Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment

Deliverable D5.6

Station Keeping Tools – alpha version

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EXECUTIVE SUMMARY

Deliverable D5.6 "Station keeping Tools – alpha version" of the DTOceanPlus project describes the details of the Deployment Design Tools module: "Station Keeping" (SK), and it represents the result of the work developed during the tasks T5.2 and T5.7 of the project.

This document summarizes both the module functionalities and the more technical aspects of the code implemented in this module. The SK tools provides the user with a set of functionalities to design and assess the station keeping system, namely the foundation base, the mooring lines and the anchors. The functionalities of the SK module from the previous versions of DTOcean have been improved and new functionalities have been added. The main improvements are the implementation of frequency domain approach, fatigue analysis of mooring lines, increased flexibility of the mooring system modelling and robust design of foundation bases and anchors.

The Business Logic of the code, i.e. the actual functions of the SK module where the physics is modelled, has been implemented in Python 3. Moreover, the code is provided with an Application Programming Interface (API), developed in OpenAPI, in order to interact and communicate with the other modules of the DTOceanPlus platform. The Graphical User Interface (GUI) is to be further developed, consistently with the other modules, in Vue.js, allowing the user to interact easily with the SK tool, inputting data and visualizing results.

The Business Logic of the code has been verified through the implementation of unit tests, guaranteeing easy maintainability for future developments of the tool. A Section of Examples completes the present document, showing some capabilities of the tool.

Further work will imply the development of the GUI, as well as improvement and testing of the communication between other modules of the DTOceanPlus suite.

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ABBREVIATIONS AND ACRONYMS

SC	Site Characterization
SF	Safety Factor
SK	Station Keeping
ULS	Ultimate Limit State
FLS	Fatigue Limit State
UHC	Ultimate Holding Capacity
CPL	Complexity level
EC	Energy Capture
ED	Energy Delivery
MBL	Minimal Breaking Load
MC	Machine Characterization
SG	Stage Gate
SI	Structured Innovation
LMO	Logistics & Marine Operations
RAMS	Reliability, Availability, Maintainability and Survivability
ESA	Environmental and Social Impact
SLC	System Lifetime Costs
DoF	Degrees of Freedom
Hs	Wave height
Tp	Wave peak period

1. INTRODUCTION

1.1 SCOPE AND OUTLINE OF THE REPORT

Deliverable D5.6 "Station Keeping Tools – alpha version" of the DTOceanPlus project includes the details of the Assessment Design tools module: "Station Keeping" (SK), and it represents the result of the work developed during the tasks T5.2 and T5.7 of the projects.

This document summarizes:

1) The use cases and the functionalities of the Station Keeping module, namely providing the user with the design and assessment of the mooring system and foundations. The theoretical background and references used for the modelling and designing are also presented (Section 2).
2) The actual implementation of the tool, describing the architecture of the tool, the technologies adopted for the implementation and the results of the testing (Section 3).
3) A set of extensive examples, to provide the reader with an overall view of the capabilities of the tools (Section 4)

1.2 SUMMARY OF THE DTOCEANPLUS PROJECT

The Station Keeping tool belongs to the platform of tools "DTOceanPlus" developed within the EU-funded project DTOceanPlus (https://www.dtoceanplus.eu/).

DTOceanPlus will accelerate the commercialization of the Ocean Energy sector by developing and demonstrating an open source suite of design tools for the selection, development, deployment and assessment of ocean energy systems (including sub-systems, energy capture devices and arrays).

At a high level, the suite of tools developed in DTOceanPlus will include:

- **Structured Innovation tool (SI)**, for concept creation, selection, and design.
- **Stage Gate tool (SG)**, using metrics to measure, assess and guide technology development.
- **Deployment tools**, supporting optimal device and array deployment:
  - *Site Characterization (SC):* to characterize the site, including metocean, geotechnical, and environmental conditions.
  - *Machine Characterization (MC):* to characterize the prime mover;
  - *Energy Capture (EC):* to characterize the device at an array level;
  - *Energy Transformation (ET):* to design PTO and control solutions;
  - *Energy Delivery (ED):* to design electrical and grid connection solutions;
  - ***Station Keeping*** *(SK):* to design moorings and foundations solutions;
  - *Logistics and Marine Operations (LMO):* to design logistical solutions and operation plans related to the installation, operation, maintenance, and decommissioning operations.
- **Assessment Tools**, to evaluate projects in terms of key parameters:
  - *System Performance and Energy Yield (SPEY):* to evaluate projects in terms of energy performance.

- *System Lifetime Costs (SLC):* to evaluate projects from the economic perspective.
- *System Reliability, Availability, Maintainability, Survivability (RAMS):* to evaluate the reliability aspects of a marine renewable energy project.
- *Environmental and Social Acceptance (ESA):* to evaluate the environmental and social impacts of a given wave and tidal energy projects.

These will be supported by underlying common digital models and a global database, as shown graphically in Figure 1-1.

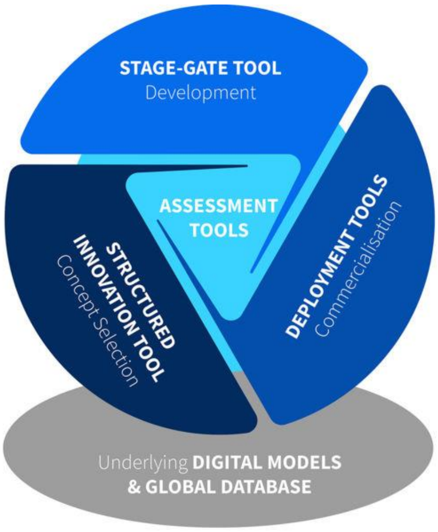

FIGURE 1-1: REPRESENTATION OF DTOCEANPLUS TOOLS

2. USE CASES AND FUNCTIONALITIES

2.1 FUNCTIONALITIES OVERVIEW

The SK module supports the design of the mooring and foundation subsystems. The tool deals with the full design of:

- Foundation base for fixed devices: gravity foundation base, pile
- Mooring system and anchors for floating devices: mooring line, drag anchor, pile, dead weight anchor, suction anchor

The technical-economic approach allows an automated design process and the fast design and selection of the best technology fitting the farm configuration:

- Automated design of catenary mooring system (see Section 2.3.5)
- Automated design of foundation base and anchors (see Sections 2.3.7 and 2.3.8)

The models existing in the previous versions of DTOcean (DTO1 and DTO2) are improved with further functionalities:

- In order to strengthen the connection with the other modules, the SK-module is delivered with APIs (Application Programming Interface) that are documented by following the OpenAPI Specification standard (see Section 3.1.2)
- Mooring systems, foundation bases and anchors are designed based on the bathymetry description
- Novel mooring layout configurations are made possible by the flexibility offered by the improved mooring system modelling capabilities (see Section 2.3.5.1):
    - customizable line type definition (catenary lines, taut lines)
    - possibility to model mooring line with multiple line segments
    - possibility to include buoyancy elements and clump weight in the mooring system
    - possibility to moor several devices to a master structure
- Ultimate Limit State (ULS) analysis and automated design of mooring system are now based on frequency domain analysis (see Sections 2.3.2), while it was based on a static analysis approach in the previous versions of DTOcean
- Fatigue Limit State (FLS) analysis of mooring lines has been implemented (see Section 2.3.4)

In addition, the SK module provides the comprehensive design solution of the mooring system in form of a MAP++ input file. The data structure of this file format is close to the format used by commercial software such as Orcina Orcaflex, Principia Deeplines or SINTEF SIMA; thus this functionality facilitates the interface between the SK module of DTOceanPlus and the aforementioned software.

Note that, within the DTOceanPlus workflow, the Energy Delivery (ED) module is run before the SK module. Since the ED module requires some input data about the dynamic umbilical cable, its mechanical design is performed within the ED module.

2.2 THE USE CASES

The Generic User Case can be generally summarized as shown in Figure 2-1.

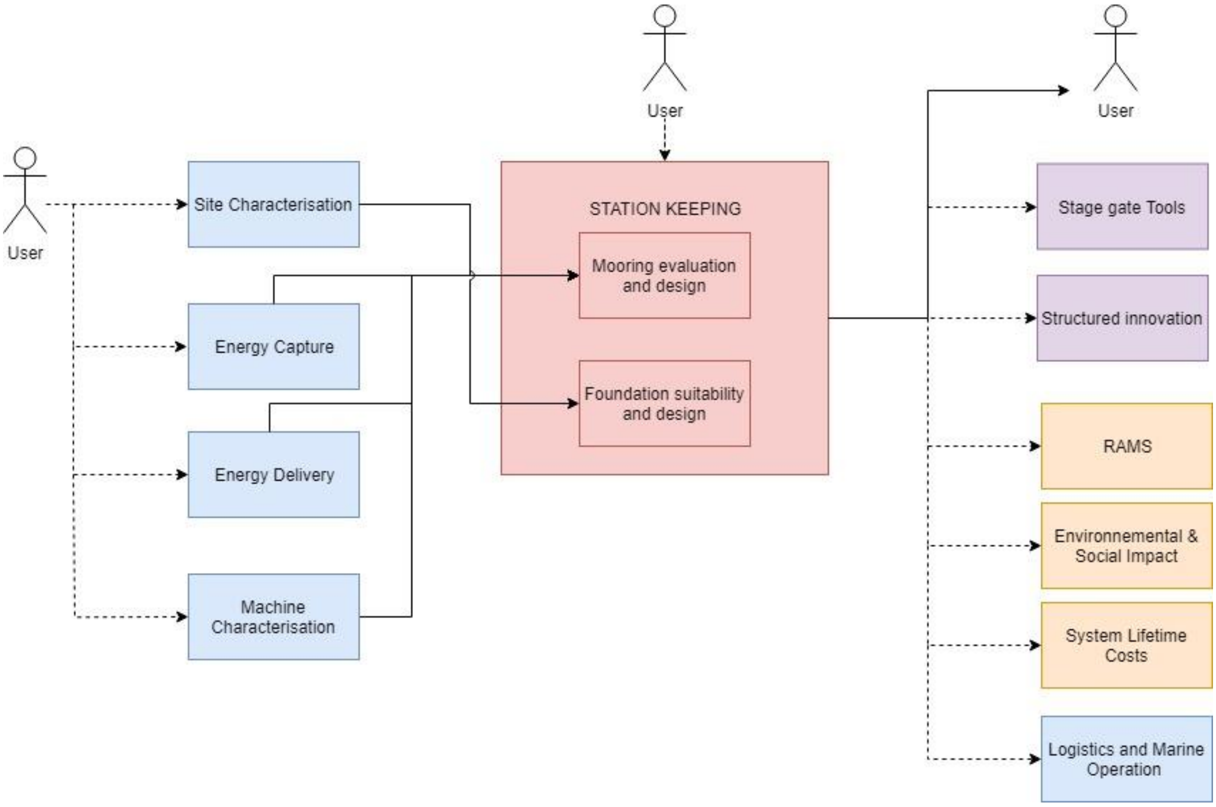

FIGURE 2-1: GENERIC USE CASE FOR USING THE STATION KEEPING TOOLS

The User can:

1) Run SK after running the set of Deployment Design tools of DTOceanPlus.
2) Use SK in standalone mode.

By considering the two Use cases mentioned above, Table 2-1 summarizes the dependencies of the SK module from/to other modules in DTOceanPlus.

TABLE 2-1: DEPENDENCIES OF SK FROM/TO OTHER MODULES IN DTOCEANPLUS

Modules that provide services that SK consumes	Modules that are consuming services from SK
Site Characterization (SC), Energy Capture (EC), Energy Delivery (ED), Machine Characterization (MC)	Structured Innovation (SI), Stage Gate (SG), Logistics & Marine Operations (LMO), System Reliability, Availability, Maintainability, Survivability (RAMS), Environmental and Social Impact (ESA), System Lifetime Costs (SLC)

2.2.1 USE CASE AFTER DEPLOYMENT DESIGN TOOLS

In this case, the User will run one or more Deployment Design Tools and then he/she will run the SK module to carry out the design of mooring and foundations for the device/array. The user will be asked to complete the inputs data that is needed to run the module. A report with all the results and graphs will be exposed to the user.

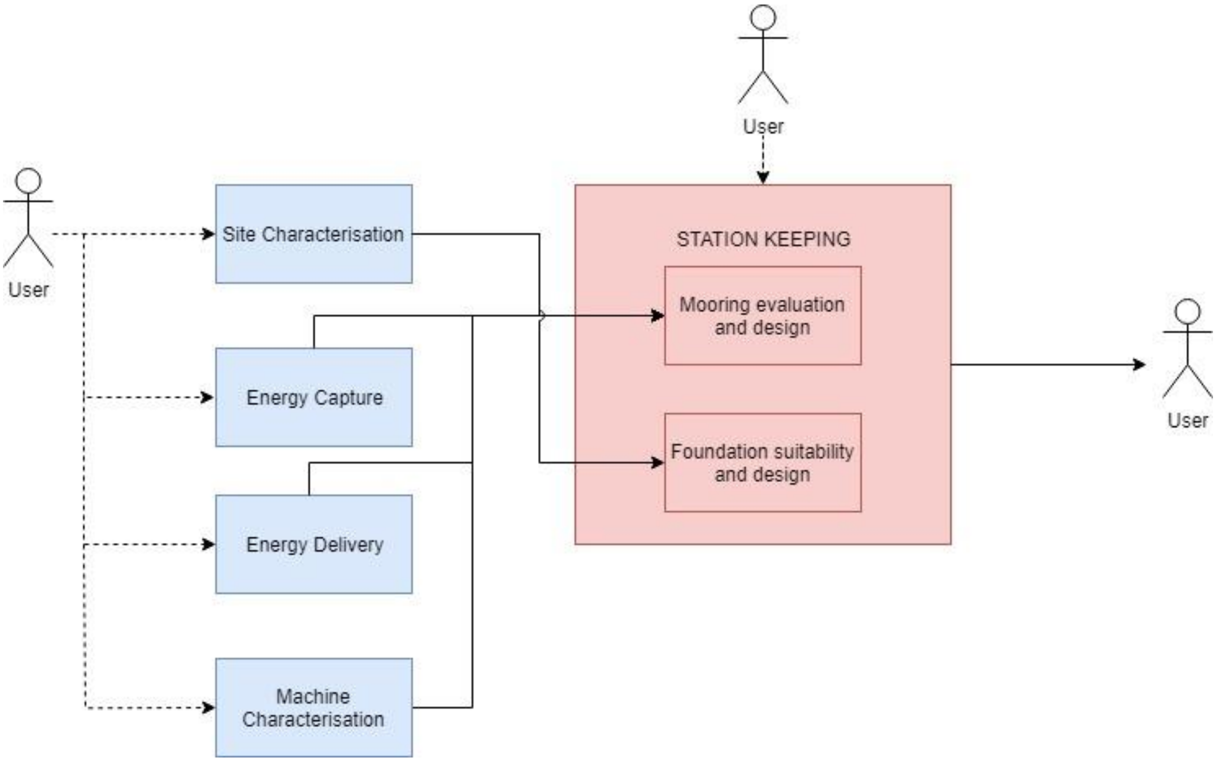

FIGURE 2-2: USE CASE FOR USING THE STATION KEEPING TOOLS AFTER RUNNING THE DEPLOYMENT DESIGN TOOLS

2.2.2 STANDALONE MODE

In this Use Case, the user wants only to run the SK module, to get the mooring and foundation design of a specific device. The user, in this case, will provide all the required inputs and he will be exposed to the overall results of the assessment.

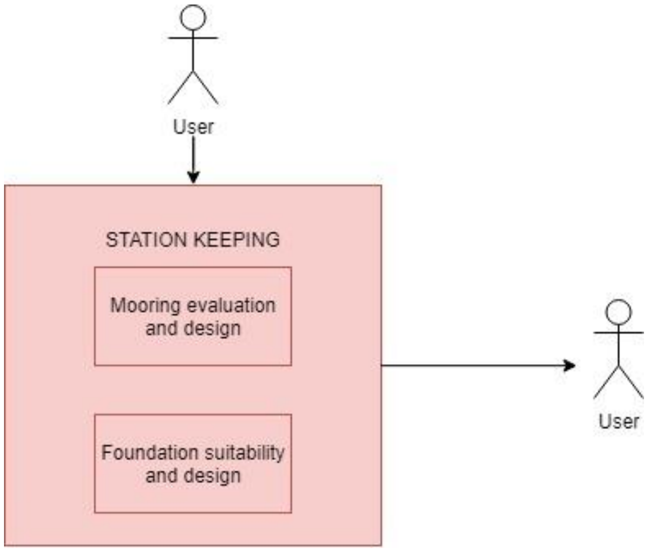

FIGURE 2-3: USE CASE FOR USING THE STATION KEEPING TOOLS STANDALONE

2.3 THE FUNCTIONALITIES

The Station Keeping (SK) Module produces outputs and assessments based on the following main functionalities:

1. **Static analysis:** Static analysis of the device is performed. The main outputs are the equilibrium position of the device and the amplitude of the environmental forces that apply on the device and the tension in the lines of the mooring system.
2. **Dynamic analysis:** Dynamic analysis of the floating device is performed in frequency domain. The main outputs are the main six degrees of freedom motions in terms of power spectra.
3. **ULS analysis:** Ultimate Limit State analysis of the mooring lines segments is performed. Maximum expected tensions and ULS criteria check in each line segments are the main outputs. For a fixed structure, the main output is the maximum expected force on the foundation base.
4. **FLS analysis:** Fatigue Limit State analysis of the mooring lines segments is performed. Cumulated fatigue damage and stress range long term distribution of each line segment are the main outputs.
5. **Mooring system design**: A mooring system based on catenary lines is designed. Number of lines, chain diameter, length of lines and anchor points positions are the main outputs. For catenary system, an automated design algorithm is available.
6. **Soil properties:** The mechanical and physical properties of the soil are determined based on the soil type.
7. **Foundation suitability:** The type of foundation base (for fixed structure) and anchor (for floating structures) are selected based on the soil type and the type of external loads.
8. **Foundation design:** Foundation base and anchors are designed. Dimensions and type of foundation base and anchors are the main outputs.
9. **Hierarchy and bill of materials:** a hierarchy and a bill of materials are produced based on the mooring system design and foundation design.
10. **Environmental Impact:** a set of metrics required by the Environmental and Social Acceptance (ESA) module is computed based on the mooring system design and foundation base/anchor design.

In order for the modules of DTOceanPlus to be used at different stages of a development project, the code has been implemented so that it can cope with 3 levels of complexity (CPL). The CPL are universal for the DTOceanPlus tools. The main idea is that the precision and fidelity of the results increases with increasing CPL, while the amount and complexity of the required inputs increases as well. In the SK module, the logic and methods used for the calculation are the same for each CPL. The main difference between the different CPL is the precision and availability of input data:

- CPL1 and CPL2
    - hydrodynamic data of the floater are not available from the MC module. Instead, the user can choose a set of hydrodynamic data from a pre-generated database with different simple floater geometries
    - the user might want to define a mooring system but lacks some input. An automated algorithm for design of a catenary mooring system is available
- CPL3
    - hydrodynamic data of the floater are available from the MC module.
    - mooring system input is required. Results from the Catenary Mooring System Design performed at CPL1 and CPL2 can be used.

For each level of complexity, Table 2-2 summarizes the available functionalities, and Table 2-3 summarizes the required inputs.

TABLE 2-2: FUNCTIONALITIES AND COMPLEXITY LEVELS IN THE SK MODULE

Functionality	Availability at CPL1	Availability at CPL2	Availability at CPL3
Static Analysis	Yes	Yes	Yes
Dynamic Analysis	Yes	Yes	Yes
ULS Analysis	Yes	Yes	Yes
FLS Analysis	Yes	Yes	Yes
Mooring System Design	Custom/Automated	Custom/Automated	Custom
Foundation Base/Anchor Design	Yes	Yes	Yes
Hierarchy and Bill of Materials	Yes	Yes	Yes
Environmental Impact	Yes	Yes	Yes

TABLE 2-3: INPUTS AND COMPLEXITY LEVELS IN THE SK MODULE

Inputs	CPL1	CPL2	CPL3
Environmental conditions	Required	Required	Required
Device properties	Required	Required	Required
Description of mooring system	Not required	Not required	Required
Parameters for ULS Analysis	Default values	Default values	Required
Parameters for FLS Analysis	Default values	Default values	Required
Parameters for Foundation base/Anchor design	Default values	Default values	Required

2.3.1 STATIC ANALYSIS

Objectives

- Compute static loads and reaction forces applying on the considered device from the following sources: wind, current, mooring system, device buoyancy and weight (hydrostatic restoring forces), mean wave drift forces.
- Compute position of the device that corresponds to static equilibrium

Inputs

TABLE 2-4: INPUTS TO PERFORM A STATIC ANALYSIS

Inputs description	Origin of the Data	Data Model in SK	Units
Hs – significant wave height	SC	float	[m]
Tp – wave peak period	SC	float	[s]
Dir – wave direction	SC	float	[deg]
Vw – wind velocity	SC	float	[m/s]
Dirw – wind direction	SC	float	[deg]
Vc– current velocity	SC	float	[m/s]
Dirc– current direction	SC	float	[deg]
Pos_type – positioning type	User/MC	string	‘moored’ or ‘fixed’
P_dry - Device profile, dry part	User/MC	string	‘cylinder’ or ‘rectangle’
H_dry - Device height, dry part	User/MC	float	[m]
B_dry - Device width, dry part	User/MC	float	[m]
P_wet - Device profile, wet part	User/MC	string	‘cylinder’ or ‘rectangle’
H_wet - Device height, wet part	User/MC	float	[m]
B_wet - Device width, wet part	User/MC	float	[m]
M – Device mass	User/MC	float	[kg]
cog – Center of gravity position of the device	User/MC	float	[m]
K - Hydrostatic restoring matrix	User/MC	float	[N/m], [N.m/m] , [N/rad] , [N.m/rad]
Mooring system model	User/Computed	MAP++ model	Only required if Pos_type is ‘moored’
Dr – rotor diameter	User/MC	float	Optional [m]
Ph – hub position	User/MC	float	Optional [m]
Ct – thrust coefficients	User/MC	float array	Optional

Methods and Outputs: steady and reaction forces

The steady and reaction forces are computed using the inputs given in Table 2-4. The models used for the calculation of the wind force, current force, mean wave drift force, mooring system force and buoyancy and weight forces are detailed in the following Sections. We consider the device to be a 6-dofs rigid body (3 translations and 3 rotations).

1. Wind force model

The wind force Fw is computed as:

$$Fw = \frac{1}{2}\varrho_a C_w V_w^2 A_{p\_dry} \quad \textbf{EQ. 1}$$

where ϱ_a is the air specific mass, C_w are the wind force coefficients and A_{p_dry} the projected area.

C_w are the wind force coefficients computed from the main dimensions H_dry and B_dry, using the shape coefficients for a cylinder if P_dry is 'cylinder' and for a rectangle if P_dry is 'rectangle'. Default values of the shape coefficients of a cylinder are taken from [1], Figure 6.6. Default values of the shape coefficients of a rectangular box are taken from [1], Table 5.5, where we assume that the length and the width of the box are equal to B_dry.

A_{p_dry} is computed from the main dimensions H_dry and B_dry.

The wind force is then projected on the local axes of the device. The obtained force components dep end on the wind direction and the device orientation.

2. Current force model

The current force F_c is computed as:

$$F_c = \frac{1}{2}\varrho C_c V_c^2 A_{p\_wet} \qquad \textbf{EQ. 2}$$

where ϱ is the water specific mass C_c are the current force coefficients and A_{p_wet} the projected area.

C_C is computed from the main dimensions H_wet and B_wet, using the shape coefficients for a cylinder if P_wet is 'cylinder' and for a rectangle if P_wet is 'rectangle'. Default values of the shape coefficients of a cylinder are taken from [1], Figure 6.6. Default values of the shape coefficients of a rectangular box are taken from [2].

A_{p_wet} is computed from the main dimensions H_wet and B_wet.

The current force is then projected on the local axes of the device. The obtained force components depend on the current direction and the device orientation.

3. Rotor force model

In case of a tidal energy converter, the user has the possibility to model a rotor. In that case, the rotor force applied on the device is calculated as follows:

$$F_{rotor} = \frac{1}{2}\varrho C_t V_c^2 A_{rotor} \qquad \textbf{EQ. 3}$$

where $A_{rotor} = \frac{\pi {D_r}^2}{4}$ is the rotor area and C_t the rotor thrust coefficients. The current force is then projected on the local axes of the device. The obtained force components depend on the current direction. It is assumed that the rotor always faces the current.

4. Mean wave drift force

Table 2-5 summarizes the approach used for the calculation of the mean wave drift force F_{wa} . The selected approach depends on the device profile type (cylinder or rectangular), and if the device is fixed or floating. In all cases, the mean wave drift force is a function of the device dimensions (B_wet, H_wet and P_wet). The mean wave drift force is computed for the following regular wave:

- A period T equal to Tp;
- A wave height H equal to Hmax, where Hmax is the maximum wave height as computed in [1], Section 3.5.11.

TABLE 2-5: MODELS FOR MEAN WAVE DRIFT CALCULATION

Device type	Device profile	Approach
Floating	cylinder	[3]
Fixed	cylinder	[4]
Floating or fixed	rectangular	[5]

For a floating cylinder, the mean wave drift force F_{wa} is given by (see details in [3]):

$$F_{wa} = \frac{5}{16} \rho g A^2 r \pi^2 k^3 r^3 \qquad \textbf{EQ. 4}$$

where $A = \frac{H}{2}$ is the wave amplitude, r is the cylinder radius, ρ is the water density and k is the wave number.
For a fixed cylinder, the mean wave drift force F_{wa} is given by (see details in [4]):

$$F_{wa} = \frac{5}{16} \rho g A^2 r \pi^2 k^3 r^3 (1 + \frac{2kh}{\sinh{(2kh)}}) \qquad \textbf{EQ. 5}$$

where $A = \frac{H}{2}$ is the wave amplitude, r is the cylinder radius, ρ is the water density, k is the wave number and h is the water depth.
For a floating or fixed rectangular box, the mean wave drift force F_{wa} is given by (see details in [5]):

$$F_{wa} = \frac{1}{2} \rho g A^2 {C_r}^2 B_{wet} \qquad \textbf{EQ. 6}$$

where $A = \frac{H}{2}$ is the wave amplitude, ρ is the water density, B_{wet} is the width of the wet part of the device, and C_r is the reflection coefficient corresponding to the wave period T. The reflection coefficients documented in [5] are used by default; they corresponds to a barge with a draft/water depth ratio of 0.175. Figure 2-4 shows them as function of the wave frequency.

The mean wave drift force is then projected on the local axes of the device. The obtained force components depend on the wave direction and the device orientation. For a device that is not surface-piercing, i.e. that is totally submerged, the mean wave drift force is zero.

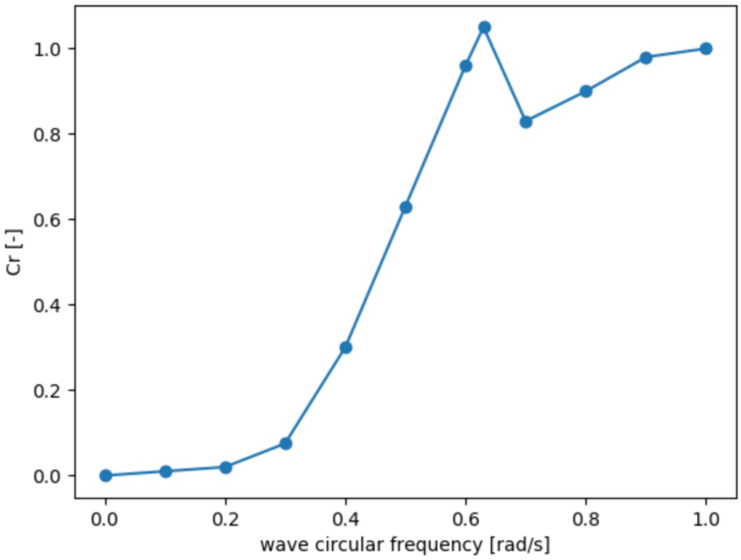

FIGURE 2-4: DEFAULT REFLEION COEFFICIENTS FOR A RECTANGULAR BOX

5. Mooring system force

The mooring system force F_{moor} that applies on the device is computed using the MAP++ library developed by NREL [6]. The modelling capabilities and necessary inputs are detailed in Section 2.3.5.1.

For a given position of the device, the tension in each line segment is computed based on a quasi-static approach by using:

- Catenary equations
- Linear spring equation for taut lines

The mooring system force F_{moor} is a function of the device position and orientation. It is the sum of all the forces from the lines applying at the fairleads of the device.

More details about the modelling possibilities in MAP++ library can be found on the dedicated website[1].

6. Weight and buoyancy force

The weight and buoyancy forces are represented by the hydrostatic matrix K. Given a reference position x_0, the hydrostatic force of a device at position x is given by:

$$F_{res}(x) = -K(x - x_0) \qquad \textbf{EQ. 7}$$

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[1] https://map-plus-plus.readthedocs.io/en/latest/input_file.html.

Methods and Outputs: equilibrium calculation

The static equilibrium calculation consists in finding the equilibrium position x_{eq} of the device so that, for a given environmental condition, the sum of the static forces that applies on the device at that position is equal to zero:

$$F_w(x_{eq}) + F_c(x_{eq}) + F_{rotor}(x_{eq}) + F_{wa}(x_{eq}) + F_{moor}(x_{eq}) + F_{res}(x_{eq}) = 0 \qquad \textbf{EQ. 8}$$

This problem is solved with a gradient descend optimisation algorithm, using the function 'minimize' of the *scipy.optimize* python library.

The SK module also include the possibility to model a 'master structure'. A master structure is a rigid body moored to the seabed. The devices can be moored to a master structure. The mooring system of a master structure is to be user-defined similarly to a device mooring system, as specified in Section 2.3.5.1. Figure 2-5 shows 4 devices (small vertical cylinders) moored to a master structure (black rectangle). When Static Analysis has been run independently for all the devices, the forces that the mooring lines of the devices apply on the master structure are summed and static equilibrium calculation is performed for the master structure (with the devices modelled by forces at that point). We can see that the problem is decoupled in two parts:

- Perform Static Analysis for each device, considering the master structure as fixed
- Perform Static Analysis for the master structure, using the sum of mooring forces from each device as external forces applied on the master structure

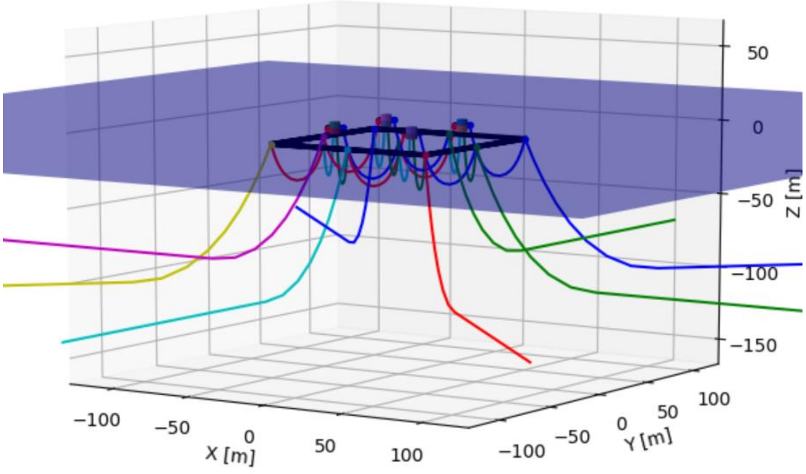

FIGURE 2-5: EXAMPLE OF DEVICES MOORED TO A MASTER STRUCTURE

2.3.2 DYNAMIC ANALYSIS

The dynamic analysis is based on frequency domain approach. This functionality is associated to Limit State assessments (ULS and FLS) and is thus not directly exposed to the end user; it is called by the ULS Analysis and FLS Analysis.

Objectives

- Compute the Response Amplitude Operator (RAO) of the device at a given position. In practice, this position is the static equilibrium position x_{eq} resulting from the Static Analysis.
- For a given wave spectrum, compute the motion response power spectra S_{xx} of the device.

Inputs

TABLE 2-6: INPUTS TO PERFORM DYNAMIC ANALYSIS

Inputs description	Origin of the Data	Data Model in SK	Units
Hs – significant wave height	SC	float	[m]
Tp – wave peak period	SC	float	[s]
Dir – wave direction	SC	float	[deg]
M – mass matrix of the device	MC	float array	[kg]
A – added mass matrix of the device	MC	float array	[kg]
B – damping matrix of the device	MC	float array	[N.s/m]
K – hydrostatic restoring matrix of the device	MC	float array	[N/m]
Fe – 1st order wave force transfer function	MC	complex array	[N/m]
ω – frequencies for which A, B and Fe are given	MC	float array	[rad/s]
Mooring system model	User/Computed	MAP++ model	

Methods and Outputs

The first step of the dynamic analysis is to compute the RAO of the device, from wave elevation η to response motion x. For a given environmental condition, the static equilibrium position x_{eq} of the device is computed in the Static Analysis. The RAO is computed as follows:

$$H(\omega) = [-\omega^2(M + A) + j\omega B + (K + K_{moor})]^{-1} F_e \qquad \textbf{EQ. 9}$$

where K_{moor} is the linearized stiffness matrix representing the restoring force from the mooring system at the static equilibrium position x_{eq}:

$$K_{moor} = \frac{\partial F_{moor}}{\partial x}(x_{eq}) \qquad \textbf{EQ. 10}$$

The second step of the Dynamic Analysis is to compute the response spectra of the device motion S_{xx}. In order to do so, the wave elevation spectrum $S_{\eta\eta}$ is computed from Hs and Tp, using the JONSWAP formulation from the DNV-RP-C205 [1] with a default value for the non-dimensional peak shape parameter equal to 3.3. The response spectra of the device motion are then computed as follows:

$$S_{xx} = H(\omega) S_{\eta\eta} H(\omega)^* \qquad \textbf{EQ. 11}$$

where the symbol $*$ indicates the complex conjugate transpose of a complex matrix.

2.3.3 ULS ANALYSIS

Ultimate Limit State analysis (ULS) is performed for the mooring system of a floating device, using a method based on DNVGL-OS-E301 [7], Section 2.7.

Objectives

Compute the maximum expected tension experienced by each line segment and compare it to its corroded Minimum Breaking Load (MBLc).

Inputs

TABLE 2-7: INPUTS TO PERFORM ULS ANALYSIS

Inputs description	Origin of the Data	Data Model in SK	Units
Inputs necessary for Static Analysis and Dynamic Analysis (Sections 2.3.1 and 2.3.2)	Various	Various	
MBLc – Corroded Minimum Breaking Load of each line segment	User	float array	[N]
Sf– safety factor	User	float	[-]
Hs – Hs values of the 100 years {Hs,Tp} contour	SC	float array	[m]
Tp – Tp values of the 100 years {Hs,Tp} contour	SC	float array	[s]
Vw – 100 years wind velocity	SC	float	[m/s]
Vc – 10 years current velocity	SC	float	[m/s]

Methods and Outputs

As recommended in [7], Section 1.2.5, the environmental conditions used for the ULS Analysis are as follows:

1. Waves: 100-year return period contour of {Hs,Tp}
2. Wind velocity: 100-year return period
3. Current: 10-year return period

The waves, wind and current are assumed to be colinear. All directions from 0 deg to 360 deg are to be studied.

The ULS analysis consists in the following steps:

- Step 1: select an environmental condition: waves ({Hs,Tp}), wind (Vw), current (Vc) and a direction
- Step 2: perform a Static Analysis. The main output is the device static equilibrium position x_{eq} under mean loads.
- Step 3: perform a Dynamic Analysis. The main output is the device motion response spectra S_{xx}.
- Step 4: compute the device maximum expected dynamic excursions of each degree of freedom $X_{\max}$ as follows:

$$X_{\max} = x_{eq} + \sigma_{xx}\sqrt{2\ln\ N_x} \qquad \textbf{EQ. 12}$$

where σ_{xx} is the standard deviations of the motion responses and N_x is number of wave-frequency platform oscillations during the duration of the environmental state.

The standard deviations σ_{xx} are determined from the motion spectra S_{xx} as follows:

$$\sigma_{xx} = \sqrt{\int_0^\infty S_{xx}(\omega)d\omega} \qquad \textbf{EQ. 13}$$

Considering that the duration of a sea state is 3 hours, we use the mean period of the motion spectra to determine the number of oscillations N_x of each degrees of freedom as follows:

$$N_x = \frac{3600 * 3}{2\pi\sqrt{\frac{\int_0^\infty S_{xx}(\omega)d\omega}{\int_0^\infty S_{xx}(\omega)\omega^2 d\omega}}} \qquad \textbf{EQ. 14}$$

The first two components of X_{max} are the horizontal translations; they correspond to the maximum offset O_{uls} in the horizontal plane.

- Step 5: compute the maximum expected tension in each line segment T_{max}, equal to the tension in the line when the device position is equal to X_{max}. Since the tension value can vary along the line segment, T_{max} is taken as the maximum of the tensions at both ends of the line segment.

- Step 6: compare the maximum tension of each line segment to its corroded Minimum Breaking Load (MBLc) by computing the following criteria:

$$C_{uls} = \frac{T_{max} * S_f}{MBL_c} < 1.0 \qquad \textbf{EQ. 15}$$

The safety factor S_f is to be chosen by taking into account that the approach that is implemented uses a quasi-static model of the mooring lines, and a frequency domain calculation. The default value is 1.7. For further details about the choice of S_f value, we refer to [7], Section 4.2.

- Step 7: perform steps 1-6 for all {Hs,Tp} couples and all directions from 0deg to 360deg.

The main outputs of the ULS Analysis are given in Table 2-8.

TABLE 2-8: OUTPUTS FROM ULS ANALYSIS

Outputs description	Data Model in SK	Units
Tmax – maximum tension in all line segments, for all environmental conditions, and all weather directions	float array	[N]

Outputs description	Data Model in SK	Units
Culs – ULS design criteria for all line segments, environmental conditions, and weather directions	float array	[-]

The ULS analysis of a fixed device only includes estimation of the maximum loads using the Static Analysis.

The ULS analysis of a master structure consists in the following steps:

- Perform ULS Analysis for each device
- Perform Static Analysis for the master structure:
    - The total external force applied on the master structure is the magnitude of the complex sum of the forces from the devices, where their magnitude corresponds to the maximum tensions obtained from the ULS analysis, and the phase corresponds to the position of the device and the wave peak period.
    - The maximum tensions of the mooring lines of the master structure T_{max} are obtained from the tensions computed for the master structure at equilibrium position.

2.3.4 FLS ANALYSIS

Fatigue Limit State analysis (FLS) is performed for the mooring system of a floating device, using a method based on [7], Section 6.3.

Objectives

Compute the line segment cumulated damage during the lifetime of the mooring system.

Inputs

TABLE 2-9: INPUTS TO PERFORM FLS ANALYSIS

Inputs description	Origin of the Data	Data Model in SK	Units
Inputs necessary for Static Analysis and Dynamic Analysis (Sections 2.3.1 and 2.3.2)	Various	Various	
aD – intercept parameter of the S-N curve	User	float array	[-]
m – slope of the S-N curve	User	float array	[-]
{Hs_lb,Hs_up} – bins of significant wave height Hs	SC	float array	[m]
{Dp_lb,Dp_up} – bins of wave direction Dp	SC	float array	[deg]
Pb –probability of occurrence of each {Hs,Dp} bin	SC	float array	[-]
Tp – wave peak period associated with each {Hs,Dp} bin	SC	float array	[s]
Vw – wind velocity associated with each {Hs,Dp} bin	SC	float array	[m/s]
Dirw – wind direction associated with each {Hs,Dp} bin	SC	float array	[deg]
Vc – current velocity associated with each {Hs,Dp} bin	SC	float array	[m/s]
Dirc – current direction associated with each {Hs,Dp} bin	SC	float array	[deg]
T_lifetime – Lifetime duration of the mooring system	User	float array	[s]
γ_{fls} - safety factor for fatigue limit state	User	float	[-]

Methods and Outputs

Based on the recommendations in [7], Section 6.3.1, the environmental conditions used for the FLS Analysis are discretized in two-dimensional bins: significant wave height Hs and wave direction Dp. For each bin, the probability of occurrence is required, as well as the associated peak period and current and wind velocities and directions.

The FLS analysis consists in the following steps:

- Step 1: select a {Hs,Dp} bin. The corresponding environmental condition is defined as follows:
    - Hs value is taken as the upper bound of the considered bin
    - Dp value is taken as the centre of the considered bin
    - Wind velocity and direction associated with the considered bin
    - Current velocity and direction associated with the considered bin
- Step 2: perform a Static Analysis. The main output is the device static equilibrium position x_{eq}. In addition, for each line segment, we compute the tension T_{eq} in the line when the device position is equal to x_{eq}.
- Step 3: perform a Dynamic Analysis. The main output is the device motion response spectra S_{xx}.
- Step 4: compute the standard deviations of motion responses as follows:

$$\sigma_{xx} = \sqrt{\int_0^{\infty} S_{xx}(\omega) d\omega}$$ **EQ. 16**

- Step 5: for each line segment, compute the tension T_{eq_σ} in the line when the device position is equal to $X_\sigma = x_{eq} + \sigma_{xx}$.
- Step 6: for each line segment, compute the standard deviation of the tension σ_T as follows:

$$\sigma_T = \left|T_{eq\_\sigma} - T_{eq}\right|$$ **EQ. 17**

Since the tension may vary along the line segment, σ_T is taken as the maximum of the values at both ends of the line segment.

- Step 7: for each line segment, compute the standard deviation σ_S of the stress process as:

$$\sigma_S = \frac{\sigma_T}{A_{cs}}$$ **EQ. 18**

where A_{cs} is the cross-Sectional area of the line; i.e. for a chain of nominal diameter D, $A_{cs} = \frac{2\pi D^2}{4}$, and for a rope of diameter D, $A_{cs} = \frac{\pi D^2}{4}$, as recommended in [7], Section 6.1.2.

- Step 8: compute the damage d_i of the line segment due to the environment no. *i* selected in Step 1. As in the approach detailed in [7], Section 6.3.5, it is assumed that the low-frequency content of the stress process is negligible. This assumption is applied here because we do not have access to the low-frequency motion of the device in the current version of the SK module. A narrow-banded assumption is applied to give:

$$d_i = \frac{\nu_{0i} T_i}{a_D} \left(2\sqrt{2}\sigma_S\right)^m \Gamma(\frac{m}{2} + 1) \qquad \textbf{EQ. 19}$$

where Γ is the gamma function, $\{a_D, m\}$ the S-N curve parameters of the line segment, T_i the total duration of the environment no. *i*, and ν_{0i} is the mean up-crossing period of the stress process. T_i is given by:

$$T_i = T_{lifetime} * P_{bi} \qquad \textbf{EQ. 20}$$

The value of ν_{0i} is computed based on the wave spectrum $S_{\eta\eta}$ as follows:

$$\nu_{0i} = \frac{1}{2\pi \sqrt{\frac{\int_0^\infty S_{\eta\eta}(\omega) d\omega}{\int_0^\infty S_{\eta\eta}(\omega)\omega d\omega}}} \qquad \textbf{EQ. 21}$$

Using the wave spectrum to compute ν_{0i} is an approximation. The ideal method would be to use the stress range spectrum, which we do not have access to in the current version of the code, because of the quasi-static formulation used in the MAP++ library.

- Step 9: perform step 1 to step 8 for all the environmental conditions
- Step 10: compute the total cumulated damage $D_{lifetime}$ of each line tension during the lifetime of the mooring system by summing the damages d_i due to each environmental condition:

$$D_{lifetime} = \sum_{i=1}^{n} d_i \qquad \textbf{EQ. 22}$$

where n is the number of environmental conditions.

- Step 11: compute FLS criteria:

$$C_{fls} = 1 - \gamma_{fls} * D_{lifetime} \geq 0 \qquad \textbf{EQ. 23}$$

where γ_{fls} is the safety factor for fatigue limit state. Default value is 8. For more details about the choice of safety factor value, we refer to [7], Section 6.4.

The main outputs of the FLS Analysis are given in Table 2-10.

TABLE 2-10: OUTPUTS FROM FLS ANALYSIS

Outputs description	Data Model in SK	Units
σ_S – standard deviation of the stress process, for all line segments and all environmental conditions	float array	[MPa]
Cfls – FLS design criteria for all line segments, environmental conditions, and weather directions	float array	[-]

The FLS analysis is not performed for a fixed device or a master structure.

2.3.5 MOORING SYSTEM DESIGN

The user can choose to define a custom mooring system (Section 2.3.5.1), or use the automated catenary mooring system design (Section 2.3.5.2).

2.3.5.1 CUSTOM MOORING SYSTEM DESIGN

Objectives

Allow the user to define a custom mooring system

Inputs

The input data used to model the mooring system are given in Table 2-11. They are divided in three categories:

- **Node**: a node can be an anchor point fixed to the seabed, a fairlead point fixed to the device or a point that connects two or more lines segments together. A constant force, a buoyancy volume or a mass can be defined at a node. Several nodes can be defined.
- **Line type**: a line type contains the material properties of a line segments, e.g. elasticity, diameter, mass per unit length, friction coefficient with the seabed. Several line types can be defined.
- **Line segment**: a line segment is defined by two nodes, one line type and the unstretched length of the segment. Several line segments can be defined.

TABLE 2-11: INPUTS FOR CUSTOM MOORING SYSTEM DESIGN

Inputs description	Category	Data Model in SK	Units
Node number- node identity number	Node	integer	
Node type – Vessel, Connect or Fix	Node	string	
Position – node position (x,y,z)	Node	float array	[m]
Point_mass – mass point attached to the node	Node	float	[kg]
Point_volume – buoyancy volume attached to the node	Node	float	[m3]
Line type number – line type identity number	Line type	integer	
Mass_in_air – mass density of the line in air	Line type	float	[kg/m]
Diameter – line diameter used to compute weight in water	Line type	float	[m]

Inputs description	Category	Data Model in SK	Units
ea – line elasticity	Line type	float	[N]
Cb – friction coefficient on the seabed	Line type	float	[-]
Mbl – minimum breaking load	Line type	float	[N]
Mblc – corroded minimum breaking load	Line type	float	[N]
aD – intercept parameter of the S-N curve	Line type	float	[-]
m – slope of the S-N curve	Line type	float	[-]
Line number – line segment identity number	Line segment	integer	
Line segment type number – identity number of the line type	Line segment	integer	
Node1 number – identity number of node at end1 of segment	Line segment	integer	
Node2 number – identity number of node at end2 of segment	Line segment	integer	
Line length – unstretched line segment length	Line segment	float	[m]
Flag – optional flag. Use "LINEAR_SPRING" for taut lines	Line segment	string	

Those input data are used to write a MAP++ input file which is read by the MAP++ library.

More details about the modelling possibilities in MAP++ library can be found on the dedicated website[2]. Figure 2-6 shows an example of a mooring system modelled in MAP++.

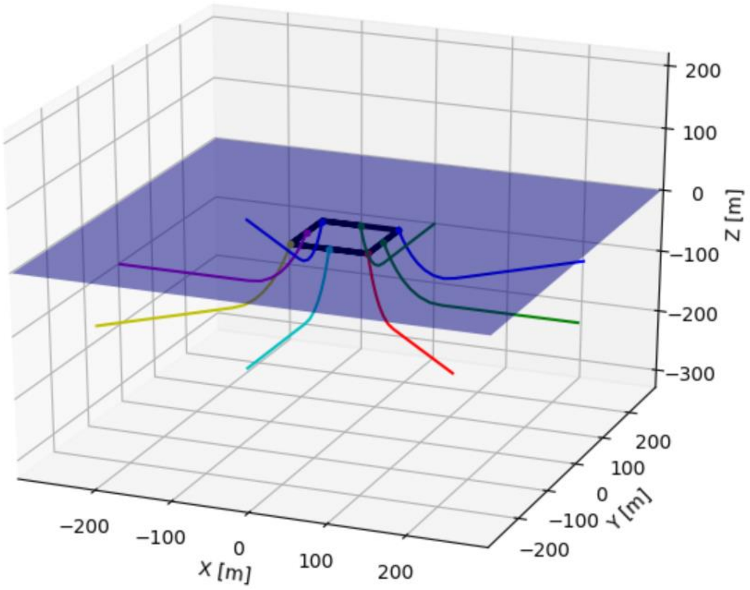

FIGURE 2-6: EXAMPLE OF A MOORING SYSTEM MODELLED USING MAP++ LIBRARY

2.3.5.2 AUTOMATED CATENARY MOORING SYSTEM DESIGN

For CPL 1 and CPL2, it is expected that the end-user has not yet defined the design of the device mooring system. A robust algorithm has been implemented to perform the automated design of a

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[2] https://map-plus-plus.readthedocs.io/en/latest/input_file.html.

catenary mooring system. This algorithm is based on common engineering practice and return of experience when designing a catenary mooring system.

Objectives

Perform the design of a catenary mooring system.

Inputs

TABLE 2-12: INPUTS TO PERFORM CATENARY MOORING SYSTEM DESIGN

Inputs description	Origin of the Data	Data Model in SK	Units	Default value
Inputs necessary for ULS Analysis (Section 2.3.3)	Various	Various		
Chain catalogue – list of chain type and properties	Catalogue module	Various		
Nlines_min – minimum number of mooring lines	User	float	[-]	3
Nlines_max – maximum number of mooring lines	User	float	[-]	10
Pten_min – minimum pretension in the mooring lines	User	float	[% of MBL]	0.03
Pten_max – maximum pretension in the mooring lines	User	float	[% of MBL]	0.06
O_max – maximum allowable total offset (static+dynamic)	User	float	[m]	30
Teig_min – minimum horizontal eigenperiod	User	float	[s]	30
C_td – coefficient of touchdown length reduction	User	float	[-]	0.95

The inputs in Table 2-12 specific to the design of the catenary system are proposed with default values, but the user has the possibility to modify them.

Mooring line catalogue

The chain catalogue is extracted from the line catalogue that contains a list of line component properties of different diameter. For each line type, the following properties are given:

TABLE 2-13: LINE CATALOGUE

Property name	Property description	Data Model	Units	Example
catalogue_id	Component ID in the catalogue	string		« chain_1 »
type	Line type	string		« chain »
material	Line material	string		« steel »
chain_link_diameter	Link diameter if line is of type "chain"	float	[m]	0.111
diameter	Line diameter used to compute the weight in water	float	[m]	0.3
ea	Elasticity of the line	float	[N]	1.8E+08
weigth_in_air	Weight in air of the line	float	[kg/m]	130
mbl	Minimum breaking load	float	[N]	137000
cost_per_meter	Cost per meter of the line	float	[€/m]	134
ad	SN-curve parameter ad	float	[-]	600000
m	SN-curve parameter m	float	[-]	3

Methods and Outputs

The goal of the algorithm is to design a catenary system, i.e. to identify the following quantities:

- The number of mooring lines N_{lines}
- The length of the mooring lines L
- The diameter of the mooring lines D
- The mooring radius R_{anch}

Those quantities define a mooring system that needs to satisfy the following criteria:

- Criterion 1: the pretension at the fairlead in each line T_{pre} is between the specified values:

$$P_{ten\_min} < \frac{T_{pre}}{MBL} < P_{ten\_max}$$

- Criterion 2: the ULS analysis criterion is satisfied:

$$C_{uls} \leq 1$$

- Criterion 3: the device offset O_{uls} obtained from ULS analysis is smaller than the specified offset:

$$O_{\mathrm{uls}} \leq O_{\mathrm{max}}$$

- Criterion 4: the horizontal eigen period T_{eig} of the system is larger than the specified eigen period:

$$T_{\mathrm{eig}} \geq T_{\mathrm{eig\_min}}$$

In addition, the total cost of the mooring system needs to be minimized, thus the following quantities are to be minimized:

- The number of mooring lines N_{lines}
- The unstretched length of the mooring lines L
- The diameter of the mooring lines D

In order to simplify the problem, we assume the following:

- The mooring lines are uniformly distributed around the device
- Each mooring line is made of a unique line segment of type chain

The algorithm used to determine the quantities N_{lines}, L, D and R_{anch} consists in the following steps:

- Step 1: set N_{lines} equal to N_{lines_min}

- Step 2: initiate the mooring system with:
    - N_{lines} mooring lines
    - D equals to the minimum chain diameter available in the catalogue

- L computed as the theoretical minimum line length to avoid vertical force on anchor point when the tension reaches the value of the minimum breaking load of the line ([8], Eq. 8.19)

  $$L = h\sqrt{2\frac{MBL}{m_w gh} - 1}$$

  where h is the water depth, MBL the minimum breaking load of the line segment and m_w the weight in water per unit length of the line segment.

- R_{anch} so that the theoretical pretension is 10% of MBL ([8], Eq.8.21):

  $$R_{anch} = L - h\sqrt{1 + \frac{2a}{h}} + a * arccosh\,(1 + \frac{h}{a})$$

  where $a = \frac{0.1*MBL}{m_w g}$.

- Step 3: compute static equilibrium of the moored device as done in the Static Analysis, without environment. This obtained tension in the lines is the actual pretension. Adjust the value of L so that Criterion 1 (pretension) is satisfied. A dichotomy algorithm is used.

- Step 4: compute the maximum dynamic offset O_{dyn_max} by performing a Dynamic Analysis (i.e. as if the floater was not moored).

- Step 5: compute the maximum acceptable mean offset $O_{st\_max} = O_{max} - O_{dyn\_max}$. If $O_{st\_max} < 0$, the design process stops and an error is sent to the user: "the maximum allowable total offset O_{max} needs to be increased". In practice, the maximum allowable offset is defined in ED module. It might be necessary for the user to run the ED module again.

- Step 6: for all the ULS environmental conditions, compute the mean offset O_{st} by performing a Static Analysis. If $O_{st} > O_{st\_max}$, increase the chain diameter by selecting the first chain type in the catalogue with a larger diameter. Equilibrium of the system is performed (perform Step 3).

- Step 7: perform Step 6 until $O_{st} < O_{st\_max}$.

- Step 8: compute the eigen period T_{eig} of the moored device in the horizontal plane. Check Criterion 4 (system eigen period > minimum user-defined period). If it is not satisfied, the design process is stops and an error is sent to the user: "the mooring system is too stiff, the maximum allowable total offset needs to be increased".

- Step 9: perform ULS (dynamic) analysis for all the environmental conditions, compute C_{uls} and the minimum touchdown length of the mooring line L_{td}.

- Step 10: check ULS Criterion 2. If it is not satisfied, proceed to next design Step 11, else proceed to final Step 12.

- Step 11: Increase the chain line diameter by selecting the first chain type in the catalogue with a larger diameter. Perform Step 3 (system equilibrium). Go back to Step 9 (ULS analysis). If it is not possible to increase the diameter because the current chain type has the largest diameter of the catalogue, add one additional mooring line $N_{lines} = N_{lines} + 1$. Go back to Step 2.

- Step 12: reduce R_{anch} and L by the value $c_{td} * L_{td}$.

The design procedure is summarized in Figure 2-7.

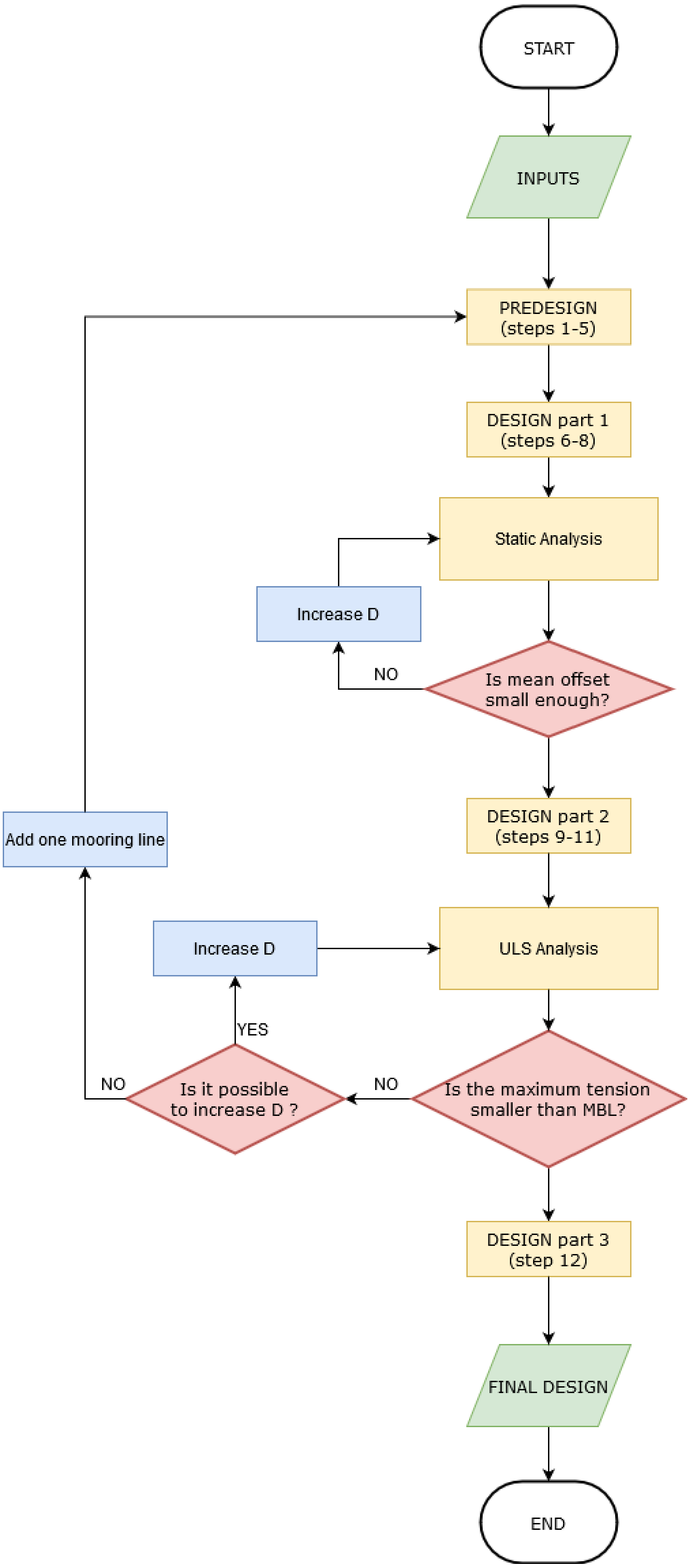


FIGURE 2-7: ALGORITHM FOR CATENARY MOORING SYSTEM DESIGN

The main outputs of the Catenary Mooring System Design are given in Table 2-14.

TABLE 2-14: OUTPUTS FROM CATENARY MOORING SYSTEM DESIGN

Outputs description	Data Model in SK	Units
N_{lines} – number of mooring lines	float	[-]
L – line length	float	[m]
D – mooring line diameter	float	[m]
R_{anch} – mooring radius	float	[m]

In addition, a MAP++ input file is generated, containing the mooring system data necessary to run a mooring analysis.

2.3.6 SOIL PROPERTIES

Objectives

In order to be able to design a foundation or anchor, soil mechanical properties are needed. For CPL1 and CPL2 the user chooses one type of soil, from the catalogue for standalone mode, or from the SC module. The type of soil will be used to attribute mechanical and physical properties to the soil that are essential to be able to dimension the foundation.

For CPL3 soil mechanical properties will be defined by the user as input information.

Inputs

The inputs needed for carrying out the assessment of the soil properties are presented in Table 2-15

TABLE 2-15: INPUTS TO DETERMINE SOIL PROPERTIES

Inputs description	Origin of the Data	Data Model in SK	Units
Soil Type	User/SC	string	"very_soft_clay", "soft_clay", "firm_clay", "stiff_clay", very_stiff_clay", "hard_clay", "very_loose_sand", loose_sand", "medium_dense_sand", "dense_sand", "very_dense_sand", "gravels_pebbles"

Methods and Outputs: Soil properties definition

Depending on the soil type, mechanical properties such as: friction angle, cohesion, buoyant weight and relative density index will be attributed to be able to design the foundations/anchors.

The soil mechanical properties values that are used are regrouped on Table 2-16, they were determined through different literature [9], [10].

TABLE 2-16: SOIL PROPERTIES CATALOGUE FOR CPL1 AND 2

Soil Type	Buoyant unit weight [kg/m³]	Friction angle [°]	Relative density index	Undrained shear strength [Pa]
Very soft clay	720	-		10e+03
Soft clay		-		20e+03
Firm clay		-		33e+03
Stiff clay	980	-		75e+03
Very stiff clay		-		150e+03
Hard clay		-		200e+03
Very loose sand	870	25	0.1	-
Loose sand		30	0.25	-
Medium dense sand		32	0.45	-
Dense sand	1060	35	0.75	-
Very dense sand		38	0.85	-
Gravels, pebbles		45		-

2.3.7 FOUNDATION SUITABILITY

Objective

The choice of foundation type depends on soil conditions. If the soil is sandy, then a shallow foundation is usually recommended. Alternatively, conventional driven piles may be used as anchors in sandy soil conditions [11].

For clay soil stratigraphy, suction anchors or suction buckets can be used. These are quicker to install and easy to remove. Conventional driven piles can also be used in clay. However, due to noise pollution while driving, driven piles may not be desirable [11].

The SK module will determine the more suitable type of foundation at the farm level. This task is performed taking into account the following aspects / criteria:

- Seabed connection type: Fixed or moored
- Soil type:
    - Cohesive soils: very soft clay, soft clay, firm clay, stiff clay, very stiff clay and hard clay
    - Cohesionless soils: very loose sand, loose sand, medium dense sand, dense sand, very dense sand and gravels/pebbles
- Seabed slope: moderate (< 10°) or steep (>10°)
- Main load orientation of the load applied to the foundation: Downward, upward, or horizontal
- Environmental impact: recovery, footprint, noise

A suitability score is given to every foundation for each of the five criteria defined above. The approach to determining foundation suitability is based on a simple sum of all criteria from the five matrices (Table 2-18 to Table 2-22) for each foundation type. The lowest score is deemed to be the most suitable for the study case that is being analysed. Matrices were built taking into account data/feedback from literature. [11] – [15].

Inputs

The inputs needed for carrying out the assessment of the foundation suitability are in Table 2-17.

TABLE 2-17: INPUTS FOR FOUNDATION TYPE SUITABILITY EVALUATION

Inputs description	Origin of the Data	Data Model in SK	Units
Soil Type	User/SC	string	"very_soft_clay", "soft_clay", "firm_clay", "stiff_clay", very_stiff_clay", "hard_clay", "very_loose_sand", loose_sand", "medium_dense_sand", "dense_sand", "very_dense_sand", "gravels_pebbles"
Soil slope	User/SC	Float	[°]
Seabed connection type	EC	String	"moored" or "fixed"

Methods and Outputs: foundation suitability

The foundation assessment class is performed through suitability matrices for each type of foundation and conditions/criteria (Table 2-18, Table 2-19, Table 2-20, Table 2-21 and Table 2-22). A value is given to every foundation for each condition/criteria, to attribute this value a review of different literature was carried out:

- **1** means it is suitable,
- **2** means that it is possible, even if not optimal, and,
- **100** that it is unsuitable.

The approach to determining foundation suitability is based on a simple sum of each parameter from the matrices.

Table 2-18 presents the suitability matrix for soil type, it summarizes all the data/feedback from documents [11]–[15]

TABLE 2-18: SUITABILITY MATRIX FOR SOIL TYPE

Type of soil	Shallow foundations	Deadweight anchors	Piles	Drag anchors	Suction caisson
Very soft clay	1	1	2	2	1
Soft clay	1	1	2	1	1
Firm clay	1	1	1	1	1
Stiff clay	1	1	1	1	1
Very stiff clay	1	1	1	1	1
Hard clay	1	1	1	1	1
Very loose sand	1	1	2	1	1
Loose sand	1	1	2	1	1

Medium dense sand	1	1	1	1	1
Dense sand	1	1	1	1	1
Very dense sand	1	1	2	1	2
Gravels, pebbles	2	2	100	100	100

TABLE 2-19: SUITABLILITY MATRIX FOR SEABED SLOPE

Seafloor topography	Shallow foundation	Gravity anchors	Piles	Drag anchors	Suction caisson
Moderate <10°	1	1	1	1	1
steep ≥ 10°	100	100	1	100	2

TABLE 2-20: SUITABILITY MATRIX FOR MAIN LOAD DIRECTION

Loading main direction	Shallow foundation	Gravity anchors	Piles	Drag anchors	Suction caisson
Downward load	1	100	2	100	1
Vertical Uplift	2	1	1	100	1
Horizontal load	2	2	2	1	2

TABLE 2-21: SUITABILITY MATRIX FOR SEABED CONEXION TYPE

Device type	Shallow foundation	Gravity anchors	Piles	Drag anchors	Suction caisson
Moored	100	1	1	1	1
Fixed	1	100	1	100	2

TABLE 2-22: SUITABILITY MATRIX FOR ENVIRONMENTAL IMPACTS

Environmental impacts	Shallow foundation	Gravity anchors	Piles	Drag anchors	Suction caisson
Recovery	2	2	100	1	2
Footprint	2	2	1	100	2
Noise	2	2	100	2	2

The output of this methodology is a list of foundations types and their score. The foundation with the smaller score will be the more suitable solution and it will be design.

2.3.8 FOUNDATION DESIGN

Objectives

The foundation design process of the SK module aims to:

- Step 1: Attribute soil mechanical parameters to the type of soil define by the user.
- Step 2: determined the most suitable type of foundation depending on seabed conditions and the type of structure;

- Step 2: Performed the dimensioning of the type of foundation based on the foundations suitability study;
- Step 3: Determine the dimensions, weight and capacity of the foundation considering its environments (loads and soil conditions).

The following foundation/anchor types are available: shallow foundations, gravity anchors, piles anchors/foundations, drag anchors and suction caisson

In order to achieve the foundation design, soil mechanical parameters, determined on §2.3.6 are affected by a safety coefficient as is proposed in [16].

$$c_{ud} = \frac{c_u}{\gamma_c}; \quad \varphi'_d = \arctan\left(\frac{\tan\varphi'}{\gamma_\varphi}\right) \qquad \textbf{EQ. 24}$$

Where,

- c_u: undrained shear strength in Pa;
- c_{ud}: design undrained shear strength in Pa;
- φ': effective internal friction angle of soil in degrees;
- φ'_d: design effective internal friction angle of soil in degrees and;
- γ_c and γ_φ are safety factors equal to 1.3.

Foundations/anchors designs are performed by using the design undrained shear strength and design effective internal friction angle of soil.

Inputs

All inputs needed to perform the foundation design are regrouped in Table 2-23.

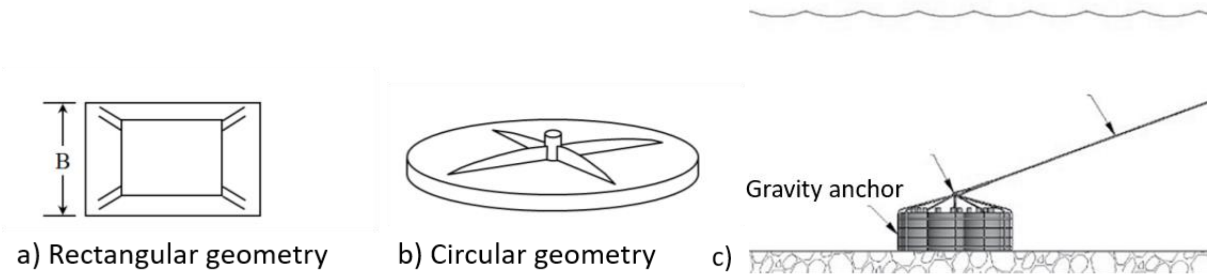
TABLE 2-23: INPUTS FOR FOUNDATION/ANCHOR DESIGN

Inputs description	Origin of the Data	Data Model in SK	Units
Level of complexity	User/SG	integer	[-]
Soil type	SC	string	"very_soft_clay" or "soft_clay" or "firm_clay" or "stiff_clay" or very_stiff_clay" or "hard_clay" or "very_loose_sand" or "loose_sand" or "medium_dense_sand" or "dense_sand" or "very_dense_sand" or "gravels_pebbles"
Soil slope	User/SC	float	[°]
Seabed connexion type	EC	string	"moored" or "fixed"
Device geometry	MC	dic	"Geometry": "cylinder" or "rectangular", "lr" or "lx": float, "ly": float
Internal friction angle of soil	Catalogue / Pandas on stand-alone mode.	float	[deg]
Undrained shear strength		float	[Pa]
Relative density index		float	[-]
Buoyant weight of soil		float	[Kg/m^3]

Type of pile tip	User / default data	string	"closed_end", "open_end"
Deflection criteria	User / default data	float	[%]

Methods and Outputs: Shallow foundations and gravity anchors

In this module shallow foundations are gravity foundations for fixed devices and deadweight anchors are gravity anchors for floating devices (Figure 2-8).



a) Rectangular geometry b) Circular geometry c)

FIGURE 2-8: A) AND B) SHALLOW FOUNDATIONS [13] , C) GRAVITY ANCHOR [14]

Figure 2-8 show circular and rectangular shallow foundations, the loading on this type of foundation may include overturning moments, which create uplift (tensile) as well as downwards (compressive) pressures, lateral and gravitational loadings [13].

The type of loading will determine the resistance mechanism developed by the soil-structure interaction:

- For compressive loads (downward), resistance is derived from the bearing capacity of the soil.
- For tensile loads (upward), resistance depends on the submerged weight of the foundation.
- For lateral loads, resistance depends on the soil-structure friction developed on the surfaces.

Figure 2-8 also shows a gravity anchor, this is a heavy object placed on the seafloor. The primary purpose is to resist the uplift and lateral forces from the mooring line. Its behaviour is practically the same as the behavior of a shallow foundation subjected to an uplift load.

The SK module propose to design circular or rectangular mattresses shallow foundations (the geometry is chosen depending on the device geometry) and circular gravity anchors. They are considered to be in concrete (density = 2400 kg/m^3).

Their minimal dimensions are established as a function of the load eccentricity (eccentricity calculation is explained below). As a general guide it is recommended that the eccentricity be less than or equal to 1/6 the foundation width/length/radius [13], in order to avoid extremely eccentric loads. The minimal foundation/anchor dimensions (length l_x, width l_y and radius r) when there is an eccentric load case will be:

- For rectangular geometry:

$$l_{x,min} = \max(6 * e_x, device\ l_x)$$

$$l_{y,min} = \max(6 * e_y, device\ l_y)$$

EQ. 25

- For circular geometry:

$$r_{min} = \max(6 * e_r, device\ r)$$

EQ. 26

The minimal/initial value of the foundations thickness is 0.3m. Dimensions will be adjusted during the foundation's verification.

When there is no eccentricity ($M_{x,uls} = 0\ and\ M_{y,uls} = 0$) minimal foundation/anchor dimension is determine:

- For rectangular geometry:

$$l_{x,min} = \max\ (1m, device\ l_x)$$

$$l_{y,min} = \max\ \left(1m, device\ l_y\right)$$

EQ. 27

- For circular geometry:

$$r_{min} = \max\ (1m, device\ r)$$

EQ. 28

In order to perform the design of shallow foundations and gravity anchors three conditions are verified:

1) Bearing capacity:

The bearing capacity Q_u is the normal resistance of the soil. The following condition is verified:

$$\frac{Q_u}{SF} > \left(V_{uls,down} + W_b\right)\left(cos\,\beta\ + H_{uls,res}\,sin\,\beta\ \right)$$

EQ. 29

where,

- $V_{uls,down}$ is the vertical (downwards) load from ULS (Section 2.3.3) load analysis (N). Its value is equal to 0 for anchor design;
- $H_{uls,res}$ is the resultant horizontal load from ULS (N). $H_{uls,res} = \sqrt{H_{uls,x}^2 + H_{uls,y}^2}$;
- W_b is the foundation's buoyant weight (N);
- β correspond to the slope of the seabed (degrees).

The default value of the safety coefficient SF is considered equal to 1, this value can be changed by the user.

In the methodology implemented it is considered that the embedment depth of the foundation is equal to zero, it means that there no bearing resistance given by overburden of the soil. In order to determine Q_u the following equation is used, it takes into account the soil resistance due to cohesion and friction.

$$Q_u = A'(q_c + q_\gamma) \qquad \textbf{EQ. 30}$$

where,

- q_c: bearing capacity stress for cohesion factor (Pa);
- q_γ: bearing capacity stress for friction (Pa);
- A': effective surface of the foundation (m^2) equal to the foundation surface when overturning moment from ULS analysis is equal to 0, otherwise the eccentricity methodology is used.

<u>Effective surface A'</u>

To perform the design when overturning moments are > 0, the overturning moment is replaced by an eccentricity so the effective surface A' can be calculated. The load center, is the point where the resultant of horizontal and vertical load is applied, it implies an eccentricity on x and y axis for rectangular design (Figure 2-9a) and on the radius axes for circular design (Figure 2-9b):

$$e_x = \frac{Overturning\ moment}{Vertical\ load} = \frac{M_{x,uls}}{V_{uls,down} + W_b};$$

$$e_y = \frac{M_{y,uls}}{V_{uls,down} + W_b}; \qquad \textbf{EQ. 31}$$

$$e_r = \frac{\sqrt{M_{x,uls}^2 + M_{y,uls}^2}}{V_{uls,down} + W_b}$$

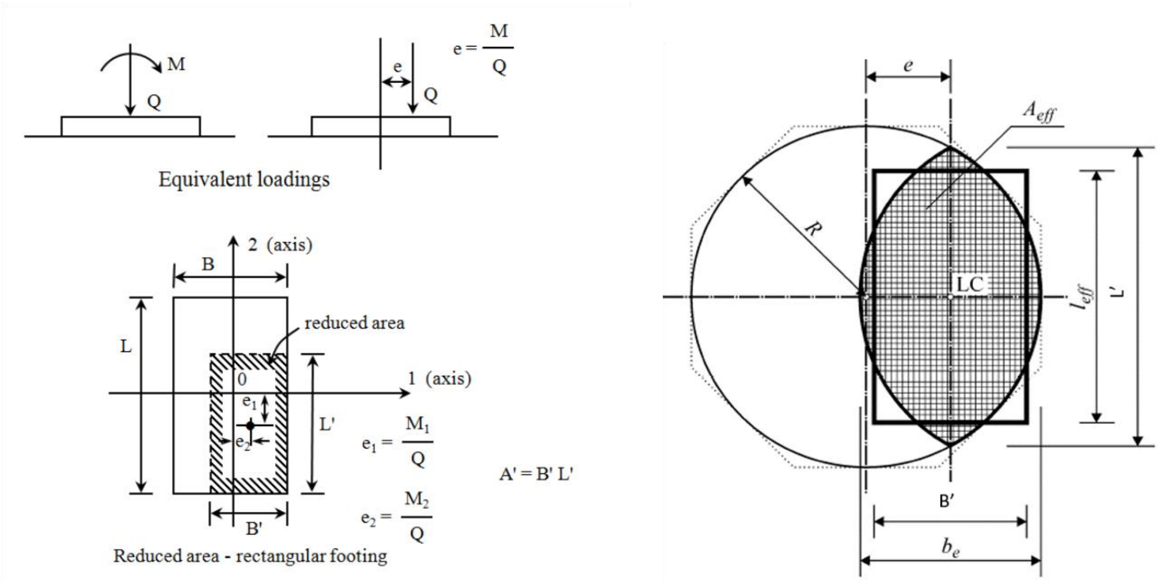


FIGURE 2-9: EFFECTIVE AREA AND ECCENTRICITY FOR A) RECTANGULAR AND B) CIRCULAR DESIGN[17]

When there is an eccentric load the method of the effective base dimension is considered. For rectangular shape, the effective length (L'), width (B') and the area are calculated using the following expressions [13]:

$$L' = \max\left(l_x - 2e_x\,;\; l_y - 2e_y\right);$$

$$B' = \min\left(l_x - 2e_x\,;\; l_y - 2e_y\right);$$

$$A' = B' \cdot L'$$

EQ. 32

For circular foundation/anchor the effective depends on the radius r and e_r [16]:

$$A' = 2\left[r^2 \arccos\left(\frac{e_r}{r}\right) - e_r\sqrt{r^2 - e_r^2}\right]$$

EQ. 33

This is recognized as the area of a circle segment and its mirrored imaged with the midpoint of their common secant located in the load application point (Figure 2-9). The width b_e and length l_e of this double segment area is:

$$b_e = 2(r - e)$$

$$l_e = 2r\sqrt{1 - \left(1 - \frac{B'}{2r}\right)^2}$$

EQ. 34

Based on this, the effective foundation area A' can now be represented by a rectangle with the following dimensions:

$$L' = \sqrt{A' \frac{l_e}{b_e}} \; ; \; B' = \frac{L'}{l_e} b_e$$ **EQ. 35**

Bearing capacity stress for cohesion q_c

The bearing capacity stress is determined using formulations from [12] and [15] :

$$q_c = c_{ud} N_c K_c$$ **EQ. 36**

Where N_c is the bearing capacity factor and K_c is a correction factors that takes into account load inclination and the impact of the foundation shape on the failure case of the foundation, $K_c = i_c s_c$. They are calculated with the following formulations; parameters are presented on Table 2-24:

- $N_c = \frac{N_q - 1}{\tan \varphi_d} \quad for\ \varphi_d \neq 0$ and $N_c = 2 + \pi \quad for\ \varphi_d = 0$
- $i_c = i_q - \frac{1 - i_q}{N_c \tan \varphi_d}$ for $\varphi_d \neq 0$ and $i_c = 1 - \left(\frac{m H_{uls,res}}{B' L' c_{ud} N_c}\right)$ for $\varphi_d = 0$
- $s_c = 1 + \left(\frac{B'}{L'} \frac{N_q}{N_c}\right)$
- $i_q = \left(1 - \frac{H_{uls,res}}{V_{uls,down} + B' L' c_{ud} \cot \varphi_d}\right)^2$
- $m = \left(\frac{2 + (L'/B')}{1 + (L'/B')}\right) \cos^2 \theta + \left(\frac{2 + (B'/L')}{1 + (B'/L')}\right) \sin^2 \theta$

TABLE 2-24: PARAMETERS DESCRIPTION FOR q_c CALCULATION

Symbol	Description	Unit
N_c	Bearing capacity factor	[-]
K_c	Correction factor	[-]
i_c	Inclination factor	[-]
i_q	Inclination factor	[-]
s_c	Shape factor	[-]
m	Exponential term	[-]
θ	Angle between the line of action of the horizontal load and the long axis of the foundations. In this case it is considered equal to $\pi/4$	[°]

Bearing capacity stress for friction q_γ

The bearing capacity stress is equal to:

$$q_\gamma = \gamma_b (B'/2) N_\gamma K_\gamma f_z$$ **EQ. 37**

Where,

- $N_\gamma = 2(1+N_q)\tan\varphi_d\ \tan(\pi/4 + \varphi_d/5)$ and $N_q = \exp(\pi\tan\varphi_d)\left[\tan\left(\frac{\pi}{4}+\frac{\varphi_d}{2}\right)\right]^2$
- $i_\gamma = \left(1 - \frac{H_{uls,res}}{V_{uls,down}+B'L'c_{ud}\cot\varphi_d}\right)^4$
- $s_\gamma = 1 - 0.4\left(\frac{B'}{L'}\right)$

Where N_γ and N_q are the bearing capacity factor, f_z is the depth attenuation factor = 1 and K_γ is a correction factors that takes into account load inclination and the impact of the foundation shape on the failure case of the foundation, $K_\gamma = i_\gamma s_\gamma$.

2) Sliding resistance:

To verify the sliding resistance the lateral resistance of the foundation should be bigger than the maximal horizontal load that can be applied:

$$\frac{H_u}{SF} > (V_{uls,down} + W_b)\,sin\,\beta + (H_{uls,res}\,cos\,\beta) \qquad \textbf{EQ. 38}$$

In order to determine the lateral load capacity of the foundation H_u, formulation is proposed on the literature and standards, they give different expressions for drained and undrained [15].

For drained conditions the cohesion of the soil can be very small, so it will be neglected. Lateral resistance is calculating as function of the maximal downward load from ULS analysis ($V_{uls,down}$):

$$H_u = V_{uls,down}\tan(\varphi_d) \qquad \textbf{EQ. 39}$$

For undrained conditions:

$$H_u = A'c_{ud} \qquad \textbf{EQ. 40}$$

3) Overturning moment:

The overturning moment condition is verified in each axe (formulation for x axis is presented below). The stability moment of the foundation/anchor should be bigger than the overturning moment applied by the environmental loads:

$$\frac{(V_{uls,down} + W_b)\cos\beta * \frac{l_x}{2}}{SF} > M_{uls,x} + (H_{uls,res} * z_{ap}) \qquad \textbf{EQ. 41}$$

- $M_{uls,x}$ is the maximal overturning moment on the x axis from ULS analysis (Nm);
- z_{ap} is the vertical distance between de seabed and the application point of maximal horizontal load (m);
- l_x is the foundation's length on the x axis (m).

The final design of the foundation/anchor is achieved when the three conditions presented are achieved, Figure 2-10 presents a diagram of the design procedure. Outputs are summarized on Table 2-25.

TABLE 2-25: OUTPUTS FOR SHALLOW FOUNDATIONS AND GRAVITY ANCHOR

Outputs	Description	Units
Slab geometry	Length on the x and y axis for rectangular foundations Diameter for circular geometry	[m]
Bearing capacity	Axial capacity of the foundation	[N]
Sliding resistance	Lateral capacity of the foundation	[N]
Stability moment	Stability moment on the x and y axis for rectangular geometry Stability moment on radial axis for circular geometry	[Nm]
Weight	Weight of the foundation	[kg]
Footprint	Footprint surface on the soil	[m^2]

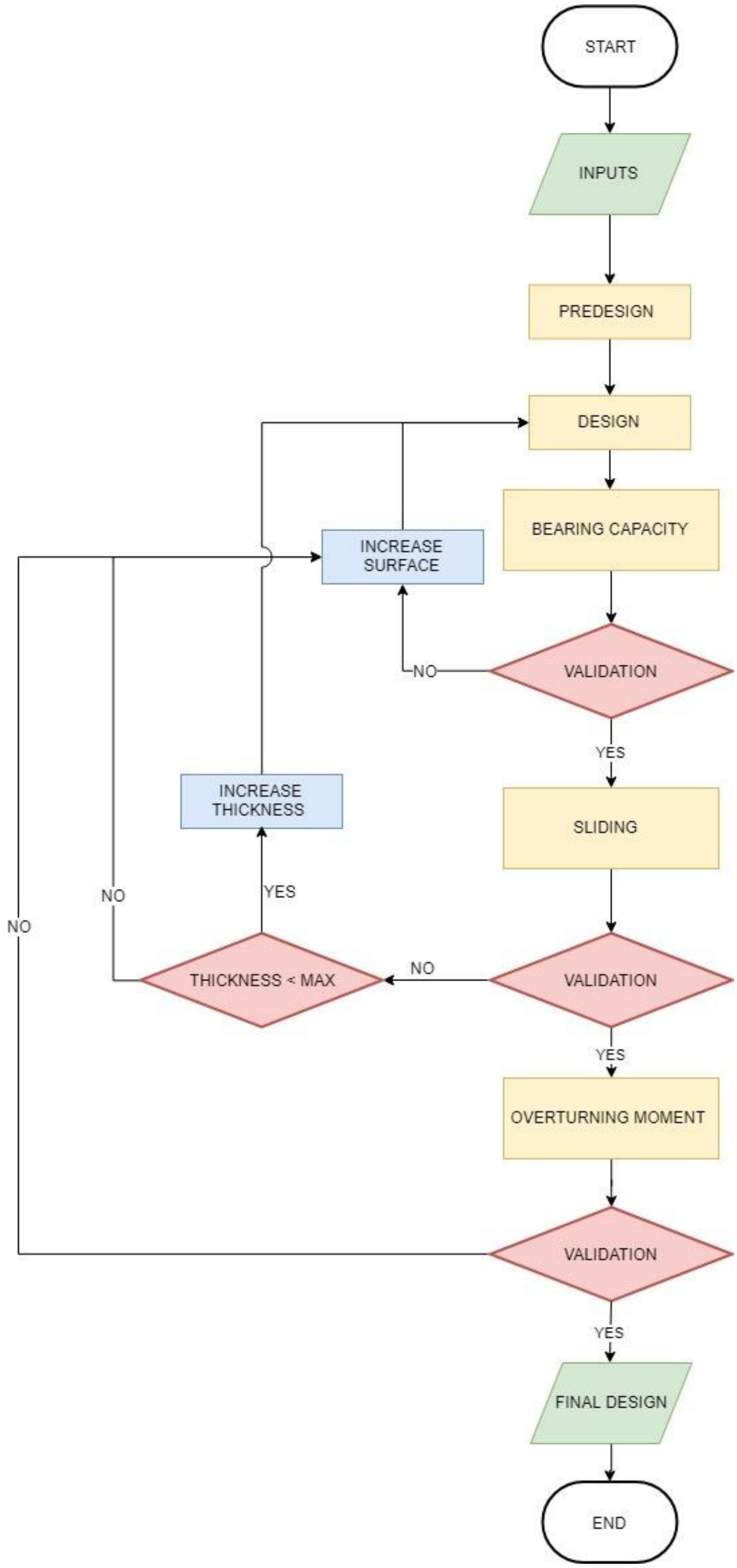


FIGURE 2-10: DESIGN PROCEDURE FOR SHALLOW FOUNDATIONS AND GRAVITY ANCHORS

Methods and Outputs: Piles foundations/anchors

The loading on this type of foundation will be the combination of structure weight and environmental loading: overturning moments, uplift (tensile) as well as downwards (compressive) pressures and lateral loadings. The SK module is able to perform the design for open-end and closed-end piles, the type of pile is defined by the user, in case there no input data the default value is "open_end".

To perform the dimensioning of this type of solution for foundations and anchoring the methodology describe in [13] was implemented without any special hypothesis to simplify it.

In order to perform the design of a steel piles the following conditions are verified:

1) **Lateral capacity:**

The lateral resistance of the pile should be bigger than the horizontal load applied by external loads. It is calculated following the formulation from [13]:

$$\frac{H_u}{SF} > H_{uls,res}$$

$$H_u = \frac{y_{max}\ (EI)}{A_y T^3 + aB_y T^2} \qquad and \qquad y_{max} = d_{crit} * D \qquad \textbf{EQ. 42}$$

Where,

- d_{crit} corresponds to the deflection criteria in %. If there is no input data for this variable a value of 5% is adopted for fixed structures and 10% for moored structures;
- D is the pile diameter in (m);
- y_{max} is the maximal displacement (m);
- E is the Young modulus of steel equal to 200e+09 Pa;
- I inertia modulus (m^4);
- T is the pile-soil stiffness in (m);
- a is the distance of the pile load attachment point above the seafloor surface in m, default value equal to 0;
- A_y and B_y are deflections coefficients given by the figures in [13] Section 5.3. Each curve is implemented in the code as an exponential equation.

2) **Axial capacity in tension:**

The axial resistance of the pile in tension is given by the friction resistance. The following condition is verified:

$$\frac{(A_s\, f_s) + W_b}{SF} > V_{uls,up} \qquad \textbf{EQ. 43}$$

Where:

- A_s is the surface area of the pile below seafloor (m^2);

- f_s is the average unit skin frictional resistance (N/m²). It is calculated using the methodology proposed by [13] for cohesive ($c_{u,d} > 0\ and\ \varphi'_d = 0$) and non-cohesive soil ($c_{u,d} = 0\ and\ \varphi'_d > 0$) soil. The maximal value for this parameter is given by [13]Section 5.3.

3) Axial capacity in compression:

The axial resistance of the pile in compression is given by the friction resistance of the shaft ($A_s f_s$) plus the tip resistance ($A_p q_p$) :

$$\frac{(A_s\ f_s) + (A_p\ q_p)}{SF} > V_{uls,down} + W_b$$ **EQ. 44**

Where:

- A_p is the area of the Section of the pile (m²);
- q_p is the unit soil bearing capacity of the pile (Pa). It is calculated using the methodology proposed by [13] for cohesive and non-cohesive soil.

4) Stress analysis of the Section:

The stress on the steel pile Section is verified following the methodology on [13], the allowable steel stress on the Section:

$$\frac{\sigma_{max,steel}}{\gamma_s} > \frac{V_{uls,min}}{A_p} + \frac{M_{max,sec}}{S_p}$$ **EQ. 45**

Where:

- $\sigma_{max,steel}$ is the allowable stress of the pile equal to 250+06 Pa;
- γ_s safety factors equal to 1;
- $M_{max,sec}$ is the maximal moment on the Section in (Nm);
- S_p is the Section modulus of the pile (m³).

Figure 2-11 show the loop of design to determine the dimensions of a pile foundation/anchor. Outputs when designing a pile are presented on Table 2-26.

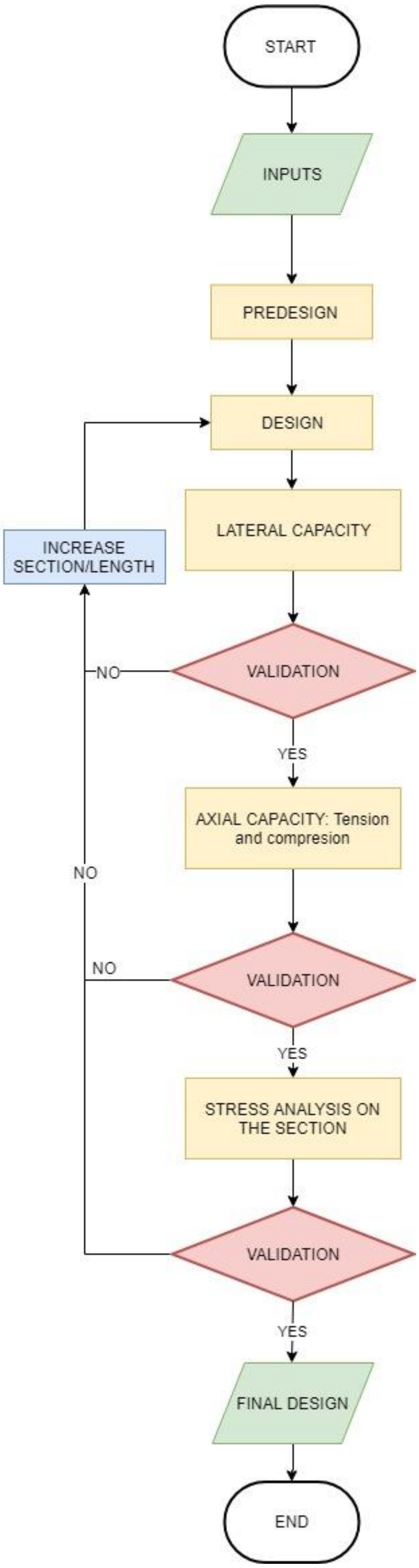


FIGURE 2-11: DESIGN PROCEDURE FOR PILES

TABLE 2-26: OUTPUTS FO PILE DESIGN

Outputs	Description	Units
Pile geometry	External diameter Wall thickness Length Maximal deflection ymax Inertia moment Stiffness	[m] [m] [m] [m] [m⁴] [m]
Lateral resistance	Lateral capacity Lateral load for design	[N] [N]
Axial resistance	Skin friction in tension Skin friction in compression Tension capacity Compression capacity Tension load for design Compression load for design	[N/m²] [N/m²] [N] [N] [N] [N]
Stress on the Section	Maximal stress on the Section	[Pa]
Mass	Mass of the foundation	[kg]
Footprint	Footprint surface on the soil	[m²]

Methods and Outputs: Drag Anchors

Drag anchors are design to resist horizontal loads, they are currently used with catenary mooring lines. Different types existed on the market, each manufacturer develop its own catalogue and specification for each type. For permanent floating structures STEVIN anchors are currently used (Figure 2-12). The methodology developed on the SK module is based on industrials data and catalogues.

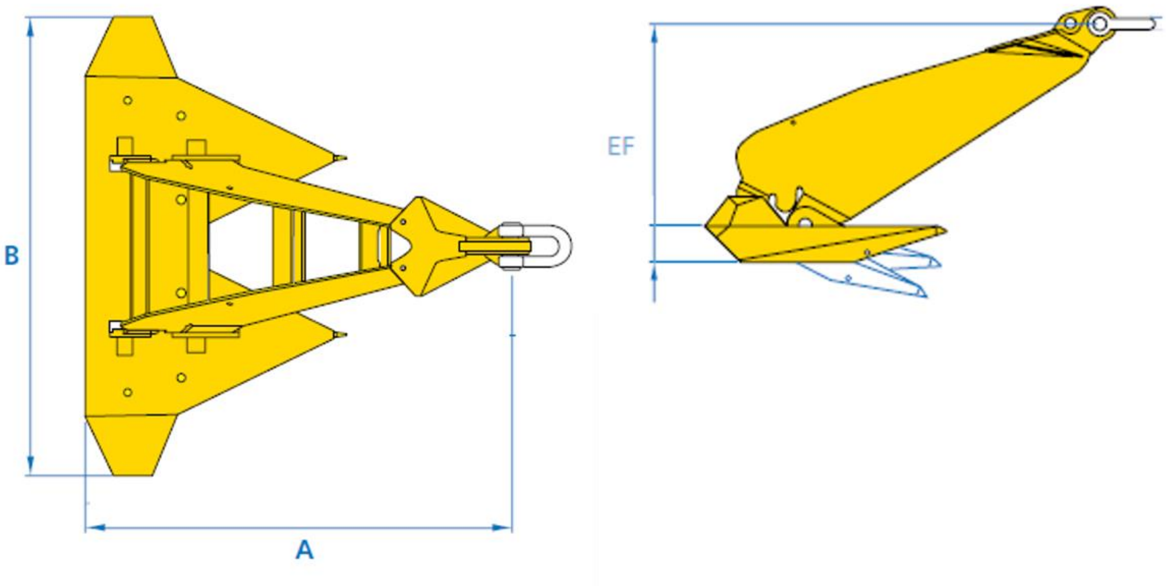


FIGURE 2-12: STEVIN DRAG ANCHORS [9]

Drag anchor design:

There is no standard geometry for drag anchors, each manufacturer has its precis design. The SK module proposed two types of anchors with different geometry. The most suitable type and size of anchor will be determine depending on the Ultimate Holding Capacity (UHC) of the anchor and the type of soil. Anchor type n°1 is considered to be more suitable for soft soils and n°2 for hard soils.

As the mooring lines are design through a quasi-static model, to guarantee a safety factor of 1.8 must be taken into account to determine the anchor design [13]:

$$UHC \; \geq H_{uls,res} * 1.8 \qquad \textbf{EQ. 46}$$

As suggested in [13], in order to determine the geometry and weight of the anchor needed the following power law is considered:

$$UHC = m\,(W)^b \qquad \textbf{EQ. 47}$$

With W equal to the anchors weight, m and b are parameters that depends on the soil type and anchor geometry. Three type of soils are considered:

- Soft soil: friction angle and/or undrained shear strength inferior to 25° and 20 kPa;
- Mid soil: sandy soils with a friction angle between 25° and 30° or/and undrained shear strength between 20 and 75 kPa
- Hard soil: sandy soils with a friction angle superior to 30° or/and undrained shear strength between 20 and 75 kPa

TABLE 2-27: SOIL TYPE DEFINITION FOR DRAG ANCHOR DESIGN

Type of soil	Internal friction angle of soil [°]	Undrained shear strength [kPa]
Soft soil	$\varphi \leq \; 25°$	$c_u \leq 20$
Mid soil	$25° \; < \varphi \leq \; 30°$	$20 \; < \; c_u \; \leq \; 75$
Hard soil	$\varphi > \; 30°$	$c_u \; > \; 75$

The relationship between the UHC and the weight for both anchors is presented on Figure 2-13 and Figure 2-14.

In order to determine the geometry of the anchor a power law between the weight and its dimension was establish applying a curve fitting to the information from the manufacture's catalogues. The relationship between the weight and the dimensions A, B and EF are presented on Figure 2-15 and Figure 2-16, bullets point on the graph corresponds to the data available on the catalogue.

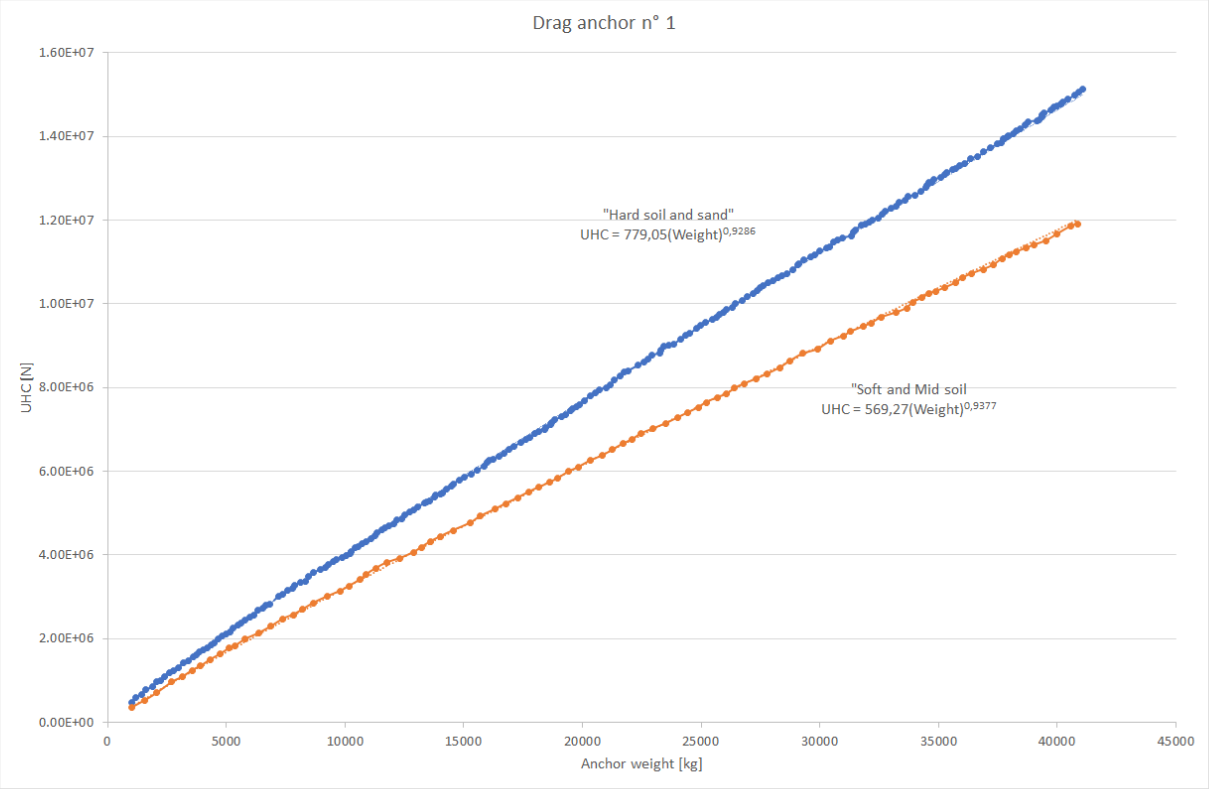


FIGURE 2-13: UHC VS. ANCHOR WEIGHT FOR DRAG ANCHOR N°1

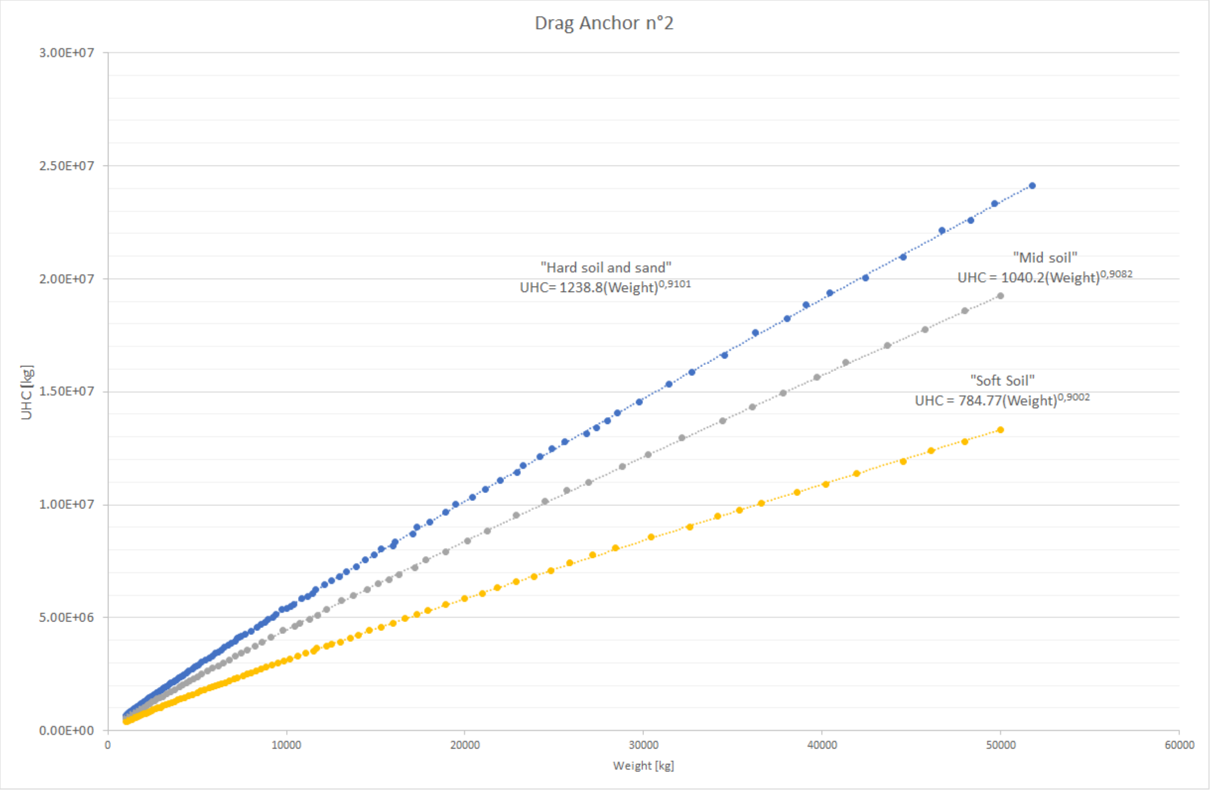


FIGURE 2-14: UHC VS. ANCHOR WEIGHT FOR DRAG ANCHOR N°2

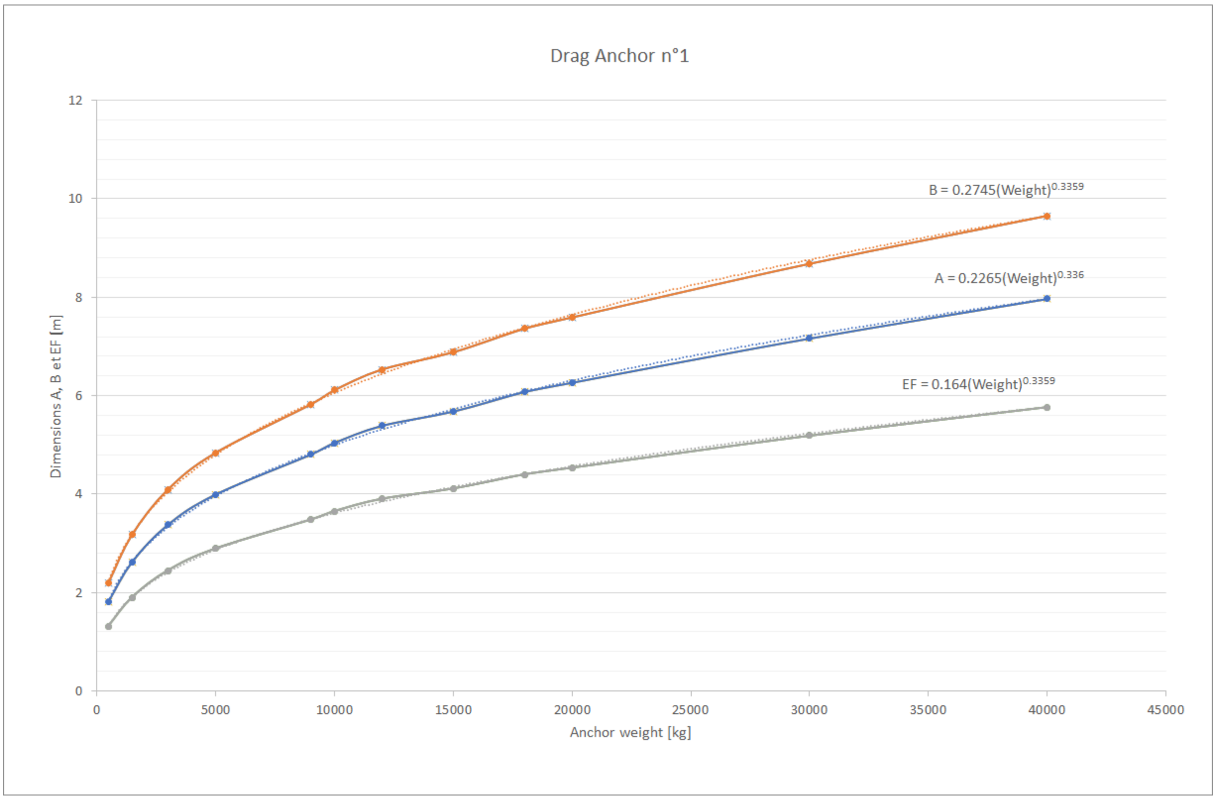


FIGURE 2-15: DIMENSIONS FOR ANCHOR TYPE N°1

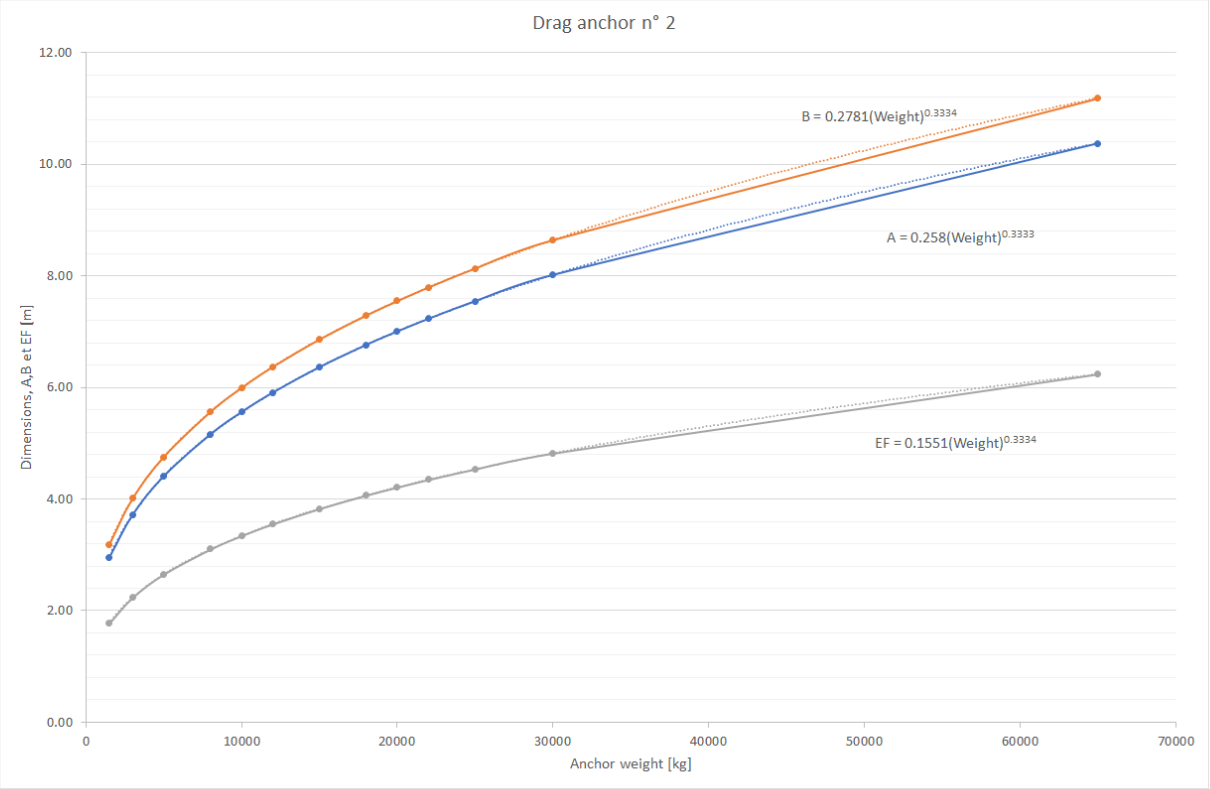


FIGURE 2-16: DIMENSIONS FOR ANCHOR TYPE N°2

Figure 2-17 summarize the steps to design a drag anchor. Inputs data for design are $H_{uls,res}$ and the Soil type. First Soil type is used to determine the more suitable anchor (n°1 or n°2) from catalogue (user can introduce a new type of anchor). Then, the UHC is calculated in order to be able to determine the anchors weight and size.

Figure 2-17 presents the loop design to determine the size and the weight of a drag anchor. Outputs given by the SK module for drag anchor design are presented on Table 2-28.

TABLE 2-28: OUTPUTS FOR DRAG ANCHOR DESIGN

Outputs	Description	Units
Type of anchor from catalogue	Anchor_n_1 Anchor_n_2	[-]
Weight	Anchor weight	[Kg]
UHC	Ultimate Holding Capacity of the anchor	[N]
Anchor geometry	Length A Length B Length EF	[m] [m] [m]
Mass	Mass of the foundation	[Kg]
Footprint	Footprint surface on the soil	[m²]

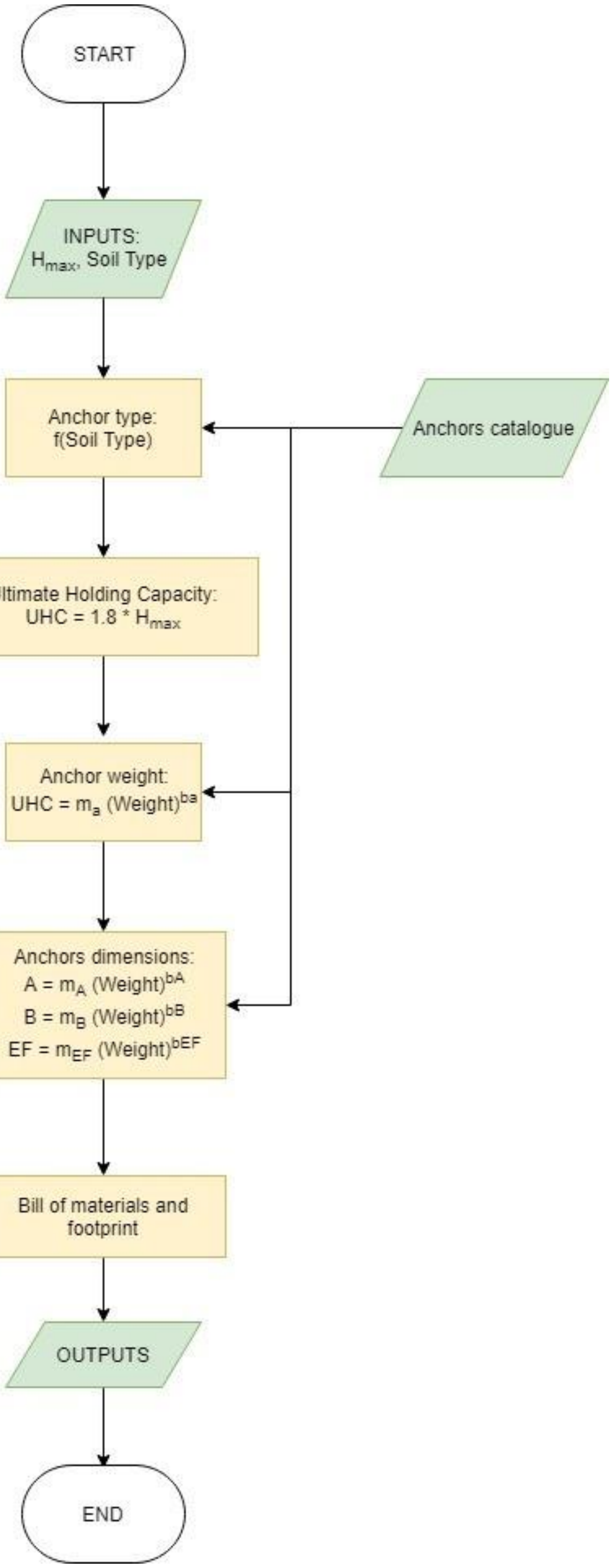


FIGURE 2-17: PROCEDURE TO DESIGN DRAG ANCHORS

Drag anchor catalogue:

Drag anchor catalogue (Table 2-29) has the information needed to perform the design of the foundation. Multiplicative and exponential coefficients mx and bx are summarizes. This parameters describes the relation between the weight of the anchor and its ultimate capacity and dimensions (Figure 2-13, Figure 2-14, Figure 2-15, Figure 2-16) .

The suitability of the anchor to the type of soil is define, a value of 1 to 3 is designated:

- 1 for high reliability
- 2 for medium reliability
- 3 for low reliability

TABLE 2-29: CATALOGUE FOR DRAG ANCHORS

	Anchor UHC in Soft Soil		Anchor UHC in medium Soil		Anchor UHC in stiff clay and sand	
Name ID	**m_soft_soil**	**b_soft_soil**	**m_mid_soil**	**b_mid_soil**	**m_stiff_soil_sand**	**b_stiff_soil_sand**
anchor_n_1	569.27	0.9377	569.27	0.9377	779.05	0.9286
anchor_n_2	784.77	0.9002	1040.2	0.9082	1238.8	0.9101

	Reliability		
Name ID	**Rel_soft_soil**	**Rel_mid_soil**	**Rel_stiff_soil_sand**
anchor_n_1	1	3	3
anchor_n_2	3	1	1

	Dimensions parameters					
Name ID	**m_A**	**b_A**	**m_B**	**b_B**	**m_EF**	**b_EF**
anchor_n_1	0.2265	0.336	0.275	0.3359	0.164	0.3359
anchor_n_2	0.258	0.3333	0.2781	0.3334	0.1551	0.3334

The user is able to add new types of anchors, however the full table must be filled. As an input information the user must specified a choice of anchor as "custom" in order to only take into account user anchors.

Methods and Outputs: Suction caisson anchors

Suction caisson comprise large diameter cylinders, in a range of 3 to 8 m, open at the bottom, and generally with a length to diameter ratio L/D in the range 3 to 6 [18].

The axial holding capacity of a suction anchor depends on the nature of the soil, in particular, its permeability. Once suction in the caisson is induced, an accumulation of excess negative water pressures in the soil takes places, for cohesive soils with high permeability it gives an advantageous plug stability that can resist uplift due to the reverse bearing capacity (Figure 2-18a) [19]. Conversely it is uncertain whether additional capacity based on the reverse end bearing should be considered for cohesionless soils, in [20] it is recommended not to consider the reverse bearing capacity when the permeability is less than $10^{-5}[m/s]$.

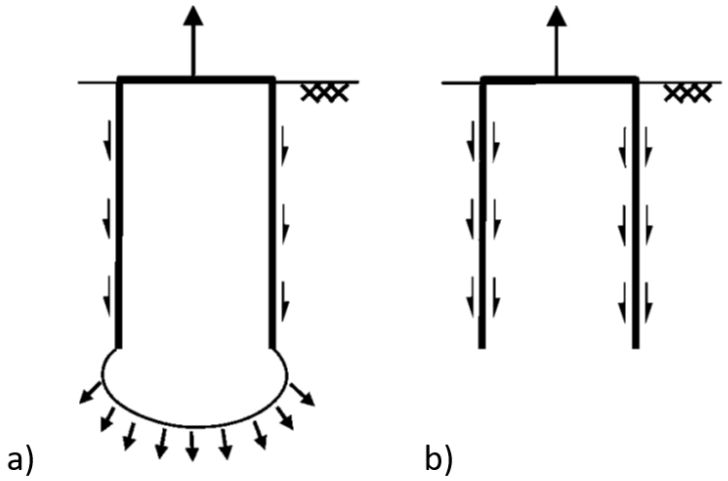


FIGURE 2-18: UPLIFT RESISTANCE OF SUCTION ANCHORS: A) ON COHESIVE SOILS; B) ON COHESIONLESS SOILS [18]

Once installed, the caisson acts like a short rigid pile. The maximum holding capacity is obtained if the chain is attached at a depth where the anchor failure mode is large translational displacement with minimal rotation [21] (Figure 2-19), the optimum load attachment point is generally at a depth between 0.6 and 0.7 of the length [14], [18] .

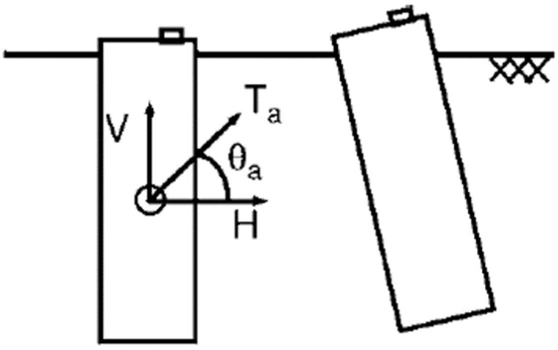


FIGURE 2-19: SUCTION ANCHOR FAILURE MODE[18]

In order to achieved the suction caisson design the SK module considers formulation available from several documents and the following hypothesis from [18]:

- Diameter range: from 3 to 8 m;
- Ration between the diameter and the wall thickness: 100 to 250;
- Ratio between length and diameter: from 3 to 6;
- Optimum load attachment point: 0.7 of the length;
- Horizontal failure occurs as pure translation.

1) Ultimate load capacity on cohesive soils:

The **uplift capacity** of suction caissons in cohesive soils is calculated as the sum of the reverse end bearing capacity, the external friction resistance between the caisson and the soil and the suction caisson's weight [14], [18]:

$$V_u = A_{cs} N_c s_{u,d} + \alpha A_s + W_{sc} \qquad \textbf{EQ. 48}$$

$$N_c = 6.2\left(1 + 0.34\arctan\left(\frac{L}{D_{ext}}\right)\right) \ for \frac{L}{D_{ext}} \leq 4.5$$

$$N_c = 9 \ for \frac{L}{D_{ext}} > 4.5$$

Where:

- A_{cs} is the cross-Section of the caisson $\left(\frac{\pi D_{ext}^2}{4}\right)$ (m²);
- N_c end bearing capacity factor;
- α adhesion factor (Pa);
- A_s is the shaft surface of the caisson $(\pi D_{ext} L)$ (m);
- W_{sc} is the caisson's weight (N);

The first term of V_u's equation represents the contribution of the reverse end bearing capacity, its formulation is inspired by the Brinch-Hansen's bearing capacity equation [22], this equation takes into account a shape factor, [23] suggest a value of 1.2 for it but, this factor is not taken into account in [6] and [12] .

The second term represents the contribution of the friction resistance, as recommended on the literature the "α-method" is considered, the adhesion factor α varies between 0 (smooth) and 1 (rough). In their study, Andersen and Jostad [21] recommended a lower bound adhesion $\alpha = 0.65$.

To determine the **lateral capacity** the method developed by [24] is recommended and mention by [14], [18], [21] and [25]. The maximum horizontal resistance is [18]:

$$H_u = L\, D_{ext} N_p c_{u,d} \qquad \textbf{EQ. 49}$$

Where,

- L is the embedded length of caisson (m);
- D_{ext} is the external diameter of caisson (m);
- $c_{u,d}$ is the design undrained shear strength (Pa).

The value of the lateral bearing capacity factor N_p depends on the location of the pad-eye, a simplified equation for uniform soils is proposed by [26]:

$$N_p = \frac{3.6}{\sqrt{\left(0.75 - \left(\frac{z_{ap}}{L}\right)\right)^2 + \left(0.45 - \left(\frac{z_{ap}}{L}\right)\right)^2}} \quad \textbf{EQ. 50}$$

Where z_{ap} is the application point of the load, the pad-eye depth (m).

2) Ultimate load capacity on non-cohesive soil:

The horizontal and vertical loading capacity of suction caissons in cohesionless soils is calculated using the formulation proposed in the literature [27] [22] [23].

The uplift resistance is calculated as the sum of the external and internal friction resistance between the caisson and the soil and the suction caisson's weight. This is based on the work of [22] [23], there is no taken into account of the effect of the stress enhancement :

$$V_u = \frac{\pi}{2}(D_{ext} - D_{int})\, L^2\, \gamma' K \tan\delta \quad \textbf{EQ. 51}$$

Where:

- D_{int} is the internal diameter (m);
- K is the average coefficient of earth pressure equal to $1 - \sin\varphi'_d$ [17] ;
- δ is the interface friction angle between the pile and the soil, $\delta = 0.5\varphi'_d$ [30]
- The lateral ultimate capacity is calculated as follow [27], [30]:

$$H_u = \frac{1}{2} D_{ext} N_q \gamma' L^2 \quad \textbf{EQ. 52}$$

Where the bearing capacity factor $N_q = e^{\pi \tan\varphi'_d} \tan^2(45° + \varphi'_d/2)$ [17]

3) Design verification:

In order to achieve the design of the caisson, it is important to verify the **general loading** conditions of vertical and horizontal loading simultaneously. Inclined loads are applied at the pad-eye, the pure vertical and pure horizontal capacities will be reduced by the presence of loading in the orthogonal direction. Interaction between vertical and horizontal loading can be modelled by developing a failure envelope [18].

The shape of the failure envelopes has been modelled by an elliptical relationship [18]:

$$\left(\frac{H}{H_u}\right)^a + \left(\frac{V}{V_u}\right)^b = 1 \quad \textbf{EQ. 53}$$

- $a = \frac{L}{D} + 0.5$
- $b = \frac{L}{3D} + 4.5$

Where, H_u and V_u are the uniaxial horizontal and vertical capacities, respectively. To guarantee the stability of the anchor, the design load case should be inside the ellipse, this means:

$$\left(\frac{H_d}{H_u}\right)^a + \left(\frac{V_d}{V_u}\right)^b < 1 \qquad \textbf{EQ. 54}$$

4) Load transfer from mudline

For suction caisson design the pad-eye is estimated at depth z_a= 0.7L from the mudline, it means that a certain length of the chain is embedded (Figure 2-20). The design load on the anchor H_d and V_d are calculated by taking into account the load reduction due to soil bearing resistance against the mooring line:

$$H_d = T_a \cos\theta_a$$

$$V_d = T_a \sin\theta_a$$

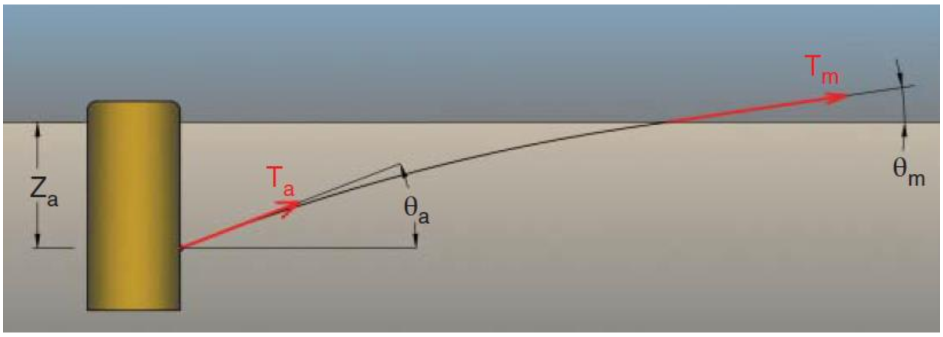


FIGURE 2-20: LOADS ON THE ANCHOR LINE [27]

The load T_m and the angle θ_m at the mudline are obtained from ULS analysis of the mooring lines of the floating device, for anchors design a safety factor of 1.8 is applied to the loads values obtained [13]:

EQ. 55

$$T_m = 1.8 * \sqrt{H_{uls,res}^2 + V_{uls}^2}$$

$$H_{uls,res} = \sqrt{H_{uls,x}^2 + H_{uls,y}^2}$$

$$\theta_m = \arctan\frac{V_{uls}}{H_{uls}}$$

Where, $H_{uls,res}$ is the resultant horizontal load from ULS analysis and V_{uls} is the vertical (upward) load.

To determine the load design T_a and the angle θ_a at the pad-eye the methodology explained in [14], [31] is used where:

$$\theta_a = \sqrt{\theta_m^2 + \frac{2Qz_a}{T_a}}$$

$$T_a = \frac{T_m}{e^{\mu(\theta_a - \theta_m)}}$$ **EQ. 56**

Where Q is the vertical soil resistance of the soil (N) and μ is the friction coefficient between the chain and the soil. Both parameters depend on the soil properties.

Cohesive soils:

The vertical soil resistance for ***cohesive soils*** is calculated with the following equations [27]:

$$Q = E_n d_b N_c c_{ud}$$ **EQ. 57**

Where:

- E_n is the normal area multiplier for chain equal to 2.5;
- d_b is the chain diameter [m];
- N_c is the bearing capacity factor equal to 11.5 [32];

For cohesive soils μ is estimated between 0.4 and 0.6 [31]. In order to perform the anchor design, the most conservative values are adopted: $\mu = 0.4$.

Cohesionless soil:

The vertical soil resistance for ***non-cohesive*** soils is calculated using the same approach, but changing the bearing capacity factor :

$$Q = E_n d_b N_q \gamma' z_a$$ **EQ. 58**

Where γ' is the buoyant unit weight of the soil (N/m^3).

Different values for the bearing capacity factor N_q can be found on the literature, values used for piles design suggested in [17] and [13] are taken into account and adapted to soil types propose by the module. For the user_preference (CL3) type of soil the value will be interpolated.

TABLE 2-30: BEARING CAPACITY FACTOR FOR PILES/SUCTION IN NON-COHESIVE SOIL

Soil Type	Friction angle [°]	Nq
Very loose sand	25	5
Loose sand	30	8
Medium dense sand	32	12
Dense sand	35	20
Very dense sand	38	40
Gravels, pebbles	45	50

For non-cohesive soils it's equal to the tangent of the interface friction angle δ between the chain and the soil ($\delta = 0.5\varphi'_d$ to $0.7\varphi'_d$ [33]). In order to perform the anchor design, the most conservative values are adopted: $\tan 0.5\varphi'_d$.

Figure 2-21 show the procedure to design a suction anchor, outputs are summarized on Table 2-31:

TABLE 2-31: OUTPUTS FOR SUCTION CAISSON DESIGN

Outputs	Description	Units
Suction geometry	External diameter Wall thickness Length Pad-eye depth	[m] [m] [m] [m]
Ultimate capacity	Lateral capacity Uplift capacity Design verification	[N] [N] [-]
Mass	Mass of the foundation	[Kg]
Footprint	Footprint surface on the soil	[m²]

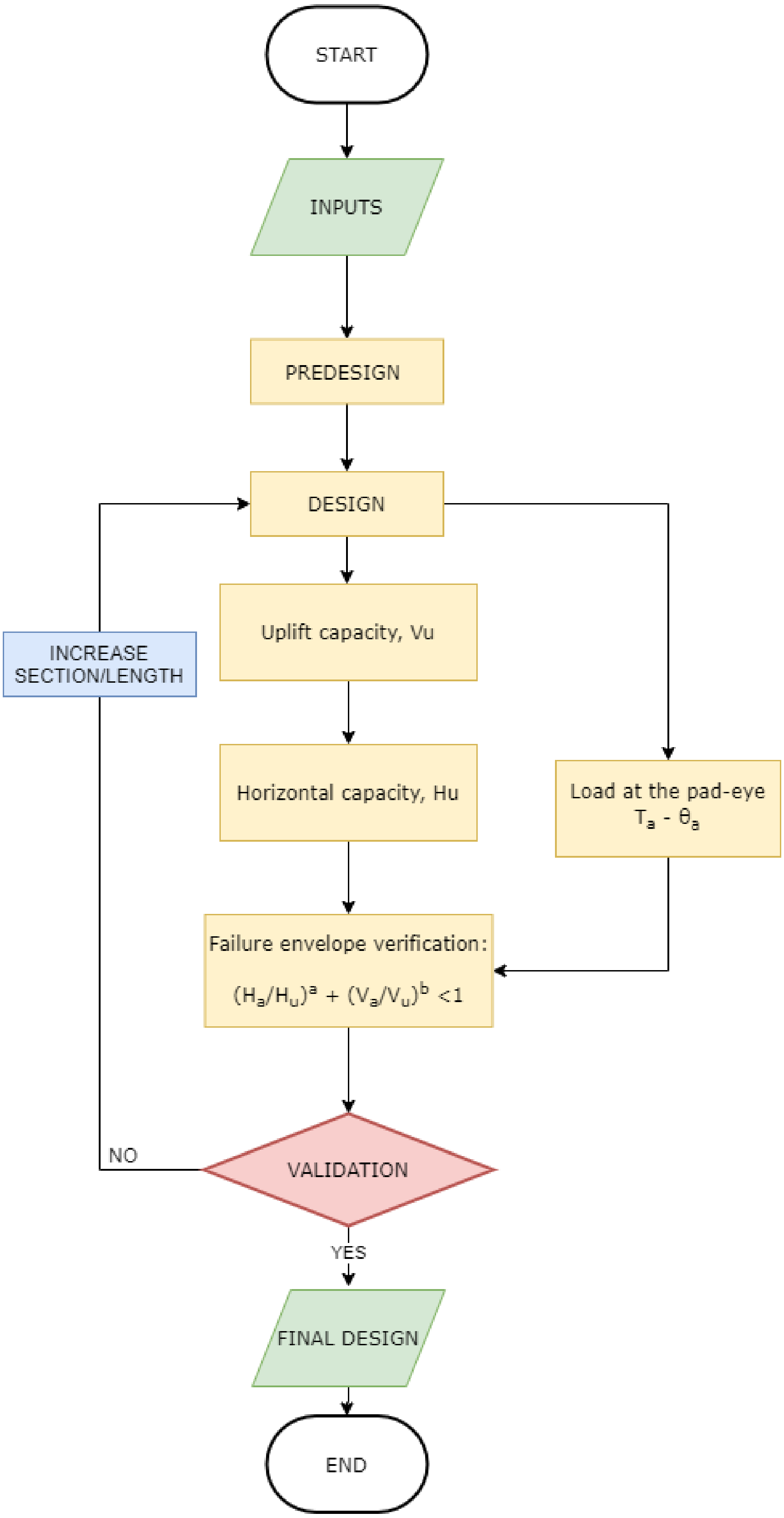


FIGURE 2-21: DESIGN PROCEDURE FOR SUCTION ANCHORS

2.3.9 HIERARCHY AND BILL OF MATERIALS

Objectives

Based on the mooring system design and foundation base/anchor design, a hierarchy of the components is constructed, as well as a bill of materials. The hierarchy is a digital representation of the component-to-component connection relationship within the station keeping system. The bill of materials is the list of components in the station keeping system, associated with their cost. Both the hierarchy and the bill of materials are used as inputs by other modules (LMAO, RAMS and SLC).

Inputs

TABLE 2-32: INPUTS FOR HIERARCHY AND BILL OF MATERIALS

Inputs description	Origin of the Data
Mooring system design	User or results from Catenary Mooring System Design
Foundation Base/Anchor design	User or results from Foundation Base/Anchor Design

Methods and Outputs: hierarchy

The hierarchy is constructed based on 3 main levels:

- *Station keeping*: represents the station keeping concept of one moored entity
- *Mooring line*: represents a collection of components linked together
- *Components*: represents a physical component, e.g. a line segment or an anchor

The hierarchy can be visualized as a table, where each line represents one of the three levels above, and the columns correspond to the output variables described in Table 2-33.

TABLE 2-33: HIERARCHY OUTPUTS

Outputs description	Data Model in SK
system	string array
name_of_node	string array
design_id	string array
node_type	string array
node_subtype	string array
category	string array
parent	string array
child	array of string array
gate_type	string array
failure_rate_repair	float array
failure_rate_replacement	float array

Methods and Outputs: bill of materials

The bill of materials is constructed as a list of components with their associated quantity and cost. It contains the variables described in Table 2-34.

TABLE 2-34: BILL OF MATERIALS OUTPUTS

Outputs description	Data Model in SK	Units
module_name	string array	[-]
catalogue_id	string array	[-]
product_name	string array	[-]
quantity	float array	[unit]
unit	string array	[-]
unit_cost	float array	[€/unit]
total_cost	float array	[€]

2.3.10 ENVIRONMENTAL IMPACT

Objectives

Based on the mooring system design and foundation base/anchor design, a set of metrics required by the ESA-module are computed.

Inputs

TABLE 2-35: INPUTS FOR ENVIRONMENTAL IMPACT

Inputs description	Origin of the Data
Mooring system design	User or results from Catenary Mooring System Design
Foundation Base/Anchor design	User or results from Foundation Base/Anchor Design

Methods and Outputs

The metrics computed for the ESA-module are the following:

- The quantity of material sorted by material type
- The total submerged surface of the station keeping system
- The footprint of the station keeping system, i.e. the area of the seabed covered by the components of the station keeping system

The quantity of material and the total submerged surface are computed from the dimensions and material quantity of the mooring system components: line segments, anchors and foundation bases.

The footprint of the line segments is computed as follows:

- A Static Analysis is performed at the initial position of the device
- The touchdown length of each segment is computed at this position
- The maximum touchdown length L_{td} among all the line segments is selected
- The footprint is computed as $\pi {L_{td}}^2$

The outputs of the Environmental Impact functionality are listed in Table 2-36.

TABLE 2-36: ENVIRONMENTAL IMPACT OUTPUTS

Outputs description	Data Model in SK	Units
footprint	float array	[m²]
submerged surface	float array	[m²]
material quantity	float array	[kg]
material	string array	[-]

3. THE IMPLEMENTATION

3.1 THE ARCHITECTURE OF THE TOOL

The DTOceanPlus tools have been implemented considering three layers:

- The Business Logic, including a set of modules, classes, libraries implementing all the functionalities of the modules.
- The Application Programming Interface (API) that will constitute the gate of the module to the other modules, that either consume the services provided by SK or whose services are consumed by SK.
- The Graphic User Interface (GUI), allowing interaction with the user in order to show results and receive inputs, besides exporting/importing data to/from files.

3.1.1 BUSINESS LOGIC

The architecture of the Business Logic of Station Keeping reflects, also in its architecture, the functionalities that were described in Section 2.

In order to help understanding how the business logic is organized and how all classes function together, Figure 3-1 shows a general diagram of its structure, a color code was adopted:

- Green: inputs data/classes needed to initiate calculations;
- Yellow: intermediate calculation classes, preparation of input data needed to achieve the design
- Red: designer, classes that perform the design/optimization of mooring and foundations
- Blue: outputs for the user and other modules.

The main methods of the classes and modules presented in the diagram are described in the following Sections.

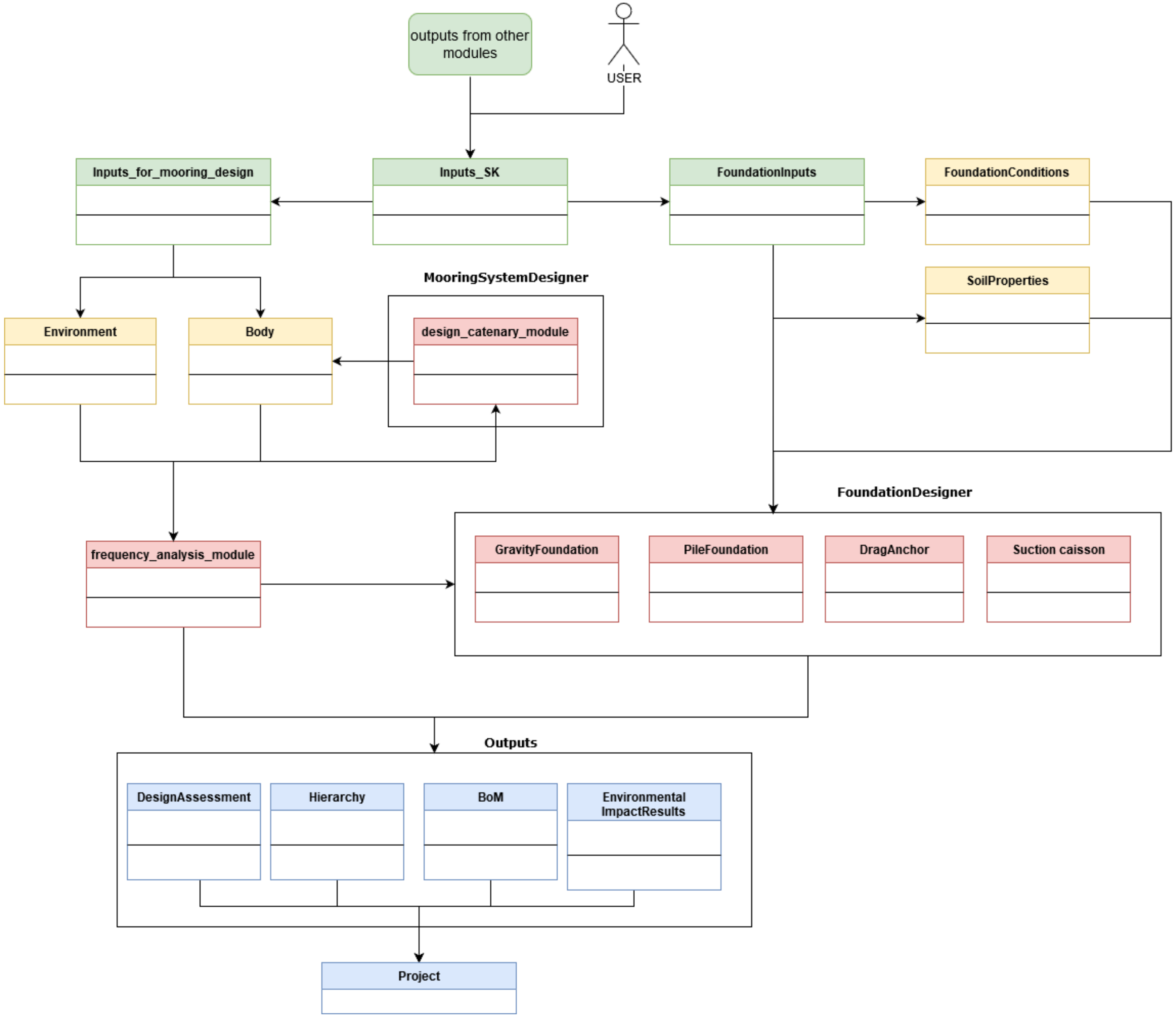


FIGURE 3-1: BUSINESS LOGIC DIAGRAM

Inputs_SK

This class regroups all inputs from other modules and from the user. Properties are the ones presented below on Inputs_for_mooring_design and FoundationsInputs

Inputs_for_mooring_design

This class regroups all inputs from other modules and from the user, necessary to perform mooring system design and assessment:

- Device mechanical and hydrodynamic properties
- Environmental conditions for ULS and FLS Analyses
- ULS Analysis parameters
- FLS Analysis parameters
- Substation properties (optional)
- Master structure properties (optional)

Environment

The Environment class regroups the data that describe the environmental conditions to study:

- Wave height, wave peak period, wave direction
- Wind velocity, wind direction
- Current velocity, current direction
- Probability of occurrence

Body

The Body class, as shown in Table 3-1, regroups the data that describes the device, master structure or substation to study:

- Device position
- Mass, mass matrix, position of center of gravity
- Wind force model
- Current force model
- Mean wave drift force model
- Mooring system force model
- Hydrodynamic properties

TABLE 3-1: MAIN METHODS FROM BODY CLASS

Method	Description	
	Objectives	Section/ Eq./Table
compute_static_force(self)	Compute the sum of the static forces that applies on the device: wind, current, hydrostatic, gravity, mooring forces	Section 2.3.1
compute_tension_in_all_lines(self)	Compute the tension in each line segments of the device mooring system	-

design_catenary_module

TABLE 3-2: FUNCTIONS FROM DESIGN_CATENARY_MODULE

Function	Description	
	Objectives	Section/ Eq./Table
design_catenary(Body,Environment)	Automated design of catenary mooring system, based on the device properties and the environmental conditions	Section 2.3.5

frequency_analysis_module

TABLE 3-3: FUNCTIONS FROM FREQUENCY_ANALYSIS_MODULE

Function	Description	
	Objectives	Section/ Eq./Table
run_frequency_analysis(Body,Environment)	Perform ULS Analysis based on the device properties and the environmental conditions	Section 2.3.3
run_fls_frequency_analysis(Body,Environment)	Perform FLS Analysis based on the device properties and the environmental conditions	Section 2.3.4

FoundationsInputs

This class uses inputs from the user and other modules to create the inputs necessary to perform the design of foundations.

TABLE 3-4: METHODS FROM FOUNDATIONSINPUTS CLASS

Method	Description	
	Objectives	Section/ Eq./Table
soil_properties(self)	Determine soil mechanical properties: friction angle, cohesion, relative density and soil buoyant weight using the soil type define by the user.	Section 2.3.6 Data from Table 2-16
soil_slope_type(self)	Classification of the soil slope in steep (≥ 10°) or moderate (< 10°). (to be used by FoundationConditions)	-
main_load(self)	Determine the direction of the main load transfer to the foundation/anchor from ULS analysis. (to be used by FoundationConditions)	-
geometry_definition(self)	The geometry preference in case a gravity foundation/anchor is needed.	Section 2.3.8
piles_inputs(self)	Definition of default values for variables if there is not user data	Table 2-23
outputs_for_design(self)	It executes **soil_properties, soil_slope_type, main_load** and **geometry_definition**. It creates a pandas table that summarize soil mechanical properties.	

FoundationConditions

The FoundationConditions class allows to determine which type of foundation/anchor solution is the most suitable for the device.

TABLE 3-5: METHODS FROM FOUNDATIONCONDITIONS CLASS

Method	Description	
	Objectives	Section/ Eq./Table
Foundation_type_evaluation(self)	Evaluation of the most suitable type of foundation using input data from FoundationsInputs	Section 2.3.7

SoilProperties

This class initiates soil properties catalogue.

TABLE 3-6: METHODS FROM SOILPROPERTIES CLASS

Method	Description	
	Objectives	Section/ Eq./Table
soil_properties_cat(self)	Initiation of soil properties catalogue	Table 2-16

GravityFoundation

This class contains methods and properties needed to perform gravity foundations/anchors design. The methodology developed on Section 2.3.8 was implemented.

TABLE 3-7: METHODS FROM GRAVITYFOUNDATION CLASS

Method	Description	
	Objectives	Section/ Eq./Table
soil_design_properties (self)	Determination of soil mechanical properties for design	EQ. 24
foundation_initial_geometry (self)	Predesign of the anchor/foundation, minimal dimensions are used.	EQ. 25, EQ. 26, EQ. 27, EQ. 28
def_geometry (self)	Definition of the geometry for calculation taking into account eccentricity	EQ. 31, EQ. 32, EQ. 33, EQ. 34, EQ. 35
compute_bearing_capacity (self)	Calculation of bearing capacity	EQ. 30, EQ. 36, EQ. 37
compute_sliding_resistance (self)	Calculation of sliding resistance	EQ. 39, EQ. 40
compute_overtuning_moment (self)	Calculation of overturning moment	EQ. 41
Increase_Section (self)	Function to increase the Section of the foundation when design conditions are not verified	
design (self)	This method executes the design procedure as shown in Figure 2-10. Design condition are verified	EQ. 30, EQ. 38, EQ. 41
outputs (self)	Outputs from design	Table 2-25

PileFoundation

This class contains methods and properties needed to perform pile foundations/anchors design. The methodology developed on Section 2.3.8 was implemented.

TABLE 3-8: METHODS FROM PILEFOUNDATION CLASS

Method	Description	
	Objectives	Section/ Eq./Table
init_length (self)	Determination of initial dimension of piles using stiffness criteria as in [13]	
compute_lateral_capacity (self)	Determine lateral resistance of the pile	EQ. 42
compute_axial_capacity (self)	Determine tension and compression axial capacity of the pile	EQ. 43EQ. 44
steel_stress_analysis (self)	Calculation of the stress on the	EQ. 45
increase_Section_incrementaly (self)	Increase the Section of the foundation when design conditions are not verified	
design (self)	This method executes the design procedure as shown in Figure 2-10. Design condition are verified	EQ. 42EQ. 43EQ. 44EQ. 45
outputs (self)	Outputs from design	Table 2-26

DragAnchor

This class contains methods and properties needed to perform drag anchors design. The methodology developed on Section 2.3.8 was implemented.

TABLE 3-9: METHODS FROM DRAGANCHOR CLASS

Method	Description	
	Objectives	Section/ Eq./Table
def_soil_type_and_anchor (self)	Definition of soil type using mechanical properties. Definition type of anchor from catalogue	Table 2-27 Table 2-29
desig_loads_from_mooring (self)	Calculation of the UHC using the resultant horizontal load from ULS analysis	EQ. 46
design (self)	This method executes the design procedure as shown in Figure 2-17. The weight and dimensions of the anchor are calculated.	EQ. 47
outputs (self)	Outputs from design	Table 2-28

SuctionAnchor

This class contains methods and properties needed to perform drag anchors design. The methodology developed on Section 2.3.8 was implemented.

TABLE 3-10: METHODS FROM SUCTIONANCHOR CLASS

Method	Description	
	Objectives	Section/ Eq./Table
init_geometry (self)	Determination of initial dimension of suction anchor using criteria define on Section 2.3.8	
compute_uplift_capacity (self)	Determine vertical resistance of the pile	EQ. 48, EQ. 51
compute_horizontal_capacity (self)	Determine lateral capacity	EQ. 49, EQ. 52
Increase_Section (self)	Increase the Section of the suction anchor	
design (self)	This method executes the design procedure as shown in Figure 2-21. General loading condition are verified (envelope)	EQ. 53; EQ. 54
outputs (self)	Outputs from design	Table 2-31

DesignAssessment

The DesignAssessment class regroups the following output data:

- mooring system design (Table 2-14)
- Results from ULS Analysis (Table 4-8)
- Results from FLS Analysis (Table 4-9)
- Results from Foundation base/Anchor design (Section 2.3.8)

Hierarchy

The Hierarchy class regroups the data describing the hierarchy of the station keeping system (Table 2-33).

TABLE 3-11: METHODS FROM HIERARCHY CLASS

Method	Description	
	Objectives	Section/ Eq./Table
populate(self,Body)	Create and populate hierarchy data from one or several instances of Body class	Section 2.3.9

BoM

The BoM class regroups the data describing the Bill of Materials of the station keeping system (Table 2-34).

TABLE 3-12: METHODS FROM BOM CLASS

Method	Description	
	Objectives	Section/ Eq./Table
populate(self,Body)	Create and populate bill of materials data from one or several instances of Body class	Section 2.3.9

EnvironmentalImpactResults

The EnvironmentalImpactResults class regroups the data describing the environmental impact of the station keeping system (Table 2-36).

TABLE 3-13: METHODS FROM ENVIRONMENTALIMPACTRESULTS CLASS

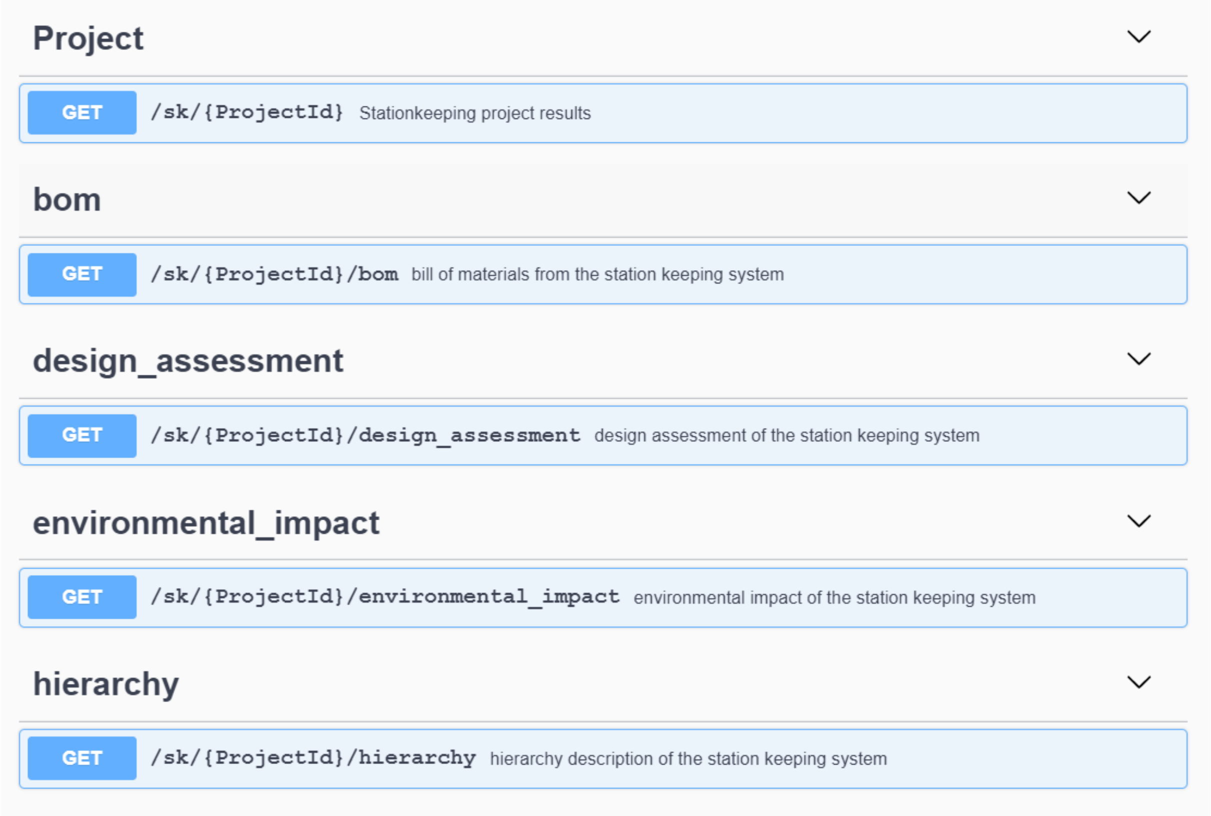
Method	Description	
	Objectives	Section/ Eq./Table
populate(self,Body)	Create and populate environmental impact data from one or several instances of Body class	Section 2.3.10

3.1.2 API

The API of the DTOceanPlus software follows a representational state transfer (REST) approach and it uses HTTP as the transport protocol. Its robustness is due to strict design principles whose development it has been based on.

The SK module API follows those principles and the language OpenAPI is adopted. An OpenAPI file was created, in json format, indicating all the paths, the services, and schemas that the SK module will consume, and that will be available to be consumed by other modules. Figure 3-2 shows the OpenAPI path for the SK module consumers.

The backend of the module receives the services from the other modules, runs the Business Logic, and then prepares the outputs for the other modules and the users. This is coded in Python 3, using Flask Blueprints.


Project

GET /sk/{ProjectId} Stationkeeping project results

bom

GET /sk/{ProjectId}/bom bill of materials from the station keeping system

design_assessment

GET /sk/{ProjectId}/design_assessment design assessment of the station keeping system

environmental_impact

GET /sk/{ProjectId}/environmental_impact environmental impact of the station keeping system

hierarchy

GET /sk/{ProjectId}/hierarchy hierarchy description of the station keeping system

FIGURE 3-2: OPENAPI PATHS FOR SK CONSUMERS

3.1.3 GUI

The graphical user interface for the Station Keeping module is an ongoing task and it will be included in the main module of the DTOceanPlus suite. The main functions of the GUI are to:

- Allow user inputs and parameters: numbers, text strings, multiple-choice dropdowns, full-fill tables;
- Allow user action, upon request or on its own initiative;
- Display (graphical) information;
- Print output report that summarizes the input and output data.

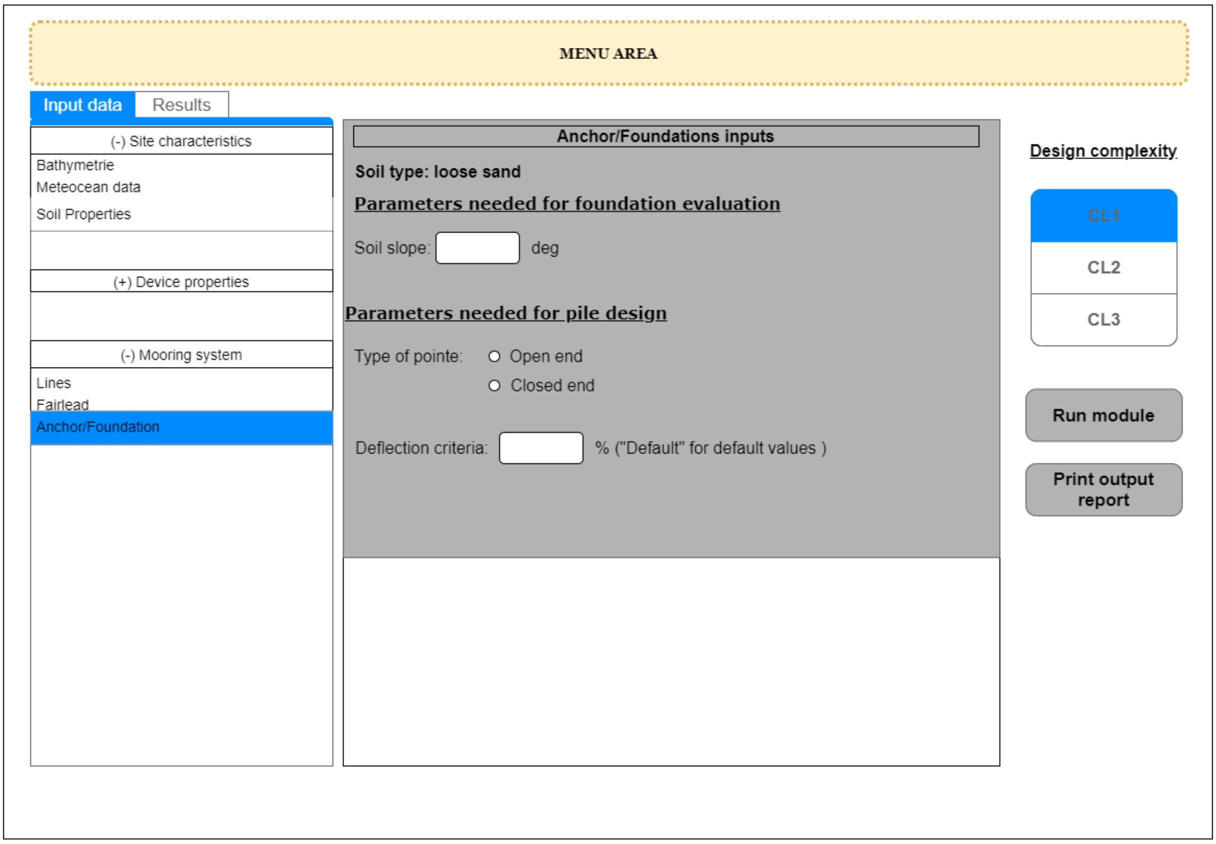
The GUI of the module (Figure 3-3 and Figure 3-4) is divided in two main parts:

- the menu on the left is used to select different sections
- the center part of the GUI contains the information of the selected section

Two main sections are available, each one with a tree:

- Inputs: a tree structure allows to get to each category that needs input data to run the module. In the example (Figure 3-3) the site characteristics category has three groups, "Bathymetry", "Environmental data" and "Soil properties". Most certainly, a third tab "Calculation parameters and options" will be inserted before the inputs tab to define whether a design or assessment computation will be performed. Those options can also be located on the right side of the screen together with the "Run Module" button.

- Results: a tree structure allows to get access to each category of result. In the example (Figure 3-4) the "Equilibrium solution" section allows to have access to the equilibrium position of the devices and loads magnitude on each mooring line.



Anchor/Foundations inputs

Soil type: loose sand

Parameters needed for foundation evaluation

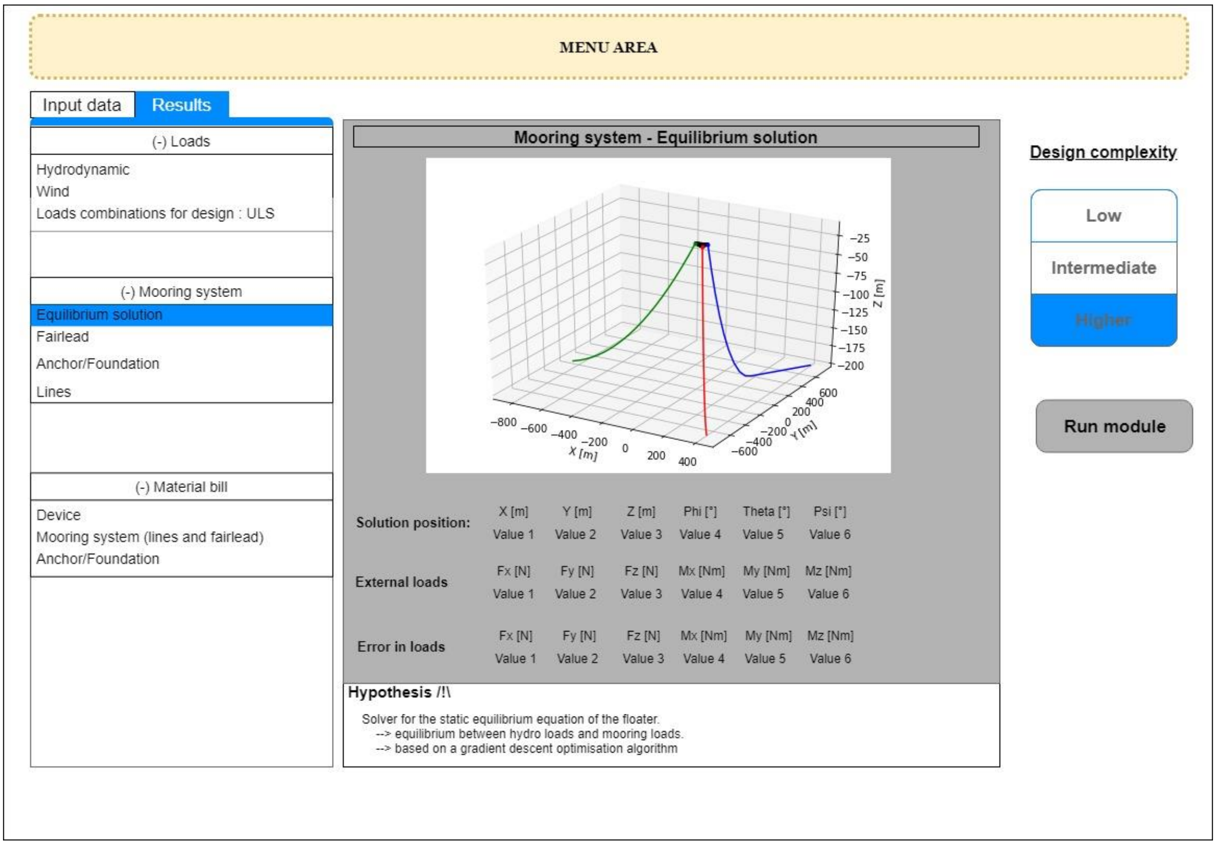
Soil slope: ☐ deg

Parameters needed for pile design

Type of pointe: ○ Open end
○ Closed end

Deflection criteria: ☐ % ("Default" for default values)

FIGURE 3-3. MOCK-UP FOR STATION KEEPING MODULE, EXAMPLE FOR INPUT DATA



Solution position:	X [m]	Y [m]	Z [m]	Phi [°]	Theta [°]	Psi [°]
	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6
External loads	Fx [N]	Fy [N]	Fz [N]	Mx [Nm]	My [Nm]	Mz [Nm]
	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6
Error in loads	Fx [N]	Fy [N]	Fz [N]	Mx [Nm]	My [Nm]	Mz [Nm]
	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6

Hypothesis /!

Solver for the static equilibrium equation of the floater.
--> equilibrium between hydro loads and mooring loads.
--> based on a gradient descent optimisation algorithm

FIGURE 3-4. MOCK-UP FOR STATION KEEPING MODULE, EXAMPLE FOR RESULTS DATA

3.1.4 THE TECHNOLOGIES

The Business Logic and the API of SK have been coded in Python version 3.6. The installation of the module requires the following packages:

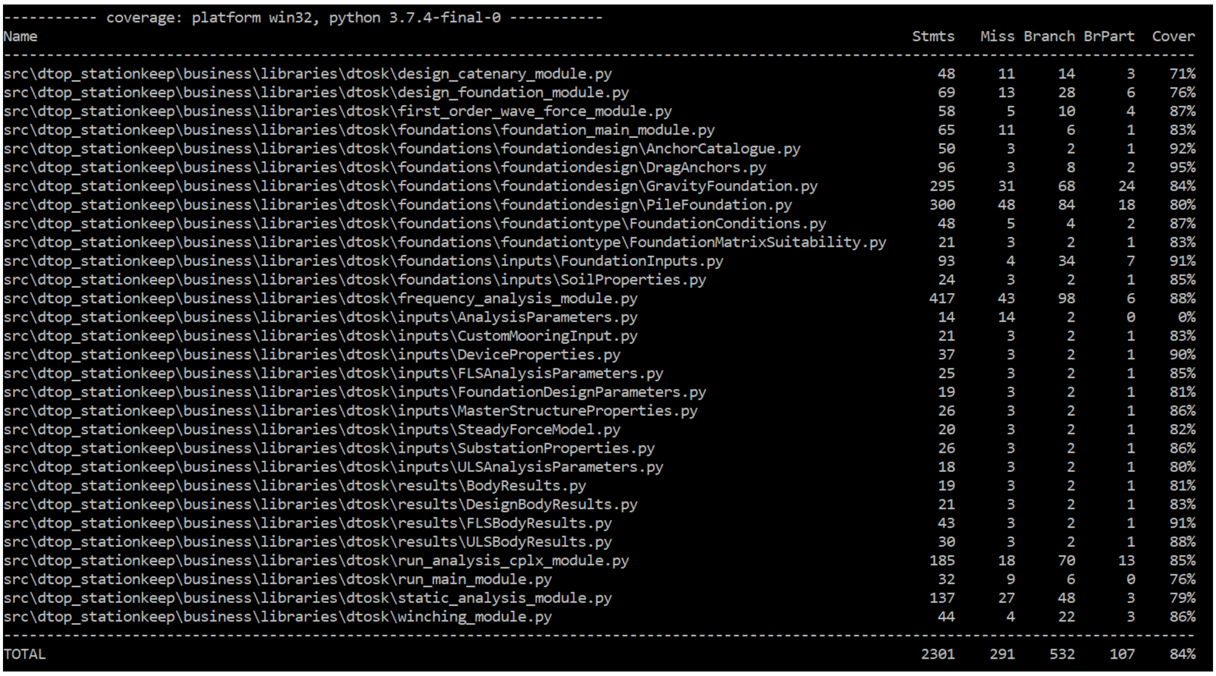
- NumPy
- Matplotlib
- Bson
- Flask
- flask-babel
- flask-cors
- requests
- pandas
- MAP++ python library [6]

The API relies on OpenAPI specification v3.0.2.

The GUI of the module will be developed in Vue.js, using the library Element-UI.

3.2 TESTING AND VERIFICATION

The implemented Business Logic was tested. In total, a set of 2301 statements are present in the Business logic. A comprehensive set of “unit tests” has been implemented covering the different functionalities (see [34]). The coverage of these tests, measured by means of the py-cov extension of the py-test library, is 84% of the Business Logic.



```
---------- coverage: platform win32, python 3.7.4-final-0 -----------
Name                                                                                                      Stmts   Miss Branch BrPart  Cover
-------------------------------------------------------------------------------------------------------------------------------------------
src\dtop_stationkeep\business\libraries\dtosk\design_catenary_module.py                                      48     11     14      3    71%
src\dtop_stationkeep\business\libraries\dtosk\design_foundation_module.py                                    69     13     28      6    76%
src\dtop_stationkeep\business\libraries\dtosk\first_order_wave_force_module.py                               58      5     10      4    87%
src\dtop_stationkeep\business\libraries\dtosk\foundations\foundation_main_module.py                          65     11      6      1    83%
src\dtop_stationkeep\business\libraries\dtosk\foundations\foundationdesign\AnchorCatalogue.py                50      3      2      1    92%
src\dtop_stationkeep\business\libraries\dtosk\foundations\foundationdesign\DragAnchors.py                    96      3      8      2    95%
src\dtop_stationkeep\business\libraries\dtosk\foundations\foundationdesign\GravityFoundation.py             295     31     68     24    84%
src\dtop_stationkeep\business\libraries\dtosk\foundations\foundationdesign\PileFoundation.py                300     48     84     18    80%
src\dtop_stationkeep\business\libraries\dtosk\foundations\foundationtype\FoundationConditions.py             48      5      4      2    87%
src\dtop_stationkeep\business\libraries\dtosk\foundations\foundationtype\FoundationMatrixSuitability.py      21      3      2      1    83%
src\dtop_stationkeep\business\libraries\dtosk\foundations\inputs\FoundationInputs.py                         93      4     34      7    91%
src\dtop_stationkeep\business\libraries\dtosk\foundations\inputs\SoilProperties.py                           24      3      2      1    85%
src\dtop_stationkeep\business\libraries\dtosk\frequency_analysis_module.py                                  417     43     98      6    88%
src\dtop_stationkeep\business\libraries\dtosk\inputs\AnalysisParameters.py                                   14     14      2      0     0%
src\dtop_stationkeep\business\libraries\dtosk\inputs\CustomMooringInput.py                                   21      3      2      1    83%
src\dtop_stationkeep\business\libraries\dtosk\inputs\DeviceProperties.py                                     37      3      2      1    90%
src\dtop_stationkeep\business\libraries\dtosk\inputs\FLSAnalysisParameters.py                                25      3      2      1    85%
src\dtop_stationkeep\business\libraries\dtosk\inputs\FoundationDesignParameters.py                           19      3      2      1    81%
src\dtop_stationkeep\business\libraries\dtosk\inputs\MasterStructureProperties.py                            26      3      2      1    86%
src\dtop_stationkeep\business\libraries\dtosk\inputs\SteadyForceModel.py                                    20      3      2      1    82%
src\dtop_stationkeep\business\libraries\dtosk\inputs\SubstationProperties.py                                26      3      2      1    86%
src\dtop_stationkeep\business\libraries\dtosk\inputs\ULSAnalysisParameters.py                                18      3      2      1    80%
src\dtop_stationkeep\business\libraries\dtosk\results\BodyResults.py                                         19      3      2      1    81%
src\dtop_stationkeep\business\libraries\dtosk\results\DesignBodyResults.py                                   21      3      2      1    83%
src\dtop_stationkeep\business\libraries\dtosk\results\FLSBodyResults.py                                      43      3      2      1    91%
src\dtop_stationkeep\business\libraries\dtosk\results\ULSBodyResults.py                                      30      3      2      1    88%
src\dtop_stationkeep\business\libraries\dtosk\run_analysis_cplx_module.py                                   185     18     70     13    85%
src\dtop_stationkeep\business\libraries\dtosk\run_main_module.py                                             32      9      6      0    76%
src\dtop_stationkeep\business\libraries\dtosk\static_analysis_module.py                                     137     27     48      3    79%
src\dtop_stationkeep\business\libraries\dtosk\winching_module.py                                             44      4     22      3    86%
-------------------------------------------------------------------------------------------------------------------------------------------
TOTAL                                                                                                      2301    291    532    107    84%
```

FIGURE 3-5: COVERAGE OF THE TESTING ON THE BUSINESS LOGIC BY MEANS OF UNIT TESTS

The unit tests coverage of the Business Logic of the SK module is high, ensuring quality of the code and guaranteeing that future developments on the same module will not break the current functionalities.

4. EXAMPLE

In this Section, an example of the SK module run is presented.

It is important to notice that none of the inputs to any of the functions corresponds to any specific technology; these are just representative values for the inputs to be used as a demonstration of the computational capability of the SK module.

4.1 INPUTS

We consider a wave energy converter consisting of a single cylindrical buoy moored to the seabed. The characteristics of the buoy are given in Table 4-1.

TABLE 4-1: MAIN CHARACTERISTICS OF THE DEVICE FLOATER

Quantity	Value	Unit
Diameter	10.0	[m]
Displacement	207.3	[m3]
Vertical position of center of gravity relative to the floater origin	-1.0	[m]

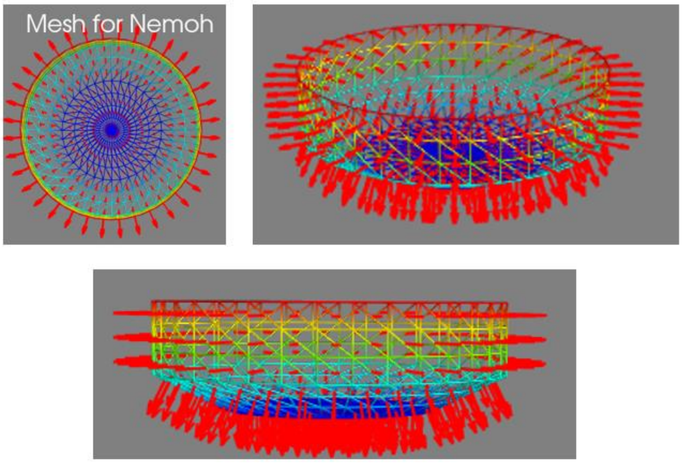


FIGURE 4-1: MESH OF THE GEOMETRY

Figure 4-1 shows the mesh of the geometry. The software NEMOH [35] was used to compute the hydrostatic and hydrodynamic properties of the floater. Note that in the context of the DTOceanPlus suite, that data is outputs from the MC and EC modules.

The geometry exposed to the wind is modelled as a cylinder of diameter 10.0m and height 4.0m above free surface level. Similarly, the geometry exposed to the current and mean wave drift forces is modelled as a cylinder of diameter 10.0m and draft 4.0m.

The considered environmental conditions for ULS analysis are shown in Table 4-2.

TABLE 4-2: ENVIRONMENTAL CONDITIONS FOR ULS ANALYSIS

Quantity	Value	Unit
Significant wave heights	12.0 / 13.0 / 14.0	[m]
Peak periods	14.0 / 15.0 / 16.0	[s]
Wind velocity	30.0	[m/s]
Current velocity	2.0	[m/s]
Weather directions	0.0 / 30.0 / 60.0	[deg]
Water depth	100.0	[m]

The input parameters for the catenary mooring system design are given in Table 4-3.

TABLE 4-3: PARAMETERS FOR CATENARY MOORING SYSTEM DESIGN

Quantity	Value	Unit
Nlines_min - minimum number of mooring lines	3	[-]
Nlines_max - maximum number of mooring lines	10	[-]
Pten_min – minimum pretension in the mooring lines	2.0	[% of MBL]
Pten_max – maximum pretension in the mooring lines	3.0	[% of MBL]
O_max – maximum total offset (static+dynamic)	30.0	[m]
Teig_min – minimum horizontal eigenperiod	30.0	[s]
C_td – coefficient of touchdown length reduction	0.95	[-]
Sf– safety factor	1.7	[-]

The environmental conditions for the FLS Analysis are given in Table 4-4.

TABLE 4-4: ENVIRONMENTAL CONDITIONS FOR FLS ANALYSIS

Hs [m]	Tp [s]	Dir. wave [deg]	Wind [m/s]	Dir. wind [deg]	Current [m/s]	Dir. current [deg]	Probability [-]
0.5	10	-75.00	5.1	-16.00	1.7	-50.00	0.324
1.5	11	-75.00	7.7	170.00	1.6	-230.00	0.14
1.5	7.5	-45.00	7.1	-99.00	1.9	-230.00	0.13
0.5	11	-110.00	5.1	160.00	1.7	-230.00	0.091
1.5	13	-110.00	8	130.00	1.6	-51.00	0.081
0.5	7.7	-45.00	4.9	-120.00	1.8	-240.00	0.079
2.5	8.1	-45.00	10	-140.00	1.9	-21.00	0.058
2.5	12	-75.00	11	110.00	1.6	-53.00	0.041
1.5	5.8	140.00	9	150.00	1.5	-240.00	0.034
2.5	14	-110.00	11	40.00	1.5	-230.00	0.022

The parameters specific to the FLS Analysis are given in Table 4-5.

TABLE 4-5: INPUT PARAMETERS FOR FLS ANALYSIS

Quantity	Value	Unit
aD – intercept parameter of the S-N curve	10	[-]
m – slope of the S-N curve	11	[-]
γ_{fls} - safety factor for fatigue limit state	8.0	[-]
T_lifetime – Lifetime duration of the mooring system	25	[years]

The parameters specific to the Foundation Suitability and Foundation Design are given in Table 4-6.

TABLE 4-6: INPUT PARAMETERS FOR FOUNDATION SUITABILITY AND DESIGN

Quantity	Value	Unit
Type of soil	Very dense sand	[-]
Seafloor slope	1	[deg]

4.2 RESULTS

4.2.1 CATENARY MOORING SYSTEM DESIGN

The main results from the Catenary Mooring System Design (see Section 2.3.5) are given in Table 4-7 and a plot of the mooring system can be found in Figure 4-2.

TABLE 4-7: OUTPUTS FROM CATENARY MOORING SYSTEM DESIGN

Quantity	Value	Unit
N_{lines} – number of mooring lines	3	[-]
L_{uns} – unstretched line length	545.5	[m]
D – mooring chain diameter	0.111	[m]
R_{anch} – mooring radius	492.3	[m]

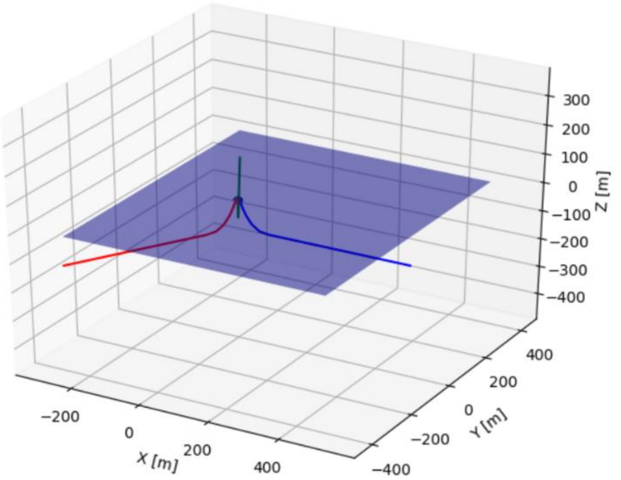


FIGURE 4-2: MOORING SYSTEM LAYOUT

4.2.2 ULS ANALYSIS

The main results from the ULS Analysis (see Section 2.3.3) are given in Table 4-8. The relatively low value of C_{uls} indicates that the design is driven by the offset (criteria 3 in Section 2.3.5).

TABLE 4-8: OUTPUTS FROM ULS ANALYSIS

Quantity	Value	Unit
Tmax – maximum tension in all line segments, for all environmental conditions, and all weather directions	2.734E+06	[N]
Culs – ULS design criteria for all line segments, environmental conditions, and weather directions (must be smaller than 1.0)	0.482	[-]

4.2.3 FLS ANALYSIS

The main results from the FLS Analysis (see Section 2.3.4) are given in Table 4-9. The relatively low values of the stress range observed in Figure 4-3 are due to the mild weather conditions chosen for the FLS analysis of this example (see Table 4-4).

TABLE 4-9: OUTPUTS FROM FLS ANALYSIS

Quantity	Value	Units
σ_S – standard deviation of the stress process, for all line segments and all environmental conditions	Figure 4-3 shows the stress range long term cumulative distribution function	[MPa]
Cfls – FLS design criteria for all line segments, environmental conditions, and weather directions (must be larger than 0.0)	0.997	[-]

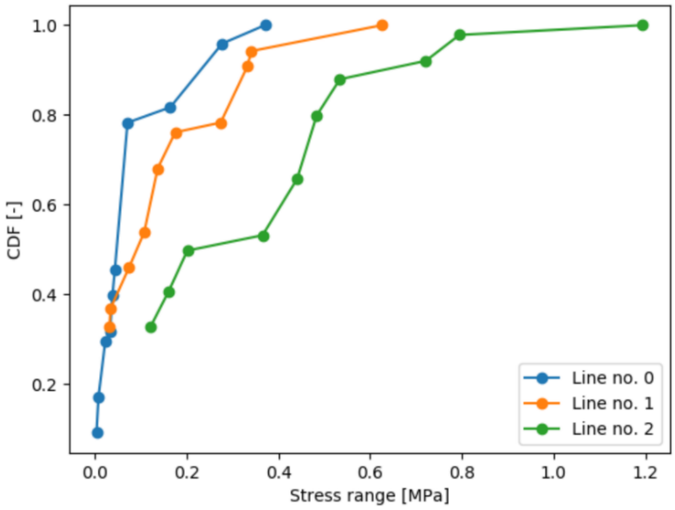


FIGURE 4-3: STRESS RANGE LONG TERM CUMULATIVE DISTRIBUTION FUNCTION

4.2.4 FOUNDATION SUITABILITY

The scores obtained from the Foundation Suitability are given in Table 4-10. The most suitable type of anchor is *Drag anchors* in this case (lowest score).

TABLE 4-10: OUTPUTS FROM FOUNDATION SUITABILITY

	Shallow foundations	Deadweight anchors	Piles	Drag anchors	Suction caisson
Total score	104	5	6	**4**	106

4.2.5 FOUNDATION DESIGN

The main characteristics of the obtained drag anchors design is given in Table 4-11.

TABLE 4-11: OUTPUTS FROM FOUNDATION DESIGN

Quantity	Value	Unit
Mass	2.8e+04	[kg]
UHC	1.4e+07	[N]
Length	7.9	[m]
Width	8.5	[m]
Height	4.7	[m]
Number of anchors	3	[-]

4.2.6 BILL OF MATERIALS

The Bill of Materials is computed using a manufactured steel price of 1.5€/kg . Table 4-12 presents the results.

TABLE 4-12: OUTPUTS FROM BILL OF MATERIALS

Module	Catalogue_ID	Name	Quantity	Unit of quantity	Unit cost	Total cost
SK	chain_41	line_type1	1.60E+03	[m]	3.70E+02	6.00E+05
SK	anchor_n_2	anchor_n_2	3	[-]	4.20E+04	1.30E+05

4.2.7 HIERARCHY

The obtained Hierarchy is presented in Table 4-14.

The highest level of the hierarchy is SK0, which represents the station keeping system of the device. SK0_x is a sub level that contains three mooring lines (SK0_x_ml_0, SK0_x_ml_1, SK0_x_ml_2). Each mooring line is composed of 2 components: a line segment and an anchor.

4.2.8 ENVIRONMENTAL IMPACT

The calculated Environmental Impact is presented in Table 4-13.

TABLE 4-13: OUTPUT FROM ENVIRONMENTAL IMPACT

Quantity	Value	Unit
footprint	530102	[m²]
submerged surface	1027	[m²]
material quantity	430743	[kg]
material	steel	[-]

TABLE 4-14: OUTPUTS FROM HIERARCHY

System	Name of node	Design ID	Node type	Node subtype	Category	Parent	Child	Gate	Repair	Replacement
SK	SK0_x	NA	System	stationkeeping	Level 2	SK0	[SK0_x_ml_0,SK0_x_ml_1,SK0_x_ml_2]	AND	NA	NA
SK	SK0_x_ml_0_seg_0	SK0_x_ml_0_seg_0	Component	line_segment	Level 0	SK0_x_ml_0	NA	NA	NA	0.00722
SK	SK0_x_ml_0_anchor_n_2_0	SK0_x_ml_0_anchor_n_2_0	Component	anchor	Level 0	SK0_x_ml_0	NA	NA	NA	0.000278
SK	SK0_x_ml_0	NA	System	mooring_line	Level 1	SK0_x	[SK0_x_ml_0_seg_0,SK0_x_ml_0_anchor_n_2_0]	AND	NA	NA
SK	SK0_x_ml_1_seg_0	SK0_x_ml_1_seg_0	Component	line_segment	Level 0	SK0_x_ml_1	NA	NA	NA	0.00722
SK	SK0_x_ml_1_anchor_n_2_0	SK0_x_ml_1_anchor_n_2_0	Component	anchor	Level 0	SK0_x_ml_1	NA	NA	NA	0.000278
SK	SK0_x_ml_1	NA	System	mooring_line	Level 1	SK0_x	[SK0_x_ml_1_seg_0,SK0_x_ml_1_anchor_n_2_0]	AND	NA	NA
SK	SK0_x_ml_2_seg_0	SK0_x_ml_2_seg_0	Component	line_segment	Level 0	SK0_x_ml_2	NA	NA	NA	0.00722
SK	SK0_x_ml_2_anchor_n_2_0	SK0_x_ml_2_anchor_n_2_0	Component	anchor	Level 0	SK0_x_ml_2	NA	NA	NA	0.000278
SK	SK0_x_ml_2	NA	System	mooring_line	Level 1	SK0_x	[SK0_x_ml_2_seg_0,SK0_x_ml_2_anchor_n_2_0]	AND	NA	NA
SK	SK0	NA	System	stationkeeping	Level 3	NA	[SK0_x]	AND	NA	NA

5. FUTURE WORK

This deliverable collects the main functional and technical aspects of the Station Keeping module (SK), implemented during tasks T5.2 and T5.7 of the DTOceanPlus project. While the module can be run in a standalone mode at the moment of writing, some work is required yet to be fully integrated in the suite of tools of DTOceanPlus:

- The OpenAPI and API are to be thoroughly tested to ensure flawless communication compatibility between the different DTOceanPlus modules
- The GUI is to be developed to be consistent with the other tools and to provide the user with an easy access to the tool and its functionalities.
- The unit tests, including Pytest, Dredd and PACT, will be improved to fix any potential bugs.

These activities will be developed within T5.2 (ongoing) and T5.9 (running once all other modules have been developed) in order to extend the functionality of the SK module from standalone to fully integrated in the DTOceanPlus toolset.

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