as an internal early-stage design support tool. It can help SF Marina compare different mooring alternatives, identify governing parameters and document the basis for preliminary chain and anchor selection. It should not be used as a complete replacement for detailed design in projects where dynamic effects, uncertain seabed conditions or high consequences of failure require more advanced analysis.

The most important future improvement is further validation of the anchor capacity model. Full-scale or controlled model testing of SF Marina's anchor geometry would increase confidence in the capacity tables, especially with respect to penetration depth and seabed type. Improved installation documentation, including anchor position, orientation, pretension and achieved penetration, would also make the calculated results more reliable in practical use.

10. Future work

Several improvements could be made to the prototype in future work. The first improvement would be to include additional mooring configurations. The current model focuses on chain and deadweight anchor arrangements. Future versions could include mixed mooring systems with rope and chain, alternative anchor layouts, multiple anchors on the same line and clearance checks close to the pontoon.

A second improvement would be to expand the seabed model. The current model uses a limited number of seabed categories. More detailed seabed options would make the anchor capacity calculation more flexible and better suited to real installation sites. This would require improved soil parameters and preferably validation against physical tests or geotechnical simulations.

The model could also be extended with more practical installation constraints. Examples include maximum allowable anchor weight for a given installation method, minimum chain clearance near the pontoon, maximum allowable uplift angle, and recommended installation tolerances. These additions would make the tool more directly connected to SF Marina's practical design process.

Another possible improvement is to include environmental load calculation directly in the workflow. The current reference case uses a predefined horizontal load. A future version could include wind, current and wave load estimation, allowing the user to move from site conditions to mooring design within the same tool.

Future thesis work could focus specifically on anchor and seabed interaction. A geotechnical study could evaluate the Pearl Harbor type anchor in different soil conditions and produce improved capacity tables for the prototype. This could include physical model tests, full-scale pull tests or numerical simulations.

Another suitable future project would be to study and improve SF Marina's installation procedure. Since installation accuracy strongly affects the reliability of the calculated result, a project focused on installation methodology, measurement routines and documentation could have a direct practical impact. This would help ensure that the assumptions used in the calculation model are actually achieved during installation.

Overall, the most important future development is validation. The prototype already provides a structured calculation workflow, but its reliability depends on the quality of the anchor capacity assumptions and the consistency of installation practice. Improving these two areas would give the greatest increase in confidence and practical value.

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