WETFEET

D3.2 - Engineering of OWC critical parts related to submergence for large scale deployment

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EXECUTIVE SUMMARY

This report presents Deliverable 3.2 of the WETFEET H2020 project – Report on the engineering of OWC critical parts related to submergence (hull, PTO sealing, auxiliary equipment, submersion and emersion operations) for large scale deployment.

This work is part of WETFEET work package 3. The purpose of this WP is to confirm the technical feasibility and potential impacts on survivability, performance and O&M of the selected breakthroughs in OWC and Symphony WECs. Target is to obtain preliminary designs for each feature through numerical and experimental testing and additional engineering analysis.

This work built upon the breakthrough specifications of Task 2.4 (Deliverable 2.3), by analyzing the design specifications and methods previously defined in task 2.4.

Some floating WECs, such as the OWC spar buoy, are operating on the surface of the ocean and - as a result - are fully exposed to storms. This is a challenge for survivability of wave energy technology (and any surface-floating structure in the ocean).

Survivability has an utmost importance in the relatively high upfront capital cost of WEC prototypes deployed offshore. Device submergence is proposed as a breakthrough concept in the WETFEET project. The topic of this report is the submergence as OWC survivability strategy (This study has focused on a single device.).

This report is composed of three parts:

- An engineering analysis of the feasibility of the submergence breakthrough for the Spar OWC
- A numerical analysis of system loads and motions under submersion during extreme conditions
- A report on 1:40 tank testing of survival loads and motions under stormy conditions

From the engineering analysis, components and technologies which are identified as the most challenging are the tensioning system, the solutions to manage mooring lines during submergence operations, the PTO protection, and the automation of the operations (including SCADA system and sensors) – see components and technology scoring matrix.

- Regarding the tensioning system, at least 4 tensioning lines are needed (for stability reasons) which need to be powered, and the choice of tensioning systems is depending on the choice of mooring line type. Subsea winches have been studied. High tensions have been highlighted in the mooring lines, which induce large capacity equipment requirements not available on the market. This equipment also presents some significant challenges of maintenance to be available for service life and are expected to be costly. Additional subsea winches may also be needed to manage some mooring lines during submergence operations to avoid their collision.
- The PTO protection presents also some major challenges as it shall be protected from water during submergence. An alternative to have external protecting device for the

PTO may be to develop a PTO designed to allow submersion without specific operations (as activation of mechanisms to close a dedicated dry chamber). This point should be studied in further details.

- Finally, automation of the submergence operation for service life with permanent availability is identified as a major technical challenge which impacts many component of the submergence. High risks have been identified on this topic: repeatability of the process because of changing environment (excitation loads, bio-fouling, corrosion, etc.), high costs.

Regarding the Experimental work performed at the Flowave tank, several different configurations were tested, representing different submergence strategies related to the storage position of the ballast water. These strategies were analysed in depth and introduced in a Orcaflex model. The results show that a submerge position is feasible to achieve and a decrease in the mooring lines is possible. indicate that a submergence strategy could be a feasible and valid strategy for a device to survive a storm condition, reducing the loads the mooring lines are subject to and therefore the risk of breaking, representing a possible breakthrough for wave energy devices.

The engineering analysis and the experimental work has focused on the solution of submergence which considers the use of winches and ballast, with taut mooring lines to achieve submergence. Other solutions may be studied, as for example laying the Spar on the Seabed (horizontally or vertically), use of surface buoys and neutrally buoyant structure through addition of more ballast.

LIST OF ACCRONYMS

AUV	Autonomous Underwater Vehicle
FAST	Function Analysis System Technique
OWC	Oscillating Water Column
PTO	Power Take Off
RAO	Response Amplitude Operator
ROV	Remotely Operated underwater Vehicle
VBRs	Vertebrae Bend Restrictors
WEC	Wave Energy Converter

1. INTRODUCTION

1.1. Objectives

This report presents Deliverable 3.2 of the WETFEET H2020 project – Report on the engineering of OWC critical parts related to submergence (hull, PTO sealing, auxiliary equipment, submersion and emersion operations) for large scale deployment.

This work is part of WETFEET work package 3. The purpose of this work package is to confirm the technical feasibility and potential impacts on survivability, performance and O&M of the selected breakthroughs in OWC and Symphony WECs. Target is to obtain preliminary designs for each feature through numerical and experimental testing and additional engineering analysis.

The topic of this report is the submergence as OWC survivability strategy. It is composed of three parts:

- An engineering analysis of the feasibility of the submergence breakthrough for the Spar OWC
- A numerical analysis of Spar OWC system loads and motions under submersion during extreme conditions
- A report on 1:40 tank testing of survival loads and motions under stormy conditions

This work built upon the breakthrough specifications of Task 2.4 (Deliverable 2.3), by analyzing the design specifications and methods previously defined in task 2.4.

1.2. Methodology overview

First, a functional analysis of the submergence breakthrough has been performed to better understand the main issues related to the Spar OWC design concept, the missing information and the choices to be made. A review of existing submergence process from WEC and other industrial process has been realized leading to considerations on potential means to submerge a system and specificities of the Spar OWC system.

Then, the engineering analysis began with a review of potential impacts of the integration of submergence system on the original spar OWC design, and of technical topics to investigate. A FAST diagram has been established to find some solutions on how to submerge the OWC. Risk analysis and experts interview (offshore engineer, expert experienced in industrial pumps, and two WEC experts) have been performed to complete the investigation and establish the list of topics to investigate. From the solutions identified within the FAST diagram it has been decided to focus on solutions where the Spar is ballasted and the mooring lines are taut to achieve submerged configuration. Then components and technologies have been investigated.

Ballasting needs, submerged position, have been studied with a parametric study aiming at getting some insight on the significant parameters, and defining preliminary values in order to search submerged configurations.

This study also permitted to define submerged configurations to be further analyzed with a motion analysis in the frequency domain. This motion analysis showed that the configurations had natural frequency within wave frequency range. Further analysis is needed to try to adapt these configurations to reduce loads and motions. Preliminary analysis of impact on the hull and PTO have been performed, it has been highlighted that pressurizing the air chamber may be a solution to adapt to high hydrostatic pressure during submergence. Solutions to submerge and emerge the Spar have been studied focusing on constructive solutions using pumps, valves and winches. The sequence to submerge / emerge, and mooring and cable technologies have also been studied. Mean to have energy available should be further studied.

In parallel of the engineering analysis a 1:40 tank testing of survival loads and motions under stormy conditions has been performed.

A model created in Orcaflex is used, where the device mass and respective center of mass are changed. A parametric study is performed where the lengths of the mooring lines are gradually decreased, mimicking the winching system, to evaluate impact in the static submergence depth and inclination and line static tensions.

A similar analysis is then performed for an extreme sea state condition (Hs=14m, Te=16s), to observe the influence in buoy position and dynamic loads in the moorings when the buoy is submerged. Comparisons are done with the reference case scenario where the device is kept at surface during the storm.

Based on the analysis performed a given set of configurations considered appropriate were defined and tested experimentally in the FloWave wave tank at a 1:40 scale, providing complementary insight on the motion and loads experienced by the spar buoy under extreme wave conditions.

2. Functional description of submergence breakthrough concept for Spar OWC

The objective of this section is to define a functional description of the submergence breakthrough in order to better understand the main issues related to OWC design concept, the missing information and the choices to be made.

The main parts are:

- Summary of all information in the project related to submergence presented as a list of specifications derived from main project documents,
- Functional analysis of the submergence process system in the form of an octopus diagram, exposing the elements interacting with the submergence system, and the main functions (services and constraints),
- Summary of these data in the form of functional specifications, showing the expected system functions, the judgement criteria, the levels of these criteria, and the flexibility. This will expose the still missing data, and the choices to be made.

2.1. Needs identification

Some floating WECs, such as the OWC spar buoy, are operating on the surface of the ocean and - as a result - are fully exposed to storms. This is a challenge for survivability of wave energy technology (and any surface-floating structure in the ocean).

Here is an extract of WETFEET Deliverable 2.1 (reference [29]) explaining the reasons to focus on submergence strategy:

Given the utmost importance of survivability in the relatively high upfront capital cost of WEC prototypes deployed offshore, device developers often preferred a retrieval strategy in anticipation of harsh environmental conditions for floating WEC prototypes during sea trials. However, in the context of a commercial array of multi-unit devices, it seems economically hardly acceptable to rely on the need to hire vessel(s) every time the forecast indicates rough climate conditions which may damage the devices.

To overcome this issue, one solution is to design the device and its structure in such a way that they can sustain the vast majority of environmental conditions observed at site. This implies applying large safety factors in the structural design process. Finding the appropriate trade-off between safety, cost and performance of the device can thus become a highly complex equation. Alternatively, devising an on-site survivability strategy allowing the protection of the device during harsh environmental conditions, which would not require the intervention of specialized vessel/equipment/personnel, appears to be an attractive solution. For this reason, device submergence is proposed as a breakthrough concept in the WETFEET project.

2.1.1. Definition of the submergence system

Submergence system: System allowing the OWC to lower its position in the water column in prevision of a storm event. It consists in all the equipment necessary to move the OWC, and to

adapt it to a submerged position. Its scope can be defined as all the equipment added to realize submergence compared to the initial reference case scenario system. In this study we consider the submergence of a single device.

2.1.2. Bull chart

The bull chart shown in Figure 2-1 illustrates the aim of the submergence mechanism.

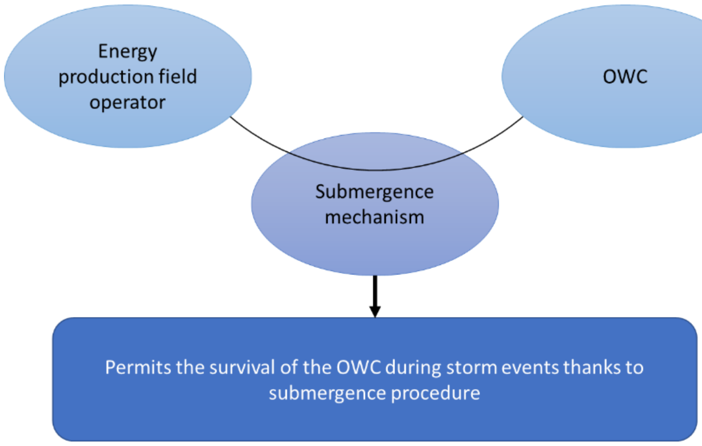


FIGURE 2-1 BULL CHART OF THE SUBMERGENCE SYSTEM

2.2. List of specifications

2.2.1. Specifications

Here is a list of specifications derived from WETFEET Project documents. Quotations used as reference of these specifications are listed in section 2.2.2.

TABLE 2-1 LIST OF SPECIFICATIONS

Specification	source
Submergence System should permit to bring OWC in a horizontal position	(1) (3) (8) (16) (17)
Submergence system should submerge the OWC as deep as possible to lower excitation forces	(2) (4) (17)
Submergence system should be activated remotely (no vessel/personnel intervention needed). Communication elements should be integrated	(5) (11) (15)
Submergence system should adapt to mooring system (including ballasts). Mooring design is modifiable. Mooring system should adapt to both operational and survival positions. Mooring lines during submergence will be taut	(6) (9) (13) (17) (18)
Equipment used for submergence should be designed for underwater conditions (pressure, water ingress), or submergence system should integrate means to seal non-waterproof equipment	(7) (10) (12)
Submergence system should avoid risks of collision with the seabed	(7)

Equipment used for submergence should be designed against corrosion issues	(7)
Submergence system should integrate redundancies where needed	(11) (12)
Responsiveness of the control system to activate submergence process should be acceptable	(11)
Submergence process should be fast enough when compared to the anticipation time estimated by weather forecast	(11)
Submergence system should respect health & safety standards	(12)
Power supply mechanism should be appropriately designed to meet the standards of offshore applications	(12)
Submergence system should adapt to dynamic cable restrictions, in both operational and survival conditions	(14)
Submergence system shall be reversible. It has to integrate both submergence and emergence process equipment	(15)

2.2.2. Sources of information

<u>Submergence Technical Note V2.0 (reference [20])</u>

(1) "it was decided to set the OWC in a horizontal position. It is believed that such a position will prevent the buoy from having large movements in survival conditions, and that there will be little pressure variations along the structure. Four different submergence depths have been taken into consideration: 1/3, 1/2, 2/3 and 3/4 of the water depth." (Section 1)

(2) "A deep OWC submergence significantly reduces the excitation forces "(Section 1)

(3) "The horizontal configuration presents some stability issues with mooring lines and buoyancy element "(Section 1)

(4) "The excitation forces and moments are just one part of the problem, and an agreement should be found between excitation forces, static pressure, stability and cables disposition" (Section 2.1).

<u>WETFEET Deliverable 2.1 (reference [29])</u>

(5) "Alternatively, devising an on-site survivability strategy allowing the protection of the device during harsh environmental conditions, which would not require the intervention of specialized vessel/equipment/personnel, appears to be an attractive solution" (Section 3.3)

(6) "Concerning the OWC spar buoy, it is envisaged to achieve device submergence by:
- actively controlling the mooring elements so that a pulling force towards the sea-bottom is applied to the fairleads of the device
- ballasting the structure to increase the submerged mass of the body
- a combination of the two previous methods " (Section 3.3)

(7) "Other critical engineering issues associated with the submergence strategy which shall be discussed include:

- Ensure proper sealing and protection of all on-board electro-mechanic and power electronic equipment fitted in the OWC spar buoy
- Risk of collision with the seabed
- Material corrosion, and in particular, the areas of the structure alternatively exposed to the atmosphere or the ocean/sea environment
- Fatigue of the critical active parts of the submergence procedure" (Section 3.3)

WETFEET Deliverable 2.3 (reference [30])

(8) "After some initial discussions within the consortium of the WETFEET project, it was decided to consider the OWC spar buoy in a fully horizontal position when being submerged. Given the relative high draft of the OWC spar buoy in relation to the water depth considered for the reference design case (80 meters water depth), it seems more appropriate to bring the OWC spar buoy in a horizontal position while being submerged." (section 4.1).

(9) "In the frame of these simulations, the buoyant part of the buoy is assumed to be filled with sea water." (Section 4.1.1)

(10) "Another critical issue to be addressed concerns the sealing considerations to protect all sensitive parts. As the WEC is being submerged, all electro-mechanical components and other parts not designed to be in contact with sea water should be put in a waterproof position. One way to achieve this would be to design caissons with bearing and/or sliding bars which could accommodate the sensitive PTO and instrumentations components through active or passive control." (Section 4.2.1)

(11) "In any case, sealing should be achieved remotely avoiding the need for the intervention of a crew at the offshore location. For this reason, sensors and control instrumentation will have to be fitted on-board to ensure communication (with redundancy where possible) with the onshore O&M station. In this configuration, the responsiveness of the control systems to activate the ballasting/winching system as well as the sealing/protecting mechanism should not only be well coordinated but also be fast enough when compared to the anticipation time estimated by the weather forecast." (Section 4.2.1)

(12) "Having this additional on-board equipment will also require some power consumption. Integration of the power supply mechanism should also be appropriately designed to meet the standards of offshore applications. Proper sealing and redundancy requirements should be followed while respecting the health & safety standards." (Section 4.2.1)

(13) "However, based on the preliminary feasibility assessment reported in the previous section, a new mooring design would be required to allow the submergence strategy to be successfully implemented. In particular, the fairlead positions should be carefully chosen to ensure stability is maintained in either floating operational position and submerged survival position. Mooring elements should also be selected and designed to facilitate the submergence process itself." (Section 4.2.1)

(14) "Since these dynamic cables have very strict design and load requirements, this element should be carefully considered during submergence. For instance, maximum curvatures, bending loads and fatigue life requirements are key factors to take into account. To this

extent, buoyancy elements and touch-down point of the umbilical should be chosen in a way that these requirements are met under both the operational (floating) and survival (submerged) modes." (Section 4.2.1)

(15) "special care should be made when ensuring a suitable restoring force will be available to carry the WEC back to its operational mode. Beyond the hydrodynamic mechanical challenge for this process, remote re-activation of all PTO equipment and connection to the grid represents another critical issue." (Section 4.2.1)

WP2 Minute Of Meeting 11th July 2016 – 11072016_WETFEET_WP2

(16) "a tilt angle is advisable rather than a fully horizontal position."[1]

WP2 Minute Of Meeting 18th March 2016 – 18032016_WETFEET_WP2

(17) ". It was agreed to look at a submergence toward a horizontal position of the OWC spar buoy with the following characteristics:

- 20% of wavelength deep
- Horizontal position stabilisation by a mooring line at the bottom (fairlead position of the moorings would be changed compare to the reference design) using the reserved process of the onsite installation – keep two floaters at the surface for stability or bringing the structure to the seabed"

WP3 Minute Of Meeting – 20161206_WETFEET_WP3

(18) "Mooring lines during submergence will be taut"

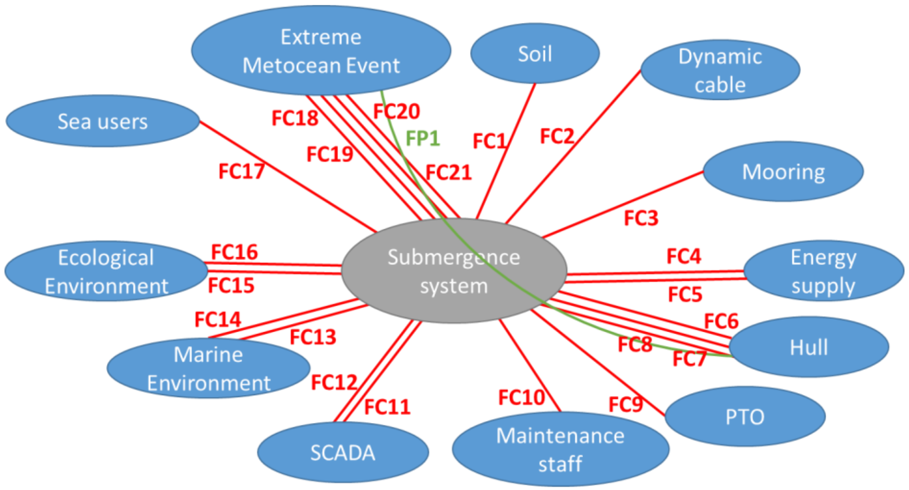
2.3. Octopus diagram

The octopus diagram is a tool from "APTE method" [7]. It permits to identify, through the analysis of system environment, the "constraint functions" and "service functions" of the system:

- A constraint functions is a limitation of designer's liberty of choice for a product.
- A service function is an expected action of the system to meet the user's needs.

The Octopus diagram for the submergence system is described on Figure 2-2.

[1] For stability reasons [30]



Functions	Description
FP1	Permit to preserve OWC integrity thanks to submergence of OWC during storm events.
FC1	Shall avoid collision of OWC with the seabed
FC2	Shall adapt to dynamic cable restrictions, in both operational and survival conditions
FC3	Should adapt to / integrate the mooring system (mooring solution can change if needed). Mooring lines during submergence will be taut.
FC4	Power supply mechanism should be appropriately designed to meet the standards of offshore applications
FC5	Shall operate with the minimum amount of energy needed
FC6	Shall adapt to OWC design without modifying much its behaviour in operational conditions
FC7	Shall adapt to OWC design without modifying much its mass
FC8	Shall permit to bring OWC in a quasi horizontal position
FC9	Shall adapt to PTO system.
FC10	Shall respect health & safety standards
FC11	Should be operable remotely (no vessel/personnel intervention needed). Comunication elements should be integrated
FC12	Shall permit a reversible process, i. e. shall integrate a solution to emerge the OWC and restore the operational mode
FC13	Shall integrate equipments resistant to corrosion
FC14	Shall integrate equipments designed for underwater conditions (pressure, water ingress), or shall integrate means to seal non waterproof equipments
FC15	Shall not poluate or interfere ecological environment
FC16	Shall be designed taking into account biofouling issues
FC17	Shall be still visible once submerged to avoid issues with sea users
FC18	Shall permit total submergence process in a minimum elapsed time
FC19	Shall permit an acceptable responsiveness of the control system to activate submergence process
FC20	Shall permit to submerge the OWC as deep as necessary during storm
FC21	Shall be able to occur up to several times per month along the design lifetime

Figure 2-2 Octopus diagram

2.4. Functional specifications

Table 2-2 shows the resulting functional specifications for the submergence system. “TBD” is for “To Be Defined” when data is missing.

TABLE 2-2 FUNCTIONAL SPECIFICATIONS

Legends	
To be defined with priority as directly needed for first calculation	
To be defined	
Assumed value	

Functions	Description	Evaluation criteria	Level	Flexibility
FP1	Permit to preserve OWC integrity thanks to submergence of OWC during storm events.	System integrity	Total integrity	Not Measurable
FC1	Shall avoid collision of OWC with the seabed	Distance min from the seabed (including OWC movements)	Nominal minimum distance from seabed system is accepted to go to be defined (ex: 10m)	Range to be defined
FC2	Shall adapt to dynamic cable restrictions, in both operational and survival conditions	To be defined Ex: minimum bending radius	Dynamic cable configuration not defined. Should be defined later. Generic dynamic cable restrictions may be chosen instead	Dynamic cable configuration not defined. Generic dynamic cable restrictions may be chosen instead

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FC3	Should adapt to / integrate the mooring system (mooring solution can change if needed). Mooring lines during submergence will be taut.	Not Measurable	Not Measurable	Not Measurable
FC4	Power supply mechanism should be appropriately designed to meet the standards of offshore applications	Compatibility of the power supply mechanism with available sources	Sources of energy available to be defined (ex: electrical, pneumatic,…)	Preference for one source of energy to define
		Compatibility of the power supply mechanism with offshore environment	To be defined	To be defined
FC5	Shall operate with the minimum amount of energy needed	Minimum amount of energy needed for the submergence and the restoration to operational mode	Nominal amount of energy available to be defined (ex:. 5 kWh)	range of capacity to be defined (ex: 4.5-5.5 kWh)
FC6	Shall adapt to OWC design without modifying much its behavior in operational conditions	Power production difference with OWC without submergence system	Acceptable difference of power production to be defined	Range of difference to be defined
FC7	Shall adapt to OWC design without modifying much its mass	Mass difference before/after adding device Constraint on COG to be defined.	Acceptable mass difference to be defined	Range of difference to be defined

FC8	Shall permit to bring OWC in a quasi-horizontal position	Angle with horizontal at submerged steady state	Nominal angle to be defined	Acceptable range of angles to be defined
FC9	Shall adapt to PTO system.	Not Measurable	Not Measurable	Not Measurable
FC10	Shall respect health & safety standards	Conformity to health & safety standard	Standards should be defined later	Preferences between the standards to be defined later
FC11	Should be operable remotely (no vessel/personnel intervention needed). Communication elements should be integrated	Distance from which it can be activated	Site dependent. Nominal value to be defined	Site dependent. range to be defined
FC12	Shall permit a reversible process, i. e. shall integrate a solution to emerge the OWC and restore the operational mode	Not Measurable	Not Measurable	Not Measurable
FC13	Shall integrate equipment resistant to corrosion	Equipment design life regarding corrosion issues	Should be defined later	Should be defined later
FC14	Shall integrate equipment designed for underwater conditions (pressure, water ingress), or shall integrate means to seal non-waterproof equipment	Maximum acceptable depth for each equipment (if flooded) = hydrostatic pressure that the sub-system can withstand	Nominal depth the equipment has to go to be defined	Range of depth to be defined

FC15	Shall not pollute or interfere with ecological environment	System emissions (e.g. oil linkages …)	Level should be defined later	Range should be defined later
FC16	Shall be designed taking into account biofouling issues	To be defined	To be defined	To be defined
FC17	Shall be always notifiable, even once submerged to avoid issues with sea users	Not Measurable	Not Measurable	Not Measurable
FC18	Shall permit total submergence process in a minimum elapsed time	Total needed time from beginning of submergence process to submergence achievement	Total nominal accepted time should be defined	Range should be defined later
FC19	Shall allow an acceptable responsiveness of the control system to activate submergence process	Total needed time to begin submergence process	Total nominal accepted time should be defined later	Range should be defined later
		Autonomy of the detection of meteorological event and of the triggering of submergence phase	To be defined	To be defined
FC20	Shall permit to submerge the OWC as deep as necessary during storm	Depth at which system can be submerged	Nominal minimum depth at which it has to be submerged: 20% of wavelength deep (reference (17))	Range of depth system should go to be defined
FC21	Should be able to occur up to several times per month along the design lifetime	Number of loops the system can afford without any on-site intervention	Number of loops should be defined later	Range should be defined later

		Frequency of submergence phases the system can afford (short and long scale)	To be defined	To be defined

Along with these functional specifications, here is a non-exhaustive list of non-quantifiable specifications:

- Simplicity
- Security
- Durability
- Robustness
- Reliability

These non-quantifiable specifications should be used in the solution choosing phase by the mean of an evaluation matrix.

The common next step according to APTE method [7] would be the investigation of solutions (methods as brainstorming or FAST diagrams can be used), and then the analysis and evaluation of these solutions (evaluation matrix).

2.5. Conclusions and missing specifications

In conclusion, here is a list of specifications which will need to be elaborated. Some choices may be discussed or made if necessary in the following steps of the engineering analysis.

- Nominal minimum distance from seabed system is accepted to go, and accepted range.
- Sources of energy available, and preferences.
- Nominal amount of energy available, and acceptable range.
- Acceptable difference of power production between initial OWC and modified (to integrate submergence breakthrough) OWC, and accepted range.
- Acceptable mass difference between initial OWC and modified (to integrate submergence breakthrough) OWC, and acceptable range, and eventually on COG.
- Nominal pitch angle for the OWC in survival configuration, and acceptable range.
- Nominal depth the equipment has to go, and acceptable range.
- Nominal minimum depth at which it has to be submerged (hypothesis of 20% of wavelength to be validated).

3. Overview of some existing submergence process

The goal of this section is to present a review of submergence process originated from Wave Energy Converters, and from non-Marine Renewable Energy applications. This will permit to have a general knowledge of submergence process in industrial applications. The aim is first to find situations in industrial context where submergence is needed, and then to analyze the concept used for each application to perform the submergence process.

3.1. Some WEC using submergence principles

This section is a brief state-of-the-art of submergence process for WEC application. It first focusses on existing WEC concepts using submergence in their operational functioning and then to focus on WEC using submergence as a survivability strategy. This work will also provide useful feedback regarding previous experimentation and technological development of submergence for WEC application.

3.1.1. Context

"Survivability is by no means a new concept to ocean engineering; ships must remain stable and structurally intact in violent sea states; the same is true for offshore oil and gas structures. While knowledge from the ship and offshore sectors can be valuable for designing wave energy converters (WECs) for survival in rough seas, the unique scale, siting and operational characteristics of WECs pose a distinct set of engineering challenges." [11]

Survivability is critical for MRE system and in particular wave energy converters that are located at high energetic sites. A key conceptual choice is the location of the system in the water column. A bottom-fixed system will only need to withstand limited loading in comparison with large loads expected if the system is floating or in the upper part of the water column.

To our knowledge, only a handful of concepts are using submergence as a strategy for survivability.

3.1.2. Existing strategies for survivability

Various strategies exist for Wave Energy Converters to switch from energy production mode into survival mode. In general, wave energy converters present an [Hs,Tp] operational zone within the shorter wave heights while it must shift to the survival mode for the higher wave heights and the very steep waves (average Hs, very small Tp) [11]. An idealized contour of WEC survival and operational modes was suggested by Coe et al. in [11] and is represented in Figure 3-1.

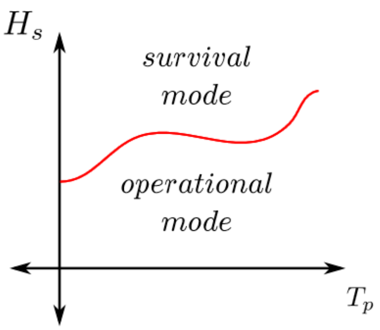


FIGURE 3-1 IDEALIZED CONTOUR OF WEC SURVIVAL AND OPERATIONAL MODES (FROM [11])

A more general overview of offshore survivability will reference multiple approach, as described below:

- Robust designs to be able to withstand extreme events:
    - e.g. O&G platforms/FPSO or Offshore Wind High Voltage Substations
- Extreme Wave-friendly designs to avoid major loading
    - e.g. Pelamis (ceased trading) with a cylinder-shape with long sections (~30m each) and a V-shaped mooring head. According to [25]: "The core theme of the Pelamis WEC concept is survivability. All Wave Energy Converters absorb power in small waves through hydrostatic forces – that is buoyancy versus weight or hydrostatic pressure. However extreme loads in waves arise from the hydrodynamic forces, namely inertia, drag and slamming. The Pelamis is very strongly coupled hydrostatically but is almost invisible to large hydrodynamic effects".
    - e.g. CETO / AWS I is a point-absorber WEC with a fully submerged design considered to be less subject to high loads during storms.
- Change of configuration (WaveStar, etc.)
    - e.g. Wavestar platform (ceased trading) [42]
        - The floaters are mounted on a machine which is founded on the seabed. All the moving parts are located above the waterline. The Wave Star machine can lift the floaters out of the water into safety position.
        - Include an air gap in order to let the foundation only withstand hydrodynamic loadings.
- Submergence
    - This strategy is detailed in the section 3.1.3 below.

General advices have been drawn previously from concept developers to justify technological choices. To avoid any position statement, several advices will simply be recalled below:

- Avoid superstructures at sea-water level that may be subject to buckling loads,
- Make technological choices that are insensible to the tidal range / avoid any rigid link with the seabed,
- Avoid any mechanical parts in direct contact with the sea environment / account for biofouling and the 4 million cycles per year,
- Avoid any mechanical stop (any inherent limit of the motion that will induce possible damage due to impacts, exception made of the mooring).
- Anticipate a relevant survival configuration

FIGURE 3-2 SURVIVABILITY OF THE PELAMIS WEC TECHNOLOGY (SOURCE:[9])

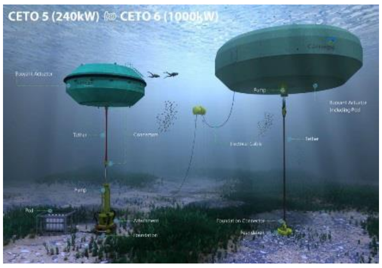


FIGURE 3-3 SCHEMATIC ILLUSTRATION OF CETO TECHNOLOGIES SUBSEA CONFIGURATION (PHOTO CREDIT: CARNEGIE WAVE ENERGY – SOURCE: [33])

FIGURE 3-4 ILLUSTRATION OF WAVE STAR CONFIGURATIONS IN OPERATION AND IN SURVIVAL MODE (SOURCE: [23])

3.1.3. Current WEC technologies using submergence as a survivability strategy

A brief benchmark of the survivability strategies of Wave Energy Converters has been carried out. The following technologies have been shortlisted since they were recorded as using submergence as a survivability strategy.

- Aquamarine's Oyster (ceased trading) [35]
  - Survivability strategy: Submergence along with near-shore positioning to avoid the most violent storms because the largest waves break naturally already before entering near-shore areas.
- Desalination Salter's duck [21]: further described in section 3.1.5.
- Laminaria system [39]: further described in section 3.1.6.
- Arrecife system [31]
  - Floating system, provided with an immersion system that will be operated in storms. The system submerges partially; hence, it avoids to be destroyed by them.
- Nemos system [41]
  - The NEMOS-system consists of an elongated floating body which is connected to the seabed by three ropes.
  - To protect the system from extreme wave loads in heavy storms, it can be lowered to calmer waters.

FIGURE 3-5 PICTURE OF OYSTER 800 DURING ASSEMBLY (SOURCE: [40])

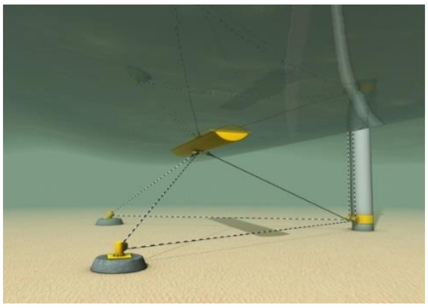


FIGURE 3-6 ILLUSTRATION OF THE NEMOS TECHNOLOGY (SOURCE: [41])

FIGURE 3-7 ILLUSTRATION OF THE ARRECIFE TECHNOLOGY (SOURCE: [32])

3.1.4. Technical analysis of the submergence concepts

3.1.4.1. Oyster

Oyster wave power technology is designed to capture the energy in nearshore waves through the oscillatory motion of a buoyant, hinged flap attached to the seabed at around 10m depth. The flap drives hydraulic pistons which push high pressure water onshore to drive a conventional hydro-electric turbine. Oyster 800 technology is attached to the seabed and its flap can be more from a vertical solution while operating to a totally submerged position in case of extreme events.

Established in 2005, Aquamarine Power deployed and tested two full-scale Oyster devices at EMEC: the 315kW Oyster 1 and the second-generation 800kW Oyster 800, spending in excess of £3m in Orkney and working with over 40 local businesses. Oyster 800 was grid-connected in June 2012 at EMEC's Billia Croo test site until the test programme ended in 2015, when the company ceased trading. TRL 8 was achieved.

Concept of the submergence process

Two technical choices for survivability have been made during the technological development:

- Location very close to the shore to ensure that the longest-wavelength waves broke to reduce extreme hydrodynamic loads,
- Submergence process with a protection configuration with the flap, on a horizontal set-up to minimize the hydrodynamic loads perceived during stormy events.

A dedicated PTO feature and a brake are needed as auxiliary systems to lower and maintain the flap in a lowered positioning.

Specificities

Submergence is used as a survivability strategy. A lowered position is preferred to limit the hydrodynamic loading during extreme events.

Submergence does interfere with the power production: the system cannot be both in the survivability configuration and operating.

The nearshore location and the relative shallow waters so that the flap can both break out of the water and be lowered into the survivability configuration significantly reduce the number of sites available for technology deployment.

3.1.5. Desalination Salter's duck

Salter's duck falls under a class of WECs known as terminators. Terminators are oriented perpendicular to wave direction. The concept is shaped like a teardrop. The nose of the teardrop faces incoming waves and bobs as they pass (roll motion). Salter's duck is usually a floating device but thanks to articulated moorings, it is able to achieve a lower positioning in the water column to adapt the effective power production and choose a lower power rating for the PTO (hence less costly).

Although multiple tank tests and numerical modelling took place, Salter's Duck was never been tested at sea. Therefore, TRL4 only is achieved.

Concept of the submergence process

Salter's duck relies on active mooring to accurately lower its positioning in the water column.

The auxiliary systems needed are winches for adequate mooring load management. Redundancy is also critical to achieve both positions-keeping and survivability mode.

In another version of Salter's duck, pumps and ballast storage are using to either ballast the system or the anchoring lines – the same way as clump weights would operate.

Specificities

Submergence is used as a regulation for power output i.e. load management as pitch control would allow wind turbines to limit the loads on the blades.

According to concept documentation submergence doesn't interfere with the power production: the system can be submerged and be operating.

The influence of submergence on efficiency has not be investigated in details.

3.1.6. Laminaria system

Laminaria's technology is a surge operated attenuator. It embodies a bespoke storm protection system to enhance the survivability of the device, allowing it to remain operational during storm events. The Laminaria constitutes a vertical surface which must interact with the horizontally travelling wave energy. As a result of the horizontal movement in the water, the Laminaria will be subjected to a tilting and translating motion which is transferred through the mooring ropes to the generators. Laminaria's technology can therefore be located as a floating

body at sea water level and can be dragged down by the innovative anchoring system to efficiently manage the loads for the PTO and the moorings.

Laminaria's wave energy converter has undergone tank testing at the Coastal, Ocean and Sediment Transport (COAST) laboratory at Plymouth University, as part of the LAMWEC project. The LAMWEC project seeks to develop and test a full-scale 200kW Laminaria WEC. TRL4 is achieved and higher TRL is targeted with the opensea test.

FIGURE 3-8 PICTURES OF LAMINARIA'S WEC TECHNOLOGY (SOURCE: [34])

<u>Concept of the submergence process</u>

Laminaria's WEC incorporates a load management and storm protection system. This storm protection system brings the WEC underneath the sea surface during extreme storm events.

The mooring lines are taut and coupled by pair. A dedicated mooring and pulley design is necessary to operate the system. Redundancy is critical for the mooring lines as they ensure both the position keeping of the system, its survivability during stormy events and regulated loads for the mooring and the PTO.

<u>Specificities</u>

Submergence is used as a regulation for power output i.e. load management as pitch control would allow wind turbines to limit the loads on the blades.

Submergence doesn't interfere with the power production: the system can be submerged and be operating.

A dedicated control strategy is necessary to accurately monitor and achieve optimized energy yield and WEC lifetime.

3.1.7. Conclusion

It has been shown that wave energy converters developers have adopted various strategies to achieve submergence.

The process consists either in:

- Pull on the mooring lines (Laminaria / Salter's Duck)

Or

- Use existing motors and fixed foundation to pull the system on the bottom (Oyster)

Or

- The Ballast – compressed air concept where sinking is performed by ballasting the system with water, and the emersion is performed by replacing these ballasts with air which was compressed (Salter's Duck alternative design)

Technical precedence is still limited for Wave Energy Converters as mainly prototype have been commissioned offshore. However it is clear that power production and optimized control strategies will be key to be able to achieve commercially viable projects.

Several topics would need to be investigated further:

- Cost/Benefit analysis: is submergence the optimal solution for survivability as it induces additional sub-systems and necessary redundancy?
- As submergence induces a minimum water depth needed for WEC installation, what impact can have the potential limitation on the market segment accessible (necessary deep location to avoid any contact with the seabed)

3.2. Some other submergence processes

This section is a brief state-of-the-art of submergence process. The objective is first to describe situations in industrial context where submergence is needed, and then to analyze the concept used for each application to perform the submergence process. Here is the list of concepts using submergence that will be described in this section (this list is not exhaustive but constitutes examples of submergence processes):

- Submarines
- Spar Upending
- Vertical Profiling Systems
- ROV / AUV
- Floating Instrument Platform (RV FLIP)
- Oil & Gas operation example: CLOV buoyancy tank

3.2.1. Submarines

A submarine is a watercraft capable of independent operation underwater. Most submarines are built for military purpose. Civil use of submarine concerns essentially oceanographic research and oil & gas exploitation.

The principle used for immersion of a submarine is the Archimedes' principle using density variation in the ballasting. During the submergence process, Air is replaced by water in the ballast chambers. By doing this, the submarine's ballast reaches approximately the same density as marine water. The overall density of the submarine exceeds density of sea water and the submarine sinks. The principle used to emerge is sensibly the same. The ballast chambers are filled with air that was stored compressed. The submarine becomes lighter and goes up to surface. Submarines usually also depend on dynamic assistance using forward motion interacting with hydrovanes to maintain stability and to keep the hull reasonably orientated

3.2.2. Spar Upending

Spars have been used for decades as marker buoys and as data buoys for gathering oceanographic data. The world's first production spar was the Neptune Spar installed in 1996 [10].

Once the spar is offloaded from the transportation vessel and rigged for installation, it is wet towed to the installation site. When the spar arrives at the installation location, it is upended by flooding the soft tank and midsection (see Figure 3-9). Once the hull is upended it is made ready for attachment of the mooring lines.

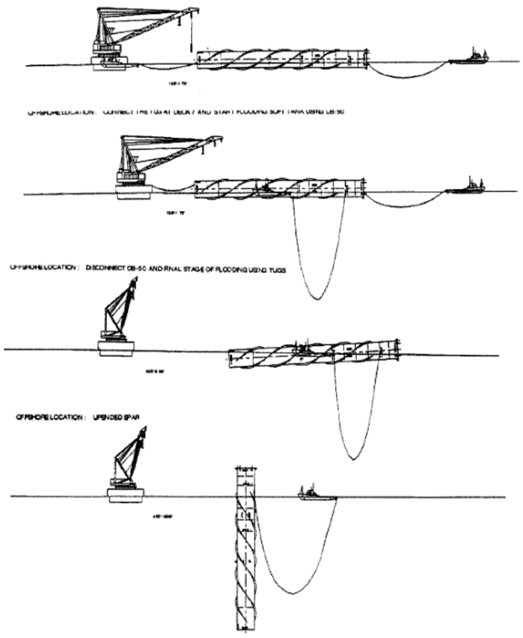


FIGURE 3-9 SPAR UPENDING SEQUENCES – SOURCE: [10]

3.2.3. Vertical Profiling Systems

Vertical Profiling Systems are generally composed of a ballast, a mooring part, a buoy, and a set of sensors to collect via telemetery high-resolution time-series vertical profile data, providing a complete spectrum of oceanographic data (physical, biochemical, optical) in real or near real-time.

Various companies on the market propose this system. A few examples are in the following:

- InterOcean VPS Systems
- NiGK Self Up/Down winch-type buoy

The system consists of three major components: a bottom-mounted underwater winch; an instrumentation package with a sensor suite for collecting data during profiling sessions; and a buoyancy element that provides the force necessary to raise the instrumentation package upward towards (or to) the surface. The underwater winch system controls the profiling speed of the instrumentation package as it rises to the surface, as

FIGURE 3-10 INTEROCEAN VERTICAL

well as the station time needed for the directional wave data collection and the "dwell" time for data telemetry at the surface. The energy is generally provided by a battery.

PROFILING SYSTEM - SOURCE: [38]

3.2.4. ROV / AUV

A remotely operated underwater vehicle (ROV) is a tethered underwater mobile device. ROVs are unoccupied, highly maneuverable, and operated by a crew aboard a vessel. They are common in deep water industries such as offshore hydrocarbon extraction and subsea telecoms. They are linked to a host ship by a neutrally buoyant tether or, often when working in rough conditions or in deeper water, a load-carrying umbilical cable is used along with a tether management system (TMS). The TMS is either a garage-like device which contains the ROV during lowering through the splash zone or, on larger work-class ROVs, a separate assembly which sits on top of the ROV.

An autonomous underwater vehicle (AUV) is a robot which travels underwater without requiring input from an operator. AUVs constitute part of a larger group of undersea systems known as unmanned underwater vehicles, a classification that includes non-autonomous remotely operated underwater vehicles (ROVs) – controlled and powered from the surface by an operator/pilot via an umbilical or using remote control. In military applications AUVs are more often referred to simply as unmanned undersea vehicles (UUVs).

The concepts employed to sink and emerge ROV and AUV is the same as for submarines. Wise use of ballast and compressed air, along with propellers permit to move these vehicles vertically in water.

3.2.5. Floating Instrument Platform (RV FLIP)

R/P FLIP (FLoating Instrument Platform) is an open ocean research platform owned by the U.S. Office of Naval Research (ONR) and operated by Scripps Institution of Oceanography. The platform is 108 meters (355 ft) long and is designed to partially flood and pitch backward 90°, resulting in only the front 17 meters (55 ft) of the platform pointing up out of the water, with bulkheads becoming decks. FLIP is designed to study wave height, acoustic signals, water temperature and density, and for the collection of meteorological data. Because of the potential interference with the acoustic instruments, FLIP has no engines or other means of propulsion. It must be towed to open water, where it drifts freely or is anchored. During towing, FLIP can reach speeds of 7–10 knots

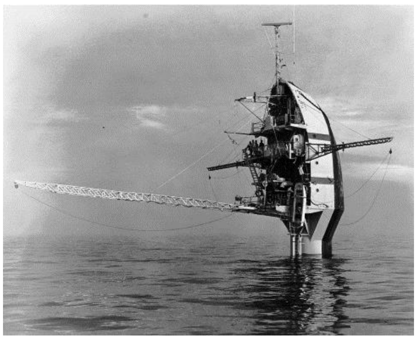


FIGURE 3-11 THE FLOATING RESEARCH PLATFORM FLIP – SOURCE: [36]

When flipped, most of the buoyancy for the platform is provided by water at depths below the influence of surface waves, hence FLIP is stable and mostly immune to wave action similar to a

spar buoy. At the end of a mission, compressed air is pumped into the ballast tanks in the flooded section and the platform, which has no propulsion, returns to its horizontal position so it can be towed to a new location.

3.2.6. Oil & Gas operation example: CLOV buoyancy tank

Here is an example of operation performed in Oil & Gas industry using submergence concept. The CLOV is a buoyancy tank brought undersea to be connected to a riser tower. Figure 3-12 and Figure 3-13 show the Riser Tower and the buoyancy tank.

Figure 3-12 CLOV buoyancy tank presentation. Riser Tower (Left) and Buoyancy Tank (right) – source: [12]

FIGURE 3-13 CLOV BUOYANCY TANK ONSHORE IN THE HARBOR – SOURCE: [12]

During the performed operation, buoyancy Tank has been separately towed offshore and docked onto the riser tower by submergence. The buoyancy Tank was lowered horizontally up to connection depth using anchor chains deployed from tugs. Then Buoyancy Tank was upended and docked onto the top structure prior to deballasting and tensioning the overall system.

3.2.7. Conclusion

From these examples, two main concepts to perform submergence can be identified:

- The Ballast –compressed air concept where sinking is performed by ballasting the system, with water, and the emersion is performed by replacing these ballasts with gas (generally air) which was compressed.
- The buoy – winch concept where sinking is performed by activating a winch that bring the floating device underwater. The buoyancy is conserved and permits, when the winch is untightened, to emerge back the device.

3.3. Specificities of the Spar OWC regarding submergence

Regarding the OWC system, solutions identified through this review could be applied: ballasting and/or using winches. However, some challenges have to be studied.

If the first concept is applied (ballast and compressed air), additional devices are required such as pumping system, compressed air tank, remote control system, etc.. These devices will be underwater in survival conditions, therefore sealing issues are critical and have to be studied. Submergence is the selected solution for survivability. Every single component involved in the submergence process is therefore required to be reliable (redundancy may be necessary). In this first case, the laying of the OWC to a horizontal position will require to study ballasting repartition along the spar length.

If the second concept is applied (buoy and winches), the mooring system should be revised to accommodate to winches solution. As for the first concept, these devices will be underwater in survival conditions, therefore sealing issues have to be studied. In this second case, the laying of the OWC to a horizontal position would equilibrate loads, additional mooring lines may be required.

Besides, no matter the concept employed to sink the OWC, the following issues require further investigation:

- Once the device is underwater, how to avoid tilt i.e. keep it laid in a horizontal position?
- The current mooring system will be loosened when the OWC will be submerged. The impact on the static and dynamic stability requires further analysis.
- If the structure is laid to a horizontal position, the dynamic cable will change orientation. This could be an issue for the cable integrity (modifications of loads, modifications of curvatures).

Furthermore, the Spar OWC system will not be able to operate during submergence as the turbine is an air turbine. On top of that, the turbine and associated butterfly valves must be adequately designed to be watertight.

In terms of suitable sites, the submergence process for survivability suppose relatively deep water sites to be able to lower the system sufficiently low to avoid any extreme loading.

In terms of risks, we can already highlight the following topics:

- Sealing / Feasibility of the submergence of an air-air turbine
- Competition between power production and survivability

4. Engineering analysis of the feasibility of the submergence breakthrough for the Spar OWC

4.1. Review of potential impacts of the addition of submergence system, and technical topics to investigate

The objective of this section is:

- to establish an overview of the main risks and main impacts anticipated for the integration of a submergence device on the OWC concept,
- to establish a list of technical topics to investigate.

This is achieved through these steps:

- breakdown the service function "submerge the OWC" in constructive solutions through a FAST diagram,
- perform a preliminary risk analysis,
- realize interviews of experts and equipment providers to question submergence main topics,
- summarize the topics to be further investigated.

4.1.1. FAST diagram

4.1.1.1. Methodology

FAST stands for "Functional Analysis System Technique". The FAST technique is used in Value Engineering to analyze costs. Fast diagrams provide a graphical representation of how functions are linked or work together in a system to deliver the intended goods or services. Functions may be performed by the process, product or system, into a How? / Why? relationship.

Here is a type example of the diagram:

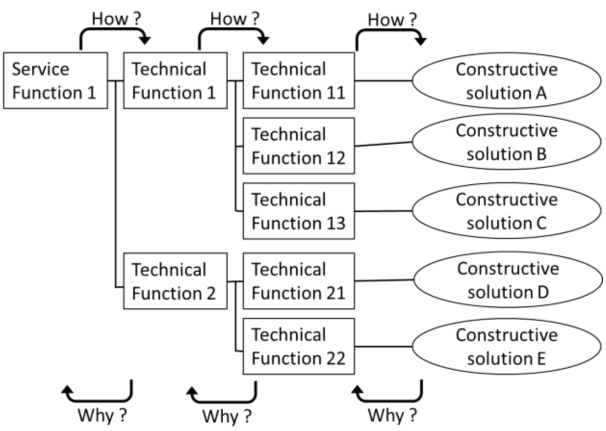


FIGURE 4-1 EXAMPLE OF FAST DIAGRAM – SOURCE [37]

The process to complete this type of diagram is from left to right, in a logic from “why?” to “how?”. Here is an example of how FAST diagram has been completed for the function “submerge the OWC”:

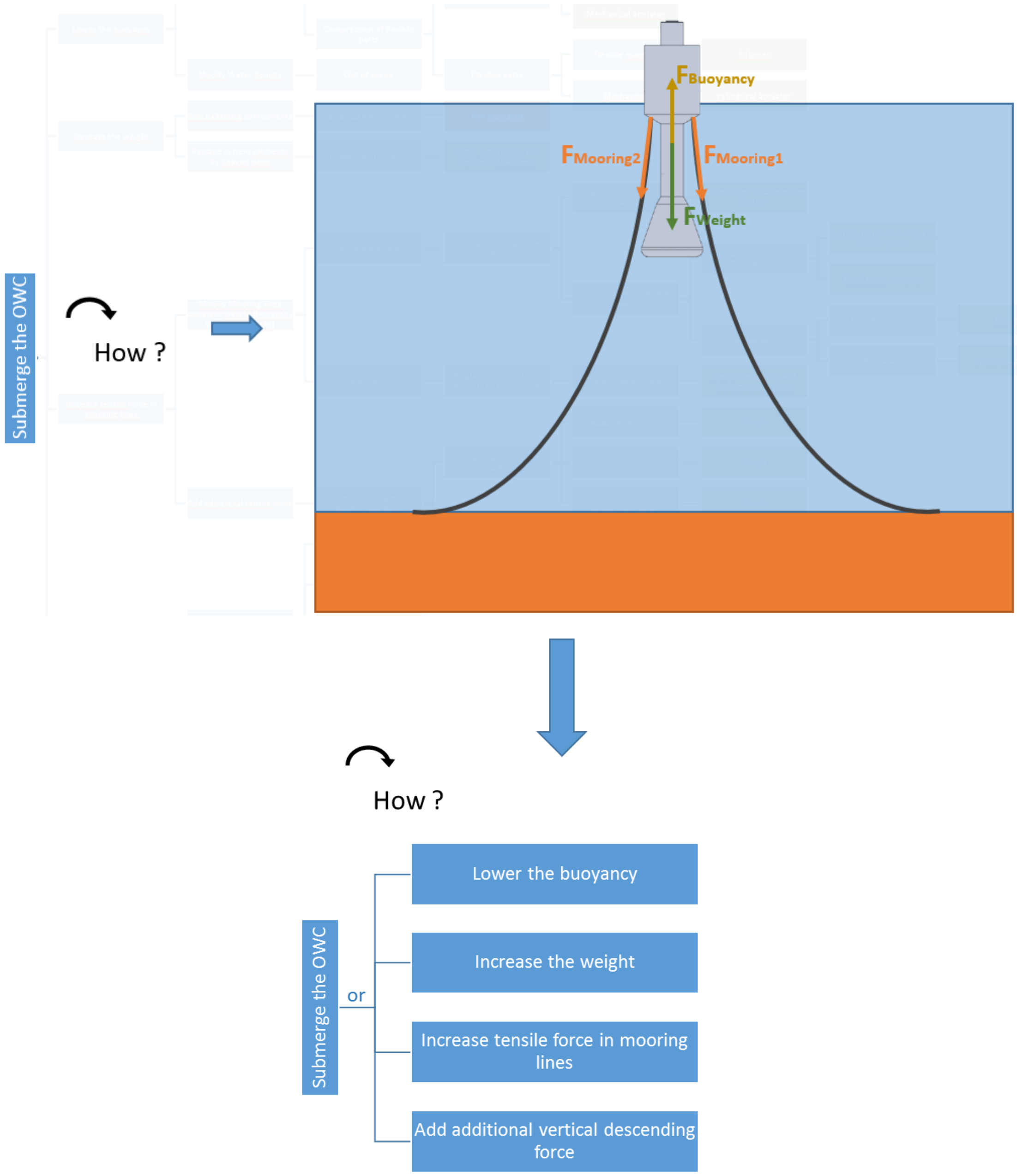


FIGURE 4-2: EXAMPLE OF PROCESS TO COMPLETE THE FAST DIAGRAM

To answer the question “How to submerge the OWC”, one can look at the force static equilibrium on the OWC, and the resulting technical functions are directly the action on each force. This process is repeated for each technical function until constructive solutions – as detailed as operational systems/tools/mechanisms – are obtained.

4.1.1.2. FAST diagram of the function “submerge the OWC”

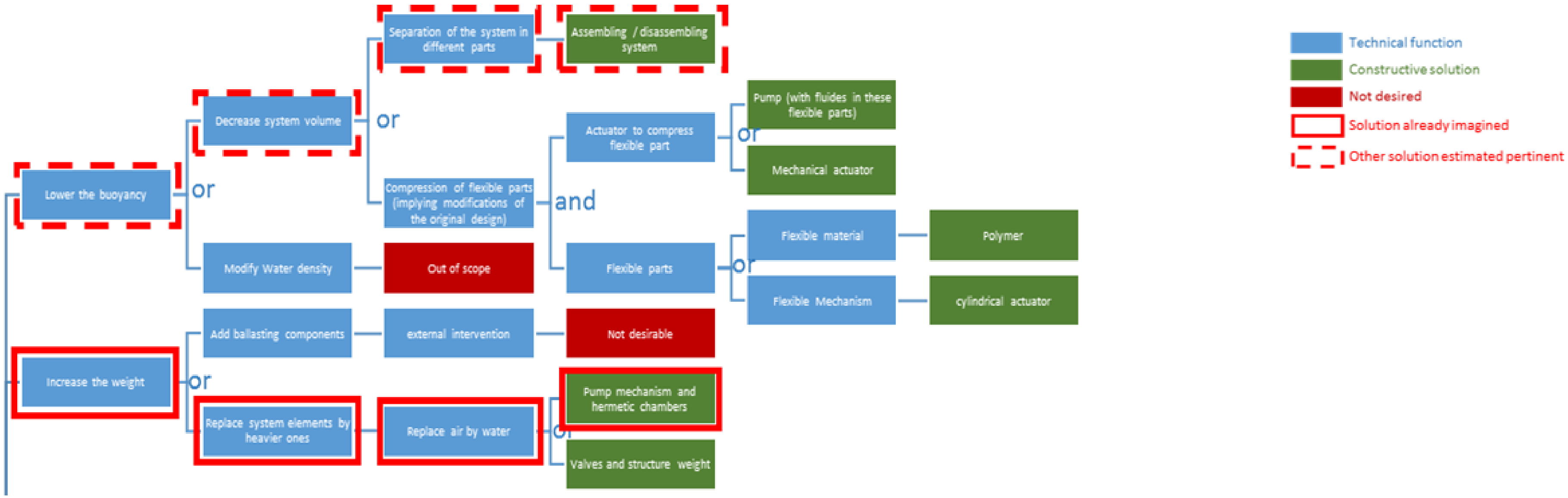
The following diagram Figure 4-3 results from the previously mentioned methodology applied on the service function “submerge the OWC”.

Please note that:

- Despite the effort to complete the diagram in a methodic way, this completion highly depends on INNOSEA’s experience. In this sense, the produced diagram shouldn’t be read as an exhaustive list of solutions. For a more detailed work, it would be interesting to cross data from multiple diagrams realized by different persons.
- The level of details is considered sufficient for this conceptual stage of the device.
- The proposed constructive solutions (green blocks) are for example only. Various components may fit for each technical function.

Moreover, as explained in the legend, path circled in red are those leading to a solution already imagined in previous WETFEET deliverables. Path circled in dotted lines are those leading to a solution considered as relevant for industrial application, and to be further investigated (subjective judgement).

Green bocks are constructive solutions. Blue blocks are technical functions. Red blocks are solutions judged non-desired.


Lower the buoyancy
or
Decrease system volume
or
Separation of the system in different parts
Assembling / disassembling system
Compression of flexible parts (implying modifications of the original design)
and
Actuator to compress flexible part
or
Pump (with fluides in these flexible parts)
Mechanical actuator
Flexible parts
or
Flexible material
Polymer
Flexible Mechanism
cylindrical actuator
Modify Water density
Out of scope
Increase the weight
or
Add ballasting components
external intervention
Not desirable
Replace system elements by heavier ones
Replace air by water
or
Pump mechanism and hermetic chambers
Valves and structure weight
Technical function
Constructive solution
Not desired
Solution already imagined
Other solution estimated pertinent

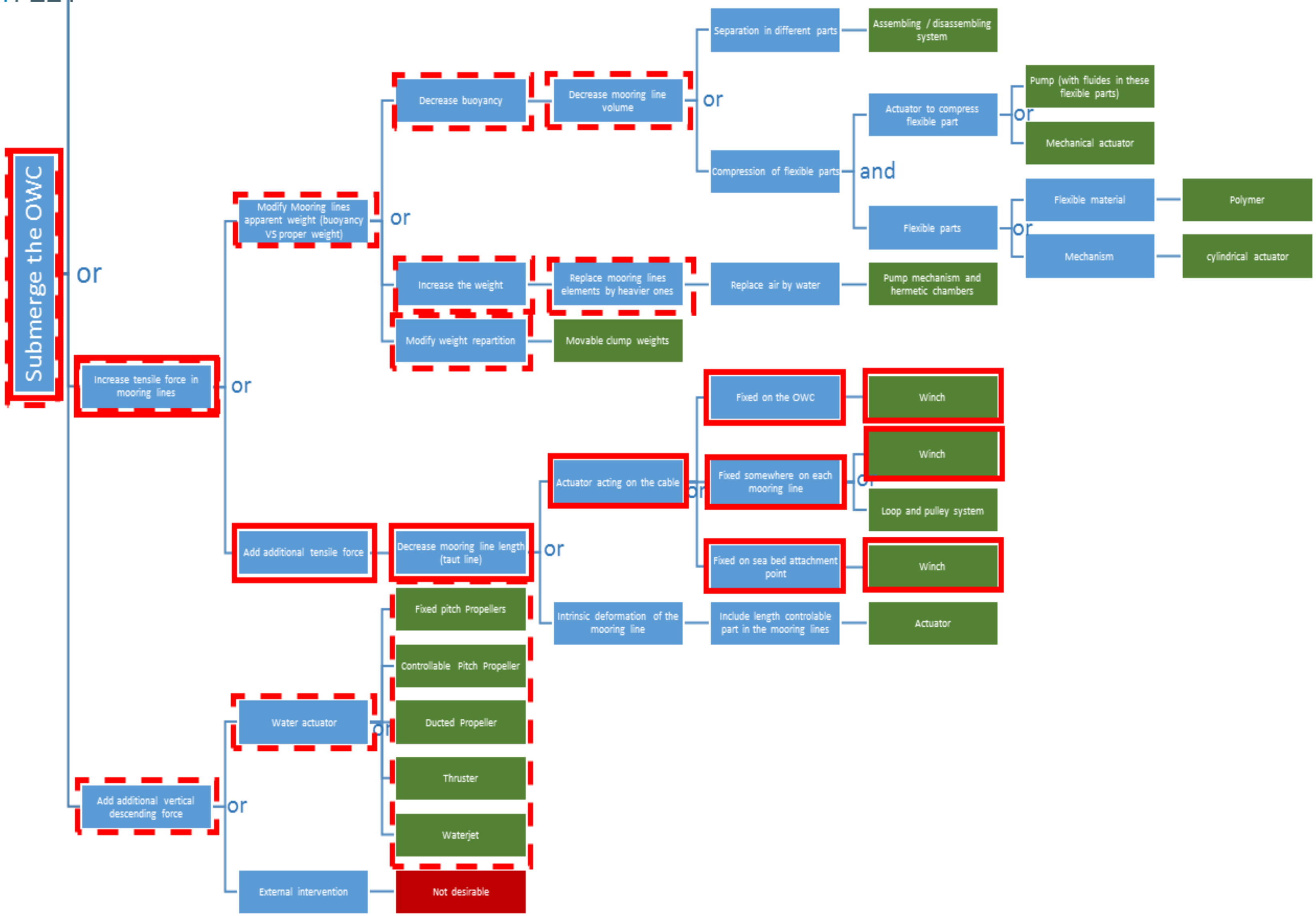


FIGURE 4-3 FAST DIAGRAM OF THE FUNCTION "SUBMERGE THE OWC"

4.1.2. Preliminary risk analysis

In order to obtain an overview of the main risks and main impacts anticipated for the integration of a submergence device on the OWC concept, a preliminary risk analysis is performed in this section.

The methodology employed is to:

1. Perform a 5-person brainstorming by going through the functional analysis to expose submergence main risks
2. Complete this list by going through submergence conceptual process to add other risks
3. Group risks in main themes
4. Propose a mitigation for each risk
5. Attribute a notation for each risk according to risk consequence, and probability, taking into account the proposed mitigation.
6. Summarize in a list of topics to investigate (detailed in section 4.1.5).

Probability classes and consequence classes are defined following recommendations of DNVGL-SE-0163 Standard (reference [13]). Table 4-1, Table 4-2 and Table 4-3 define these classes:

Table 4-1 Probabilities classes according to DNVGL-SE-0.163 (reference [13])

Class	*Name*	*Description*	*Indicative annual failure rate (up to)*	*Reference*
1	Very Low	Negligible event frequency	1.0E-04	Accidental (event not failure)
2	Low	Event unlikely to occur	1.0E-03	Strength / ULS
3	Medium	Event rarely expected to occur	1.0E-02	Fatigue / FLS
4	High	One or several events expected to occur during the lifetime	1.0E-01	Operation low frequency
5	Very high	One or several events expected to occur each year	1.0E+00	Operation high frequency

TABLE 4-2 CONSEQUENCE CLASSES FOR THE TURBINE ACCORDING TO DNVGL-SE-0163 (REFERENCE [13])

Class	*Description of consequences (impact on)*				
	Safety	*Environment*	*Operation*	*Assets*	*Cost (GBP)*
1	Negligible injury or health effects	Negligible pollution or no effect on environment	Negligible effect on production (hours)	Negligible	1k
2	Minor injuries or health effects	Minor pollution / slight effect on environment (minimum disruption on marine life)	Partial loss of performance (retrieval not required outside maintenance interval)	Repairable within maintenance interval	10k
3	Moderate injuries and/ or health effects	Limited levels of pollution, manageable / moderate effect on environment	Loss of performance requiring retrieval outside maintenance interval	Repairable outside maintenance interval	100k
4	Significant injuries	Moderate pollution, with some clean-up costs / Serious effect on environment	Total loss of production up to 1 m (GBP)	Significant but repairable outside maintenance interval	1m
5	A fatality	Major pollution event, with significant clean-up costs / disastrous effects on the environment	Total loss of production greater than 1 m (GBP)	Loss of device, major repair needed by removal of device and exchange of major components	10m

TABLE 4-3 CONSEQUENCE CLASSES FOR THE PROJECT ACCORDING TO DNVGL-SE-0163 (REFERENCE [13])

Class	Description of consequences (impact on)				
	Safety	Environment	Operation	Assets	Cost (GBP)
1	Negligible injuryor health effects	Negligible pollution or no effect on environment	Negligible effect on production (hours)	Negligible	10k
2	Minor injuries or health effects	Minor pollution / slight effect on environment (minimum disruption on marine life)	Loss of array performance (remedial activity takes place within scheduled maintenance)	Repairable within maintenance interval	100k
3	Moderate injuries and/ or health effects	Limited levels of pollution, manageable / moderate effect on environment	Loss of array performance requiring retrieval outside maintenance interval	Repairable outside maintenance interval	1m
4	Significant injuries	Moderate pollution, with some clean-up costs / Serious effect on environment	Total loss of array production up	Loss of one device or associated array infrastructure	10m
5	A fatality	Major pollution event, with significant clean-up costs / disastrous effects on the environment	Total loss of production greater than 10 m (GBP)	Loss of multiple devices and/or array infrastructure	100m

Risk consequence is evaluated differently depending on the risk nature: project risk or turbine risk. Therefore, two tables of risk are provided (respectively Table 4-5 and Table 4-6).

The Table 4-4 is then employed to qualify the risks category.

Table 4-4 Risk categories according to DNVGL-SE-0163 (reference [13])

Consequence					
Probability	**1**	**2**	**3**	**4**	**5**
5	Low	Med	High	High	High
4	Low	Med	Med	High	High
3	Low	Low	Med	Med	High
2	Low	Low	Low	Med	Med
1	Low	Low	Low	Low	Med

Notes:

Low	Tolerable, no action required
Medium	Mitigation and improvement required to reduce risk to Low
High	Not acceptable: mitigation and improvement required to reduce risk to Low (ALARP)

Here are the tables of risks resulting from the methodology described above:

TABLE 4-5 TABLE OF RISKS FOR THE DEVICE RESULTING FROM THE RISK ANALYSIS

Category	Risk Category	Risk Number	Risk Title	Description	Consequences	Nature	Suggested mitigation (if adequate)	Consequence (1-5)	Probability (1-5)	Total	Risk category
1	**Risks linked with the submergence pulling system (permitting downward traction to submerge, and traction release to emerge)**	**1.1**	**Failure of the submergence pulling system because of corrosion**	Submergence pulling system doesn't work, either while the system is at production position (sea surface) or at survival position (submerged)	- If the system is at production position (sea surface), the submergence phase can't start, binding the OWC to afford high loads during stormy event - If the system is at survival position (submerged), the emergence might be compromised obligating the spar OWC to stay	Technical	Submergence pulling system should be designed for use in marine environment	5	2	10	Medium
		1.2	**Failure of the submergence pulling system because of not supported loads (including Ultimate Limit State loads, Fatigue Limit State Loads, Accidental Limit State Loads, Service Limit State Loads)**			Technical	All the loads to be afforded by the Submergence pulling system should be correctly estimated, and security coefficient should be accounted	5	2	10	Medium
		1.3	**Failure of the submergence pulling system because of biofouling**			Technical	Submergence pulling system should be designed for use in marine environment	5	2	10	Medium

		1.4	**Failure of the submergence pulling system because damaged by collision with sea users**		submerged, unproducing	Technical	Spar OWC system should be highly visible while producing. A device should be integrated (buoy type) to warn sea users of the presence of OWC system while submerged	5	1	5	Medium
		1.5	**Failure of the submergence pulling system because of intrinsic component wear**			Technical	A preventive maintenance plan should be integrated to replace wearing parts, and to maintain submergence pulling system integrity Redundancy of equipements	5	2	10	Medium
2	**Risks linked with the submergence ballasting / deballasting system**	**2.1**	**Failure of the submergence ballasting / deballasting system because of corrosion**	Submergence ballasting / deballasting system doesn't work	- If Submergence ballasting / deballasting system is necessary to	Technical	Submergence ballasting / deballasting system should be designed for use in	5	2	10	Medium

	(permitting to modify system floatability - composed of for eg. pumps, valves, etc.)				submerge : The submergence phase can't start, binding the OWC to afford high loads during stormy event - if Submergence ballasting / deballasting system is necessary to evacuate ballast water when emerged : Ballast water stays, the OWC movements are not "normal" and energy production is altered		marine environment				
		2.2	**Failure of the submergence ballasting / deballasting system because of biofouling**			Technical	Submergence ballasting / deballasting system should be designed for use in marine environment	5	2	10	Medium
		2.3	**Failure of the submergence ballasting / deballasting system because damaged by collision with sea users**			Technical	Spar OWC system should be highly visible while producing. A device should be integrated (buoy type) to warn sea users of the presence of OWC system while submerged	5	1	5	Medium
		2.4	**Failure of the Submergence ballasting / deballasting system because of intrinsic component wear**			Technical	A preventive maintenance plan should be integrated to replace wearing parts, and to maintain submergence	5	2	10	Medium

							ballasting / deballasting system integrity Redundancy of equipements					
3	**Risks linked with the meteorological event detection system (meteorological podcasts, or dedicated sensors)**	**3.1**	**Too late detection of storm event**	The storm event is detected too late, meaning that bad sea conditions (waves, wind) appear whereas the spar OWC has not submerged yet	Spar OWC has to affords high loads due to extreme sea conditions, which could lead to system ruin	Technical	A margin should be taken on the estimated allowed time to submerge	3	2	6	Low
		3.2	**No detection of storm event**	The storm event is not detected by the meteo event detection system (meteo podcasts, or dedicated sensors)	Spar OWC has to affords high loads due to extreme sea conditions, which could lead to system ruin	Technical		5	2	10	Medium

		3.3	**More extreme conditions than predicted**	The storm event induced conditions are more extreme than what was predicted by the meteorological event detection system (meteorological podcasts, or dedicated sensors) and submersion is not engaged whereas it should have been.	Spar OWC has to affords high loads due to extreme sea conditions, which could lead to system ruin	Technical	Uncertainty of meteorological prediction has to be taken into account in submergence decision	4	2	8	Medium
4	**Risks linked with the monitoring system, SCADA (Supervisory Control and Data Acquisition) system and sensors**	4.1	**Failure of the monitoring system (sensors in particular) system because of corrosion**	Monitoring system doesn't work	The submergence phase can't start, binding the spar OWC to afford high loads during storm event	Technical	SCADA system should be kept in a watertight trunk, redundancy of equipment	2	4	8	Medium
		4.2	**Failure of the monitoring system (sensors in particular) system because of biofouling**			Technical	SCADA system should be kept in a watertight trunk, redundancy of equipment	2	4	8	Medium

		4.3	**Failure of the monitoring system system because damaged by collision with sea users**			Technical	Spar OWC system should be highly visible while producing. A device should be integrated (buoy type) to warn sea users of the presence of OWC system while submerged, redundancy of equipment	2	1	2	Low
		4.4	**Failure of the monitoring system system because of intrinsic component wear**			Technical	A preventive maintenance plan should be integrated to replace wearing parts, and to maintain submergence SCADA system integrity Redundancy of equipement	2	3	6	Low
		4.5	**Monitoring system (SCADA in particular) doesn't permit to stop emergence phase while proceeding, and a meteorological event**	SCADA system doesn't permit to stop emergence phase while	the spar OWC has to withstand high loads	Technical	Emergence phase should be designed to be fast (order of magnitude	4	1	4	Low

			happens while spar OWC is in emergence phase	proceeding, and a meteorological event happens while spar OWC is in emergence phase	induced by storm event		of 1 hour) and should allow change in command whenever desired				
		4.6	**Monitoring system (SCADA in particular) System brings the spar OWC too deep**	The submergence system bring the spar OWC too close from the seabed, or to a zone where hydrostatic pressure is higher than predicted	risks of damage on the structure if collision with the sea bed, and risk of water flooding and shell buckling if hydrostatic pressure is too high	Technical	The SCADA system should integrate redundancy in sensors, and their precision should be sufficient	5	2	10	Medium
		4.7	**Monitoring system (SCADA in particular) System doesn't bring the spar OWC deep enough**	The submergence system brings the spar OWC to a depth lower than expected	Risks of too high excitation movements of the spar OWC, resulting in high loads in system components	Technical	The SCADA system should integrate redundancy in sensors, and their precision should be sufficient	3	2	6	Low
5	**Risks linked with the mooring system designed to**	5.1	**failure of the mooring system designed to allow for submergence because of corrosion on one mooring line**	Mooring system behavior not as originally designed and	OWC movements not as originally designed,	Technical	mooring system including parts necessary for submergence	4	2	8	Medium

	allow for submergence			potentially do not permit to maintain system position	resulting in potential risk for the components, and potential energy production decrease, and potential ruin of the system		should be designed for use in marine environment				
		5.2	**failure of the mooring system designed to allow for submergence because of not supported loads (Ultimate Limit State loads, Fatigue Limit Loads, Accidental Loads, Service Loads, Snap Loads) on one mooring line**			Technical	Loads to be afforded by the mooring system parts necessary for submergence should be correctly estimated, and security coefficient should be accounted	4	2	8	Medium
		5.3	**failure of the mooring system designed to allow for submergence because damaged by collision with sea users on one mooring line**			Technical	Spar OWC system should be highly visible while producing. A device should be integrated (buoy type) to warn sea users of the presence of OWC system while submerged OWC mooring system should be designed to	4	1	4	Low

							allow station keeping in case of damage of one mooring line				
		5.4	**failure of the mooring system designed to allow for submergence because of intrinsic component wear of one mooring line**			Technical	A preventive maintenance plan should be integrated to replace wearing parts, and to maintain mooring system parts necessary for submergence integrity	4	2	8	Medium
		5.5	**failure of the mooring system designed to allow for submergence because these parts are not adapted to spar OWC submerged position (for example, because anchors were not designed to be used on taut lines)**			Technical	Mooring system should be designed taking into account submergence positions	4	2	8	Medium
		5.6	**failure of the mooring system designed to allow for submergence because mooring characteristics have changed following a submergence phase (for example because lines do**			Technical	Measures should be taken to avoid mooring system behavior modifications	3	1	3	Low

			not achieve same position as before submergence, etc.)				because of submergence phase. For example, avoid lines clashing during submergence or anchors movements during submergence position				
6	**Risks linked with the impact of submergence on spar OWC hull**	**6.1**	**Damage of spar OWC hull because of submergence induced loads**	Damage of spar OWC hull because of submergence induced loads (for example, hydrostatic loads induced by deep underwater position that could lead to buckling phenomenon)	depending on the location and the gravity of the damage, consequences may be: - water flooding in air zones - spar movements unpredicted - loss of integrity of the system	Technical	spar OWC structure should be designed taking into account submersion induced loads	5	2	10	Medium
		6.2	**Damage of spar OWC hull because of collisions with the seabed**	Damage of spar OWC hull because of collisions with the seabed while the spar OWC is in survival		Technical	Submergence process should avoid collision with the seabed. A margin should be taken on the distance	5	1	5	Medium

				position, therefore closer to the seabed			from the seabed when the spar OWC is in survival position				
7	**Risks linked with the impact of submergence on PTO (Power Take-Off) system**	**7.1**	**Damage because of water flooding induced by submersion**	The spar OWC PTO system is damaged because of water flooding during submergence phase	OWC stop producing energy	Technical	The PTO system (including dry chamber if necessary) should be designed to permit submersion	4	2	8	Medium
		7.2	**Damage because of collision with the seabed**	Damage of spar OWC PTO system because of collisions with the seabed while the spar OWC is in survival position, therefore closer to the seabed		Technical	Submergence process should avoid collision with the seabed. A margin should be taken on the distance from the seabed when the spar OWC is in survival position	4	1	4	Low
8	**Risks linked with the impact of submergence on dynamic power cable**	**8.1**	**Damage of the energy umbilical because of high curvature or high loads induced by submerged position**	The dynamic cable is damaged because of high curvature or high loads induced by	Power cable stop transferring energy	Technical	bend restrictor, anticipate power cable movements	4	2	8	Medium

				submerged position (for example, curvature induced by the transition from OWC vertical position to horizontal position)							
		8.2	**Damage of the energy cable because of collisions with mooring lines or with seabed while spar OWC is in submerged position**	Damage of the energy cable because of collisions with mooring lines or with seabed while spar OWC is in submerged position, therefore closer to the seabed		Technical	avoid possible impacts between power cable and mooring lines during both producing modes and survival modes	4	2	8	Medium
9	**Risks linked with the submergence system energy supply**	9.1	**Energy supply (to permit submergence) is not sufficient (power and / or capacity)**	The energy supply allowing to proceed submergence and emergence is unsifficient (power needed or capacity)	Submergence is not correctly achieved (not deep enough, etc.) or emergence can't be realised (system	Technical	Energy supply should be designed for multiple successive submergence procedures. Needed power should take into account potential loads	5	3	15	High

					blocked underwater)		increase (due to bio-fouling for example) Emergency Energy storage should be included to activate submergence in case of power outage				
		9.2	**Failure of the submergence system energy supply**	Submergence system energy supply is not working leading to impossible submergence or emergence of the system	Submergence or emergence is not achived, leading to potentiel ruin of the system if extreme conditions happens and system is not submerged as it should be	Technical	A preventive maintenance plan should be integrated Redundancy of equipements	5	2	10	Medium

One single risk (9.2) has been quantified as high, after mitigation. It is related with the energy availability necessary to proceed to the submergence phase.

TABLE 4-6 TABLE OF RISKS FOR THE PROJECT RESULTING FROM THE RISK ANALYSIS

Category	Risk Category	Risk Number	Risk Title	Description	Consequences	Nature	Suggested mitigation (if adequate)	Consequence (1-5)	Probability (1-5)	Total	Risk category
1	**Risks linked with the spar OWC energy production**	**1.1**	**Loss of production because submergence and/or emergence phases takes more time than expected (because of external reason as biofouling, failure etc.)**	The spar OWC spends more time than expected underwater, and unproducing	the spar OWC annual power production is overestimated	Financial		1	4	4	Low
		1.2	**The spar OWC performs more submersions than what was estimated**	Financial risk of overestimating the energy production because of unanticipated multiple submersions	the spar OWC annual power production is overestimated	Financial		2	4	8	Medium
2	**Risks linked with installation operations**	**2.1**	**Complexity of spar OWC installation because of the addition of the submergence system induces the need of a large weather window to install**	Time necessary to install the spar OWC including submergence system is large compared to site weather windows	The WEC installation is more coslty	Financial		2	3	6	Low

		2.2	**The addition of the submergence system induces a more complex installation**	Complexity of the entire spar OWC system because of the addition of a submergence system induces complexity in spar OWC installation	Financial risk of WEC being non-economically viable because complex installation equipment and/or procedures are needed (for example, the use of bigger vessels than without submergence system)	Financial		3	4	12	Medium
3	**'Risks linked with the mooring system designed to allow for submergence**	**3.1**	**Excessive cost of mooring system due to the addition of parts necessary for submergence**	Complexity of mooring system because of the addition of a submergence system induces high costs	Financial risk of WEC being non-economically viable	Financial		4	4	16	High
4	**Risks linked with maintenance**	**4**	**Maintenance complexity because of the addition of a submergence system**	Complexity of the maintenance because of the addition of a submergence system	Financial risk of WEC being non-economically viable because of	Financial		2	4	8	Medium

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				(because of the addition of components necessiting maintenance, for example winches, of pumps)	maintenance costs					

One single risk (3.2) has been quantified as high, after mitigation. It is related with the cost of the mooring system. The mooring system is expected to represent a significant cost of the whole system.

Most of the identified risks directly concern effective realization of submergence, therefore system survival (corresponding to consequence class 5).

Risk categories (Low, Medium and High) indicate that probability must be maintained under 10^{-4} annual. Proposed mitigations aim at this level for most critical risks. However, satisfying all these mitigations will have a strong impact on costs (CAPEX / OPEX).

4.1.3. Interviews with experts

Interviews of experts and equipment providers have been performed in order to dig in the submergence topics with resource persons of broader and more specialized experience.

4.1.3.1. Interview of an offshore engineer

Here are summarized the main considerations and warnings extracted from the interview of an offshore engineer:

Warnings about submergence proposed methodology

- Warning: In this proposed process, a special attention should be taken on center of buoyancy and center of gravity positions along time while ballasting water is added.
- Warning: When ballasting, special caution should be taken on valves behavior with remaining compressed air: there is a risk of brutal air releasing, inducing a quick balance modification.
- Warning:
  - The current design's lower part (ballast part) has negative floatability (buoyancy – weight). In the proposed submerged position, it implies that a high tension be applied on lines attached to the upper part of the spar (buoy part).
  - These resulting tensions may induce large ballast needs, or complexity in the moorings (piles, etc.).
- The automation of this process seems very complicated for the following reasons:
  - System dimensions' variations (fabrication tolerances induced) imply loads variations, and stability parameters difficult to anticipate. This is usually achieved by adjusting parameters in real time (human intervention)
  - The addition of this type of automation induces high costs
  - The repeatability of the process is compromised because of the changing environment (excitation loads, bio-fouling, corrosion, etc.)
- Another solution may be to voluntarily place the spar OWC on the sea floor. This could be achieved by slowly lowering the spar on a prepared floor (mattress, etc.). Attention should be taken on the spar structural behavior when submitted to its proper weight (ex: necessity to know if the spar is fabricated horizontally or vertically)
- Note on the air chambers: generally, air chambers are previously pressured to decrease risks of structural collapse – due to differential pressure. This adds a risk associated with effective sealing of the chambers.

Warnings and considerations about winches

- A disadvantage of the choice of placing the winch on the sea floor instead of placing it on the spar, is that an additional power cable is needed to power it.
- Subsea winches capacity is probably limited compared to classical winches
- A device similar to winches, called "chain jack" permits to drag chains. It is generally used for high tensions, and low speeds.

- The order of magnitude of maximum available winch traction capacity is around 500 tons (all winch types – not subsea specific (see below)).
- Winches are generally not let in tension in static configuration. Devices exist as "chain stop" to withstand tensions when winch winding is achieved. These devices could afford higher tensions than the winch.
- Placing winches in dry chambers seems complicated because:
    - Winches winding produce heat: there is a necessity to cool
    - It is necessary to power it
    - Having a dry interface is compromised by the chain/cable since it needs to go out or in the dry chamber.

Warnings and considerations about valves

- Subsea valves generally necessitate electric or hydraulic power, or the action by a ROV. In O&G industry, for pipe applications, valves are generally powered by hydraulic energy.
- The use of a combination of structural weight and open valves to flood and sink the system is a common practice in offshore applications. It is named "free flooding".

Warnings and considerations about mooring system

- Traction of catenary lines may be possible, but anchors systems should be designed to withstand vertical loads.
- No evident element permit to choose between the use of existing mooring lines to pull or the addition of dedicated pulling lines.
- It would be interesting to make a quick analysis on the cost increase induced by the submergence system on the mooring system.

Warnings and considerations about dynamic cable

- It is not critical that the dynamic cable touch sea floor. However, the configuration of the cable has to be studied in both producing and survival positions.
- In particular, bending stiffener angles on the spar should be studied. 45° angle should be affordable, 60° angle is extreme.
- Bend stiffener length is defined according to these angles. As reference, 8-10m length is quite long.

4.1.3.2. Interview of an expert experienced in industrial pumps

Here are summarized the main considerations and warnings extracted from the interview of a pump expert:

Warnings and considerations about pumps

- Warning with the use of a watertight chamber: tightness is complicated between motor shaft and pumping part
- Warning: Need to take into account working pressure when choosing pumps and valves.

- Warning: To be able to perform pumping in both ways (ballast water pumping, and flushing), the job is generally not done by the pump, but by the pipework (ex 3-way valves). Indeed, common pumps are generally not able to run in both ways. If we want to use a pump to fill the ballast and to flush away the water, we need probably 2 pumps. This may increase system cost.
- Warning on the pressure difference between surface position and submerged position – in particular with regards to the differential pressure on the hull and possibly on the working pressure of exposed components
- Warning on the movements of water in the chamber with regards to the ballast water volume control. Inaccurate monitoring issues might occur. This risk can be mitigated by the use of multiple sensors (couples of sensors). This constraint exists also in ships.

Warnings and considerations about valves

- Warning: Blowholes should be watertight in normal use. An example of component to permit it to be watertight is called "boîte dorade".
- Warning: The worst situations regarding corrosion issues are alternate wet and dry zones (due to oxygen presence), especially in marine environment. These conditions imply costly materials such as bronze.

4.1.3.3. Interview of a WEC expert

Here are summarized the main considerations and warnings extracted from the interview of a WEC expert:

Warnings about submergence proposed methodology

- It is important to define the weather conditions from which the spar should be submerged.
- There is risks of collapse when the system is put underwater while there is still air in chambers, because of pressure difference between outside the hull (hydrostatic pressure) and inside the hull. To avoid that, either increase structure thickness, either anticipate the pressure difference by increasing pressure in air chambers.
- Warning on the insurability: on a previous project with submergence, marine operations with seamen were authorized by insurance only if 3 days of weather window were available for any submergence operation. (this warning may be project specific)

Warnings about winches

- Warning on the use of multiple winches: How to be sure that the load sharing between the winches is respected?

Warnings about mooring system

- The current mooring system (including 6 lines for one WEC) seems complex.
- Modifications of mooring lines position during the submergence process may occur.

4.1.3.4. Interview of a second WEC expert

Here are summarized the main considerations and warnings extracted from the interview of a second WEC expert:

Warnings about submergence proposed methodology

- Warning on the choice of PTO: if a turbine is used, it will probably not be submersible. If an elastomer is used, it may be more adapted to submersion.
- Warning when pulling on the mooring lines: the horizontal distance between spar OWC and anchoring points (in particular in the case of catenary lines with clump weights and buoys) induces an angle between mooring lines and vertical axis. The resulting force necessary to pull is much higher than with vertical lines.
- The definition of the weather conditions from which the system has to submerge is an important matter.

Warnings and considerations about mooring system

- Warning if mooring lines are used to pull: the entire part which goes around the winch has to be exempt of clump-weights and buoys
- Warning on the anchors design: the addition of winches considerably increases the design loads (horizontal and vertical)
- Warning: The survival mode is not the « default mode ». This means that it needs a dedicated operation to set the survival mode. What if there is a lack of energy? (no communication with the shore, etc.)
- It seems easier to use dedicated lines to pull (simpler lines, no clump weights, no buoys, dedicated anchorages, etc.). However, this addition complicates the global system, and induces additional costs.
- Warning on the mooring lines used with the winches: there is a need to check if their minimum bending radius allows them to roll around the winch. For example, in another project, special mooring lines were used with flat sections instead of circular sections to allow the use with coils.

Warnings and considerations about dynamic cable

- Warning about the communication in submerged position: some of the communication means (ex: antenna) may not be working underwater. Besides, variations of dynamic cable positions may damage optic fiber.

4.1.4. Contacts of equipment providers

4.1.4.1. Contact of a Winch Provider

Here are summarized the main considerations and warnings extracted from the contact of a winch provider:

- No known subsea winch system with a capacity higher than 50 Tons seem to exist
- Warning about the integrity of the system after 20 years of corrosion
- Seeing the cable length and the capacity needed, the winch system needed seems big.
- Above 3 bar of hydrostatic pressure, tightness is a major issue

4.1.5. List of impacts and topics to investigate

Here is summarized the list of impacts and topics to investigate resulting from the previous sections:

TABLE 4-7 LIST OF IMPACTS AND TOPICS TO INVESTIGATE

<table>
<tr><th>List of impacts of the submergence on the Spar OWC</th><th>Technical topics to investigate</th></tr>
<tr><td>Addition of a submergence pulling system</td><td>

Submergence pulling system should be designed for use in marine environment.
All the loads to be afforded by the Submergence pulling system should be correctly estimated, and security coefficient should be accounted.

Particular attention should be paid to the fact that the current design's lower part (ballast part) has negative floatability (buoyancy – weight). In the proposed submerged position, it implies that a high tension be applied on lines attached to the upper part of the spar (buoy part).
These resulting tensions may induce big ballast needs, or complexity in the moorings (piles, etc.).
Warning when pulling on the mooring lines: the horizontal distance between spar OWC and anchoring points (in particular in the case of catenary lines with clump weights and buoys) induces an angle between mooring lines and vertical axis. The resulting force necessary to pull is much higher than with vertical lines.

A preventive maintenance plan should be integrated to replace wearing parts, and to maintain submergence pulling system integrity
Pulling devices should be studied – type of component, location, and functional constraints:

A disadvantage of the choice to put the winch (or pulling component on the sea floor instead of putting it on the spar, is that it necessitates the addition of a power cable to power it.
Other components than winches may be useful, and need to be investigated. For example, a device similar to winches, called "chain jack" permits to drag chains. It is generally used for high tensions, and low speeds.
Winches are generally not let in tension. Devices exist as "chain stop" to afford tensions when winch winding is achieved. These devices could afford higher tensions than the winch.
Putting winches in dry chambers (non-subsea winches) seems complicated because:

Winches produce heat, so there is a necessity to cool
There is a necessity to power it
Dry interface compromised by the chain/cable, because a part is going out or in the dry chamber.

Warning on the use of various winches: How to be sure that the load repartition between the winches is respected?
Seeing the cable length and the capacity needed, the winch system needed seems big.
Above 3 bar of hydrostatic pressure, tightness is a major issue

Corrosion of the system should be studied

Warning about the integrity of the system because of 20 years of corrosion

</td></tr>
</table>

Addition of a system to signal the presence of Spar OWC when submerged	• Spar OWC system should be highly visible while producing. A device should be integrated (buoy type) to warn sea users of the presence of OWC system while submerged
Addition of a ballasting / deballasting system	• Submergence ballasting / deballasting system should be designed for use in marine environment • A preventive maintenance plan should be integrated to replace wearing parts, and to maintain submergence ballasting/deballasting system integrity • In this proposed process, a special attention should be taken on center of buoyancy and center of gravity positions along time while ballasting water is added. • When ballasting, special caution should be taken on valves behavior with remaining compressed air: there is a risk of brutal air releasing, inducing a quick balance modification. • The use of a combination of valves and structural weight to flood the system is a common practice in offshore applications. It is named “free flooding”. When pump system is used, it is named “forced flooding”. This second method necessitates more components, but allows a better control of ballasting speed. A techno-economical study should be performed to choose between these two methods. • Special attention should be taken with the use of a watertight chamber: tightness is complicated between motor shaft and pumping part • There is a need to take into account working pressure when choosing pumps and valves. • To be able to perform pumping in both ways (ballast water pumping, and flushing), the job is generally not done by the pump, but by the pipework (ex 3-way valves). Indeed, common pumps are generally not able to run in both ways. If we want to use a pump to fill the ballast and to flush away the water, we need probably 2 pumps. This may increase system cost. • A special attention should be taken on the pressure difference between surface position and submerged position • A special attention should be taken on the movements of water in the chamber (regarding ballast water volume control). This constraint exists also in ships. This can be controlled by the use of multiple sensors (couples of sensors). • Blowholes should be watertight in normal use. An example of component to permit it to be watertight is called “boîte dorade”. • The worst situations regarding corrosion issues are alternate wet and dry zones, especially in marine environment. These conditions imply costly materials as bronze.
Addition of a meteorological event detection system	• A margin should be taken on the estimated allowed time to submerge • The possibility of non-detection of storm event should be investigated • Uncertainty of meteorological prediction has to be taken into account in submergence decision • It is important to define the weather conditions from which we want the spar

	to be submerged. • The definition of the weather conditions from which the system has to submerge is an important matter.
Impacts on SCADA system	• SCADA system should be kept in a watertight trunk • Emergence phase should be designed to be fast (order of magnitude of 1 hour) and should allow change in command whenever desired • The SCADA system should integrate redundancy in sensors, and their precision should be sufficient • The automation of this process seems very complicated for the following reasons: ○ System dimensions' variations (fabrication tolerances induced) imply loads variations, and stability parameters are difficult to anticipate. This is usually achieved by adjusting parameters in real time (necessity of human intervention) ○ The addition of this type of automation induces high costs ○ The repeatability of the process is compromised because of the changing environment (excitation loads, bio-fouling, corrosion, etc.)
Modifications of the mooring system	• Mooring system including parts necessary for submergence should be designed for use in marine environment • Mooring system should be designed taking into account submergence positions • Measures should be taken to avoid mooring system behavior modifications because of submergence phase. For example, avoid lines clashing during submergence or anchors movements during submergence position • Traction of catenary lines may be possible, but anchors systems should be designed to afford vertical loads. • No evident element permit to choose between dedicated pulling lines, or use of mooring lines to pull. • It would be interesting to make a quick analysis on the cost increase of the mooring system induced by the submergence system. • The actual mooring system (including 6 lines) seems complicated. Mooring system should be studied to check if a simpler system is possible. • If mooring lines are used to pull, the entire part which goes around the winch has to be exempt of clump-weights and buoys • Special attention should be taken on the mooring anchors design: the addition of winches considerably increases the design load (horizontal and vertical) • Special attention should be taken on the fact that the survival mode is not the « default mode ». This means that it needs a dedicated operation to set the survival mode. What if there is a lack of energy? (no communication with the shore, etc.) • It seems easier to use dedicated lines to pull (simpler lines, no clump weights, no buoys, dedicated anchorages, etc.). However, this addition complicates the global system, and induces additional costs. • Special attention should be taken on the mooring lines used with the winches:

	there is a need to check if their minimum bending radius allows them to roll around the winch. For example, in Laminaria project, special mooring lines were used with flat sections instead of circular sections to allow the use with coils. • Special attention should be taken on the elasticity of the mooring lines.
Modifications of the spar OWC hull	• spar OWC structure should be designed taking into account submersion induced loads • Submergence process should avoid collision with the seabed. A margin should be taken on the distance from the seabed when the spar OWC is in survival position • Attention should be taken on the spar structural behavior when submitted to its proper weight (ex: necessity to know if the spar is fabricated horizontally or vertically?) • There is risks of collapse when the system is put underwater while there is still air in chambers, because of pressure difference between outside the hull (hydrostatic pressure) and inside the hull. To avoid that, either increase structure thickness, either anticipate the pressure difference by increasing pressure in air chambers.
Modifications of the PTO	• The PTO system (including dry chamber if necessary) should be designed to permit submersion • Submergence process should avoid collision with the seabed. A margin should be taken on the distance from the seabed when the spar OWC is in survival position • Warning on the choice of PTO: if a turbine is used, it will probably not be submersible. If an elastomer is used, it may be more adapted to submersion.
Modifications of the dynamic cable	• Curvature of the dynamic cable should be controlled • The design of all the lines leaving the spar should avoid possible impacts between power cable and mooring lines during both producing modes and survival modes • It is not critical that the dynamic cable do touch sea floor. However, the configuration of the cable has to be studied in both producing and survival positions. • In particular, bending stiffener angles on the spar should be studied. 45° angle should be affordable, 60° angle is extreme. Bend stiffener length is defined according to these angles. 8-10m length is quite long. • Special attention should be taken about the communication in submerged position: some of the communication means (ex: antenna) may not be working underwater. Besides, variations of dynamic cable positions may damage optic fiber.
Addition of an energy supply	• energy supply should be designed for multiple successive submergence procedures. Needed power should take into account potential loads increase (due to bio-fouling for example)
Modification of the installation operations	• The addition of the submergence system could induce a more complex installation • Complexity of spar OWC installation because of the addition of the submergence system could induce the need of a large weather window to install.

	• A special attention should be taken on the insurance: on FGA previous project with submergence, marine operations were authorized by insurance only if 3 days of weather window are available.
Impacts on the energy production	• The estimation of energy production should take into account loss of production because of submergence and emergence phases. • A margin should be taken on this estimation to anticipate a potential increase in the necessary time to submerge (because of biofouling for example), and to take into account an underestimation of the number of submersion per year.
Impact on the system maintenance	• Maintenance complexity because of the addition of a submergence system should be investigated.

4.1.6. Conclusions and choices

A review of potential impacts of the integration of submergence system on the original spar OWC design, and of technical topics to investigate has been performed. A FAST diagram has been established to find some solutions on how to submerge the OWC. Risk analysis and experts interview have been performed to complete the investigation and establish the list of topics to investigate. From the solutions identified within the FAST diagram it has been decided to focus on solutions where the Spar is ballasted and the mooring lines are taut to achieve submerged configuration.

Other solutions may be studied, as for example laying the Spar on the Seabed (horizontally or vertically), use of surface buoys and neutrally buoyant structure through addition of more ballast.

4.2. Investigation of ballasting needs, submerged positions, and potential impact on hull and potential impact on stability

The objective of this section is:

- to investigate submerged position of the system,
- to investigate potential impact on the hull,
- to investigate potential impact on the stability.

The following tasks have been performed:

- Define physical criteria that will constrain the submerged position, and estimate potential submergence depth based on geometric considerations,
- Evaluate impact of this submergence on hull and on stability of the spar,
- Perform a parametric study to refine potential submerged positions based on stability of submerged position, and identified constraints.

4.2.1. Definition of expected submerged position

4.2.1.1. Criteria constraining the submerged position

The identified criteria constraining the submerged position are the following:

- Spar inclination angle: this criterion is actually driven by umbilical minimum bending radius limit and feasible bend stiffener maximum manufacturable length. Upper bound order of magnitude would be approximatively +/- 60 degrees allowable variation of umbilical product versus as built in-place product departure angle.
- Buoyancy / Wave loads ratio: the ratio between the sum of weight and buoyant force and the maximum vertical hydrodynamic force on the spar should be greater than 1 to indicate a permanent upward force on the system to ensure that lines will not be slack (see equation (4-11)).
- Mooring line capacity: in the submerged position mooring line diameters are computed to ensure that tension in lines is below the minimum breaking load (MBL) of the line. A safety factor is taken in this computation.
- Admissible material diameter: this criterion removes cases where the diameter of material used for the mooring lines is not in manufacturer's capability range.
- Winch capacity: this criterion removes cases where mooring line tension exceeds winch capacity. It should be noted that a safety factor is also applied.
- Geometric criterion: the submerged position should ensure that neither the bottom nor the top of the spar is below the seabed or above the wave trough.
- Mooring system footprint: the distance between the anchors should be smaller than a given value.

It should be noted that the aim of these criteria is not to ensure stable and adequate configuration but rather to eliminate configuration that do not respect these criteria and are thus meant not to be acceptable. These criteria and the methodology to evaluate them shall be refined at later stage. The motion analysis is performed in 5.

4.2.1.2. Preliminary calculation

Stability calculation requires the position of center of gravity and buoyancy to be known. The ballast cavity volumes which can be filled with water should also be known.

Before stability calculation a preliminary submergence zone can be assessed with geometric calculations.

Frames

There are two frames used in this study. A reference frame R_0 with origin O at mean water level, z axis upward and a local frame R_S attached to the SPAR with origin O_S located 20m below the top of the SPAR along its longitudinal axis.

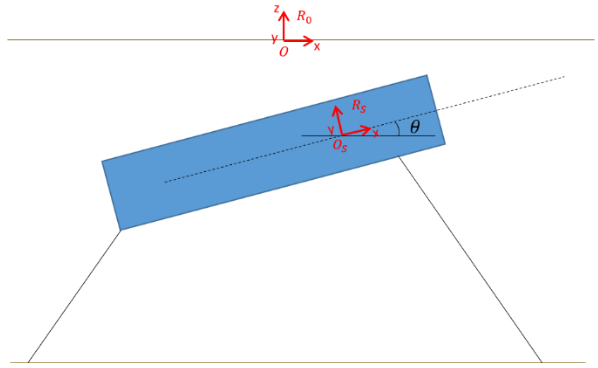


FIGURE 4-4 – FRAME DEFINITION

Ballast cavities volume assessment

The following Figure 4-5 highlights the two ballast cavities available on the SPAR.

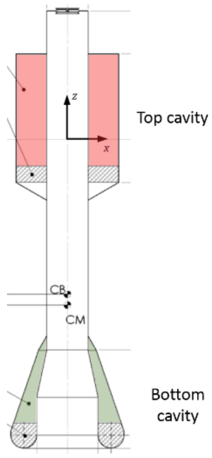


FIGURE 4-5 BALLAST CAVITIES LOCATION

The bottom ballast cavity volume available has been assessed from a CAD software. This volume does not contain the concrete ballast volume. The available bottom cavity volume is 216 m^3.

The top ballast cavity volume available has been assessed with geometric calculations. Indeed, this cavity is a tube (12m external diameter and 4.818 internal diameter) with 408,9. 10^3 kg of concrete (of density 2300 kg/m3) ballast at the bottom. The available top cavity volume is 1460 m^3.

The volume assessment calculation is summarized in the following table.

TABLE 4-8 AVAILABLE BALLAST CAVITIES VOLUME

Bottom cavity available volume (m^3)	Top cavity available volume (m^3)
216	**1460**

Center of buoyancy assessment

The center of buoyancy of the spar has been calculated because it is not the same as the one specified for the spar in operational position as the system is not fully submerged.

The coordinates of the center of buoyancy have been assessed from the CAD of the spar in the CAD software Autodesk Inventor.

TABLE 4-9 CENTER OF BUOYANCY IN SUBMERGED POSITION

CoB of SPAR in R_S (m)
(-7.49, 0, 0)

Center of gravity assessment

The center of gravity of the spar is assessed for each mass of ballast added to the spar. The mass of ballast is distributed in both ballasting cavities in order to set the center of gravity of the spar as close as possible of the center of buoyancy of the spa. This configuration will reduce moment arm effects on the spar improving its stability.

To reach this objective, total mass of ballast is split up in elementary ballast mass and then added in an iterative way at the top or the bottom depending on the location of the center of gravity respectively to the position of the center of buoyancy.

TABLE 4-10 EVOLUTION OF COG WITH BALLAST MASS

Ballast mass (% of maximum ballast mass)	CoG of the SPAR) in R_S (m)
0	-19.29
8	-17.84
15	-16.53
23	-15.33
31	-14.21
38	-13.16
46	-12.16
54	-11.21

Upon 54% of total ballast mass ($8,1.10^5$ kg), the spar sink as there is no more buoyant stock to maintain the spar.

Maximal submergence zone assessment

The spar submerged maximum and minimum pitch angles are respectively 60° and 30°. This defines a minimal submergence zone as the spar should not collide with the seabed (80-meter depth) and should be totally submerged. It should be noted that for the last point, the calculation takes into account the wave trough for the considered extreme sea state (Hs=14.8m). A security margin has been added to the top (5m) and bottom height constraints (2m).

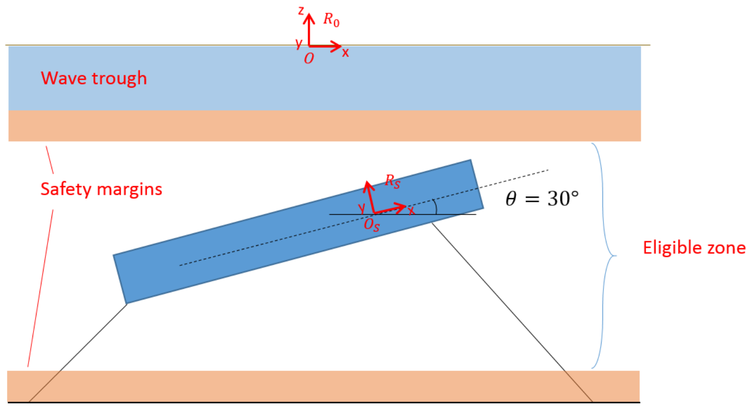


FIGURE 4-6 DEFINITION OF MINIMAL SUBMERGENCE ZONE

The calculation gives that the top of the spar should be located under 19.8m depth and the bottom of the spar should be above the seabed with a security margin of 2m (78 meters).

The calculation shows that the spar (at origin O_s) with the minimal pitch angle of 30°can be submerged between 30 and 60 meters.

Estimation of statistic maximum hydrodynamic force for a horizontally submerged Spar

For the considered sea state defined in 4.2.4.1, the statistics of the hydrodynamic excitation force given in [20] can be derived.

It should be noted that the frequency domain excitation force calculated by WAVEC was calculated for a horizontal Spar. This should be refined in later calculation, as the Spar inclination angle will influence the hydrodynamic loads.

1. A JONSWAP (Joint North Sea Wave Project) spectrum S_{wave} is computed for the considered sea state and combined with the loads RAO given in [20] to obtain a load response spectrum.

$$S_X = \int_0^{\infty} S_{wave} \left|RAO_f\right|^2 d\omega \qquad (4\text{-}1)$$

2. Extreme values are calculated based on the assumption that the response is a narrow-banded Gaussian process, so that peaks are Rayleigh distributed. These formulas are taken from [22]. The maximum hydrodynamic vertical force F_{hydro}^{max} is then taken as the expected maximum value.

   The expected extreme value F_{hydro}^{max} for a sea state of duration T equal to 3 hours is calculated using the standard deviation σ_X of X and is equal to:

$$F_{hydro}^{max} = \sqrt{2}\,\sigma_X \left(\sqrt{log\left(\frac{T}{T_{z,X}}\right)} + \frac{0.2886}{\sqrt{\log\left(\frac{T}{T_{z,X}}\right)}} \right) \qquad (4\text{-}2)$$

Where $T_{z,X}$ is the mean zero-upcrossing period defined as $T_{z,X} = 2\pi\sqrt{\frac{m_{0,X}}{m_{2,X}}}$.

With m_0 and m_2 the 0 order and 2 order moment of the spectrum S_X computed with $m_{n,X} = \int_0^\infty \omega^n \, S_X d\omega$.

The maximum statistic force magnitude has been estimated for the 4 different submergence depths defined in [20]. The results are shown in the following table.

TABLE 4-11 EVOLUTION OF MAXIMUM STATISTIC FORCE WITH DEPTH

H1 (1/3) 26.67m	H2 (1/2) 40.00m	H3 (2/3) 53.33m	H4 (3/4) 60.00m
4.25E+06 N	2.76E+06 N	1.62E+06 N	1.19E+06 N

Finally, the hydrodynamic force has been interpolated between the given minimal and maximal depths producing this plot allowing us to compute the buoyancy for the correct submergence depth range.

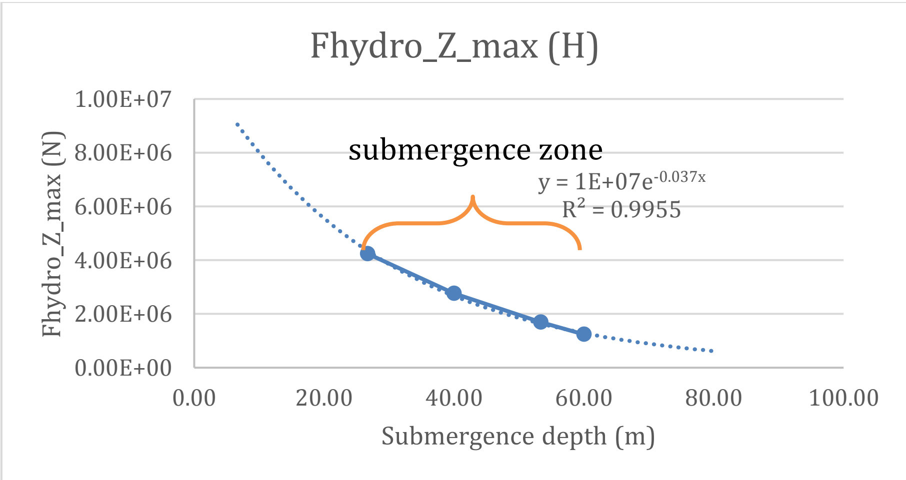


FIGURE 4-7 INTERPOLATION OF MAXIMUM STATISTIC FORCE WITHIN SUBMERGENCE ZONE

4.2.2. Potential impact on hull and potential impact on stability

4.2.2.1. Impact on hull

The integration of a submergence process as a survival strategy for the spar OWC has an impact on the hull through two ways:

- The submergence system necessitates the addition of components on the spar. Some of these components have to be attached to the structure, therefore, local modifications of the hull are needed. They also add some weight to the global structure.
- The strategy to bring the structure deeper under water than it does during production induces an exposure to high hydrostatic loads. And it has been shown in WETFEET WP2 studies (reference [30]) that pressure differential between the inside of air chambers and the outside increases the risk of buckling. Therefore, this strategy may have direct impact on hull design.

These two sources of impact on the hull will be described in following sections.

Impact on the hull related to the addition of components

The main components expected to be added on the spar are the following:

- Winches (either fixed on the spar, or on the seabed) and pulleys if necessary
- Pumps
- Valves and pipework

Here are summarized data of the type winch which would be added:

- Subsea Winch,
- Maximum capacity of 50t,
- Mass of around 3-5 tons,
- Approximative dimensions: 2000x2000x2000 (mm).

If we suppose that 4 mooring lines are used to pull (meaning 4 winches), It would represent a mass increase of around 20t, i.e. around 1-2%.

Regarding the volume needed, Figure 4-8 shows the approximate volume of a winch aside the spar OWC.

FIGURE 4-8: APPROXIMATIVE VOLUME NEEDED FOR ONE WINCH COMPARED TO THE SPAR OWC

Impact on hull relative to PTO protection

Some components, in particular the PTO, may need modifications to allow the submersion. This should be studied further in the project, in particular to determine if the tightness issue should be integrated in PTO design, or if it should be managed by a dedicated component in form of a hermetic caisson.

Impact on the hull related to deeper submersion

Previous study performed in WP2 (reference [30]) has shown that pressure differential induced by hydrostatic pressure and air zones in the spar OWC increase considerably the risk of buckling of the hull. This issue can be managed either by increasing steel plates thicknesses, either by increasing the pressure in the air chambers.

As the submergence implies to bring the spar OWC deeper than it does in operational mode, the question here is to estimate the need of thickness increase to respect strength criteria in this new situation, and estimate the benefits of pressurizing the air chambers.

Preliminary calculations have been performed with the Design 3 (proposed in [30]). Only the impact of the hydrostatic force corresponding to an immersion at 35m depth with a pitch angle of 38° with vertical has been checked. No motions, mooring loads, hydrodynamic loads etc, could be considered, as they were unknown at this stage.

These calculations do not indicate the need of reinforcement. Note that design 3 was designed for extreme load case, and spar OWC induced movements during this previous study already brought the spar underwater.

Taking into account all relevant loads in submerged position would be necessary in later stages, and may results in necessity to reinforce the structure.

Another possible strategy to account for additional hydrostatic pressure would be to pressurize the air chambers.

The benefits of pressurizing the air chambers is to minimize a negative relative pressure on the inside of the shell. Hence, buckling phenomenon are determined by the types of loads acting on the shell: compressional loads and inside relative depression are favorizing buckling. By pressurizing the air zones, the relative pressure on the inside of the shells can be controlled.

To illustrate these phenomenon, here is the way buckling strength is calculated according to DNV-RP-C202 Standard (reference [16]):

The characteristic buckling strength of shells is defined as:

$$f_{ks} = \frac{f_y}{\sqrt{1 + \bar{\lambda}_s^{\,4}}} \qquad (4\text{-}3)$$

Where

$$\bar{\lambda}_s^{\,2} = \frac{f_y}{\sigma_{j,Sd}} \left[\frac{\sigma_{a0,Sd}}{f_{Ea}} + \frac{\sigma_{m0,Sd}}{f_{Em}} + \frac{\sigma_{h0,Sd}}{f_{Eh}} + \frac{\tau_{Sd}}{f_{E\tau}} \right]$$

$$\sigma_{j,Sd} = \sqrt{(\sigma_{a,Sd} + \sigma_{m,Sd})^2 - (\sigma_{a,Sd} + \sigma_{m,Sd})\sigma_{h,Sd} + \sigma_{h,Sd}^2 + 3\tau_{Sd}^{\,2}}$$

$$\sigma_{a0,Sd} = \begin{cases} 0 \; if \; \sigma_{a,Sd} \geq 0 \\ -\sigma_{a,Sd} \; if \; \sigma_{a,Sd} < 0 \end{cases}$$

$$\sigma_{m0,Sd} = \begin{cases} 0 \; if \; \sigma_{m,Sd} \geq 0 \\ -\sigma_{m,Sd} \; if \; \sigma_{m,Sd} < 0 \end{cases}$$

$$\sigma_{h0,Sd} = \begin{cases} 0 \; if \; \sigma_{h,Sd} \geq 0 \; internal \; net \; pressure \\ -\sigma_{h,Sd} \; if \; \sigma_{h,Sd} < 0 \; external \; net \; pressure \end{cases}$$

Stress related to internal pressure in the shell is $\sigma_{h,Sd}$: "design circumferential stress in the shell". As can be seen, a net negative pressure (corresponding to $\sigma_{h,Sd} < 0$) induces an increase of $\bar{\lambda}_S^{\,2}$ which in turn reduces the global buckling strength. In the other side, if $\sigma_{h,Sd}$ is kept

positive by pressurizing the air chambers, $\sigma_{h0,Sd}$ is kept null, and the buckling strength is not downgraded.

4.2.3. Impact on stability

The potential impacts on stability in submerged position are addressed below:

- Stability in yaw and roll has not been studied in this present study.
- Current not modelled here could have an impact on the stability.
- The ballast mass distribution in the cavities assumes that cavities are separated. It should avoid free surface effects. Some instabilities could still arise from this.
- Four lines on six are used in the submergence process. The two lines left have not been taken into account in the present study and could modify the weight of the total system.
- Manufacturing margins have not been taken into account and could modify the volume, weight and positions of center of buoyancy and gravity of the spar, impacting the stability in submerged position.
- The marine growth on the system and mooring lines has not been modelled and could increase the weight of the overall system impacting the stability in submerged position. Here is an assessment of the potential impact of marine growth on structure weight:
  <u>Calculation of additional mass due to marine growth after 2 years:</u>

    The additional mass from marine growth is the mass of marine growth on the spar (computed from a CAD software) with respect to [17] and the mass of marine growth on lines.

    The mass of marine growth on the spar should be about 18% of the total mass of the spar. The mass of marine growth on lines is computed with respect to [13] with the mooring set from [26] (similar to the one from experimental work in section 6) (submerged below 40m) and should be about 2% of the total mass of the spar.

    Therefore, the additional mass (no buoyancy considered) due to marine growth on the spar would be about **20% of the total mass of the spar**. The marine growth can impact the stability.
- The stability in case of an accidental event has not been studied. More information on the risks of the submergence arising from accidental events can be found in section 4.1.5.

4.2.4. Parametric study

The parametric study aims to find a set of stable submerged positions ensuring the criteria listed in section 4.2.1.1, and detailed below.

4.2.4.1. Properties of the configuration studied and criteria values considered

<u>Environmental conditions</u>

The water depth is 80.0 m. The water density is 1025 kg/m^3. The environmental conditions to investigate in this study are survivability conditions (from [20], sea state 4).

TABLE 4-12 EXTREME SEA STATE CONSIDERED FOR THE STUDY

Return period (s)	Hs (m)	Te (s)	Tp (s) based on PM	JONSWAP peak parameter

100	**14.8**	**17.4**	**20.28**	**1**

Spar system

The spar system is considered in 2D plan (xOz). Consequently, the system is connected to two mooring lines only on the same plan (xOz).

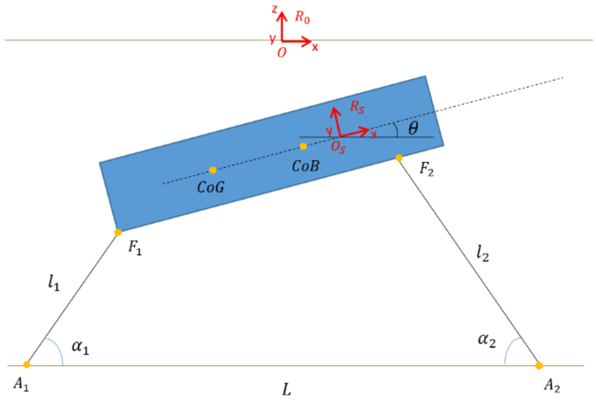


FIGURE 4-9PARAMETRIZATION OF THE SPAR AND ITS MOORING SYSTEM

The inclination angle of the spar with the seabed is defined with θ. The main characteristics of the spar are defined in Table 4-13 below. The CoG with ballast is defined with x_G.

TABLE 4-13 MAIN CHARACTERISTICS OF THE SPAR

CoB (m) x_B	(-7.49,0,0)	Local frame R_S
CoG (m) with no ballast	(-19.29,0,0)	Local frame R_S
Total mass (Tons) with no ballast	1217,4	-
Total volume (m^3)	2134.92	-

Mooring system

The system needs at least two lines to be submerged and tilted. As the study is done in 2D (in plan xOz), the mooring system is made of two mooring lines. The fairlead F_1 is an existing fairlead on the spar's bottom which can be re-used. The second fairlead F_2 has been installed near the top of the spar (this is not an existing fairlead point in the initial design) to be able to tilt the spar submerged position.

The following Table 4-14 details the position of fairleads on the spar.

TABLE 4-14 MAIN CHARACTERISTICS OF THE MOORING SYSTEM

Fairlead F_1 (x_{F_1}, z_{F_1})	(-35,3,0)	Local frame R_S
Fairlead F_2 (x_{F_2}, z_{F_2})	(-4.28,-3,0)	Local frame R_S
Line type	Chain or Wire	-

The mooring line types are chain grade 3 or wire. The mooring system is defined by 5 parameters:

- α_1: the mooring line angle between the seabed and the line 1 (attached to F_1).
- α_2: the mooring line angle between the seabed and the line 2 (attached to F_2).
- l_1: the length of the line 1.
- l_2: the length of the line 2.
- L: the horizontal distance on the seabed between A_1 and A_2.

4.2.4.2. Methodology

<u>Overview</u>

Parametric study of submerged position stability consists in assessing the stability of a set of eligible submerged position defined by the combination of all the following parameters:

- mooring system parametrization,
- submergence depth d,
- mass of ballast m_b.

The objective of the parametric study is to derive a feasibility matrix which shows the feasibility (configuration ensuring the criteria and stable) of each of the eligible configuration.

The parametric study is divided in several steps:

1. Preliminary calculations
   a. Calculations of quantities CoG, CoB, ballast available volumes
   b. Definition of criteria
   c. Computation of maximal hydrodynamic force
2. Loop on different parameters
   a. Stability assessment
   b. Derivation of tensions in lines, top/bottom spar positions, mooring system.
   c. Checking of criteria
   d. Saving/Discarding the configuration
3. Results concatenation

The methodology of the study is summarized in Figure 4-10, and is detailed in the following sections.

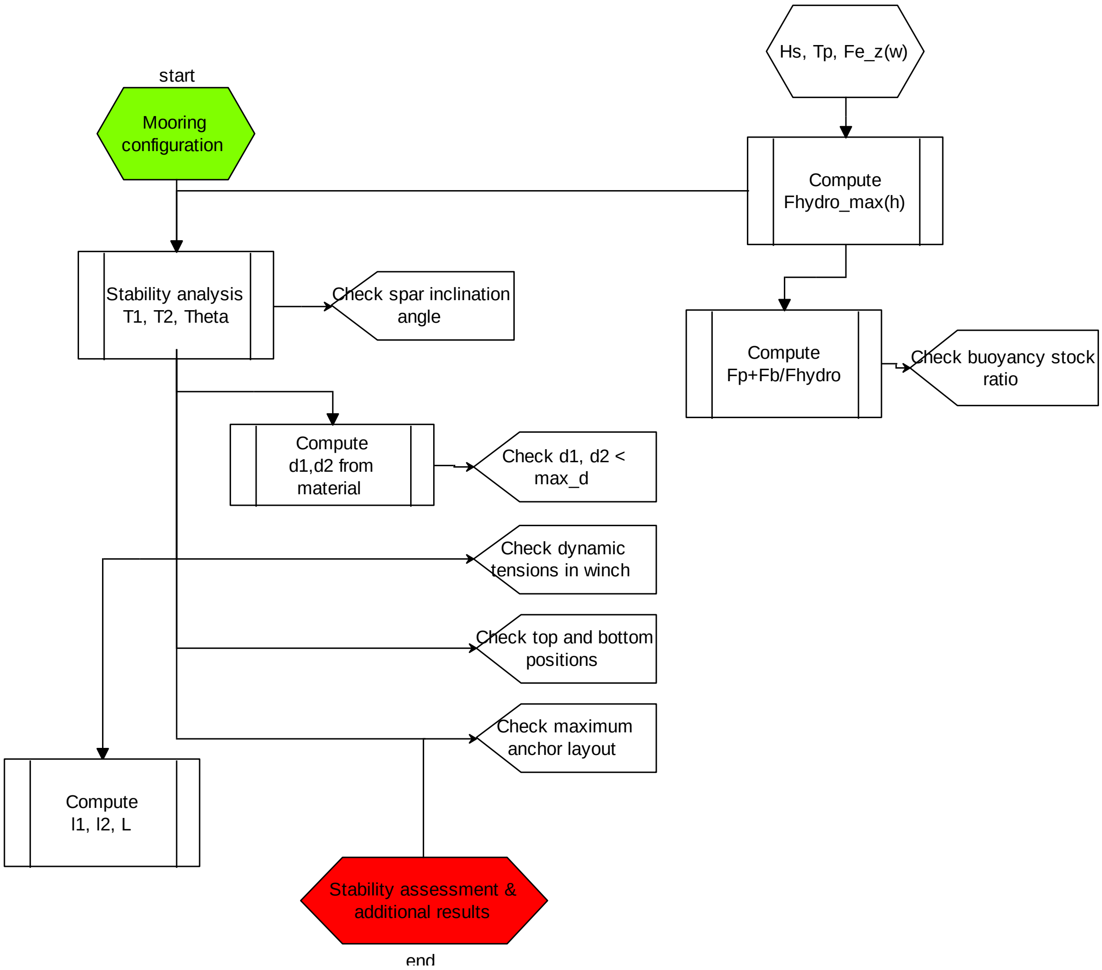


FIGURE 4-10 METHODOLOGY WORKFLOW

Hypothesis

The main hypotheses of the study are:

- System has been simplified as thicknesses of the structural elements have not been taken into account in the stability study for geometric calculations. Still the correct total mass of the structure has been used.
- Stability study is achieved in two dimensions in xOz plan. Only the tilt angle, vertical and horizontal translations will be assessed. This hypothesis has the following consequences:
    - roll, yaw angles and transverse motions are not studied here.
    - mooring system is made of two lines.
    - fairleads are then located along the main axis of the spar. The y coordinate in frame R_0.is null.
- Weight of mooring lines is not taken into account.
- There is no drag on the spar or the lines.
- Lines are considered taut and with an infinite stiffness.
- No current is added in the study.
- The hydrodynamic force is not taken into account in the stability assessment. This force is used only for the calculation of the buoyancy / wave loads ratio. Only the vertical

component is used, no moment arms are taken into account and the force is applied on one application point.
- Dynamic effects are neglected. This is considered sufficient for this preliminary stage, but should be considered in further developments.

Stability assessment in equilibrium position

The stability assessment in equilibrium position without external loads is performed for each configuration and is described in this section.

The set of configurations studied here is defined with:

- α_1 and α_2 in [0, 90] degrees,
- submergence depth d in [0, 80] meters,
- mass of ballast m_b in [0, 1.5E6 kg = 100% of maximum ballast mass which can fit in cavities].

with α_1, α_2, defined in Figure 4-11.

The following loads are acting on the spar:

- The weight $\overrightarrow{F_P} = -(m + m_B)g\vec{z}$,
- The buoyant force $\overrightarrow{F_B} = \rho g V_0 \vec{z}$,
- The mooring force in line 1 $\overrightarrow{T_1}$,
- The mooring force in line 2 $\overrightarrow{T_2}$

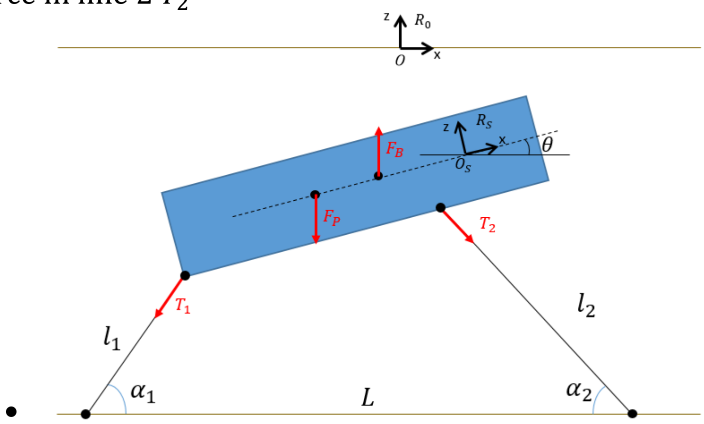


FIGURE 4-11 LOADS ASSESSMENT ON THE SPAR

The stability assessment resolves the equilibrium of the spar which can be written in the three following equilibriums.

The equilibrium of forces on x axis $\sum F_x = 0$ which can be developed as:

$$T_1^x + T_2^x = 0 \quad (4\text{-}4)$$

The equilibrium of forces on z axis $\sum F_z = 0$ which can be developed as:

$$\overrightarrow{F_P} \cdot \vec{z} + \overrightarrow{F_B} \cdot \vec{z} + T_1^z + T_2^z = 0 \quad (4\text{-}5)$$

The equilibrium of moments around y axis $\sum M_y = 0$ which can be developed as:

$$M_P(O_S) + M_B(O_S) + M_{T_1}(O_S) + M_{T_2}(O_S) = 0 \tag{4-6}$$

Where:

- $T_1^x = -T_1 \cos(\alpha_1)$
- $T_1^z = -T_1 \sin(\alpha_1)$
- $T_2^x = T_2 \cos(\alpha_2)$
- $T_2^z = -T_2 \sin(\alpha_2)$

Solving this system of equations for a given configuration $(d, m_b, \alpha_1, \alpha_2)$ will give the tilt angle θ of the spar and the tensions in both lines. If there are solutions to this system it is considered as stable.

Detailed system of equations:

$$T_2 = \frac{\rho g V_0 - (m + m_B)g}{(\sin(\alpha_2) + \cos(\alpha_2) \times \tan(\alpha_1))} \tag{4-7}$$

Note: a ½ factor is added in the equations to take into account that the mooring system studied is fictive. The system is normally constituted with four lines, so T_1 and T_2 are then distributed into each line.

$$T_1 = T_2 \times \frac{\cos(\alpha_2)}{\cos(\alpha_1)} \tag{4-8}$$

$$\theta = arctan(-\frac{a}{b}) \tag{4-9}$$

With:

$$\underbrace{[-\rho g \mathrm{V}_0 x_B + (m + m_B) g x_G + T_1(x_{F_1} \sin(\alpha_1) - z_{F_1} \cos(\alpha_1)) + T_2(x_{F_2} \sin(\alpha_2) + z_{F_2} \cos(\alpha_2))]}_{a} \cos(\theta)$$
$$+ \underbrace{[T_2(z_{F_2} \sin(\alpha_2) + x_{F_2} \cos(\alpha_2)) + T_1(z_{F_1} \sin(\alpha_1) - x_{F_1} \cos(\alpha_1))]}_{b} \sin(\theta) = 0$$

Now that θ, T_1 and T_2 are computed the checks can be performed.

<u>Checking of spar inclination angle</u>

The tilt angle coming from the stability assessment is checked following this equation

$$30° < \theta < 60° \tag{4-10}$$

Those extremum values are arising from the limits of the bend restrictor of the umbilical. More information can be found in section 4.3.4.

Checking the buoyancy / wave loads ratio

The maximum expected hydrodynamic force, weight and buoyant force are known, therefore this criterion is checked following this equation

$$\frac{F_P + F_B}{F_{hydro}^{max}} > 1 \times \gamma_b \tag{4-11}$$

γ_b is arbitrary chosen equal to 1, this should be refined at later stage.

Checking the MBL and diameter of the mooring lines

This check consists in finding a minimal bar diameter of each line ensuring that the tension in each line is below the MBL with respect to a mooring line factor

$$T_1, T_2 \times \gamma_m < MBL(d) \tag{4-12}$$

For a chain Grade 3 the following relation between the MBL (in kN) and bar diameter of the chain (in m) can be applied (taken from [24])

$$MBL = 1.37E4\ d^2(44 - 80d) \tag{4-13}$$

For a wire the following relation between the MBL (in kN) and bar diameter of the chain (in mm) can be applied (taken from [24])

$$MBL = 900\ d^2 \tag{4-14}$$

Solving the previous equations when knowing tensions in lines gives the minimal bar diameter ensuring that line does not break.

Then this diameter is checked to ensure that it can be manufactured. The maximal value is given in [15].

$$d < d_{max} \tag{4-15}$$

Checking the tension in winch

The tensions T_1 and T_2 in lines are also the tensions in the respective winches linked to those two lines. A winch is defined with a maximum allowable traction capacity T_{winch}^{max}. The check follows this equation

$$T_1, T_2 \times \gamma_{winch} < T_{winch}^{max} \tag{4-16}$$

γ_{winch} is the winch factor for allowed tension.

Checking the top and bottom spar position

When the tilt angle θ is known, the upper point and lower point of the spar are assessed.

The upper point must be below the mean water level and more precisely below the wave trough for the sea state considered with respect to a height coefficient. The coordinate u_z of the upper point U of the spar should ensure the following equation

$$u_z < H_s + \gamma_{height} \quad (4\text{-}17)$$

The lower point must be above the seabed (located at -80m) with respect to a height coefficient. The coordinate b_z of the lower point B of the spar should ensure the following equation

$$b_z > -80 + \gamma_{height} \quad (4\text{-}18)$$

Checking the mooring system footprint

The mooring system footprint is the horizontal distance between the two anchors A_1 and A_2 with respective x coordinate in R_0, a_x^1 and a_x^2.

The parametrization of the mooring configuration generation creates configurations where α_1 and α_2 are very small. The consequence of that layout is that anchors must be very far from each other to satisfy the low line angles, increasing in the same time the footprint. However, this parameter should not be too long compared to the size of the spar. That is why a constraint has been set.

This footprint is limited to a maximum length to be close to the configuration defined in [26] (similar to the one from experimental work in section 6).

$$|a_x^2 - a_x^1| < L_{max} \quad (4\text{-}19)$$

4.2.4.3. Criteria values considered for the study

The following table summarizes the different values for the criteria defined in section 4.2.1.1

Please note that the factors for winch, footprint, height, have been chosen arbitrary and should be refined at later stage. The factor for mooring line is based on [13] and has been changed to 4 to consider that no excitation loads or motions were considered.

TABLE 4-15 CRITERIA VALUES CONSIDERED FOR STUDY

Criterion	Criterion value
Spar inclination angle (°)	30° < θ < 60°
Min buoyancy / wave loads ratio γ_b	1.0
Mooring line safety factor γ_m	4.0
Admissible diameter d_{max} (m) for chain	0.185
Admissible diameter d_{max} (m) for wire[2]	0.165
Allowed dynamic tension in winch T_{winch}^{max} (T)	50.0
Safety factor on winch tension γ_{winch}	2.0
Maximum mooring system footprint L_{max} (m)	170
Safety margin γ_{height} used to check spar top and bottom position (m)	2.0

[2] This maximum diameter is an estimation of maximum existing diameter, no constraints on winch are considered (constraints on winches are to be considered at later stage).

4.2.4.4. *Sensitivity of the constraints criteria*

The **buoyancy / wave loads ratio** is a major constraint to the study as shown in the following figure

submergence depth / ballast mass	5	10	15	20	25	30	35	40	45	50	55	60	65	70
0.0E+00	1.15	1.38	1.66	2.00	2.41	2.89	3.48	4.19	5.04	6.07	7.30	8.78	10.57	12.71
1.2E+05	1.01	1.22	1.46	1.76	2.12	2.55	3.07	3.69	4.45	5.35	6.44	7.74	9.32	11.21
2.3E+05	0.88	1.05	1.27	1.53	1.84	2.21	2.66	3.20	3.85	4.63	5.57	6.70	8.07	9.71
3.5E+05	0.74	0.89	1.07	1.29	1.55	1.87	2.25	2.70	3.25	3.91	4.71	5.67	6.82	8.20
4.6E+05	0.60	0.73	0.88	1.05	1.27	1.53	1.84	2.21	2.66	3.20	3.85	4.63	5.57	6.70
5.8E+05	0.47	0.56	0.68	0.82	0.98	1.18	1.42	1.71	2.06	2.48	2.98	3.59	4.32	5.20
6.9E+05	0.33	0.40	0.48	0.58	0.70	0.84	1.01	1.22	1.46	1.76	2.12	2.55	3.07	3.69
8.1E+05	0.20	0.24	0.29	0.34	0.41	0.50	0.60	0.72	0.87	1.05	1.26	1.51	1.82	2.19
9.2E+05	0.06	0.07	0.09	0.11	0.13	0.16	0.19	0.23	0.27	0.33	0.39	0.47	0.57	0.69
1.0E+06	-0.07	-0.09	-0.11	-0.13	-0.15	-0.19	-0.22	-0.27	-0.32	-0.39	-0.47	-0.56	-0.68	-0.82
1.2E+06	-0.21	-0.25	-0.30	-0.36	-0.44	-0.53	-0.64	-0.76	-0.92	-1.11	-1.33	-1.60	-1.93	-2.32
1.3E+06	-0.35	-0.42	-0.50	-0.60	-0.72	-0.87	-1.05	-1.26	-1.52	-1.82	-2.19	-2.64	-3.18	-3.82
1.4E+06	-0.48	-0.58	-0.70	-0.84	-1.01	-1.21	-1.46	-1.76	-2.11	-2.54	-3.06	-3.68	-4.43	-5.33
1.5E+06	-0.62	-0.74	-0.89	-1.07	-1.29	-1.55	-1.87	-2.25	-2.71	-3.26	-3.92	-4.72	-5.68	-6.83

FIGURE 4-12 BUOYANCY / WAVE LOADS RATIO VARIATION WITH DEPTH AND BALLAST

The couple (ballast mass, submergence depth) is valid when the criteria from equation (4-11) is verified. Upon 50% of total ballast mass (8.1E5 kg), the spar sinks as there is no more buoyant stock to maintain the spar. The spar must not be ballasted upon 50% of the maximum mass of ballast.

The **allowed dynamic tension in winch** is the most important constraint of the study. There are no eligible configurations which ensure this constraint. It has to be noted that the maximum allowed dynamic tension in winch has been set to 4.9E5 N (50 tons) (refer to 4.3.1). The minimal tension in all the configurations is around 102 tons. This analysis shows that one winch is not enough to hold the tension of the line.

It has to be noted that this criterion has been disabled to continue the study but it has been outlined that some technical solutions may exist to remove this constraint (refer to section 4.3.1).

The tensions in lines are not a constraint for the line material. The **minimal mooring diameter** assessed from equation (4-13) is always below the maximal diameter whenever the line material is chain or wire. This constraint has no impact on this study.

The constraint on **top and bottom spar not colliding the seabed** is a major constraint in 80-meter water depth. As outlined in the following figure it has a lot of impact when the spar is the most vertical (more than 50% of the zone is discarded).

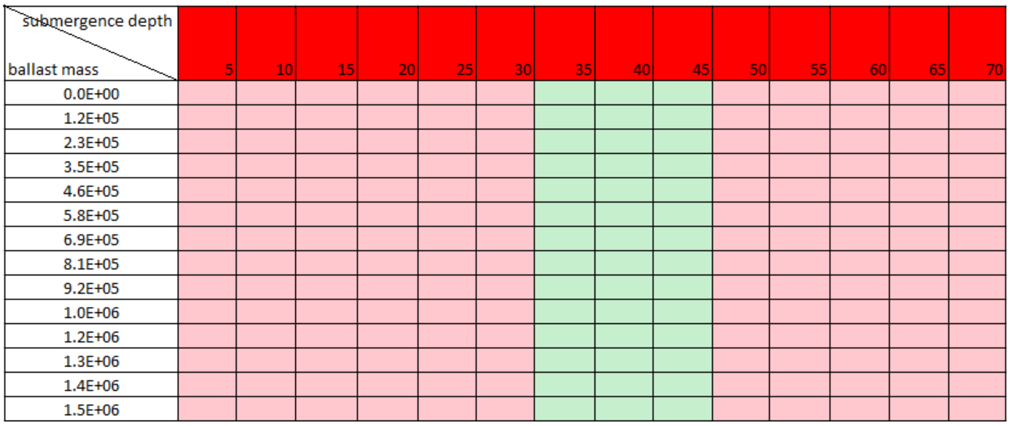


FIGURE 4-13 MINIMAL SUBMERGENCE ZONE

When the spar is more horizontal the acceptable zone is wider and located between 30 and 60 degrees as outlined in the following figure.

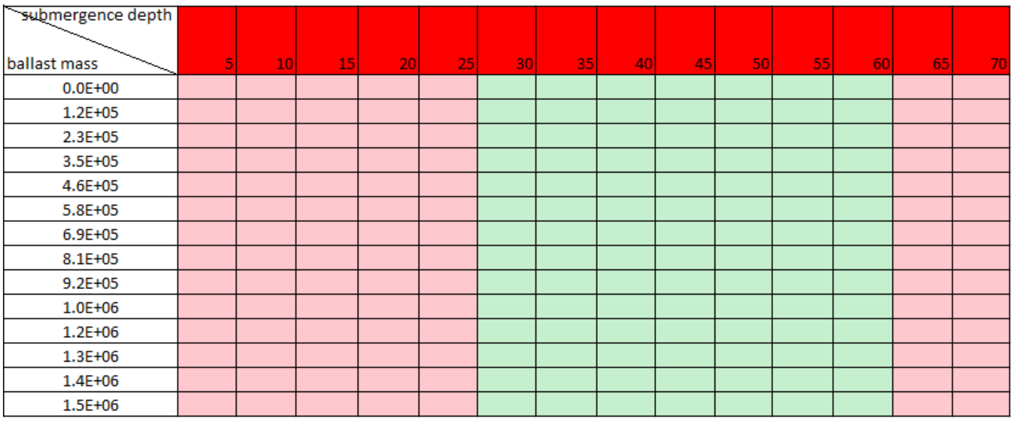


FIGURE 4-14 MAXIMAL SUBMERGENCE ZONE

The **tilt constraint arising from the bend restrictor** umbilical removes the submerged positions where the spar is nearly horizontal. This constraint reduces the number of eligible configurations because when the spar is nearly horizontal the submergence zone is wider.

The **anchor layout constraint** discard all configurations where anchors are too far from each other.

Finally, the constraints which impact the study are the allowed tension in winch, the inclination angle of the spar and the geometric layout. Care has to be taken on the choice of winches and umbilical's bend stiffener. It is also important to outline that the length of the spar is large compared to the shallow water depth. This justify why this criterion is one of the major constraints.

4.2.4.5. Results of the parametric study

As outlined in the previous section, the constraints on the winches have been disabled for the results shown in this report.

The results of the parametric study are summarized in the following feasibility matrix. Each cell of the matrix corresponds to several mooring systems but with the same ballast mass and submergence depth. If the cell is valid (at least one of the configuration is stable and ensure the criteria defined) otherwise no configurations is acceptable for the given ballast mass and submergence depth.

submergence depth(m) / ballast mass (tons)	5	10	15	20	25	30	35	40	45	50	55	60	65	70
0	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
115	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
230	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
345	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
460	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
575	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE
690	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE
805	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE
920	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1035	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1150	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1265	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1380	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1495	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

FIGURE 4-15 FINAL FEASIBILITY MATRIX OF THE SUBMERGENCE (WITH WIRE)

It has to be noted first that each cell contains a lot of configurations (defined with α_1, α_2). The number of eligible configurations inside the valid (green) zone of the matrix above is around 1000. It is then difficult to select some configurations to continue the study with motion analysis of submerged configuration. The choice of configurations is explained in section 4.2.4.6.

The acceptable configurations are located between 30 and 60 meters depth because the inclination of the spar discards shallow and deep submergence and are ballasted up to 54% of the available total ballast mass.

Upon 50% of ballast mass (8.1E5 kg), the spar sinks as there is no more buoyant stock to maintain the spar so no configurations are eligible in the second half of the feasibility matrix.

Figure 4-16, Figure 4-17, and Figure 4-18 show some example configurations. It has to be noted that the lines here are fictive. That is why the fairleads and anchors are centered along the main axis of the spar.

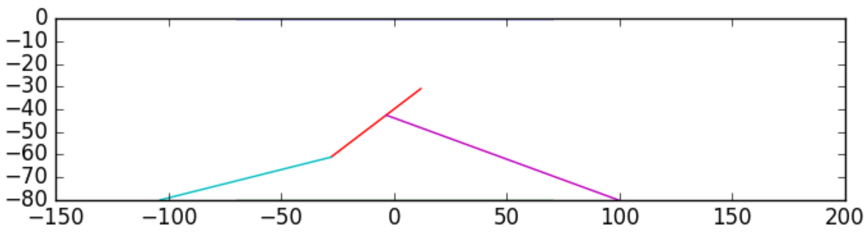


FIGURE 4-16 ONE EXAMPLE ELIGIBLE MOORING SYSTEM IN THE CELL (3.45E+05 KG, 30.0M)

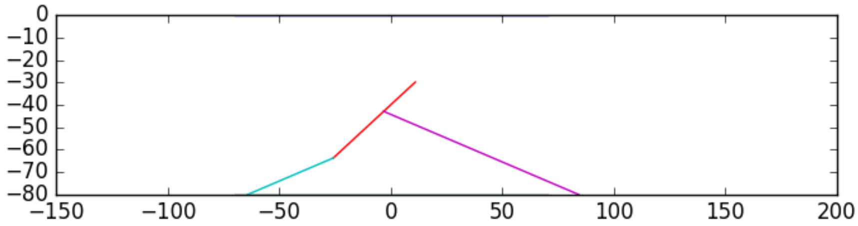


FIGURE 4-17 ONE EXAMPLE ELIGIBLE MOORING SYSTEM IN THE CELL (0.0 KG, 35.0M))

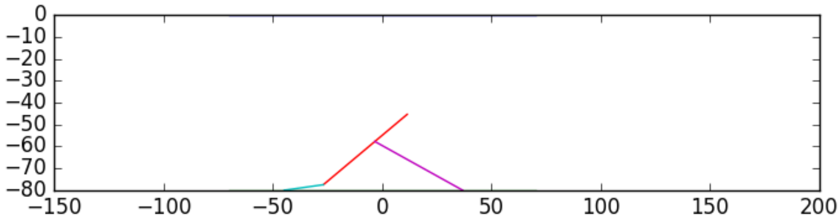


FIGURE 4-18 ONE EXAMPLE ELIGIBLE MOORING SYSTEM IN THE CELL (5.75E+05 KG, 45.0M)

4.2.4.6. Limitations of this parametric study

The stability assessment is achieved in 2D. Therefore, the first limitation arising is that 3D effects are not considered. It means that roll or yaw instabilities could appear.

Then the weight and volume and the spar could differ from the reality for several reasons:

- Manufacturing tolerances,
- Simplification of design (thicknesses and stiffeners),
- Weight of lines not modelled in the study,
- Marine growth not modelled in the study.

Those differences change the weight assessment of the spar and could introduce instabilities and change in the targeted submerged position.

No dynamic effects are taken into account in a stability study.

- It should be noted that motion could arise when wave is above the spar.
- Snap loads in lines could also be an issue even if a mooring factor has been used.

The hydrodynamic force is normally distributed on the spar surface. In the study this force is concentrated on one application point. This could modify the equilibrium and thus the stability of the spar.

Finally, some loads are not modelled in the study such as current load and mooring line stiffness load along the line.

These limitations may change the results of the present study and should be investigated later.

The aim of this parametric study is not to design configurations, but to get some insight on the significant parameters, and to have preliminary values were to search submerged configurations.

4.2.5. Conclusion

Conclusion of the parametric study

Submergence of spar in case of extreme event is challenging to model because different elements will contribute to the motion of the spar. Several hypotheses have been defined to allow us to have a preliminary estimation of its stability in submerged position and the impact of this submergence on the hull and on the stability of the spar.

In order to understand the role of the different parameters (e. g. mooring system, ballast, submergence depth) a parametric study has been carried out to obtain all stable submerged position of the spar. Some constraints have been defined to select a set of stable submerged positions. The aim of this parametric study is not to design configurations, but to get some insight on the significant parameters, and to have preliminary values were to search submerged configurations.

It has been chosen that the spar tilt angle is between 30 and 60 degrees (due to constraint driven by umbilical minimum bending radius limit and feasible bend stiffener maximum manufacturable length), it implies a submerged depth between 30 and 60 meters. The other important conclusion of this study is that the choice of winch is important. The biggest winch found in section 4.3.1 is not enough to stand the tensions of the submerged spar. Another solution should be investigated (see section 4.3.1).

Finally, the main limitations of this study and their impact on the submergence highlight that

- Roll and yaw stability should be investigated.
- The global weight assessment sensitivity to spar stability should be studied as several factors could modify the volume, the mass and the positions of CoG and CoB of the spar. In addition, the equipment required for submergence have also an impact on the total weight assessment of the system.
- A high capacity subsea system should be found to pull and keep the spar submerged.
- Motion and mooring loads under system motions have to be studied.

Regarding the impact of submergence on the hull, preliminary calculations indicate that design 3 proposed previously in [30] (design including stiffeners) is likely to afford the hydrostatics loads related to submergence, further analysis should be performed considering relevant environmental loads and motions.

Choice of submerged configurations considered for further motion analysis

Two submerged positions considered for motion analysis has been chosen from the matrix of results following different rules:

- Ballast mass is maximized to decrease tension in mooring lines as it is an issue for the existing industrial winches.
- Mooring system footprint should be close to the configuration defined in [26] (similar to the one from experimental work in section 6) as this mooring system has already been designed and used in other studies of the project.

The location of the configurations chosen are shown in the following Figure 4-19.

submergence depth(m) / ballast mass (tons)	5	10	15	20	25	30	35	40	45	50	55	60	65	70
0	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
115	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
230	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
345	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
460	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE
575	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE
690	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE	FALSE	FALSE
805	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE
920	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1035	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1150	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1265	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1380	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
1495	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE

FIGURE 4-19 LOCATION OF CONSIDERED SUBMERGED POSITIONS IN FEASIBILITY MATRIX

The shallowest submerged position characteristics are detailed in the following Table 4-16. In this shallow configuration, the hydrodynamics loads are expected to be higher, impacting spar dynamic behavior and lines loadings and risk of spar rising out of water.

TABLE 4-16 SHALLOWEST SUBMERGED POSITION

Position in Z of point O (m) in R_0	-35	
Spar inclination (deg) in R_0	41.94	
Water ballast mass (kg)	6.90E5	All the ballast is added in the top cavity of the spar.
Z coordinate of CoG of ballasted spar in R_S (m)	-12.16	
Anchor 1 in R_0	(-108.62, 0, -80)	No y coordinate as the mooring line is fictive and on xOz plan
Anchor 2 in R_0	(62.71, 0, -80)	No y coordinate as the mooring line is fictive and on xOz plan
Line 1 tension (N)	2.23E6	
Line 2 tension (N)	2.46E6	
α_1 (deg)	8	
α_2 (deg)	26	
Mooring system footprint (m)	171.33	

This configuration is drawn on the following Figure 4-20.

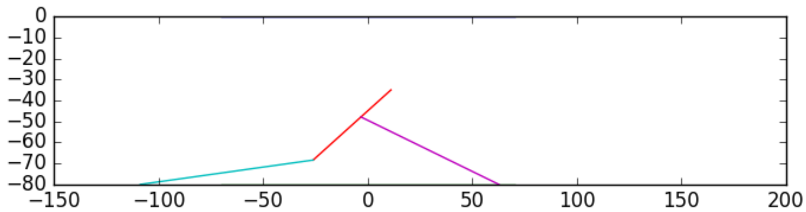


FIGURE 4-20 SHALLOWEST SUBMERGED POSITION DRAWING (CHOSEN FOR MOTION ANALYSIS)

The deepest submerged position characteristics are detailed in the following Table 4-17.

TABLE 4-17 DEEPEST SUBMERGED POSITION

Position in Z of point O (m) in R_0	-45	
Spar inclination θ (deg) in R_0	32.18	
Water ballast mass (kg)	6.90E5	All the ballast is added in the top cavity of the SPAR.
Z coordinate of CoG of ballasted spar in R_S (m)	(-12.16, 0, 0)	
Anchor 1 in R_0	(-102.29, 0, -80)	No y coordinate as the mooring line is fictive and on xOz plan
Anchor 2 in R_0	(70.69, 0, -80)	No y coordinate as the mooring line is fictive and on xOz plan
Line 1 tension (N)	3.85E6	
Line 2 tension (N)	3.69E6	
α_1 (deg)	5	
α_2 (deg)	17	
Mooring system footprint (m)	172.99	

This configuration is drawn on the following Figure 4-21.

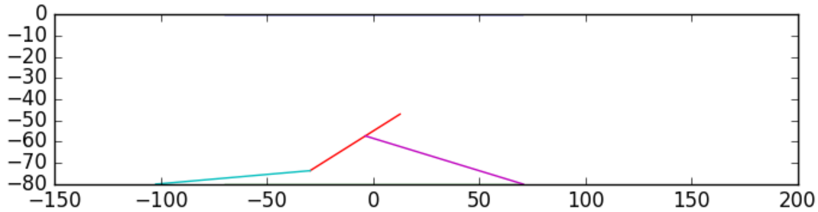


FIGURE 4-21 DEEPEST SUBMERGED POSITION DRAWING

It has to be noted that the lines here are fictive. That is why the fairleads and anchors are centered along the main axis of the spar.

4.3. Components / technologies investigations

4.3.1. Investigation of solutions to submerge and emerge the OWC

The objective of this section is to get an overview of the technical solutions available to perform the submergence of the spar OWC (i.e. bringing the spar OWC from sea surface to the under-water survival position), and their related impacts.

From the FAST diagrams presented in section 4.1.1, the constructive solutions that has been evocated previously in WETFEET project have been identified. An overview of the available equipment on the market regarding these constructive solutions has been performed. Then a sequence for the submergence of the spar OWC has been proposed together with a sequence for the emergence. Impacts related to these components have then been listed, and Main challenges related to these components have been summarized.

4.3.1.1. Constructive solutions anticipated within WETFEET project

As evocated above, a FAST diagram describing possible constructive solutions to answer to the technical function "submerge the spar OWC" has been performed in section 4.1.1. Among the possible constructive solutions presented, two corresponded to concepts evocated in previous exchanges within WETFEET Project. Here are recalled these two constructive solutions:

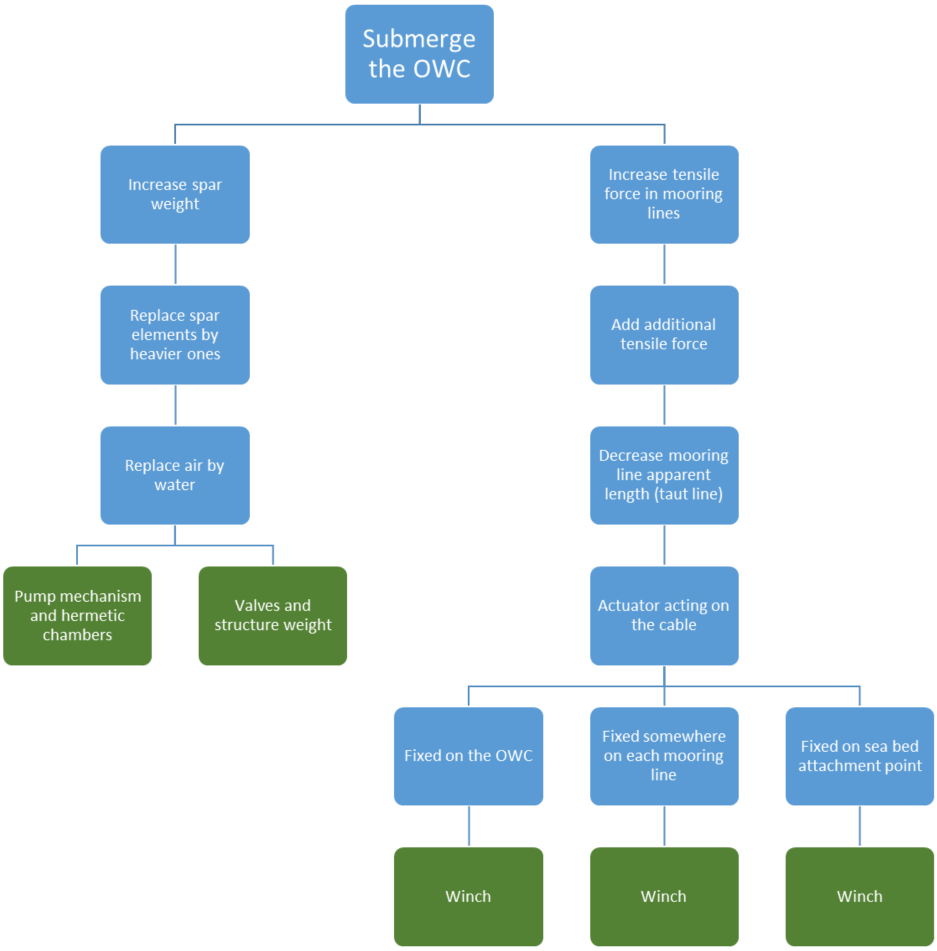


FIGURE 4-22 CONSTRUCTIVE SOLUTIONS

These two solutions can be read as:

1. Submergence of the OWC by increasing tensile force in the mooring lines, through the addition of a tensile force by decreasing mooring line apparent length using actuator acting on the lines as winch.
2. Submergence of the OWC by increasing the spar weight by replacing air by water using pump mechanism and hermetic chambers and/or valves.

Please note that the current selected solution will be a mix of these two options (both ballasting and pulling on the mooring lines are envisaged in the same solution) Combining these two options permit to decrease necessary pulling force.

For this preliminary development phase, we chose to first study the components corresponding to these concepts. These components are:

- Winches
- Pumps

- Valves

For each one of these components, a table have been created, resuming potential providers found on the market, and the corresponding component main characteristics.

Please note that despite winch have been highlighted as a constructive solution to fit with the technical function "pulling with the mooring lines", other components may fit, for example chain jacks, but are not studied here.

4.3.1.2. Proposed main steps to submerge the spar OWC

Here is proposed a chronology of main steps achieved to submerge the spar OWC:

1. Storm detection
2. Activation of submergence process
3. Flooding of empty compartments operating dedicated valves, or pumping system
4. Pulling by the winches
5. When the desired amount of ballast water has filled ballast zones, closing of the valves
6. Pulling with the winches until desired depth is reached
7. Maintaining the position during storm event

Note that two options are envisaged to flood the system, one where the ballast water is to be added by the mean of pump system, and one with valves (respectively forced flooding or free flooding).

4.3.1.3. Proposed main steps to emerge the spar OWC

Here is proposed a chronology of main steps achieved to emerge the spar OWC:

1. Activation of the emergence process
2. Lose tension in winches until emergence
3. Flushing the ballast water by the mean of pumps
4. Closing valves, and beginning to produce again

Following the information and warnings gathered along the entire engineering study, modifications and refinements of submergence and emergence scenario will be proposed.

4.3.1.4. Identified components' main characteristic

Please note that:

- This list of providers results from a web research. It is not meant to be exhaustive, but aims to give an overview of providers which may fit with the solution needs.
- The technical characteristics showed are those available on providers' websites and technical documents. However, products can also be designed on demand.

- Description column corresponds to a quotation of text issued from the corresponding document, when a description is provided. Otherwise, it corresponds to the main component title.

Winches

Most of the winches available on the market of offshore components are not subsea winches. However, subsea winches do exist, and only one supplier has been identified with limited capacity. Following the contacts and interviews (see section 4.1.3), it appears that non-subsea winches will be unlikely to use because the possibility to keep non-subsea winch in dry chamber seems compromised by the interface between the winch and the cable or chain.

Table 4-18 resumes some potential winch providers and the main characteristics of winches they can provide.

The "Submersible" column has been added to recall that most of the winches found on the market are not submersible. However, some submersible winches exist, as the one of Fischer Offshore Company, but with limited capacity.

Pumps

Table 4-19 resumes some potential pump providers and the main characteristics of pump they can provide.

Valves

Table 4-20 resumes some potential valves providers and the main characteristics of valves they can provide.

TABLE 4-18 POTENTIAL WINCH PROVIDERS AND MAIN CHARACTERISTICS OF WINCHES THEY CAN PROVIDE

Provider	description	submersible [Yes/No]	Traction capacity [Te]	speed [m/min]	energy type	weight [Tons]	cable type	size [mm]	source
TSC Ansell Jones Ltd	"A 120Te hydraulic winch and HPU capable of pretensioning the mooring chains on the turret of an FPSO"	N	120 in installation mode 25 in riser mode	3m/min in installation mode 6 m/min in riser mode	hydraulic	27	114mm chain or 62mm winch wire	no data	http://www.anselljones.com/includes/data/120Te_Case_Study.pdf
Ansell Jones	FPSO Installation / Riser Winch	N	up to 600	no data	no data	no data	no data	no data	http://www.t-s-c.com/upload/file/2015-05/Winches_Mooring_Packages_Brochure_1138KB_.pdf
North sea winches LTD	"Supplied as Single or Double drum with either in-line or waterfall configuration up to 500 tons load, based around a centrally or end mounted gearbox with hardened gears running on spherical bearings with oil bath lubrication."	N	up to 500	no data	no data	no data	no data	no data	http://nswinches.co.uk/images/brochure.pdf
North sea winches LTD	"Decommissioning winches are available up to 200Te line load with Hydraulic or electric drives which can be supplied with Constant Tension or Active Heave Compensation."	N	up to 200	no data	no data	no data	no data	no data	http://nswinches.co.uk/
Ellsenmarine	Technical parameter of offshore mooring winch	N	2 to 50	9 to 12		2.5 to 25	anchor chain/rope of 12mm to 128mm diameter	from 1400x1625x10	http://ellsenmarinewinches.com/offshore-winch/

								50 to 4750x2 800x38 50	
Fisher Offshore	FRN150 Hydraulic Winch	N	150	no data	hydraulic	35 (tare) 73 (gross)	wire rope	5760L x 2500W x 3520H	http://www.fisheroffshore.com/what-we-do/rental-winches/hydraulic-winches/
Fisher Offshore	RMC30 hydraulic winch	Y	Up to 50	no data	hydraulic	3.7 excluding wire rope, 7.2 gross	wire rope	1970L x 1530W x 1950H	http://www.fisheroffshore.com/files/9714/2355/8551/RMC_30_with_graph.pdf
greenmonster offshore	50TE single drum hydraulic winch	N	50	no data	hydraulic	no data	36mm diameter rope : 1348m 44mm diameter rope : 1013m 52mm diameter rope : 658m	no data	http://www.greenmonster.com.au/products/hire-equipment/winches/50te-single-drum-hydraulic-winch.aspx
Hatlapa Marine Equipment	chain pulling winch	N	40 70	100 m/ min 60 m/ min	hydraulic	4.2 without motor 5.4 with motor	70mm or 127mm K3 grade stud link chain	no data	http://www.cargotec.com/en-global/macgregor/products/Deck-machinery/Pages/Chain-pulling-winches.aspx
Hatlapa Marine Equipment	secondary winch	N	up to 130	up to 45m/min	electric	no data	up to 4250m of 83mm rope or 1600m of 203mm rope	no data	http://www.macgregor.com/en-global/macgregor/Pages/default.aspx
Hatlapa Marine Equipment	secondary winch	N	up to 180	up to 87 m/min	hydraulic	no data	up to 5,300 m of 76 mm rope or 1,600 m of 203 mm syn. Rope	no data	http://www.macgregor.com/en-global/macgregor/Pages/default.aspx
Timberland Equipment Limited	Anchor And Mooring Winches For Offshore Vessels	no data	no data	no data	no data	no data	chains, wire rope, synthetic	no data	http://timberlandequipment.com/industries/offshore-oil-gas/anchormooring-winches/

Righini ravenna	Offshore Winches	no data	no data	no data	no data	no data	no data	no data	https://righiniravenna.com/category-project/winches/
NFM Technologies	Offshore Winches	no data	no data	no data	no data	no data	no data	no data	http://fr.nfm-technologies.com/-Petrole-gaz-.html
IMECA	Offshore Winches	no data	no data	no data	no data	no data	no data	no data	http://www.imeca.reel.fr/produits/treuils/
Hatlapa Marine Equipment	secondary winch	N	up to 180	up to 87 m/min	hydraulic	no data	up to 5,300 m of 76 mm rope or 1,600 m of 203 mm syn. Rope	no data	http://www.macgregor.com/en-global/macgregor/Pages/default.aspx

TABLE 4-19 POTENTIAL PUMP PROVIDERS AND MAIN CHARACTERISTICS OF VALVES THEY CAN PROVIDE

Provider	description	submersible [Yes / No]	Dry working [Yes / No]	fluid type	flow [m3/h]	head mlc [m]	differential pressure [bar]	design pressure [bar]	energy type	weight [Tons]	size [mm]	source
EUREKA	EUREKA SURV 68 BALLAST PUMP SYSTEMS	Y	no data	Sea Water	300-3000	no data	2 to 20	40	electric	no data	no data	http://www.eureka.no/pumps/api-610-ballast-pump-arrangement-with-eureka-oh4-and-bb2-pump-configurations/api-610-ballast-pump-weureka-oh4-bb2-pump/
ALE	Submerged ballast pumps	Y	no data	Sea Water	1000-2400	no data	no data	no data	hydraulic	2400 and 4800	410 dia x 1378 and 600 dia x 1511	http://www.ale-heavylift.com/wp-content/uploads/2014/01/EQUIPMENT-DATA-SHEET-Submerged-Ballast-Pumps.pdf
EUREKA	Ballast pump with submerged electric motor	Y	no data	Sea Water	no data	no data	no data	no data	no data	no data	no data	http://www.eureka.no/pumps/ballast-pump-with-submerged-electric-motor/ballast-pump-with-submerged-electric-motor-component-descriptions/
FRAMO	Ballast submerged pump	Y	no data	Sea Water	no data	no data	no data	no data	no data	no data	no data	http://www.framo.com/default.aspx?pageId=28

WARTSILA	Deepwell ballast pump	Y	Y	Sea Water	60-2500	25-60	no data	no data	electric	500-1800	see detailed dimensions on the technical document	http://cdn.wartsila.com/docs/default-source/product-files/pv/pumps/svanehoj-type-c2g-sub.pdf?sfvrsn=4
SULZER	Multiphase Pumps	Y	Y	Oil, gaz, water	Up to 4500	Up to 180	Up to 1100	No data	Electric	No data	No data	http://www.sulzer.com/en/Products-and-Services/Pumps-and-Systems/Multiphase-Pumps

TABLE 4-20 POTENTIAL VALVES PROVIDERS AND MAIN CHARACTERISTICS OF VALVES THEY CAN PROVIDE

Provider	description	submersible [Yes / No]	nominal diameter [mm]	size [mm]	nominal pressure [bar]	Kv	Flow [m3/h]	weight [kg]	source
Sectoriel	Electrovannes inox	N	13-150	66-310	7 to 16	3-315	9 to 950 at 10 bar	max 50 kg	http://www.sectoriel.fr/vdoc/easysite/sectoriel/fr/informations-generales/Electrovannes
VALNOR Stavanger	DBB Valves, Subsea Valves, Control Valves, Solenoid Valves	Y & N	no data	no data	no data	no data	no data	no data	http://www.valnor.no/media/55c1c1ce98922.pdf
DGI	butterfly valves including hydraulic actuator for ballast system of a concrete pontoon	Y	no data	no data	no data	no data	no data	no data	http://www.dgi-solutions.com/solutions/ballast-control-systems/ballast-system-izmit-bay/
CLA-VAL	Shipboard Piping Systems Solutions	Y & N	no data	no data	no data	no data	no data	no data	http://www.cla-val.com/documents/pdf/MarineBrochure.pdf
hydracon	hydracon subsea solenoid valves : "FEATURE : •SEAWATER SUBMERSIBLE TO 10,000 FEET • BUBBLE-TIGHT CLOSURE • SMALL & LIGHTWEIGHT	Y	3	50.8 x 142.24 x 99.06	207	0.2422	0.72 at 10 bar	1.63	http://www.hydracon.com/subsea-valves/subsea-solenoid-valves/

	• LOW POWER CONSUMPTION • NO ADJUSTMENTS = LOW MAINTENANCE • SHOCK RESISTANT • LONG LIFE & HIGH RELIABILITY"								
Rexroth Bosch Group	Seawater resistant marine valves	no data	no data	no data	no data	no data	no data	no data	https://www.boschrexroth.com/en/xc/industries/machinery-applications-and-engineering/marine/products-and-solutions/industrial-hydraulics/valves/valves
Bifold FluidPower Limited	subsea Valve Range	Y	no data	no data	up to 760	0.00865 to 0.2076	0.026 to 0,625 at 10 bar	no data	http://www.bifold.co.uk/ranges/subsea.html
Lisk	Subsea solenoid valve	Y	no data	71.1 x 35 x 35	380	no data	59 at 138 bar	no data	http://www.gwlisk.com/wp-content/uploads/2016/06/Subsea-Solenoid-Valve-Detail-Sheet.pdf
Cameron	Valve Solutions for Offshore Production	no data	no data	no data	no data	no data	no data	no data	https://cameron.slb.com/-/media/cam/resources/2015/10/13/19/55/valve-solutions-for-offshore-production.ashx

4.3.1.5. List of impacts

Here are summarized the main impacts of the integration of these potential components on the spar OWC design.

General impacts

- For these devices if automatic submergence is desired, they will all need to be powered, instrumented and controlled from remote location. This will add complexity on every component.

Impacts related to winches

- A winch fixed on the spar has an impact on the system weight.
- A winch fixed on the seabed necessitates a fixed anchorage (pile, suction pile, gravity base) whose holding capacity corresponds to the capacity of the winch, and designed to account for maximum operational and accidental capacities.
- Winch necessitates energy intake. A winch placed on the seabed necessitates a dedicated power cable.
- Winch let in hold position when targeted tension level is reached. Higher tensions could possibly be accepted in this configuration.
- The order of magnitude of available subsea winches max capacity is around 50 tons. Therefore, the use of winches to perform submergence may need multiple traction lines.
- Winches may constrain the type of mooring line (chains, wire, rope, etc.) used on mooring lines extremities.
- Usual offshore winches seem inappropriate to submergence. The use of subsea winches seems more appropriate. The use of such unusual device will have an impact on global system cost.
- The addition of winches on the system will have an impact on installation complexity, and therefore in installation cost.

Impacts related to pumps

- The addition of pumps in the system induces an impact on global system cost.
- The addition of pumps in the system may require a maintenance. This may increase global system cost.
- The use of pump to submerge the spar OWC necessitates the addition of pipework.
- Pumps necessitate energy intake.

Impacts related to valves

- The addition of valves in the system induces an impact on global system cost.
- The addition of valves in the system may require a maintenance. This may increase global system cost.
- The use of valves to submerge the spar OWC necessitates the addition of pipework.

- Solenoid valves necessitate energy intake., control system and extra wiring from the control system to the valve.

4.3.1.6. Conclusion and Technical challenges

Among the various existing solutions to perform submergence of the spar OWC, the selected solution consists in ballasting the spar to reduce its floatability, and pulling with winches acting on mooring lines to bring the spar OWC to its submerged position.

The impacts of this conceptual solution on the original spar OWC are the integration of components as:

- Winches
- Valves
- Pumps
- SCADA system
- Energy supply

Following the interviews of experts and providers, a list of warnings and considerations have been drawn. This is fully detailed in section 4.1.5. Hereafter the main challenges for these components are summarized.

Regarding the winches, as mentioned above, it appears that non-subsea winches will be unlikely to use because the possibility to keep non-subsea winch in dry chamber seems compromised by the interface between the winch and the cable or chain. Therefore, two possibilities exist:

- Design a special dry chamber allowing the use of conventional offshore winches underwater, and solving the interface issue identified above,
- Use Subsea winches

Regarding subsea winches, it appeared, following the study of main providers' products, that existing subsea winches have limited capacity, of around 50T. But it appeared, following the study performed in section 4.2, that submergence process will necessitate a traction capacity greater than 50T per traction line. If the choice is made to use subsea winches, a choice will have to be made between:

- Use specially designed (non-existent for now) subsea winches, with greater capacity than 50T. Discussion with providers will be necessary to identify the construction limits and the capacity needed,
- Use more lines to pull the spar OWC in submerged position, which would allow to use more than 4 subsea winches,
- Add a step in the sequence of submergence:
    - First, increase the ballast water (compared to the amount identified in 4.2) to reduce necessary pulling force under 50T per traction line,
    - and once submergence position is achieved, lock the lines,
    - then increase system floatability by releasing compressed air (to flush out water from ballast tank) to obtain the desired floatability,
- Other solutions.

Besides, a choice will have to be made regarding the location of the winches: either fixed on the spar OWC structure, either fixed on the sea bed. Table 4-21 presents some advantages and disadvantages of the two choices.

TABLE 4-21 PROS AND CONS OF WINCHES FIXED ON THE SPAR VERSUS FIXED ON THE SEABED

Location of the winches	Advantages	Disadvantages
On the spar OWC structure	+ Accessibility for maintenance	- Impact on spar OWC weight (but limited, as explained in 4.2.2.1) and hydrodynamic behavior - Need for structure modifications (seafastenings)
On the seabed	+ No impact on the spar OWC weight neither on its hydrodynamic behavior	- Difficult access for maintenance

No matter the location choice, the mooring lines used to pull will need to be exempt of any device as buoys or clump weights for all the length supposed to be winded.

The use of pumps in offshore applications is common, however the pumping system (pumps and associated pipework) needed for the submergence of the spar OWC gathers various challenging specifications as:

- Changing environment (alternatively emerged and submerged)
- Varying working pressure
- May need to pump various phases (water and air)
- Need for pumping in both ways
- Need for a precise control of water intake

Regarding valves, the choice to perform submergence without marine operations induces addition of an automation systems. Valves will therefore need to be electrically powered. The use of valves to flood the system (free flooding) induces also complexity of the control of water ballast intake. Appropriate sensors set will have to be integrated.

4.3.2. Investigation of sequence to submerge / emerge the Spar OWC

The objective of this section is to study the sequence of steps to submerge and to emerge the spar OWC. This sequence is based on the selected submergence system concept as presented in section 4.1.6 and submerged position selected in 4.2.5. This section shows:

- A description of the sequences of steps to submerge the spar OWC
    - Description of the required action
    - Description of the monitoring which will be used to end this action
- Description of each equilibrium situation at each step
    - Position of the spar buoy
    - Line length

- Indicative line tension
- Drawing of the situation

4.3.2.1. Hypothesis

A simplified catenary mooring system is used for this section instead of the semi taut mooring system defined in [27] (similar to the one from experimental work in section 6). This simplification has been done as the primary aim of this section is to define the constraints of submergence process on mooring configuration and layout design. Tensioning systems are installed on 2 top (numbered 1 and 2, anchor with x negative) and 2 bottom (numbered 1 and 2, anchor with x positive) mooring lines (see Figure 4-23 for line numbering). The line 1 and 2 lengths in submerged position and anchor positions are taken from a selected configuration of the parametric study (section 4.2). The 2 remaining lines (1 top line and 1 bottom line, numbered 3) keep their length constant during the submergence process. The length of these lines was chosen sufficiently long to limit the impact of these lines on the spar buoy position.

The submergence process is investigated in the absence of environmental loads which will modify the position of the spar buoy and the mooring line tension.

The mooring lines considered for this study are spiral strand wire with a diameter of 100 mm. This diameter has been chosen from a selected configuration of the parametric study (see section 4.2.5). Mooring tensions provided in this report are indicative and in the absence of dynamic excitation. The umbilical power cable is not investigated in this study and its impact on the spar buoy position is considered negligible.

The sequence to submerge the spar buoy is presented in this section. The sequence to emerge the spar buoy is considered to follow the same steps but in the reverse order.

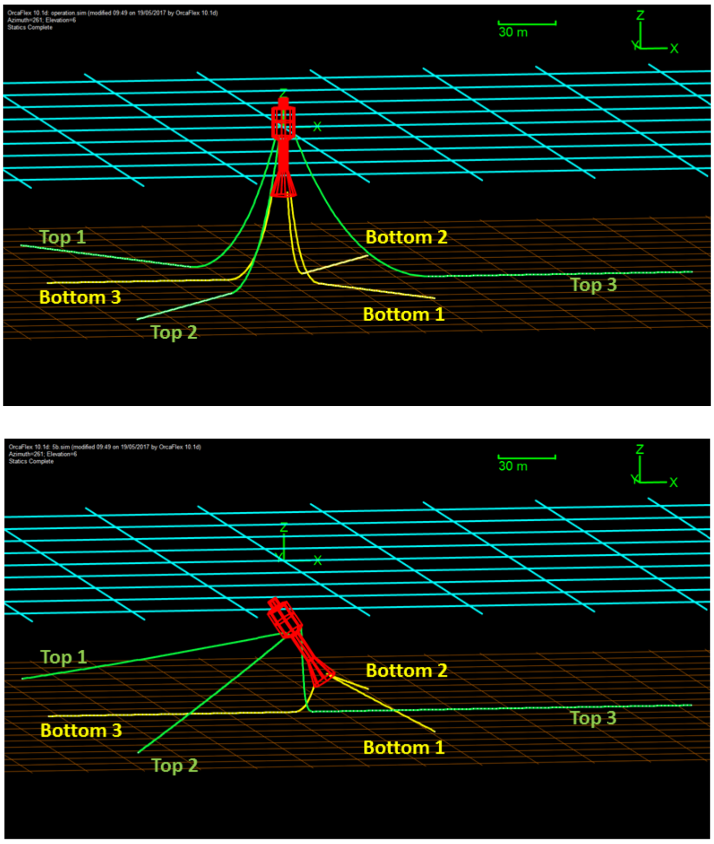


FIGURE 4-23 SPAR BUOY AND MOORING LAYOUT: LINE NUMBERING (IN OPERATIONAL AND SUBMERGED POSITION)

4.3.2.2. Sequence investigation

Step 1: Storm detection and submergence scheduling

Step 1.1: Weather forecasts: Storm predicted

Weather forecasts are used to predict meteorological conditions and sea states above the system operational limits (wave sensors may also be used to inform on local sea state).

Step 1.2: Weather window available to perform submergence before the storm

When a storm is predicted, a suitable weather window before the storm is chosen to submerge the spar buoy. The submergence sequence should be conducted in a moderate sea state, and submergence for extreme conditions is likely to be problematic but should be evaluated during detailed design phase.

Step 1.3: Submergence procedure scheduling

The submergence starts at the beginning of the previously selected weather window. The weather forecast data are used to predict the more favorable meteorological conditions when the spar buoy will be released.

Step 2: Activation of submergence process

The spar buoy is in its operational position, with 3 bottom mooring lines and 3 top mooring lines. All top mooring lines have the same length. Similarly, all bottom mooring lines have the same length.

The ballasts of the spar buoy are empty. The PTO is either sealed during this step, either able to be submerged.

The initial line length and tension and mean spar buoy position are detailed below.

TABLE 4-22 LINE LENGTH AND TENSION DURING STEP 2

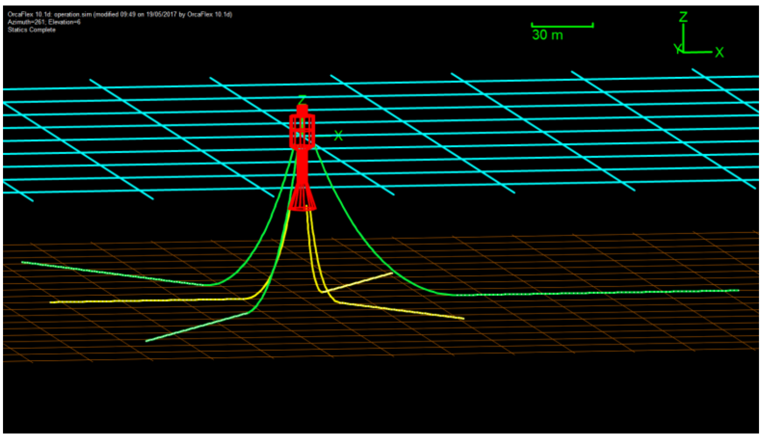
	Length (m)	approximate Tension (kN)
Bottom 1 and 2	150	22.4
Bottom 3	150	22.4
Top 1 and 2	250	48.7
Top 3	250	48.7

TABLE 4-23 SPAR BUOY MEAN POSITION DURING STEP 2

	Position (m or deg)
X	0
Z	0
Pitch (angle to vertical)	0

TABLE 4-24 SPAR BUOY WEIGHT (STRUCTURE) AND SUBMERGED VOLUME DURING STEP 2

Property	Unit	Value
SPAR Buoy weight	Tons	1217
SPAR Buoy submerged volume	m3	1468



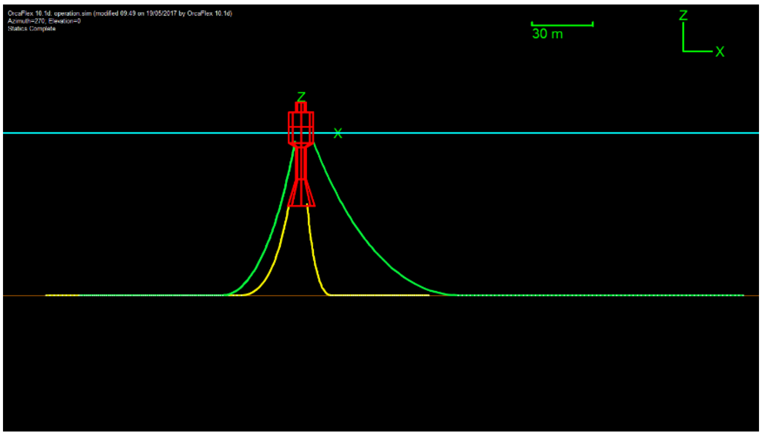


FIGURE 4-24 SPAR BUOY AND MOORING LAYOUT DURING STEP 2 (OPERATIONAL POSITION)

Step 3 and 4: tightening of bottom mooring lines and ballasting of the spar buoy

Steps 3 and 4 occur simultaneously. The aim of doing these operations at the same time is to facilitate the ballasting of the spar buoy and to sink the spar buoy, without observing large tensions in the tensioning system.

- Step 3: The bottom mooring lines 1 and 2 are tensioned.
- Step 4: the spar buoy ballasts are filled with water.

This double step should be conducted before inclining the spar buoy to facilitate the filling of the ballasting chambers.

The steps are detailed below. The resulting mooring line length and tension and spar buoy position are described below.

Step 3.1: Activating 2 bottom tensioning systems to tighten bottom pulling lines

The bottom lines 1 and 2 are shortened and tensioned. The tension is kept under a given limit or the length of the line is used for controlling the tensioning of the line. The buoy should be fully submerged at the end of step 3-4.

Step 4.1: Valve opening or pump activation

The ballasting chambers are filled at the same time.

Two systems could be installed to fill the ballasting chambers:

- The valves of the ballasting chambers are open to let the water in and the air out of the ballasting chambers. Check valves could be used to set priority between chambers.
- The water is pumped inside the ballasting chambers.

Step 3.2 and 4.2: Closing of the valves or stopping the pumps and stopping the 2 bottom tensioning systems

The valves are closed or the pumping systems are stopped when the desired volume of water is measured inside the ballasting chambers. The tensioning system is stopped when the bottom

lines are taut at a given tension or at a given length. This is detected by measuring tension or length of the bottom lines.

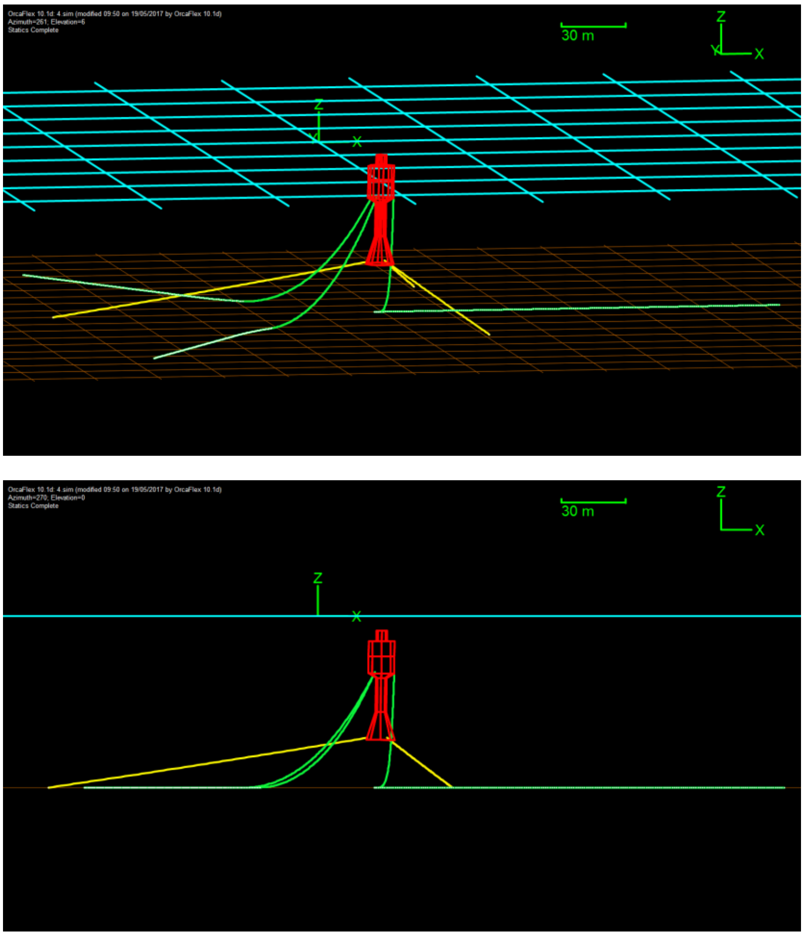


FIGURE 4-25 SPAR BUOY AND MOORING LAYOUT AT THE END OF STEP 3-4: TENSIONING OF BOTTOM LINES AND BALLASTING OF THE SPAR BUOY

TABLE 4-25 LINE LENGTH AND TENSION AT THE END OF STEP 3-4

	Length (m)	approximate Tension (kN)
Bottom 1 and 2	111.65	5100
Bottom 3	150	2800
Top 1 and 2	250	50
Top 3	250	23

TABLE 4-26 SPAR BUOY FINAL POSITION AT THE END OF STEP 3-4

	Position (m or deg)
X	29.7
Z	-21.8
Pitch (angle to vertical)	0.7

TABLE 4-27 SPAR BUOY WEIGHT (STRUCTURE + BALLAST) AND SUBMERGED VOLUME AT THE END OF STEP 3-4

Property	Unit	Value
SPAR Buoy weight	tons	1907
SPAR Buoy submerged volume	m^3	2135

<u>*Step 5 a-b: lowering of the spar to desired submergence position*</u>

The aim of this step is to lower the spar buoy in the desired submerged position. The 2 active top mooring lines are progressively getting taut until their final calculated length is achieved. It can be noted that tension in top line 1 and 2are nearly tripled between steps 5a and 5b. This means that the tension in those lines highly depends on the submerged position and is highly sensitive to line length.

TABLE 4-28 LINE LENGTH AND TENSION AT THE END OF EACH PHASE OF STEP 5. IN RED THE MODIFIED LENGTHS

		Length (m)		**Approximate Tension (kN)**	
Step	Previous step	a	b	a	b
Bottom 1 and 2	130	111.65	111.65	3569	4292
Bottom 3	150	150	150	861	8
Top 1 and 2	250	230	217	1079	2942
Top 3	250	250	250	25	20

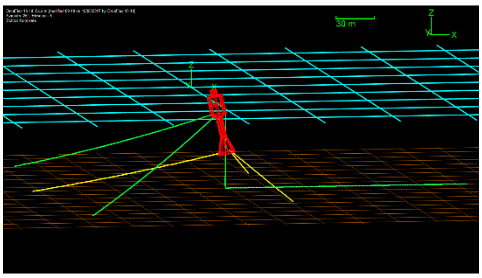
Table 4-29 SPAR Buoy final position at the end of each phase of Step 5

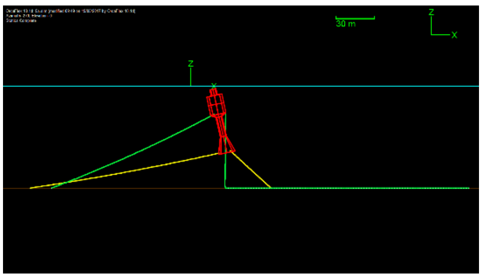
	Position (m or deg)	
	a	b
X	20.5	2.0
Z	-17.1	-33.2
Pitch (angle to vertical)	-12.4	-33.4

TABLE 4-30 SPAR BUOY WEIGHT (STRUCTURE + BALLAST) AND SUBMERGED VOLUME DURING STEP 5

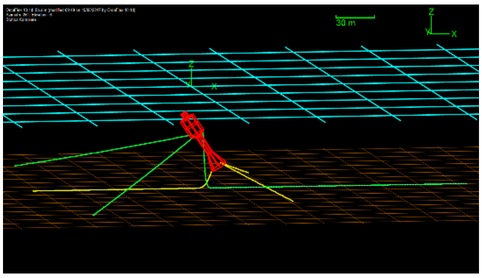
Property	Unit	Value
SPAR Buoy weight	tonnes	1907
SPAR Buoy submerged volume	m^3	2135

a





b



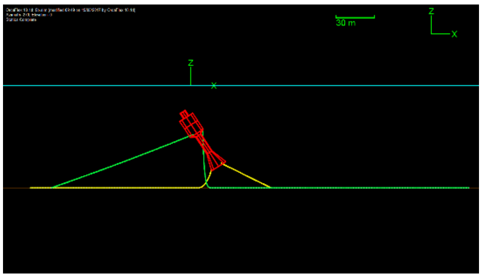


FIGURE 4-26 SPAR BUOY AND MOORING LAYOUT DURING STEP 5: LOWERING OF THE SPAR BUOY TO ITS SUBMERGED POSITION

4.3.2.3. Conclusion

The properties of the mooring system during the steps presented previously are summarised in this section.

TABLE 4-31 SPAR BUOY WEIGHT (STRUCTURE + BALLAST WHEN RELEVANT) AND SUBMERGED VOLUME DURING STEP 5

Property	Unit	Value at the end of Step2	Value at the end of Step 3-4 to 5b
SPAR Buoy weight	tons	1217	1907
SPAR Buoy submerged volume	m^3	1468	2135

TABLE 4-32 LINE LENGTHS AT THE END OF THE DIFFERENT STEPS. IN RED THE MODIFIED LENGTHS

Length (m)				
Situation at the end of step	2 (Operation)	3-4	5a	5b (submerged)
Bottom 1 and 2	150	111.65	111.65	111.65
Bottom 3	150	150	150	150
Top 1 and 2	250	250	230	217
Top 3	250	250	250	250

TABLE 4-33 LINE TENSIONS AT THE END OF THE DIFFERENT STEPS

Tension (kN)				
Situation at the end of step	2 (Operation)	3-4	5a	5b(Submerged)
Bottom 1 and 2	22,4	5100	3569	4292
Bottom 3	22,4	2800	861	8
Top 1 and 2	48,7	50	1079	2942
Top 3	48.7	23	25	20

View at the end of step	Side view	3D view

2 (operation)

3-4

5a

5b (submerged position)

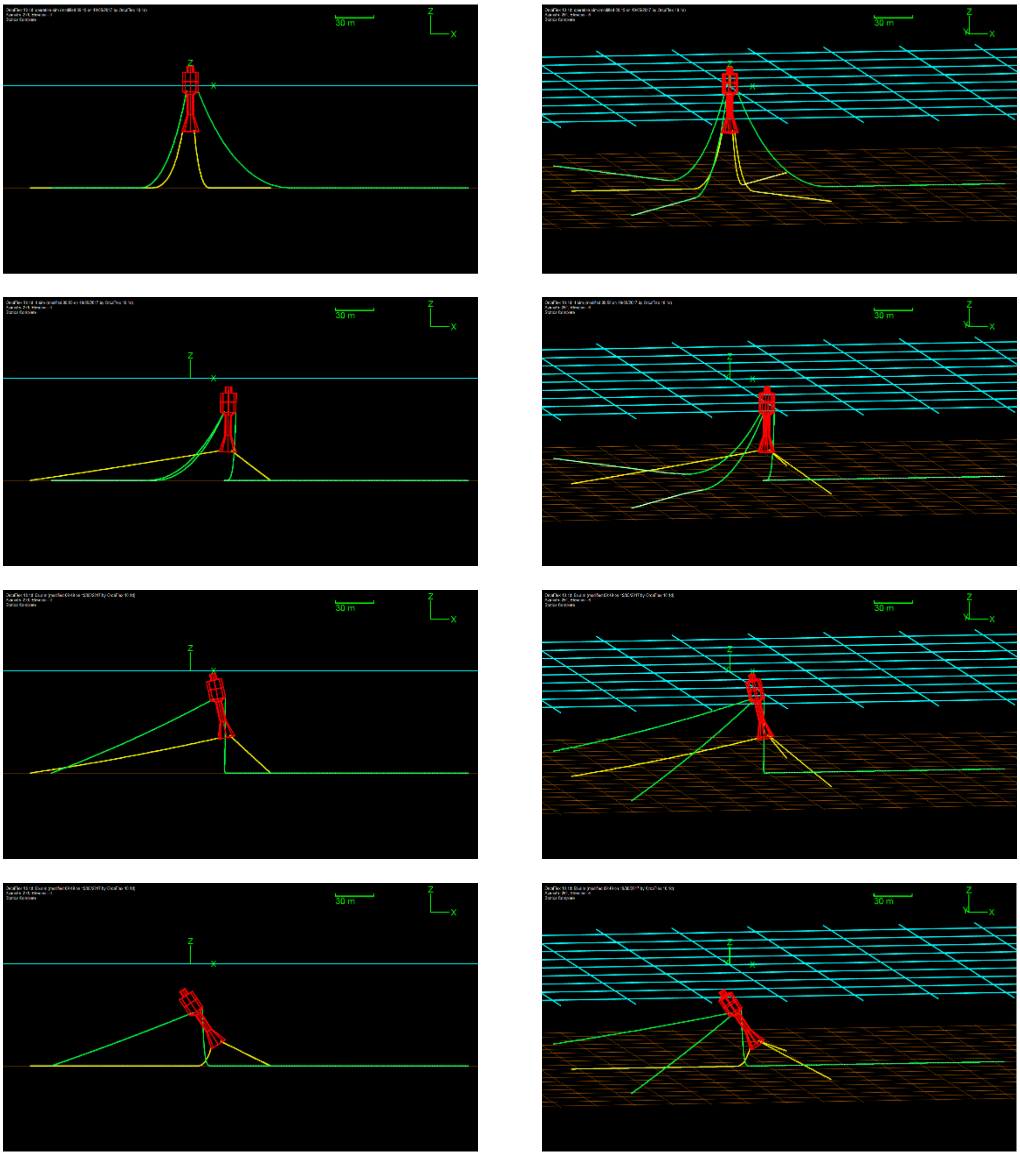


FIGURE 4-27 SPAR BUOY AND MOORING LAYOUT DURING THE WHOLE SUBMERGENCE PROCESS

4.3.3. Investigation of mooring technologies

The objective of this section is to assess the impact of the integration of a submergence system in the spar OWC on the mooring system. First the main technical challenges relative to submergence issued from the interviews of experts (see section 4.1.3) and further analysis are listed. Then the sequence detailed in section 4.3.2 is analysed with a focus on the evolution of mooring configurations to highlight resulting design constraints. An overview of the available equipment on the market is performed, in particular anchorage technologies. Finally, the potential impacts of submergence system integration on the spar OWC on the mooring system are listed.

4.3.3.1. Main technical challenges

- The proposed mooring system for submergence and power cable system (including 6 mooring lines and 1 umbilical) is complex.
- Additional dedicated lines (in addition to the 6 existing mooring lines) could be used to pull the spar buoy in its submergence position. These lines would be simple: no clump weights, no buoyancy elements. However, this addition makes the global system more complex, and induces additional costs.
- The line length should be reduced only at one extremity of the mooring line (fairlead or anchor), in order to limit the number of tensioning equipment.
- The position of the mooring lines is modified during the submergence process. Some mooring lines become slack. Mooring configuration should be designed using clump weights, buoyancy elements and wire to avoid a) contact with the seabed and OWC spar and b) chain entangling.
- Catenary lines become taut during submergence. This is feasible; however anchors should be designed to afford vertical loads. In addition, the tension in the mooring lines is higher because of this pulling. In submerged position, the taut mooring lines have an angle with the vertical. Because of this angle, the resulting force necessary to pull the SPAR buoy is higher than with vertical lines.
- Materials used in mooring lines are:
    - Wire rope: Wire rope are generally coated as a function of the required design life, so they may not be suitable with some tensioning equipment which may damage the coating.
    - Chains: They may require specific tensioning equipment.
    - The bending radius of wire rope may be a limit for the tensioning equipment.
    - Clump weights and buoyancy elements: these elements should be located sufficiently far from the tensioning equipment because they cannot be coiled.
- The study was conducted for the given fairlead positions. The fairlead positions may be modified in the future to improve the stability in pitch in operation of the spar buoy, and this will modify the results of this study.
- The cost increase of the mooring system induced by the submergence system will be significant.

4.3.3.2. Analysis of the submergence process sequence

The different steps for the submergence, the chosen mooring system and the mooring line numbering have been defined in section 4.3.2.

The chosen mooring system for submergence uses 1 tensioning system per line. 4 lines are to be equipped with this functionality for submergence.

Several impacts of the chosen submergence system are highlighted in this section:

- With the existing mooring system, contact is likely to occur between a mooring line and the spar buoy during submergence and in the final submerged position. A possible mitigation is discussed below.

* Some mooring lines are getting taut during submergence and remain taut for the final submerged position. The impacts on anchors and tensioning systems are discussed below.
* Some mooring lines are becoming slack and having a right angle with the seabed. The impact on the mooring system is discussed below.

Contact between top line 3 and the hull

In Step 3 to 5b (see section 4.3.2), it can be seen that top line 3 is getting in contact with the spar buoy (Figure 4-28). It should be taken into account that the mooring system has been simplified for this study. A catenary mooring system has been studied instead of a semi-taut mooring system. However, the same problem occurred with semi-taut configuration from [27] (similar to the one from experimental work in section 6) (Figure 4-29).

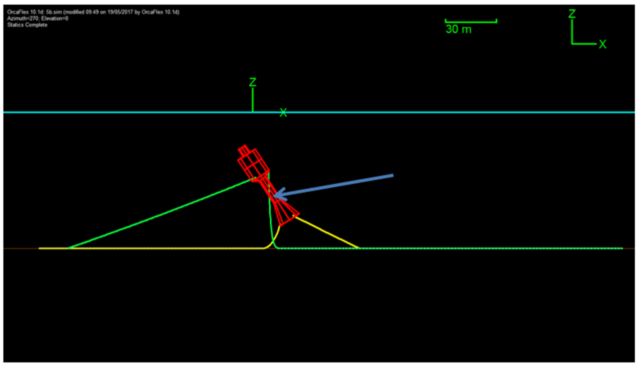


FIGURE 4-28 : TOP LINE 3 COMING IN CONTACT WITH THE SPAR BUOY (BLUE ARROW)

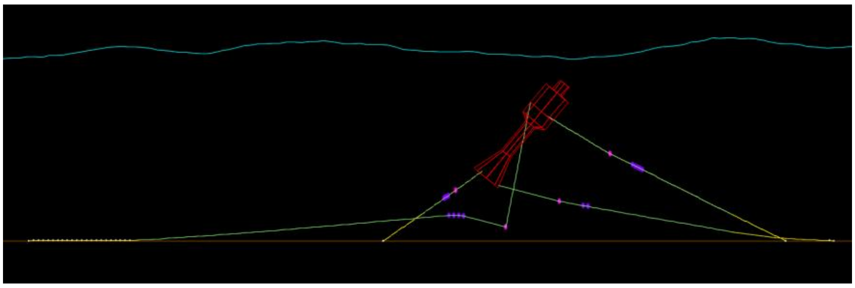


FIGURE 4-29 : PROPOSED MOORING DESIGN (SEMI-TAUT) FROM [27] (SIMILAR TO THE ONE FROM EXPERIMENTAL WORK IN SECTION 6) IN SUBMERGENCE POSITION

Contact should be avoided between any elements of the mooring system and the spar for several reasons:

* Clump weight: the clump weight has not been modelled in this study. Contact between a clump weight and the spar buoy should be avoided because this is likely to damage the spar buoy.
* Buoyancy element: the buoyancy elements have not been modelled in this study. Contact between a buoyancy element and the spar buoy should be avoided as it may damage the buoyancy element.
* Chain at the fairlead: the mooring system has been modelled in this study using a wire line. In reality, chain is likely to be used for several meters at the fairlead. Contact between the chain connected at the fairlead and the spar buoy should be avoided

because of the high impact loads of the chain on the spar buoy. The chain will damage the coating of the spar buoy, which will accelerate corrosion.
- Wire: Contact between the wire and the spar buoy should be avoided because impacts on the wire may damage the wire.

A solution could be to reduce the length of top line 3 during the submergence process but this means the addition of a tensioning system. This solution increases the complexity of the mooring system. For example, the drawing in Figure 4-30 shows the system in submergence position with top line 3 with a length of 220 m instead of 250 m.

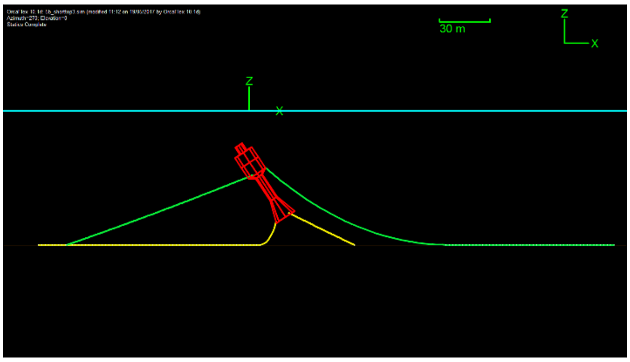


FIGURE 4-30 : EXAMPLE OF EQUILIBRIUM POSITION IN SUBMERGED POSITION WITH TOP MOORING LINE 3 WITH A REDUCED LENGTH

Another solution would be to change the relative orientation of the top and the bottom mooring system and rotate the bottom mooring system by an angle of 180°. However, this solution would need some adjustments in the operational and in the submergence position:

<u>In the operational position</u>, the top and the bottom mooring lines are in contact near their touchdown point (Figure 4-31). This may not happen with the semi taut mooring system. This could be mitigated:

- by changing the anchor positions and using shorter top mooring lines. See for example Figure 4-32. Dynamic contact between the mooring lines when the buoy moves should be investigated in more details.
- by having an offset of 10 to 30° between the top and the bottom mooring lines (Figure 4-34). However, this needs to be investigated in the submerged position as this system is imbalanced. Similarly, dynamic contact between the mooring lines when the buoy moves should be investigated in more details.

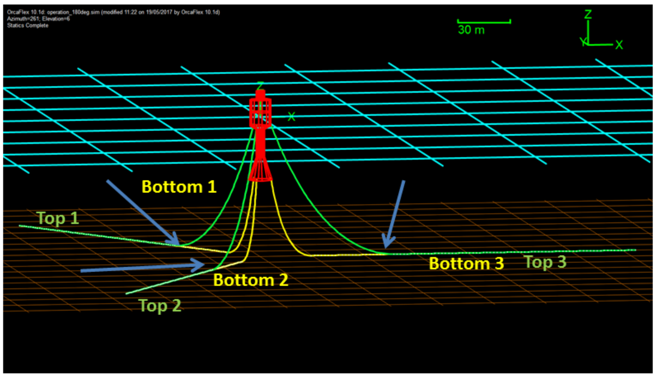


FIGURE 4-31 : EXAMPLE OF EQUILIBRIUM POSITION IN OPERATIONAL POSITION WITH THE BOTTOM MOORING SYSTEM ROTATED BY 180°. CONTACT BETWEEN THE TOP AND BOTTOM MOORING LINES (BLUE ARROW)

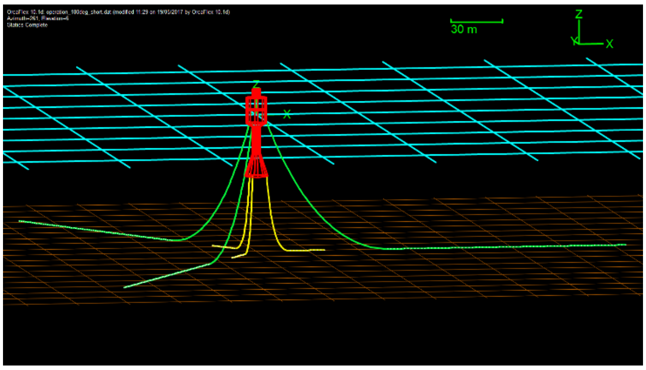


FIGURE 4-32 : EXAMPLE OF EQUILIBRIUM POSITION IN OPERATIONAL POSITION WITH THE BOTTOM MOORING SYSTEM ROTATED BY 180°, SHORTENED AND WITH CLOSER ANCHOR POINTS.

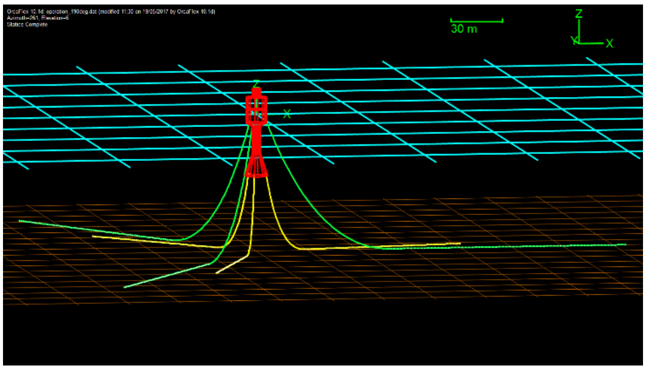


FIGURE 4-33 : EXAMPLE OF EQUILIBRIUM POSITION IN OPERATIONAL POSITION WITH THE BOTTOM MOORING SYSTEM ROTATED BY 190°

<u>In the submerged position</u>, bottom lines 1 and 2 and top line 3 are used to pull the buoy and are shortened.

A parametric study was conducted on the line lengths. However, no appropriate line lengths were found which could lead to the requested equilibrium position, especially to approach the position in Z of the spar buoy. This is because tension in top line 3 is too high. With this configuration, top line 3 alone should pull the buoy when 2 lines were used previously.

The force to pull the buoy is high because the mooring system should provide a sufficient tension a) to sink the ballasted buoy, because its buoyancy is higher than its mass; b) to rotate

the buoy, when the moment arm caused by the buoyancy and weight of the buoy tends to move the buoy back vertically.

An example of an obtained equilibrium position is shown in Figure 4-34.

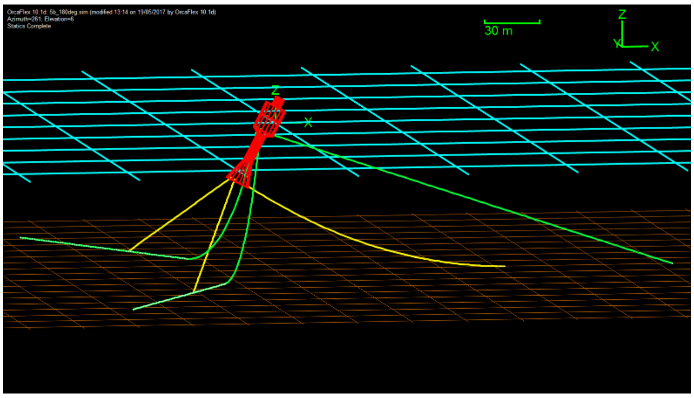


FIGURE 4-34: EXAMPLE OF EQUILIBRIUM POSITION IN SUBMERGENCE POSITION WITH THE BOTTOM MOORING SYSTEM ROTATED BY 180° FOR GIVEN LINE LENGTHS.

Taut mooring lines

The top and bottom mooring lines 1 and 2 are getting taut which means their anchor should be able to accommodate vertical loads.

The tensioning system can be installed at the fairlead or at the anchor point if the fairlead or the anchor point can accommodate the tensioning system.

A tensioning system can coil one type of line only and cannot coil a clump weight. This results in limited length of lines which can be pulled. The crosses in Figure 4-35 shows the maximum length of line which can be pulled.

For the mooring system provided in [27] (similar to the one from experimental work in section 6), the length of lines which can be coiled is limited by:

- If tensioning system at the fairlead: length of line between the fairlead and the clump weight ("section 1")
  - for the top mooring system: 75.515 m
  - for the bottom mooring system: 25.78 m
- if tensioning system at the anchor point: length of chain ("section 3")
  - for the top mooring system: 46.2 m
  - for the bottom mooring system: 43.1 m

This means that the reduced length of line by the tensioning system should be within limits above.

In the submergence sequence study (section 4.3.2), the bottom line length was reduced by 38.35 m and the top line length by 33 m. This means that with this submergence position, if the tensioning system is installed at the fairlead, then the bottom mooring line cannot be fully coiled to reach the submergence position.

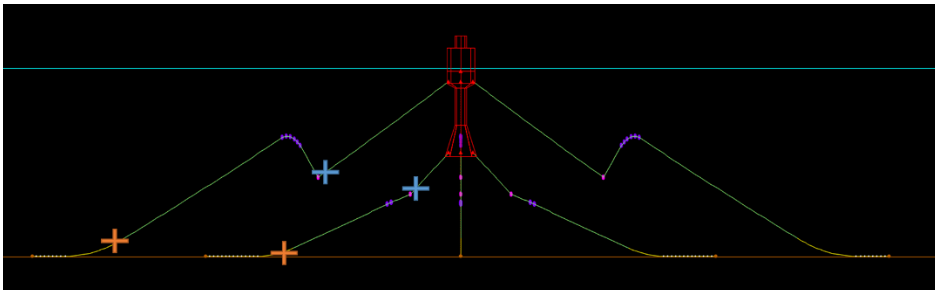


FIGURE 4-35 : LIMITED LENGTHS OF PULLING: FROM FAIRLEAD TO BLUE CROSSES IF THE TENSIONING EQUIPMENT IS AT THE FAIRLEAD, FROM ORANGE CROSSES TO ANCHOR IF THE TENSIONING EQUIPEMENT IS AT THE ANCHOR

Risk of chain entanglement

In Step 4, there is a risk of chain entanglement in top mooring line 3 for the chosen mooring line length (Figure 4-36). The chain is completely slack and might get entangled. This is also likely to occur with the chosen semi taut configuration [27] (similar to the one from experimental work in section 6) because of the short distance between the bottom fairlead and the seabed in the submerged position. The clump weight should also avoid being on the seabed.

A simple mitigation would be to optimise the length of top mooring line 3 to minimize its impact on the submergence sequence while staying taut. If this is not feasible, a mitigation could be to keep tension in this line, which means that an additional tensioning system would be required.

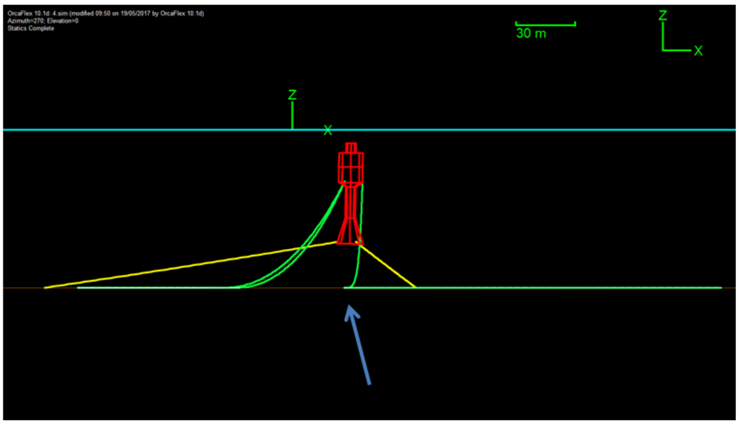


FIGURE 4-36: RISK OF CHAIN ENTANGLEMENT WHEN TOP LINE 3 IS SLACK (BLUE ARROW)

4.3.3.3. Mooring technologies equipment

Overview of existing anchor technologies

The role of an anchor is to keep a mooring line attached to a fixed point on the seabed. The main requirements for an anchor are to be able to resist to high loads, horizontal and in some cases vertical, in a given seabed type (soft to hard), to be easy to install and to be cost-effective.

Different anchor designs are available:

- dead weight,
- drag embedment anchor,

- vertically loaded anchor,
- pile anchor,
- suction anchor.

The properties of each type of anchor (costs, appropriate seabed, water depth, vertical loads, possibility to accommodate a tensioning system, manufacturer and maximum capacity) are detailed below and summarized in Table 4-34. This list is not exhaustive and novel anchor types could also be considered such as screw anchors or drop anchors.

Dead weight anchor

Dead weight (Figure 4-37, from [28]), also known as gravity anchor, is the simplest anchor. The holding capacity is provided by the weight in water of the anchor, and by the friction of the anchor on the seabed. This type of anchor is usually in cast-iron or concrete. However, this type of anchor is not very efficient: the anchor may need to be significantly large and heavy. Consequently, this type of anchor may be difficult to handle to provide a given holding efficiency.

Drag embedment anchor

Drag embedment anchor (Figure 4-38, from [28]) penetrates partly or fully in the seabed and the holding capacity is provided by the resistance of the soil in front of the anchor. This type of anchor can accommodate large horizontal loads, however, it can only accommodate limited vertical loads. These anchors are often used with a catenary mooring system, with sufficiently long chains lying on the seabed to avoid vertical loads. This type of anchor requires a soft seabed (sand or mud) where it can penetrate.

Vertically loaded anchor

Vertically loaded anchor (VLAs, Figure 4-39, from [28]), also known as plate anchor is a new type of anchor, which is an improvement of the drag embedment anchor because it can accommodate larger vertical loads. It is installed much deeper than a traditional drag embedment anchor.

Driven pile anchor

Pile anchor (Figure 4-40, from [28]) is a hollow steel pipe which is driven deeply into the seabed with a hammer or vibrator, (or they can be drilled into the seabed) using a designated (and expensive) installation methodology. The holding capacity is provided by the friction of the soil along the pile and by the lateral soil resistance. This type of anchor can accommodate horizontal and vertical loads.

Suction pile anchor

Suction anchor (Figure 4-41, from [28]) is a variation of the pile anchor, with a larger diameter, which is installed in soft soils with a pump, using pressure difference. Present designs are mostly adapted for deep waters (1000 m) counting on the additional hydrostatic pressure force to improve the efficiency of the system. For shallower water, new designs might be envisaged.

TABLE 4-34 SUMMARY OF ANCHOR PROPERTIES

Anchor	Costs (hardware and installation)	Type of seabed	Typical water depth [8]	Accommodate vertical loads (Y/N)	Can accommodate a tensioning system (Y/N)	Manufacturer	Max capacity	Reference
Dead weight	Low	any (sufficiently hard)	Shallow	Y	Y	FMGC (cast iron) Many manufacturers for concrete	Depends on crane capacity (installation)	
Suction pile anchor	High	very soft clay, medium clay	Deep	Y	Y	Delmar InterMoor Vryhof anchors	27000 kN	https://www.osti.gov/scitech/servlets/purl/1178273
Driven pile anchor	High	very soft clay, medium clay, sand	Shallow	Y	Y	InterMoor	27000 kN	https://www.osti.gov/scitech/servlets/purl/1178273
Drag-embedment anchor	Medium	very soft clay, medium clay, hard clay, sand	Shallow	N	N	Bruce anchors Vryhof anchors InterMoor	5000 kN	NCEL
Vertical Load Anchor (VLA)	High	very soft clay, medium clay	Deep	Y	N	Bruce anchors Vryhof anchors	20000 kN	http://www.vryhof.com/flipbooks/STEVMANTA_VLA_May2015_flipbook/files/inc/ae5715bfd3.pdf

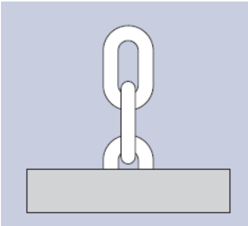


FIGURE 4-37: EXAMPLE OF DEAD WEIGHT ANCHOR [28]

FIGURE 4-38: EXAMPLE OF DRAG EMBEDMENT ANCHOR [28]

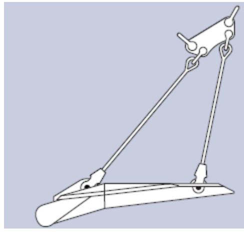


FIGURE 4-39: EXAMPLE OF VERTICALLY LOADED ANCHOR (VLA) [28]

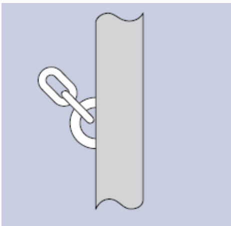


FIGURE 4-40: EXAMPLE OF PILE ANCHOR [28]

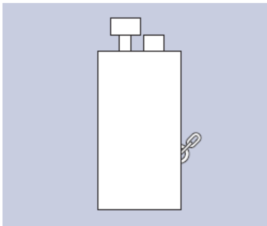


FIGURE 4-41: EXAMPLE OF SUCTION ANCHOR [28]

4.3.3.4. Discussion on choice of anchors

Based on this review,

- Dead weight anchors can be used but their weight is a limiting parameter for installation. The tensioning system can be located on top of the anchor.
- Suction and driven pile can be used with a soft seabed. The tensioning system can be located at the anchor point. Both anchors have large holding capacity, which are suitable with the expected tensions during the submergence process. Both anchors are capable of resisting horizontal and vertical loads. Suction anchors will be preferred in deep water when driven pile anchors will be preferred in shallow water. Therefore, driven pile anchors are more relevant for this project.
- Drag embedment anchors do not accommodate vertical loads. They can be used only if an additional system avoids vertical loads during submergence and if the tensioning equipment is located at the fairlead. In addition, the seabed should be soft. Also, their maximum holding capacity seems to low in comparison with the estimated mooring line tension. The tensioning system cannot be located directly at the anchor point. Drag embedment anchors do not seem appropriate for this project.
- VLA anchors provide large holding capacity which is suitable with the expected tensions during the submergence process. They can be used in a soft seabed in deep water. Therefore, the water depth at the site may not be sufficient. The tensioning system cannot be located directly at the anchor point. Therefore, this type of anchor may not be relevant for this project.

For drag embedment anchor not allowing vertical loads an option which could be envisaged is to have a deviation sheave which would ensure loads remain horizontal. Sheave would be mounted on its associated anchor and tensioning system should be floater side. This system is

shown in Figure 4-42. This option can also be used with dead weight and suction and pile anchors, to limit vertical loads and to keep tensioning system onto the anchors.

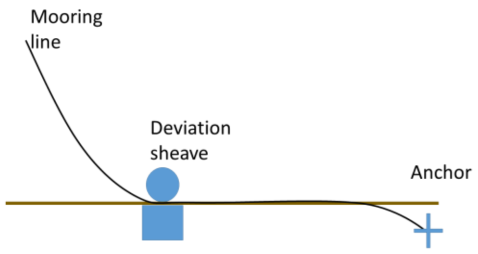


FIGURE 4-42 : OPTION TO AVOID VERTICAL LOADS ON ANCHORS

4.3.3.5. List of impacts of submergence on mooring system

Submergence requires the use of at least 4 tensioning systems on 4 lines. This may have a significant impact on the cost of the whole system. The choice of tensioning systems depends on the choice of mooring line type.

A tensioning system can coil one type of line only and cannot coil a clump weight. This results in limited length of lines which can be pulled.

Dead weight anchors or driven pile anchors seems suitable anchor solutions allowing submergence. The choice of the final anchor will mainly depend on the seabed type, on the design load and on the tensioning system. The position of the tensioning system (at the fairlead or at the anchor) may also depends on the anchor type.

In addition, during submergence, clump weights should avoid being on the seabed. This may have an impact on the length of the different sections of lines.

4.3.4. Investigation of power cable protection technology

The objective of this section is to have an overview of the technical solutions available for the protection of the power cable of the spar OWC during submergence and their related impacts. The submergence of the spar has been investigated in section 4.3.

This section is organised as follows:

- Identify and conclude on the impact on submergence on the dynamic power cable
- Explain the need of a protection of the power cable and its impact
- Identify solutions for protection of the cable during operation

The output is:

- A list of equipment and their characteristics
- A list of impacts related to this equipment

4.3.4.1. Different positions of the SPAR OWC during its lifetime and consequences on the bending of the power cable

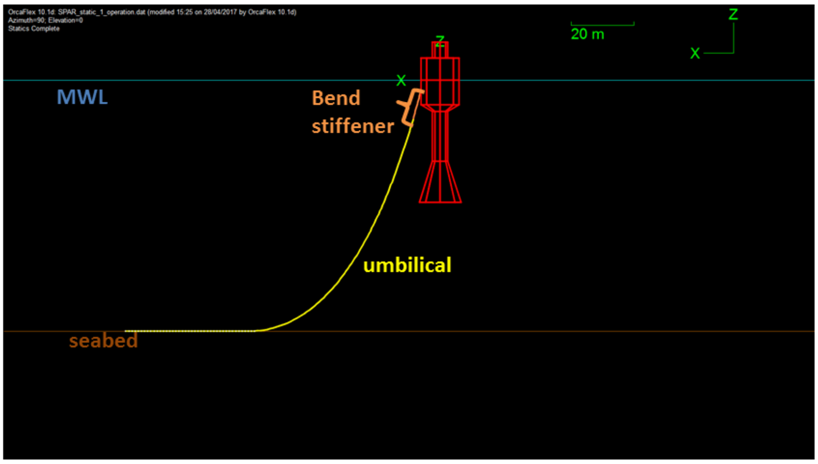
A power umbilical cable is connected to the SPAR buoy. The power umbilical cable is attached once the SPAR buoy is installed on site with its moorings. The power cable is relatively light, with a low stiffness and with a low tension due to the considered water depth and product weight in water.

The spar OWC is upright during operation. During storms, the SPAR buoy is lowered and laid down. The SPAR buoy may not be kept perfectly horizontal but with an angle of 30 to 60° with the horizontal.

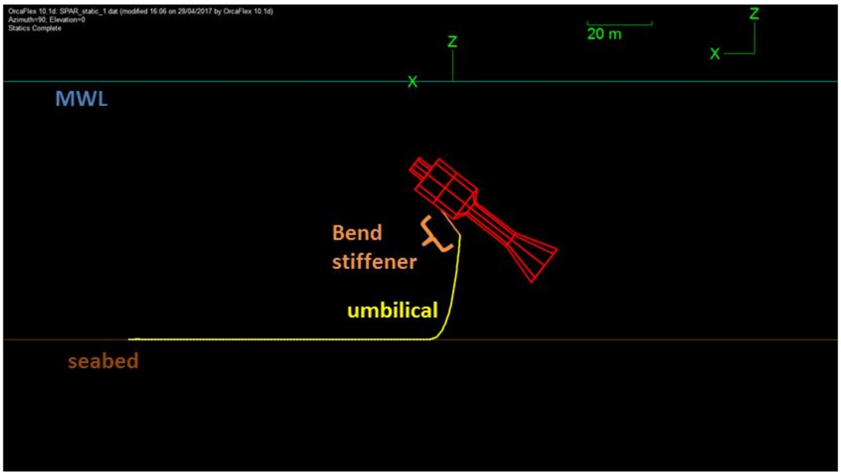
The position of the cable relatively to the SPAR buoy has not been defined yet. A conceptual sketch (Figure 4-43) has been drawn with a hypothetic cable connection position and a hypothetic SPAR buoy submergence position. . A bend stiffener has been chosen for the sketch but other solutions will be discussed in this section. The umbilical chosen for the sketch has a catenary shape but the umbilical can have a different shape, for example a lazy-S shape. The aim of this sketch is to highlight the impact of submergence of the spar on the dynamic cable.

This sketch shows that during submergence and associated rotation the curvature of the cable can be locally significantly increased at the fairlead. In addition, external loads generated by the sea and by the motions of the SPAR buoy may generate large stresses on the umbilical and may cause damage to its structure because of over bending and/or fatigue at the spar interface.

Therefore, a local protection is required at the fairlead to limit the curvature of the cable. The protection is clamped to the SPAR at an angle corresponding to the natural umbilical departure for normal in place configuration. Solutions for protection of the cable during operation are identified in the following section. Equipment design capacity might also become limiting parameter for submergence operation itself.



(a)



(b)

FIGURE 4-43 IMPACT OF SUBMERGENCE OF THE SPAR ON THE DYNAMIC CABLE FOR A GIVEN SPAR BUOY SUBMERGENCE POSITION AND A GIVEN CABLE CONNECTION POSITION; A) OPERATIONAL POSITION; B) POSSIBLE SUBMERGENCE POSITION AND CABLE POSITION

4.3.4.2. Identified main characteristics of components

<u>*Bend stiffeners*</u>

Bend stiffeners (Figure 4-44) can be used to limit the curvature of the cable by adding a local stiffness to the cable at the point of connection in order to limit bending stresses and curvature to acceptable levels.

Bend stiffeners available on the market of offshore components are made of moulded polyurethane elastomers. Polyurethane elastomer is chosen because of its low modulus and high elongation at break. In addition, this material is light and does not require any corrosion protection system.

Each bend stiffener is designed individually to protect the umbilical minimum bending radius under a defined tension and angle combinations, meeting the load cases (tension vs angle) of each application. For this application, the bend stiffeners should be sufficiently long in order to avoid the line to exceed its radius of curvature at the end of the bending stiffeners. However, the length should be kept reasonable for installation purposes (for example required length on deck and handling on installation vessel). An order of magnitude of length for this concept is 5 to 10 m.

The design of a bend stiffener takes into account:

- Umbilical diameter
- Operational environment (water)
- Interface requirements with load bearing steelwork/end termination
- Fatigue loads and cycles. (for dynamic bend stiffener design)
- Tension and angle combination. (for dynamic bend stiffener design)

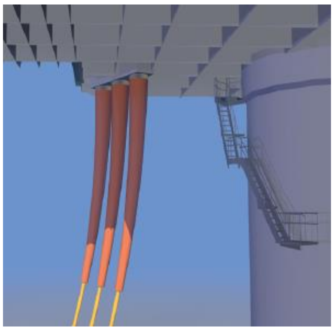
Several types of bend stiffeners exist:

- Static: mainly used for protection during installation
- Dynamic: used for protection during the service life
- Some manufacturers also propose split bend stiffeners: used for facilitating installation

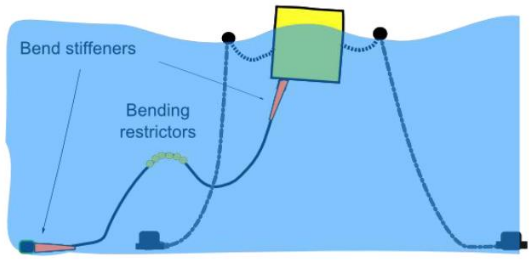
The dynamic bend stiffeners are the one relevant for this study.

Several international offshore standards can be followed for bend stiffeners design: API17-L1 [2], API17-L2 [3], AWS D11 [4] and EN ISO 15641-1 [19].

Table 4-35 summarises some potential bend stiffener providers and the main characteristics of bend stiffeners they can provide. Most of the manufacturers do not provide properties of the bend stiffeners because they are project specific.



a)



b)

FIGURE 4-44 EXAMPLE OF SHAPE AND LOCATIONS OF BEND STIFFENERS; A) BEND STIFFENERS USED IN PARALLEL; EXAMPLE FROM BMP (SEE REFERENCE IN TABLE 4-35); B) POSSIBLE LOCATION OF BEND STIFFENERS ON A WEC (SOURCE: [1])

TABLE 4-35 EXAMPLES OF SOME PROVIDERS AND CHARACTERISTICS OF BEND STIFFENERS

Provider	description	External line diameter [mm]	Length [m]	Weight per limiter [kg]	External diameter [mm]	source
EXSTO	Dynamic and static bend stiffeners	30-400	1.2-8	15-3500	300-2000	http://www.exsto.com/DYNAMIC-OR-STATIC-BEND-STIFFENERS,106
Trelleborg	Static and dynamic bend stiffeners	Project specific	Project specific	Project specific	Project specific	http://www.trelleborg.com/en/offshore/products/bend--control--solutions/subsea--bend--stiffeners
Bardot	Static, dynamic and split	Project specific	Project	Project	Project specific	http://www.bardotgroup.com/fr/solutions-surf/controle-des-rayons-de-courbure/bend-stiffener

	bend stiffeners		specific	specific		http://www.bardotgroup.com/fr/solutions-surf/controle-des-rayons-de-courbure/bend-stiffener
BMP	Static, dynamic and split bend stiffeners	no data	no data	no data	no data	http://www.bmpworldwide.com/pdf/Offshore_Energy_Products.pdf
Balmoral	Dynamic, and static bend stiffeners; split bend stiffeners	Project specific	up to 14 m	Project specific	Project specific	http://www.balmoral-group.com/balmoral-offshore/index.php/products/surf-products/bend-stiffeners
Plastiprene	Static and dynamic bend stiffeners	Project specific	up to 12 m	Project specific	Project specific	http://www.plastipreneoffshore.com.br/pdf/cat_bend.pdf

Dynamic bend restrictors

Dynamic bend restrictors (Figure 4-45) are manufactured from a number of interlocking elements. They are also called Vertebrae Bend Restrictors (VBRs). They can be made of polyurethane or steel, or a combination of both materials, depending on loading conditions. Steel bend restrictors may be more appropriate for this study, considering the load cases, dynamic behaviour and associated loadings.

However, bend stiffeners do have a better behaviour in a dynamic environment than dynamic bend restrictors for example in terms of fatigue. Bend stiffeners should be preferred in this study.

Table 4-36 summarises some potential bend restrictor providers and the main characteristics of bend restrictors they can provide.

(A) (B) (C)

FIGURE 4-45 DYNAMIC BEND RESTRICTORS; A) POLYURETHANE VBR, B) STEEL VBR; C) HYBRID VBR FROM ABCO SUBSEA [31]

TABLE 4-36 EXAMPLES OF SOME PROVIDERS AND CHARACTERISTICS OF DYNAMIC BEND RESTRICTORS

Provider	description	External line diameter [mm]	MBR (m)	Weight per half limiter [kg]	source
EXSTO	polyurethane or steel VBR	30 to 400	0.5 to 15	0.5 to 100	http://www.exsto.com/BEND-RESTRICTORS?var_ajax_redir=1
ABCO subsea	steel VBR	100 to 400	no data	no data	http://www.abcosubsea.com/wp-content/uploads/2014/06/steel-vbrs.pdf
Trelleborg	subsea and renewable VBR	no data	no data	no data	http://www.trelleborg.com/en/offshore/products/bend--control--solutions

Bell mouth

Bell mouths (Figure 4-46) consist of multiple cones of various diameters.

Bell mouths may be used to eliminate the need of bend stiffeners or bend restrictors. However, they are less suitable for congested locations. In addition, they are less appropriate for a dynamic use, and the clash of the umbilical line on the wall of the bell mouth may damage the umbilical. In addition, the bell mouth should be sufficiently long to avoid bending of the umbilical line at the exit of the bell mouth. Consequently, this solution is less appropriate for this study.

Table 4-37 summarises some potential bell mouth providers.

FIGURE 4-46 EXAMPLE OF BELL MOUTH (SEE REFERENCE IN TABLE 4-37)

TABLE 4-37 EXAMPLES OF SOME PROVIDERS AND CHARACTERISTICS OF BELL MOUTHS

Provider	source

Ostsee Staal	http://www.ostseestaal.de/index.php/en/business-portfolio/industry/offshore-components
Kersten Europe	https://www.renewableconstructions.com/en/bellmouths

4.3.4.3. Impact of proposed solutions

The solutions proposed below allow a reduction in the curvature of the cable. However, they do have some impacts on the whole system:

- Additional weight on the system
- Change in behaviour of the power cable
- Increased installation complexity
- Corrosion for elements in steel
- Additional cost

4.4. Components / technologies scoring

Table 4-38 summarizes the outcome of the engineering analysis. It classifies the analyzed equipment and technology regarding their estimated criticality for submergence, their estimated technical maturity, their estimated impact on maintenance, and their estimated impact on cost.

Despite the effort to complete the scoring matrix in a methodic way, this completion highly depends on partial judgement. It is recommended to review this scoring at later development stage.

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TABLE 4-38 COMPONENTS / TECHNOLOGIES SCORING

Topic	Equipement / Technology	A - Criticality for submergence	B - Technical Maturity	C - Maintenance	D - Cost	E - Score	Alternative solutions / mitigations
		5: essential component / technology 1 : composant / technology for for annex functions	*5: existing component, low risks identified 3 : existing component, high risks identified 0 : non existing component*	*5 : low expected impact 0 : high or unknown expected impact*	*5 : low expected impact 0 : high or unknown expected impact*	*Mean score Mean(B,C,D) 5: highest score 0 : lowest score*	
Ballasting / Tensionning means							
	Tensionning system: *Use of at least 4 tensioning systems.The choice of tensioning systems depends on the choice of mooring line type. Subsea winches have been studied. Need for subsea winch of large capacity (non existent) or use of multiple winches to increase capacity or use existing winches with limited capacity but temporary increase ballast to submerge or other innovative solutions. Powered.*	5	1,5	0	0	0,4	High tensions have been highlighted in the mooring lines, which induce large capacity equipment requirements not available on the market. Other solutions may be studied, as for example laying the Spar on the Seabed (horizontally or vertically), use of surface buoys and neutrally buoyant structure through addtion of more ballast.

	Pumping system: *Adapted to changing environment (alternatively emerged and submerged), varying working pressure, may need to pump various phases (water and air), need for pumping in both ways, need for a precise control of water intake. Powered.*	5	3	1	2,5	2,3	
	Valves: *Appropriate sensors for precise control of water intake. Adapted to changing environment (alternatively emerged and submerged), varying working pressure). Powered.*	5	4	3	3	3,3	
	Energy supply to underwater equipements: *If equipements are located on the seabed (eg. Winches), need additional system (eg. Cables) for energy suply to these systems.*	5	3	4	1	2,3	
Moorings							
	Anchor supporting large vertical loads: *Dead weight anchors or driven pile anchors seems suitable anchor solutions.*	5	5	5	1	3,0	
	Additional mooring lines: *Solution studied requires additional mooring lines at the bottom of the Spar OWC.*	5	5	5	1	3,0	
	Equipement to manage mooring lines during submergence operations: *Avoid line entenglement, avoid line clashing etc.*	4	2	1	1	1,3	
Power cable							
	Solutions to ensure cable integrity: *Bend stiffeners or bend restrictors or Bell mouth.*	4	4	5	2,5	3,5	

PTO							
	PTO Protection: *Eventual protection of the PTO.*	4	2	1	1	1,3	PTO designed to allow submergence without specific protection.
Spar hull							
	Eventual reinforcement of the hull structure or air chamber pressurizing.	3	5	5	4	4,5	
Other							
	Mean to have energy available.	5	3	5	2	3,0	
	Automation system, SCADA system, sensors: *Challenge to remotely automate the submergence for service life with permanent availability* *(Challenge example: considering fabrication tolerance, weight variation due to marine growth for eg., functionnal sensors).*	5	1	0	1	0,8	This is identified as a major technological challenge, which impacts many component of the submergence. High risks are identified on this topics.
	Signalisation system: *Signalisation system to locate the submergence zone for sea users during submergence.*	1	5	4	4	4,3	

Weighted score	**2,3**

*SUM(A_i*E_i)/SUM(E_i)*

5. Numerical analysis of Spar OWC system loads and motions under submersion during extreme conditions

The objective of this technical note is to describe the numerical analysis of Spar OWC system loads and motions assessment considering submersion during extreme conditions.

A parametric study has been performed (see section 4.2.4) to estimate potential submerged positions based on static state stability. Two selected configurations analysed in the present section.

The preliminary parametric study has defined an estimation of a static equilibrium position of the SPAR, the line properties and the anchors positions (see section 4.2.4), with the limitations linked with the parametric study.

A selected configuration from the parametric study is analysed with OrcaFlex. OrcaFlex static analysis calculates the static position of the SPAR and the mooring system equivalent mooring stiffness matrix.

The motion of this configuration is then analysed in the frequency domain using linear potential flow theory. According to this, RAOs and statistics are calculated for a given sea state (see section 5.3).

This preliminary motion analysis makes some hypothesis. The motion is calculated using linear potential flow theory which suppose small motions, and small amplitudes. The mooring is modelled as a linear stiffness matrix, which validity has not been verified, its validity is limited to small motions (especially for vertical motion as lines are taut). Only rough estimation of dampings are considered, and should be further analysed at later stage. Contribution of second order effects, and nonlinear effects are not considered. These hypotheses are made as the aim of this study is to have some first estimation of the submerged behaviour of the system, a simple model was needed to be able to study different configurations (2 have been tested in the end). All these hypotheses shall be verified at later stage.

5.1. Description of the configuration analyzed

5.1.1. Reference frames

There are two frames used in this study:

- The global reference frame R_G with origin O_G at mean water level, x axis horizontal along wave direction and z axis vertical upward.
- The local frame R_L attached to the SPAR with origin O_L located 20m below the top of the SPAR along its longitudinal axis. x, y and z axis of the local frame are oriented in order to be identical to x, y and z axis of the global frame when the spar is at static state in operational mode.

Reference frames and the deepest point of the SPAR (B) are shown in Figure 5-1 below.

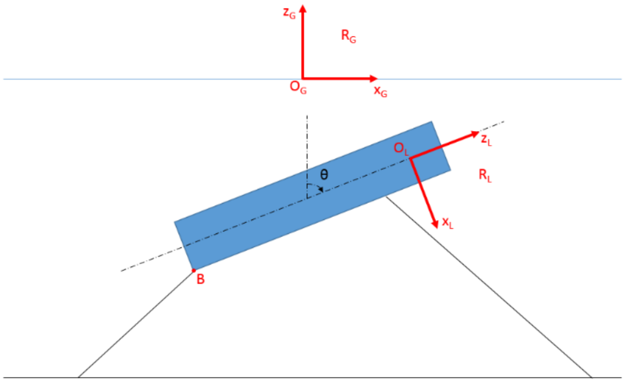

FIGURE 5-1 GLOBAL (R_G) AND LOCAL (R_L) REFERENCE FRAMES

5.1.2. Spar OWC submerged configuration

Two configurations are tested in this study:

- Configuration 1: smallest submergence of the 2 configurations selected from the parametric study is chosen.
- Configuration 2: highest submergence of the 2 configurations selected from the parametric study results is chosen. This configuration is tested because the wave loads will be smaller than configuration 1 and the lines are shorter thus stiffer. The SPAR OWC movement might then be smaller for the configuration.

SPAR OWC parameters for both submerged configurations are listed in Table 5-1 below. OrcaFlex static study equilibrium positions for both configurations are shown in Figure 5-2, Figure 5-3, Figure 5-4 and Figure 5-5 below.

Static equilibrium positions are slightly different between parametric study and Orcaflex study. The differences are mainly due to:

- The stiffness of the mooring lines considered in Orcaflex model and not in the parametric study;
- The mass of the mooring lines considered in Orcaflex model and not in the parametric study.

The Orcaflex static equilibrium position will be use for the study.

TABLE 5-1 SPAR OWC SUBMERGED CONFIGURATIONS

Category	Variable		Config 1	Config 2	Unit	Reference frame
Spar static equilibrium (parametric study)	Position in Z of point O_L	Z_{OL}	-35.00	-45,00	m	R_G
	Spar inclination (see Figure 5-1)	Θ	48.06	57,82	°	-
Spar static equilibrium (Orcaflex study)	Position in Z of point O_L	Z_{OL}	-33.03	-42.72	m	R_G
	Spar inclination (see Figure 5-1)	Θ	33.46	42.26	°	-
	Line 1 tension	T1	4.30E+06	5,96E+06	N	-

Line tension[3]	Line 2 tension	T2	2.93E+06	3,97E+06	N	-
Spar	Mass	M	1.22E+06		kg	-
	Center of gravity	Z_{COG}	-19.29		m	R_L
	Inertia in O_L	Ixx	7.78E+08		kg/m²	R_L
		Iyy	7.78E+08		kg/m²	R_L
		Izz	2.91E+07		kg/m²	R_L
Ballast	Center of gravity	Z_{B1}	0.42		m	R_L
	Mass	M_{B1}	6.90E+05		kg	-
Spar + Ballast	Mass	M	1.91E+06		kg	-
	Center of gravity	Z_{COG}	-12.16		m	R_L
	Inertia in O_L	Ixx	7.78E+08		kg/m²	R_L
		Iyy	7.78E+08		kg/m²	R_L
		Izz	2.91E+07		kg/m²	R_L

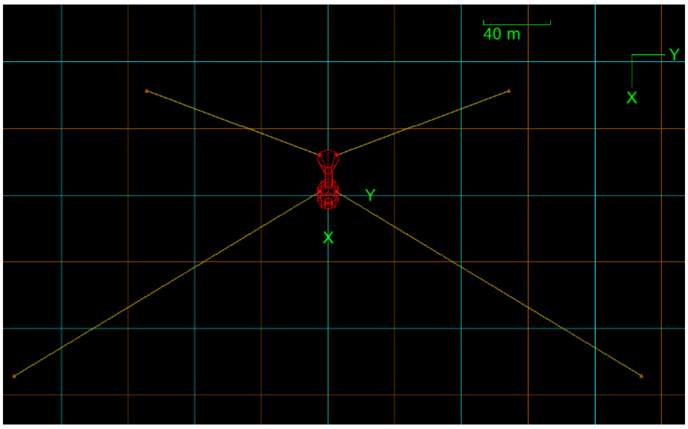

Figure 5-2 SPAR static equilibrium position – top view – configuration 1

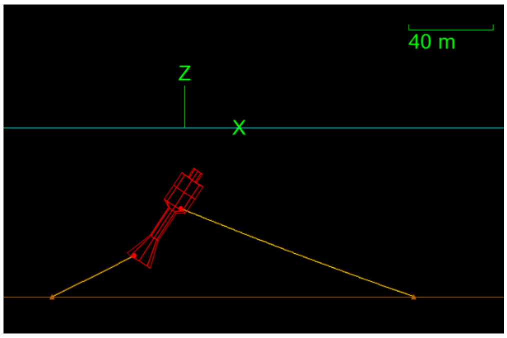

Figure 5-3 SPAR static equilibrium position – side view – configuration 1

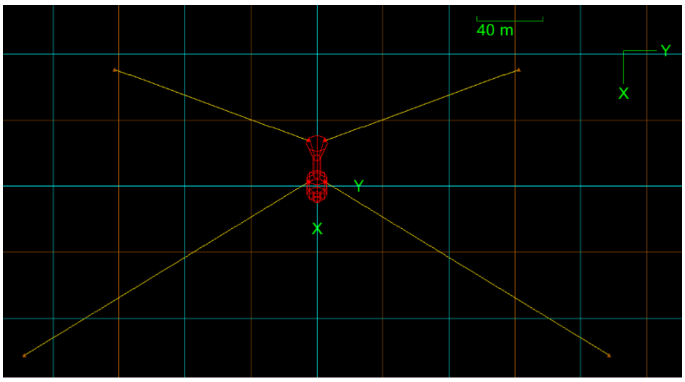

Figure 5-4 SPAR static equilibrium position – top view – configuration 2

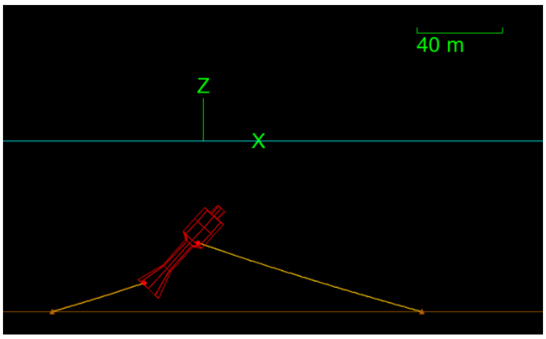

Figure 5-5 SPAR static equilibrium position – side view – configuration 2

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[3] See reference in Table 5-4

5.1.3. Hydrostatic properties

The hydrostatic properties of the SPAR OWC for both configurations are given in Table 5-2 below. Hydrostatic roll and pitch stiffnesses are linearized at static equilibrium position.

TABLE 5-2 SPAR OWC HYDROSTATIC PROPERTIES

Category	Variable		Config 1	Config 2	Unit	Reference frame
Hydrostatic	Displacement	Δ	2134.92		m^3	-
	Center of Boyancy	Z_{COB}	-7.79		m	R_L
	Hydrostatic stiffness in O_L	Kh_{44}	3.33E+07	4.06E+07	Nm/rad	R_G
		Kh_{55}	3.33E+07	4.06E+07	Nm/rad	R_G

5.1.4. Hydrodynamic properties

Hydrodynamic loads are calculated with a linear potential flow theory. Also, quadratic drag damping is added to the SPAR. Quadratic dampings are calculated with the following formula:

$$B_i = \frac{1}{2}\rho_w C_d A_i \tag{5-1}$$

With:

- B_i the quadratic damping for the i direction;
- ρ_w the sea water density;
- C_d the drag coefficient chosen, as a rough estimation (this should be refined at later stage).
- A_i the projected area for the i direction (see Figure 5-6). This area is computed based on an approximation of the normal projected area.

This is a rough damping estimation which has been applied in absence of other data. It should be refined at later stage. A generalized Morison formulation along the spar which takes into account spar inclination may be more appropriate.

The hydrodynamic damping properties of the SPAR OWC for both configurations are given in Table 5-3 below.

TABLE 5-3 SPAR OWC HYDRODYNAMIC DAMPING PROPERTIES

Category	Variable		Config 1	Config 2	Unit	Reference frame
Damping	Drag coefficient	Cd	0.60		-	-
	Normal projected area	A	380.26		m^2	-
	Surge projected area	A_x	317.24	281.43	m^2	R_G
	Heave projected area	A_z	209.66	255.73	m^2	R_G

	Surge quadratic damping surge	B_x	97552.32	86540.88	kg/m	R_G
	Heave quadratic damping heave	B_z	64470.57	78635.77	kg/m	R_G

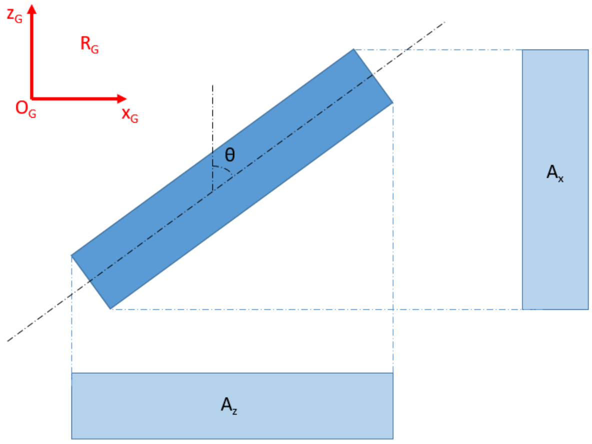


FIGURE 5-6 SPAR PROJECTED AREA

5.1.5. Mooring properties

Mooring lines properties for both configurations are given in Table 5-4 below. As shown in Figure 5-2, 4 lines are used to maintain the SPAR OWC at submerged position.

Mooring lines are made of spiral strand steel cable which mechanical properties are calculated with the following formulas:

$$MBL = 900\ d^2 \qquad (5\text{-}2)$$

$$EA = 90\,000\ d^2$$

With:

- MBL the minimum breaking load of the line (in Newton);
- d the diameter of the line (in millimeters);
- EA the axial stiffness per unit length of the line.

TABLE 5-4 SPAR OWC MOORING LINES PROPERTIES

Category	Variable		Config 1	Config 2	Unit	Reference frame
Mooring lines 1	Diameter	d1	0.10	0.13	m	-
	Lineic mass	m1	50.00	84.50	kg/m	-
	Axial lineic stiffness	EA1	9.00E+08	1.52E+09	N	-
	Minimum breaking load	MBL1	9.00E+06	1.52E+07	N	-
	Length	L1	111.65	125.14	m	-
	Anchor position	X	-62.71	-70.69	m	R_G
		Y	±108.62	±122.44	m	R_G
		Z	-80.00	-80,00	m	R_G
	Fairlead position	X	-3.00		m	R_L

		Y	±5.20		m	R_L
		Z	-35.00		m	R_L
Mooring lines 2	Diameter	d2	0.10	0.13	m	-
	Lineic mass	m2	50.00	84.50	kg/m	-
	Axial stiffness	EA2	9.00E+08	1.52E+09	N	-
	Minimum breaking load	MBL2	9.00E+06	1.52E+07	N	-
	Length	L2	217.06	203.39	m	-
	Anchor position	X	108.62	102.29	m	R_G
		Y	±188.14	±177.17	m	R_G
		Z	-80.00	-80,00	m	R_G
	Fairlead position	X	3.00		m	R_L
		Y	±5.20		m	R_L
		Z	-4.28		m	R_L

Mooring stiffness matrix have been calculated with Orcaflex linearization module. It has to be noted that:

- Configuration 2 is stiffer than Configuration 1 in surge due to the smaller line angle with horizontal in configuration 2.
- Configuration 2 is less stiff than Configuration 1 in heave due to the higher line angle with vertical in configuration 2.

5.1.6. Environmental conditions

Environmental conditions used for this study are given in Table 5-5 below.

TABLE 5-5 ENVIRONMENTAL CONDITIONS

Category	Variable		Value	Unit
Environmental conditions	Water density	ρ_w	1025,00	kg/m³
	Water depth	h	80,00	m
	Specific height	Hs	14,80	m
	Spectrum enhancement factor	γ	1,00	-
	Peak period	Tp	20,28	s

5.2. Description of the numerical model

5.2.1. Theoretical description of the numerical model

SPAR OWC motions RAOs are calculated with a frequency domain motion analysis based on the following equation according to Nemoh conventions:

$$(M + M_a)\,\ddot{X} = F_e\cos(\omega t - \varphi) - (B_{rad} + B_{lin})\dot{X} - (K_h + K_m)X \qquad (5\text{-}3)$$

Which could be linearized in frequency domain:

$$-(M + M_a)\,\omega^2 X_0 = F_e + (B_{rad} + B_{lin}) i\omega X_0 - (K_h + K_m) X_0 \qquad (5\text{-}4)$$

The motion can then be calculated:

$$X_0 = \frac{F_e}{(-(M + M_a)\,\omega^2 - (B_{rad} + B_{lin}) i\omega + (K_h + K_m))} \qquad (5\text{-}5)$$

With:

- M the inertia matrix;
- M_a the added mass matrix depending of wave frequency;
- Fe the wave excitation forces depending of wave frequency;
- B_{rad} the radiation damping matrix depending of wave frequency;
- B_{lin} the linearized quadratic drag damping matrix;
- K_h the hydrostatic stiffness matrix;
- K_m the mooring stiffness matrix;
- X the SPAR OWC motion depending of wave frequency,
- φ The phase of excitation loads.

The added mass matrix, the radiation damping matrix and the wave excitation forces (incident and diffracted waves) are calculated with Nemoh a Boundary Element Methods (BEM) code dedicated to the computation of first order wave loads on offshore structures [5] .

The mesh used has 1501 faces. To simplify the mesh and calculation, the internal water column is closed.

The expected extreme value ${}^{max}X$ for a sea state of duration T equal to 3 hours is calculated using the standard deviation σ_X of X and is equal to:

$${}^{max}X = \sqrt{2}\,\sigma_X \left(\sqrt{log\left(\frac{T}{T_{z,X}}\right)} + \frac{0.2886}{\sqrt{\log\left(\frac{T}{T_{z,X}}\right)}} \right) \qquad (5\text{-}6)$$

Where $T_{z,X}$ is the mean zero-upcrossing period defined as:

$$T_{z,X} = 2\pi \sqrt{\frac{m_{0,X}}{m_{2,X}}} \qquad (5\text{-}7)$$

With m_0 and m_2 the zero order and 2 order moment of the (one-sided) wave spectrum S_X:

$$m_{n,X} = \int_0^\infty \omega^n\, S_X d\omega \qquad (5\text{-}8)$$

The significant value ${}^{sign}X$ T is calculated using the standard deviation σ_X of X and is equal to:

$$sign_X = 2\ \sigma_X \qquad (5\text{-}9)$$

5.2.2. Limitations

Some limitations for this calculation are summarized in Table 5-6 below.

Table 5-6 Calculation limitations

	Theory	Hypothesis	Limitations
Ocean load model	Wave loads : Linear Potential Flow (1st order)	Non-rotational flow	
		Inviscid flow (viscous drag forces neglected)	Viscous effects on SPAR might be important due to large motions.
		Linear waves: wave amplitude small compared to wavelength [2]	Large waves considered are out of linear wave scope.
		Wave amplitude small compared to body dimensions (Keulegan-Carpenter number below 4 or 5)	Might not be verified for extreme waves.
		Motion of the body are small relative to body dimensions	Large displacements will be a limitation.
		The response is a narrow banded Gaussian process, so that the peaks are Rayleigh distributed	
		Nonlinear wave effects (second order or higher) do not affect body motions	Second order effects may induce large motion if natural frequencies are excited. Higher order effects may appear on stiff systems.
Mooring system model	Linear stiffness matrix	Force displacement relationship is linear	Large displacements will be a limitation.
		Lines in static equilibrium at all time	Dynamics of the lines are not modelled.
		Hydrodynamic loads on lines neglected (drag, inertia)	Viscous effects on lines might be important on SPAR motion.
		Elastic lines (linear elasticity)	Steel cables may have a non-linear stiffness.
		Flexion stiffness neglected	
		Torsion stiffness neglected	
		Internal friction neglected	
Motion	Frequency domain	Small motion around a mean position is assumed.	Large movements will be out of the theory scope.
		Hydrodynamics is linearized.	Hydrodynamic viscous effects on the floater can be important.
		Mooring system is linearized.	Hydrodynamic viscous effects on the lines can be important

5.3. Results

5.3.1. Response amplitude operator

Surge, Heave and Pitch motions Response Amplitude Operators (RAOs) of O_L in R_G are shown for both configurations in Figure 5-7, Figure 5-8 and Figure 5-9 below.

Surge motion RAOs show:

- A resonance at 0.33 rad/s, 0.73 rad/s and 1.07 rad/s respectively of 1.5 m/m, 1.9 m/m and 0.4 m/m for configuration 1;

- A resonance at 0.33 rad/s, 0.79 rad/s respectively of 1,1 m/m and 0.9 m/m for configuration 2;

Heave motion show:

- A resonance at 0.33 rad/s, 0.73 rad/s and 1.07 rad/s respectively of 2.8 m/m, 2.0 m/m and 0.3 m/m for configuration 1;
- A resonance at 0.33 rad/s, 0.79 rad/s respectively of 2.5 m/m and 1.2 m/m for configuration 2;

Pitch motion show:

- A resonance at 0.33 rad/s, 0.73 rad/s and 1.07 rad/s respectively of 7,9 deg/m, 7.4 deg/m and 0,7 deg/m for configuration 1;
- A resonance at 0.33 rad/s, 0.79 rad/s respectively of 5.2 deg/m and 4.7 deg/m for configuration 2;

Resonances are at the same frequencies for the 3 degrees of freedom due to mooring couplings. Resonances amplitudes and frequencies close to wave frequencies may induce large moments of the SPAR when subjected to extreme sea states. Linear potential flow theory is based on small movement around equilibrium position. Large movements of the SPAR are out of scope f the theory.

It is advised to modify the configurations to try to shift the resonance period out of wave frequency range. It could be interesting to lower surge stiffness and increase heave stiffness to displace surge resonance to low frequencies and heave resonance to high frequencies.

5.3.2. Vertical wave induced loads

Comparison of vertical wave induced loads and mooring vertical pre-tensions is shown for both configurations in Table 5-7 below. It shows that mooring vertical pre-tensions slightly lower than maximal vertical wave induced loads. Differences with preliminary parametric study come from the fact that the SPAR is considered horizontal for the wave loads calculation in the parametric study.

It is advised to decrease the ballast mass to increase pre-tension, and avoid line becoming slack.

It has to be noted that due to mooring couplings horizontal wave loads may induce vertical motions of the SPAR. Also, wave vertical induced loads are smaller for configuration 2 due to its deepest position.

TABLE 5-7 COMPARISON OF VERTICAL WAVE INDUCE LOADS AND MOORING VERTICAL PRE-TENSIONS

Category	Variable		Config 1	Config 2	Unit
Vertical load comparison	Maximal vertical wave induced load	$F_{z,wave}$	3.84E+06	2.93E+06	N
	Mooring vertical pre-tension	$F_{z,mooring}$	2.75E+06		N

Maximal vertical wave induced calculation methodology is explained in section 5.2.1. Mooring vertical pre-tension is calculated with the following formula:

$$F_{z,mooring} = -Mg + \rho \Delta g \quad (5\text{-}10)$$

With:

- M the total mass of the SPAR OWC;
- g the gravity acceleration;
- ρ the fluid volumic mass;
- Δ the SPAR OWC displacement.

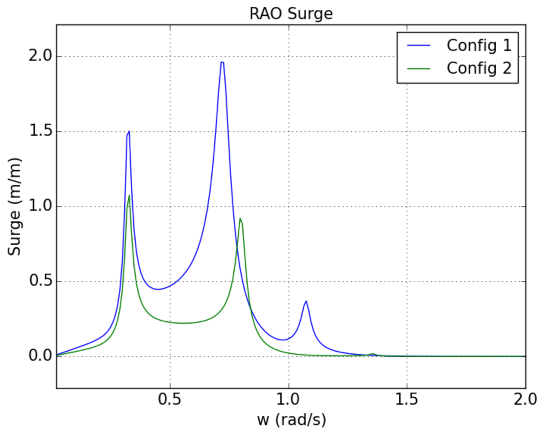


FIGURE 5-7 SURGE SPAR OWC MOTION RAO OF O_L IN R_G

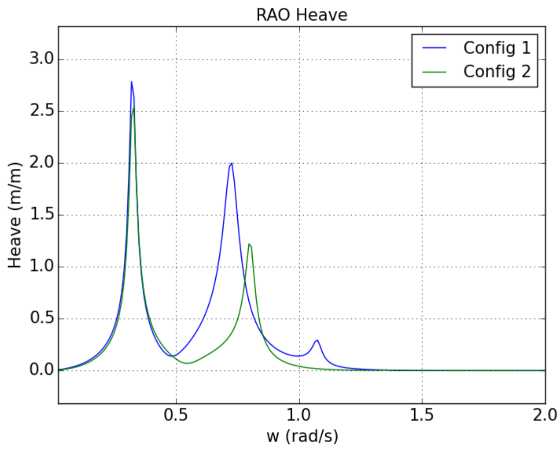


FIGURE 5-8 HEAVE SPAR OWC MOTION RAO OF O_L IN R_G

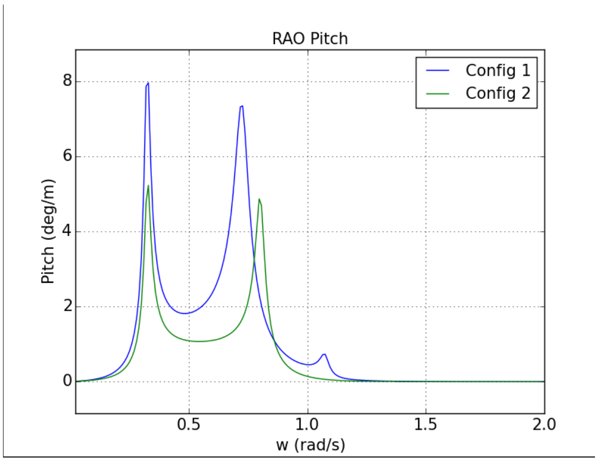


FIGURE 5-9 PITCH SPAR OWC MOTION RAO OF O_L IN R_G

5.4. Conclusion and further work

The study showed that the SPAR motions and the risk of collision with the seabed for both studied configurations are large for the considered sea state. Linear potential flow theory is based on small movement around equilibrium position. Large movements of the SPAR are out of scope of the theory. The configuration 2 showed smaller motions than the configuration 1 due to the fact that wave induced loads are smaller and mooring system is stiffer.

Further analysis could be done to minimize SPAR OWC motions:

- The mooring configuration could be modified to shift resonance out of wave frequency. It could be interesting to lower surge stiffness and increase heave stiffness to shift surge resonance to low frequencies and heave resonance to high frequencies. It could be interesting to study if it could be achieved by decreasing distance between anchors in order to decrease the angle between the lines and the vertical. Another configuration from the parametric study may be a better starting point from these considerations. It should be noted that the 2 studied configuration were chosen to have anchors positions close to initial anchors position from [26] (similar to the one from experimental work in section 6). Changing these positions may require adapting the operational mooring system or to use dedicated pulling lines and anchors. Those solutions were not studied in the present study.
- A less ballasted configuration could be tested to increase pretension and try to avoid line becoming slack. Another configuration from the parametric study may be a better starting point from these considerations.
- A more accurate estimation of quadratic damping values should be done.

6. 1:40 tank testing of survival loads and motions under stormy conditions

6.1. Design of the experiments

Within the Wetfeet project work package related to inter-mooring connections between devices within an array (WP6), experiments were performed at Plymouth wave tank, where it was seen that the reference case of the device had significant pitch. In this scenario, the mooring system consisted of three mooring lines attached to the top part of the device.

Besides this, also within the Wetfeet project, the effect of the so-called negative spring is analysed, where the impact of different configurations of the spar inner chamber, in the device performance, and in particular in the heave motion is performed.

If there is significant pitch motion of the buoy, it becomes difficult to understand which impacts can be correlated to heave and the negative spring effect, in the device performance. It was then seen needed to reduce the pitch motions of the buoy.

For this, an extra set of three mooring lines, similar to the ones used on the top part, were added to the lower end of the submerged part of the converter. These are rotated from the upper ones by 180º in order to avoid collision between the upper and lower mooring line. For the lower part, a slightly smaller radius is used to reduce the footprint area (see Table 6 2).

This mooring design with two set of mooring lines is also aligned with the goal of designing a submergence process, since they can be used as an active element of the submergence strategy. If the mooring lines are attached, both in the upper and lower part, to winch systems, the cables could be stretched to tension (while other eventually un-stretched) to reach the submergence position. The winches could be directly controlled and used to ensure and monitor the submergence process.

Taking this into account, a model created in Orcaflex was used, where the device mass and respective centre of mass were changed. Based on this, a parametric study was performed where the lengths of the mooring lines were gradually decreased, mimicking the winching system, to evaluate impact in the static submergence depth and inclination and line static tensions.

A similar analysis is performed, for an extreme sea state condition, to observe the influence in buoy position and dynamic loads in the moorings. Comparisons are done with the reference case scenario where the device is kept at surface during the storm. Based on this, a given set of configurations considered appropriate, were chosen and tested experimentally in the FloWave wave tank at a 1:40 scale, providing complementary insight on the motion and loads experienced by the spar buoy under extreme wave conditions.

6.2. Submergence by Water Ballasting

Considering the dimensions of the buoy, it was estimated that a total water volume of around 906 t would have to be pumped or allowed inside the buoy. However, the location of where this

water mass is placed inside the buoy is not necessarily obvious and will result in different vertical and horizontal centre of mass.

As mentioned before, in order to have the buoy submerged it was considered that it would be beneficial if the buoy would reach a horizontal or tilted position in order to reduce the force of the acting water particles (in storm condition) and to allow deeper submergences not constrained by the water depth (and length of the buoy). Therefore, a displacement in the horizontal centre of mass, from the equilibrium zero position, is considered beneficial. Regarding the vertical centre of mass, it should be such that it does not place the buoy in an unstable position (statically and dynamically).

Considering the buoy shape and construction, two main areas are identified as being possible to be filled with water, as they are in the initial design considered to be filled with air. These are the top floater and the lower cone shaped part of the buoy as seen in Fig. 1 marked in yellow.

Initially it was considered to fill up only the half top part of the floater section, in order to displace the horizontal centre of mass and force the buoy into a horizontal position. Different incremental methods where considered in order to achieve this in an incremental consecutive process, mimicking the submergence process. Each incremental increase of mass, will result in a different submerged position and angle.

The different incremental methods are related to the way the top cylinder is divided, in different chambers to be consequently filled, increasing the water mass and displacing the vertical and horizontal centre of mass. Three different approaches, illustrated in Fig. 6-1, are considered dividing the cylinder in H: horizontal slices, V: vertical slices or C: consecutive cylinders. The approach was applied to half of the top floater cylinder, in order to displace the centre of mass horizontally, as previously mentioned.

For each of these methods, two variations are possible, related to the order, or direction, by which the chambers are consecutively filled. For the case of the horizontal slices from bottom to top (Hbt) or vice-versa (Htb), for the case of the vertical slices from the center of the half circle to the outside (Vco) or vice-versa (Voc) and for the consecutive cylinders from inside to outside (Cio) or vice-versa (Coi).

To calculate the volume and therefore the mass of water for each chamber, simple geometric calculations were performed, while as for the centre of mass, the centroid theory was used for the different geometries. These calculations were later compared and verified with a SolidWorks model of the buoy.

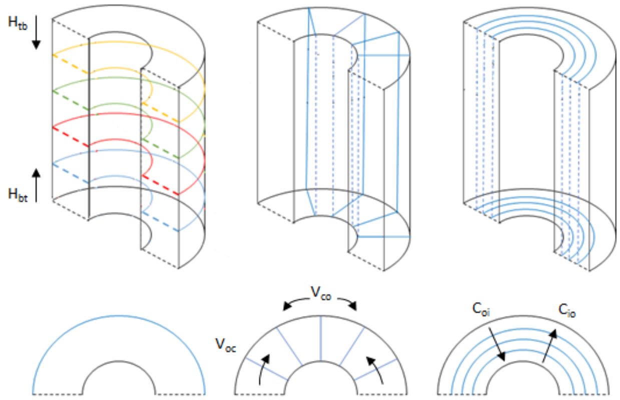


FIG. 6-1 - DIVISION METHODS USED FOR THE TOP FLOATER CYLINDER: HORIZONTAL SLICES, VERTICAL SLICES OR CONSECUTIVE CYLINDERS.

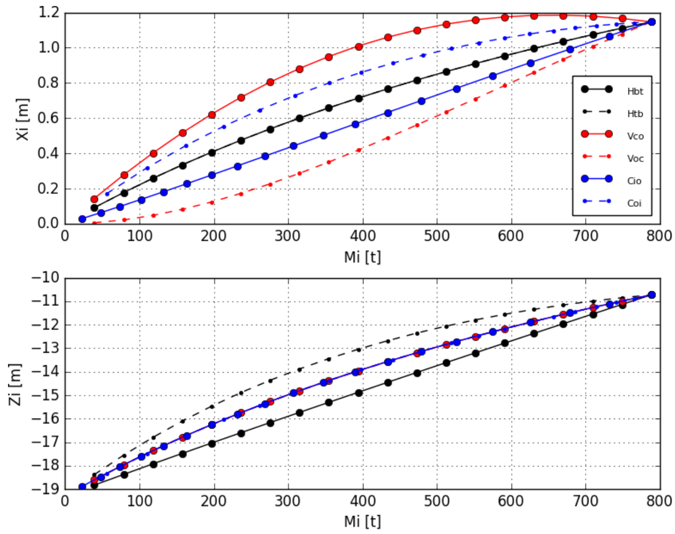


FIG. 6-2 – HORIZONTAL AND VERTICAL CENTRE OF MASS FOR THE DIFFERENT DIVISION METHODS WITH INCREMENTAL MASS INCREASE AS MORE CHAMBERS ARE FILLED.

These were used to calculate the different mass increment and consequently horizontal and vertical centre of mass. The results for the different methods are presented in Fig. 6-2. A division in 20 chambers is presented.

It can be seen that the methods that allows for a more favourable (in terms that a higher value of horizontal centre of mass will allow for a more horizontal submerged position) is the division of the top cylinder in vertical slices (Vco). This method is also interesting for reasons that will be explained in the next section.

It can be seen, as expected, that the end point, where the entire half of the cylinder is filled, is the same for every method. It also represents the maximum value of mass and displacement of centre of mass that can be obtained by filling up completely one half of the cylindric floater section.

This incremental values of total mass and centre of mass were applied to the developed Orcaflex model in order to calculate the submerged positions for each point. The results are presented in Fig. 6-3.

These points can be used to estimate and mimic the submergence process as water is consecutively introduced in the different chambers.

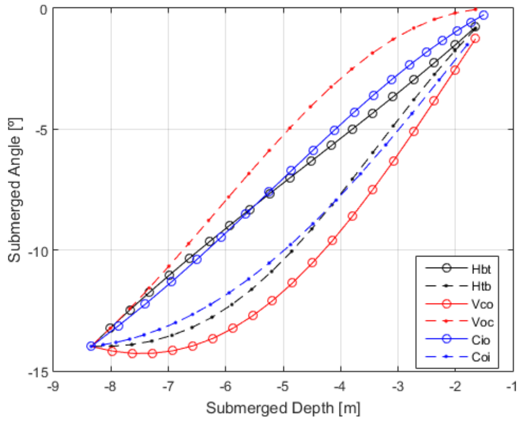


FIG. 6-3 – SUBMERGED POSITION, IN TERMS OF WATER DEPTH AND ANGLE OF THE BUOY, FOR THE DIFFERENT DIVISION METHODS AND INCREMENTAL CHAMBERS FILLED WITH WATER.

In fact, considering that the necessary water volume required is around 906 t, it can be seen that, considering the buoy dimensions, filling up the buoy top half part (around 729 t) is not sufficient and an extra mass is necessary (around 177 t). Regardless of this, the previous exercise is interesting as it provides insight on how to fill up extra required chambers and for the representation of the actual submergence process and the consecutive depths and angles obtained.

Different strategies are possible on how to reach this total mass. This can be either in the in the lower part of the buoy (total capacity around 285 t) or other side of the top half (total capacity around 729 t), as mentioned previously. An additional option would be to have the possibility to close the inner tube (which was around 951 t capability), with a mid-water column butterfly valve. However, this configuration was considered to not be practical in physical terms and abandoned.

Taking these remarks into account, different submerged configurations are possible to obtain or to be considered. This is illustrated in Fig. 6-4. The section in the buoy in black represents the parts of the buoy that would be filled (totally or partially) with water.

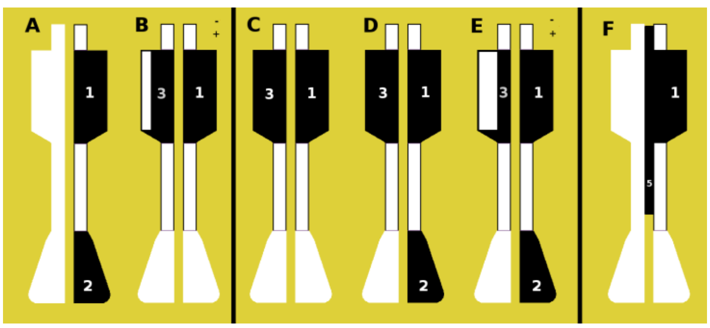


FIG. 6-4 - REPRESENTATION OF THE DIFFERENT POSSIBLE SUBMERGENCE STRATEGIES.

Configuration A represents the scenario where half of the top floater section is fully filled with water together with the lower section in an amount starting from the base of the buoy to match the necessary water volume.

Configuration B is the scenario where besides the half top part being filled, the necessary extra water mass is filled on the other side of the cylinder. For this purpose, the submergence process studies in the previous section suggest that the more favorable method of filling the other side of the floater are the with vertical slices (option Vco) since it is the one that allows for a lower increase range of the horizontal center of mass. Given that, in practical terms, the top cylinder would be divided in chambers (to avoid water sloshing and as studied in the previous section), in fact two variations of the B configuration were studied. One (B-) where the number of chambers used is almost enough to reach the mass but does not exceed it (equivalent to floor function) and another (B+) where it is guaranteed that there is at least the required value of mass, even if exceeding (ceil function).

The results in terms of extra and total mass and horizontal and vertical centre mass, for the different strategies, are presented in Fig. 6-5. It can be seen that the different configurations represent different centres of mass which will result in different submerged depth positions and angles.

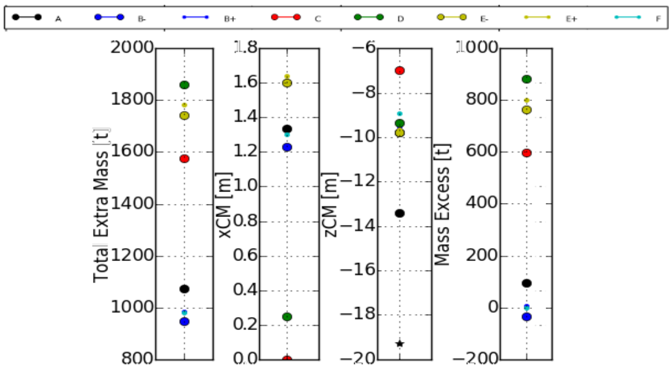


FIG. 6-5 – EXTRA MASS, HORIZONTAL AND VERTICAL CENTER OF MASS AND EXCESS MASS IN RELATION TO MASS NEEDED TO SUBMERGE BUOY, FOR THE DIFFERENT STRATEGIES.

As before, the values were introduced in Orcaflex in order to calculate the submerged positions for configurations A and B±. These configurations are the ones where the mass is just, or slightly less, than the one necessary to submergence the buoy (extra submergence from mooring lines winching).

Extra configurations (C - entire top floater filled with water, D - top floater and half-bottom part filled and E - similar to B but also half-bottom part filled) could be considered where the mass increase is larger than the necessary, forcing the buoy to sink to the bottom and where an extra floater would be released and filled with air in order to keep the buoy in a hydrodynamic equilibrium midway the surface and the bottom.

This extra floater would be released from the buoy, to counteract the extra exceeding mass and allow for an equilibrium point. It would be released from the buoy and filled up with air, through air pumps existing in the buoy. However, given the technical difficulties and impracticalities that such approach would result in, namely in terms of re-submerging the buoy, as is explained next, this approach was also abandoned.

6.3. Submergence Strategies Submergence by Cable Winching

Since only either a floating or submerged sunk position are stable equilibrium points, the water pumping method is considered to be used only to a point that the device is barely floating and the remaining downwards vertical pull to fully submerge, will come, not from weight, but from the moorings pulling force.

It is then proposed that, besides the devices having water pumps, to have also winches to which the mooring cables are attached to, which after (or while) the water pumping is performed; are used to further submerge the buoy, by winching the cable, reducing their lengths (or slacking them depending on the cable considered).

This method has another advantage, related to the emergence process and return of the device to the normal floating position, after the storm has passed. In this case, after the severe weather conditions have passed, it is only a matter of restoring the mooring cables to normal length and the device can reach the surface. Once it does, it is possible to use the water pumps to pump the water out, pumping air in, that enters the buoy from the section of the device which is reaching the surface.

Initially the cables that were considered to be actively used to hold the device in the submerged position were the pair of cables 2|3 and 5|6. The remaining cables 1 and 4, were considered to have a cable length long enough for their tensions to be negligible compared to the other ones.

Starting from the semi-submerged position resulting from water ballasting (starting point marked in red in Fig. 6-6 and Fig. 6-7), the length of these two set of mooring cables 2|3 and 5|6 were varied in a parametric study to perform further submerging and to analyse, initially, the influence in static position and static mooring force and following, in storm conditions in a set of extreme waves (Hs = 12 m and Tp = 18 s).

The static forces and maximum loads in the moorings were then compared to the ones in the reference case where the device is kept at surface during the storm.

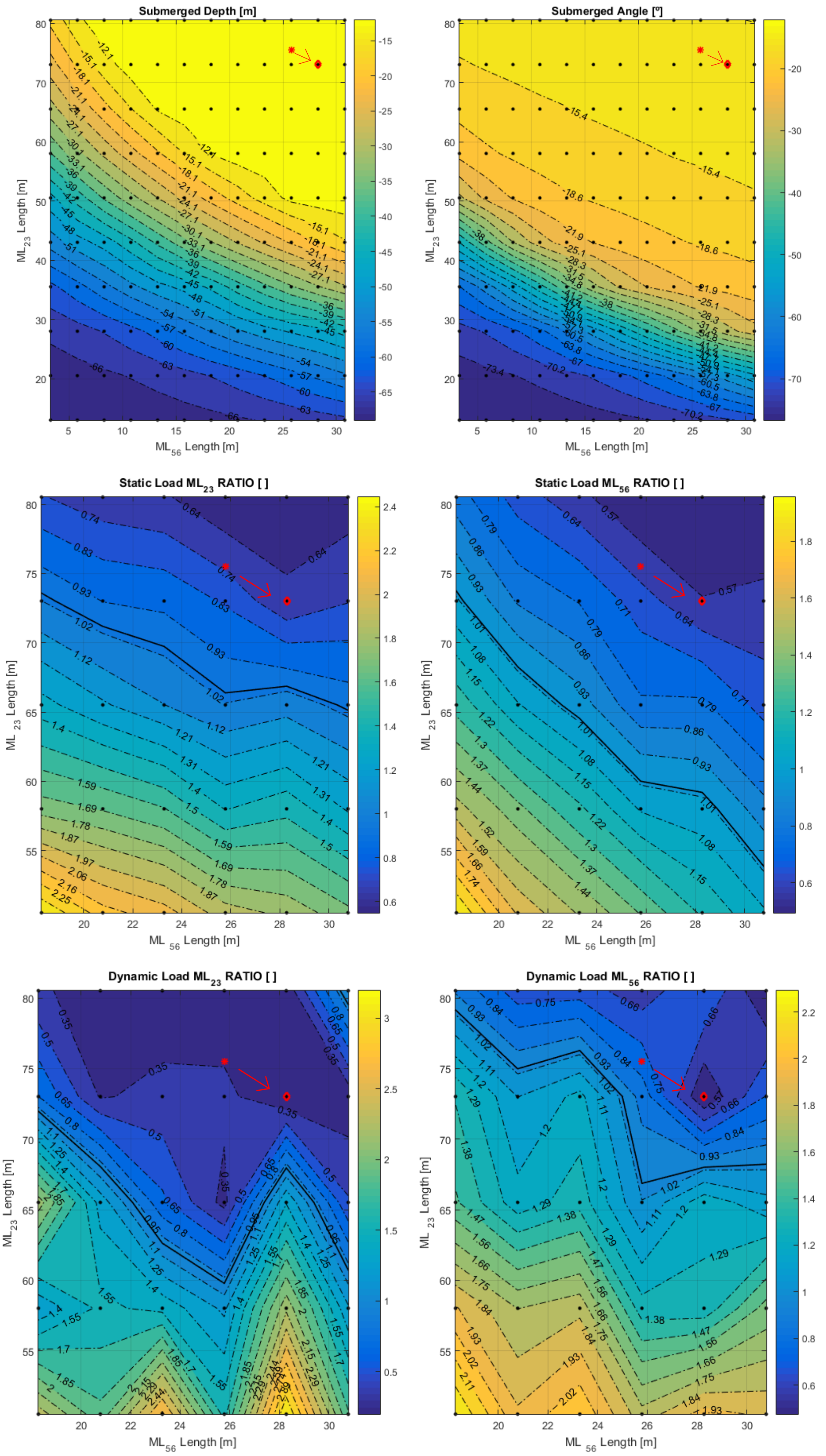
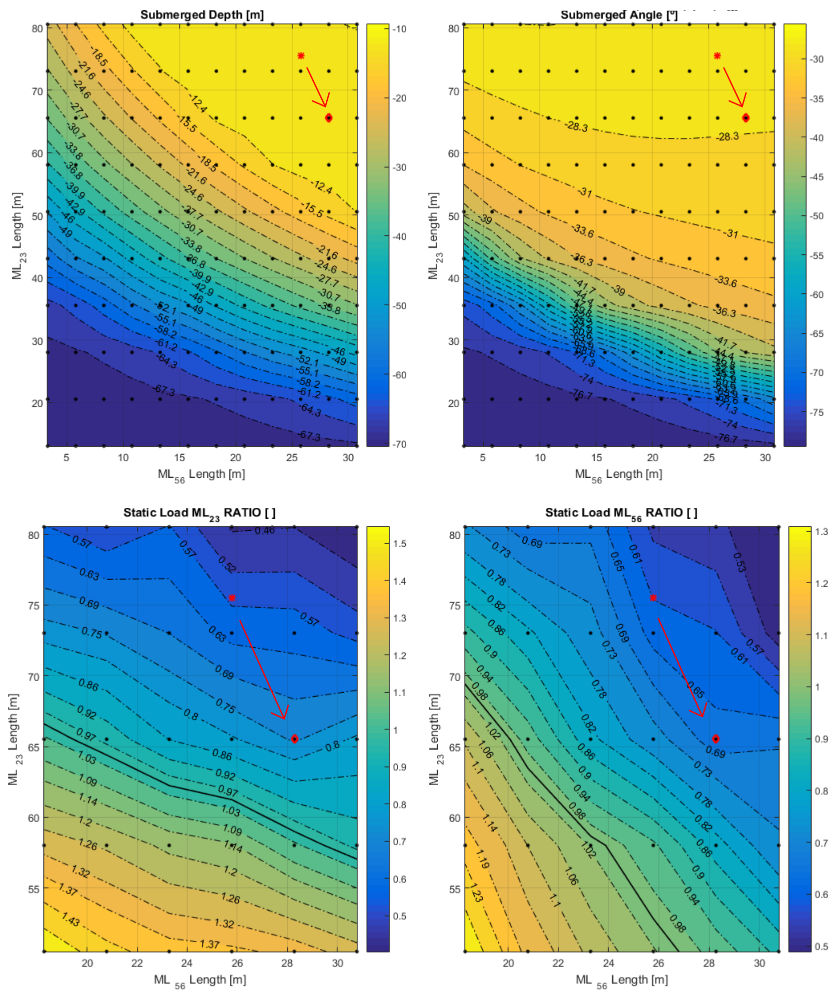


FIG. 6-6 - MOORING LINE LENGTH PARAMETRIC STUDY FOR CONFIGURATION A.

The limitation in terms of cable length that can be winched is (besides the physical limitation of the winches themselves), related to the original length of the first cable section between device and sink weight.

Both a slight increase of cable length (un-winching) and a decrease up to the point where the clump weight reaches the device were considered. Further focus is given in a reduction up to half length of the first section, since further than these resulted in significantly larger static and dynamic loads in the cables. In the case of un-winching, this would be done, by realising cable previously coiled, increasing the cable length.

From these results a set of points (marked red as final points in Fig. 6-6 and Fig. 6-7), were chosen to be used as submerged positions (in the following experimental work) for the different configurations.



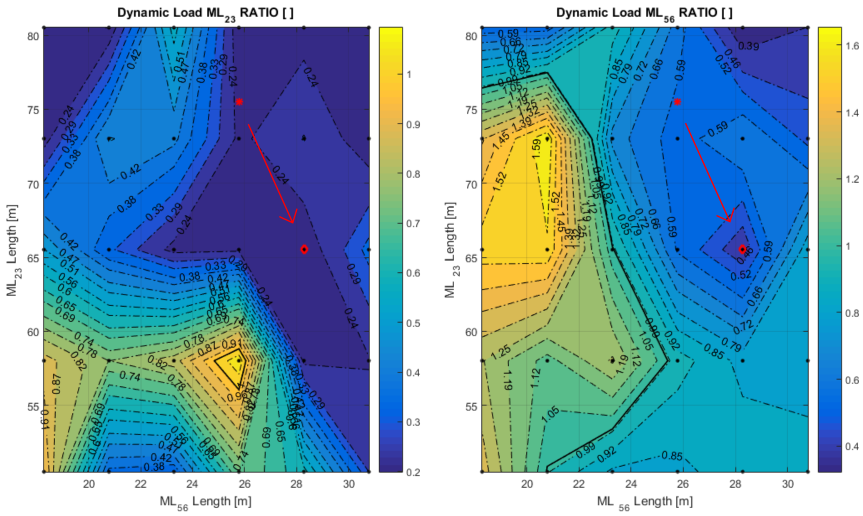


FIG. 6-7 – MOORING LINE LENGTH PARAMETRIC STUDY FOR CONFIGURATION B-.

The points were chosen in order to reduce as much as possible the maximum dynamic loads in storm condition, in the range where the loads are smaller than the reference case (ratio = 1 marked as solid line).

Fig. 6-6 presents the parametric analysis performed for configuration A while Fig. 6-7 for configuration B+.

Having defined the lengths of cables 2|3 and 5|6, their lengths were fixed and the remaining cables 1 and 4 lengths varied in a similar parametric study to assess if their lengths should be increased or decreased to better accommodate the displacement of the submerged buoy. The final values used can be seen in Table 6-7.

6.4. Experimental Testing

6.4.1. Flowave Tank Test

The FloWave Ocean Energy Research Facility is a unique asset for developing and testing marine energy devices. The tank is 25 m diameter and has a working test volume depth of 2 m. Because the tank is circular and therefore non-directional, waves and currents can act in any combination and in any relative direction across the large central test volume. A rising tank floor enables quick and easy installation of individual wind, wave or tidal devices, or arrays of them.

6.4.2. Model Scaling

The experiments were performed at 1:40 scale, with scaling performed according to the standard Froude scaling. The model values are the following (Table 6-1 and

Table 6-2):

TABLE 6-1 – EXPERIMENTAL MODEL PARAMETERS.

Geometry	Real scale	Part Scale	
Depth	80	2	*m*
Buoy Height	50,991	1,275	*m*
Buoy Draft	35,985	0,8996	*m*
Top buoy diameter	12,000	0,3000	*m*
Lower max diameter	13,218	0,3305	*m*
Inertial	**Real scale**	**Part Scale**	
Buoy Weight	1,22E+06	19,016	*kg*
Iyy	3,25E+08	3,1699	*kg m²*
Izz	2,91E+07	0,2842	*kg m³*
*Center of Mass**	19,268	0,4817	*m*
*Center of Buoyancy**	18,042	0,4511	*m*

**distance from MWL (Mean Water Level)*

TABLE 6-2 – EXPERIMENTAL MOORING PARAMETERS.

Moorings	Real scale	Model Scale	
Upper Set			
Mooring Radius	210	5,25	*m*
Length of line section 1	75,515	1,888	*m*
Length of line section 2	114,645	2,866	*m*
Length of chain laid (section 3)	46,3	1,158	*m*
Chain weight per unit length	4800	3	*N/m*
Clump weight (on rope) dry mass	73270,7	1,144855	*kg*
Position of clump weight (dist. from fairlead)	75,515	1,888	*m*
Number of floats in section 2 [-]	6		
Float net buoyancy	9843,69	0,154	*kg*
Lower Set			
Mooring Radius	150	3,75	*m*
Length of line section 1	25,78	0,645	*m*
Length of line section 2	61,75	1,544	*m*
Length of chain laid (section 3)	68,1	1,703	*m*
Chain weight per unit length	4800	3	*N/m*

Clump weight (on rope) dry mass	16133,3	0,252083	*kg*
Position of clump weight (dist. from fairlead)	25,78	0,645	*m*
Number of floats in section 2 [-]	1		
Float net buoyancy	230,91667	6 x 0,004	kg
cables			
Elasticity	350	8,75	kN

6.4.3. Experimental Setup

Given the tank characteristics, with pre-defined anchoring points spread out through the wave tank floor, some adjustment had to be done to both the horizontal distance between the device and the different anchoring points and the length of the chain portion laying in the bottom. The errors or differences of these adjustments, when compared to the initial design introduced, is reflected in Table 6-3.

TABLE 6-3 – EXPERIMENTAL ERRORS IN POSITION FOR THE DIFFERENT CABLES (REAL SCALE).

cable	Initial Design		Lab Setup		diff [%]	
	D [m]	angle [º]	D [m]	angle [º]	D	angle
1	210	0	213,64	0,8	1,73	
2	210	120	199,84	119,7	-4,84	-0,25
3	210	-120	210	-118,1	0	-1,58
4	150	180	141,6	178,9	-5,6	-0,61
5	150	300	151	300,08	0,67	0,03
6	150	60	161,16	57,9	7,44	-3,5

TABLE 6-4 – EXPERIMENTAL DIFFERENCES IN PARAMETERS.

	Position [m]			Orientation [deg]		
	X	Y	Z	Rot.1	Rot. 2	Rot. 3
initial	0	0	-1,292	0	0	0
lab	0,238	0,02	-1,397	0,011	0,091	-0,284
diff	0,24	0,02	-0,11	0,01	0,09	-0,28
	Upper mooring tension [kN]			Bottom mooring tension [kN]		
	cable 1	cable 2	cable 3	cable 4	cable 4	cable 5
initial	348,2	348,2	348,2	338,93	338,93	338,93

lab	340,88	345,94	346,54	355,67	337,51	338,34
diff %	-2,15	-0,65	-0,48	4,71	-0,42	-0,18

This new configuration was introduced in the numerical model to analyse the influence in the static position and mooring loads experienced by the device. The results are presented Table 6-4.

The model device was constructed in fibre glass and a slight difference in the total mass existed, but this was seen not to be relevant (see Table 6-5) and was accordingly compensated in the numerical model.

TABLE 6-5 – DEVICE MASS COMPARISON BETWEEN REAL SCALE AND MODEL SCALE.

Model Scale	Real Scale	diff	diff %
19,61 kg	1255040 kg	37640 kg	3,092 %

The extreme sea wave conditions used to simulate a storm condition were limited by the tank capabilities and are the ones presented in Table 6-6.

For the purpose of comparison, the device was initially tested in the reference configuration, meaning it would stay at the sea surface during the occurrence of a storm. This is considered the baseline reference case and the initial mass and mooring line lengths are used.

TABLE 6-6 – SURVIVABILITY CONDITIONS TESTED.

Sea State	H_s [m]		T_p [s]	
	model scale	real scale	model scale	real scale
SS1	0,22	8,8	2,72	17.2
SS2	0,2	8	2,91	18.4
SS3	0,18	7,2	3,06	19.35
SS4	0,17	6,8	3,21	20.28

TABLE 6-7 - SUBMERGENCE CONFIGURATIONS (REAL SCALE).

Mechanism	Characteristic		A	B-	B+
water ballasting	**Horizontal CM [m]**		**1,18088**	**1,14644**	**1,1524**
	Vertical CM [m] (MWL)		**-13,819**	**-10,177**	**-9,9596**
	Extra Mass [t]		**847,808**	**875,136**	**911,616**
cable winching: <u>upper moorings</u> (cable section	**Original Length [m]**	cable 1	75,52	75,52	75,52
		cable 2 & 3	75,52	75,52	75,52
	Variation length [m]	cable 1	20,00	0	0
		cable 2 & 3	*-2,5*	*-10*	*-17,5*

device-weight)	**Final Length [m]**	**cable 1**	**95,52**	**75,52**	**75,52**
		cable 2 & 3	**73,02**	**65,52**	**58,02**
cable winching: **<u>lower moorings</u>** (cable section device-weight)	**Original Length [m]**	cable 4	25,78	25,78	25,78
		cable 5 & 6	25,78	25,78	25,78
	Variation length [m]	cable 4	20,00	*12,00	*12,00
		cable 5 & 6	2,5	2,5	2,5
	Final Length [m]	**cable 4**	**45,78**	***37,78**	***37,78**
		cable 5 & 6	**28,28**	**28,28**	**28,28**

After the initial reference case was performed, for the four sets of storm wave conditions mentioned, with the corresponding motions and tensions forces being registered, three submergence configurations were set up and tested, with different increases of mass and/or change in mooring line lengths (in the device-weight section of the cable). A summary of the conditions (JONSWAP spectrum) can be seen in Table 6-7

Given the physical limitations of the model constructed, it was not possible to place directly water inside the device. Therefore, in order to mimic the mass increase through water pumping inside, lead weights were added outside the device, in pre-calculated positions. This was done in way that the corresponding vertical and horizontal centre mass would match as much as possible the corresponding submergence configuration with water mass inside.

Since this results in further water mass being displaced by the system device plus extra weights, additional mass had to be added in order to compensate for the extra buoyancy. An illustration of the submerged experimental layout, with the weights added to the outside of the buoy, can be seen in Fig. 6-8.

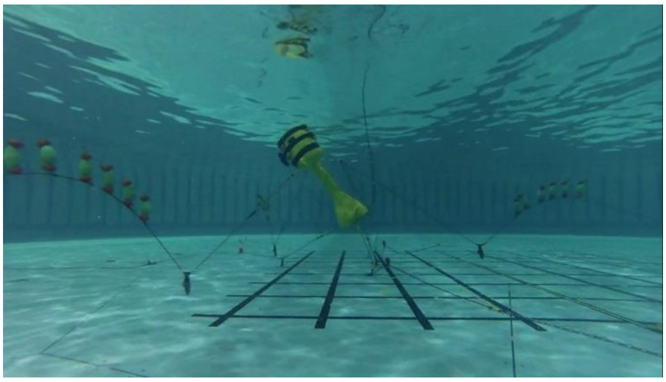


FIG. 6-8 – WAVE TANK PICTURE OF TESTS FOR SUBMERGENCE CONFIGURATION B+.

For the purpose of measuring the position of the buoys both an underwater video motion capture system (Qualisys) and an accelerometer were used. To measure the tensions in the mooring lines, four load sensors (Interface WMC-100, submersible sensor, range 450 N, precision ±0.15) were placed in some of the attachment points between the mooring line and the device. The attachments were chosen in order to be representative of the overall system

considering the symmetry in relation to the incoming wave direction, so that loads would be measured in symmetric lines (see Fig. 6-9).

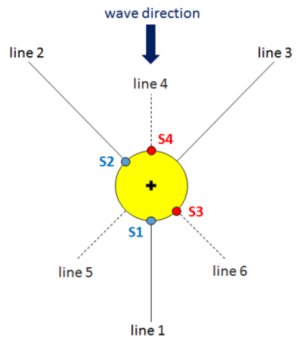


FIG. 6-9 – SCHEMATIC OF MOORING ARRANGEMENT AND LOAD SENSORS POSITION. TOP VIEW.

For the upper mooring set, S1 is the sensor that represents the loads in mooring line 1 and S2 the sensor for mooring line 2 (and as a result of symmetry similar to mooring line 3). For the lower mooring set, S3 is the sensor that represents the loads in mooring line 6 (and as a result of symmetry mooring line 5) and S4 the sensor for mooring line 4.

6.4.4. Experimental Results

As mentioned before load sensors were used to measure the loads on the mooring lines and a video position acquisition system was used to register all 6 degree of motion of the buoy. The data was used to compare the different submerged configurations with the reference case where the buoy is left at the free surface during the occurrence of the storm.

Results are presented in terms of a ratio in relation to the reference case, for both the means and maximum loads and positions. A value lower than 1 indicates that it is favourable when compared to the reference case. This is especially meaningful when referring to the loads the moorings experience.

Fig. 6-10 presents the results for the 4 different sensors (S1-S4) mean and maximum loads in each configuration and sea state and Fig. 6-11 the ratio of the mean position and Fig. 6-12 the ratio of the maximum position.

During the test it was seen that line 4 in configuration B- presented some snapping loads so it was decided to add an extra section (of 12 m) of cable to cable 4 in order to avoid this. In the experimental results presented next, the initial configuration is then referred to as B-0 while the improved or altered configuration with extra cable section as B-. This also gives further insight to the influence of the cable (un)winching in submerge position.

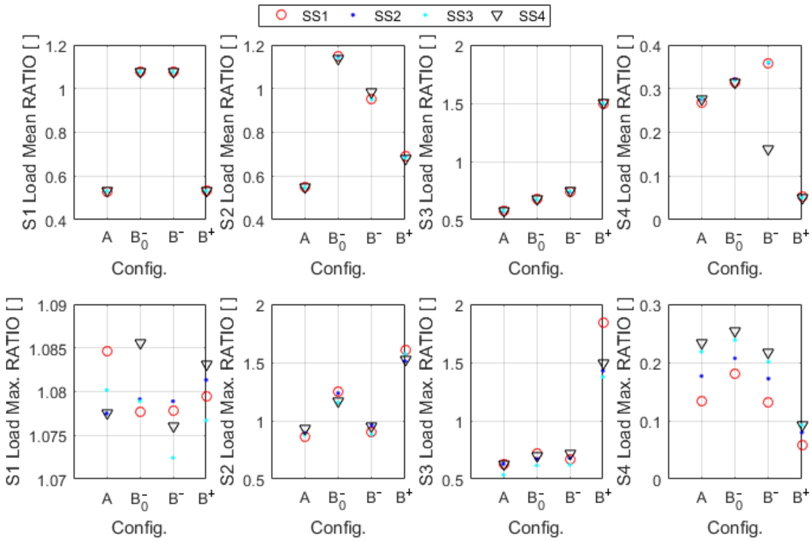


FIG. 6-10 - S1-S4 SENSORS MEAN AND MAXIMUM LOADS IN EACH CONFIGURATION AND EXTREME SEA STATE. SEA STATES SS1-SS4 AS IN TABLE 6-6.

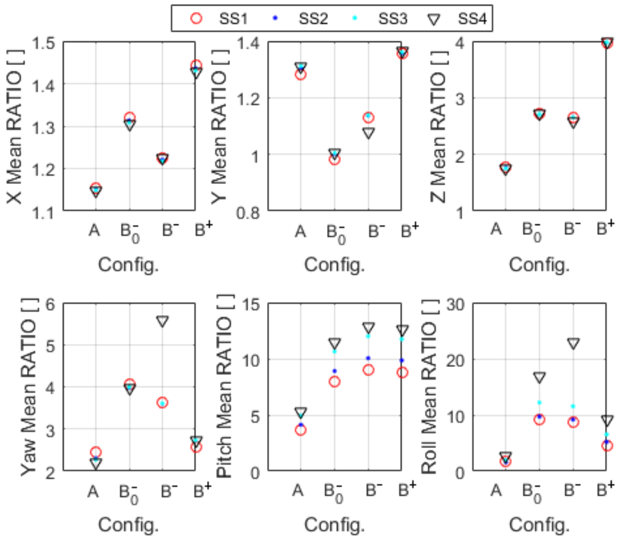


FIG. 6-11 - DEVICE MEAN POSITION FOR THE DIFFERENT MODES AND FOR EACH CONFIGURATION AND EXTREME SEA STATE. SEA STATES SS1-SS4 AS IN TABLE 6-6.

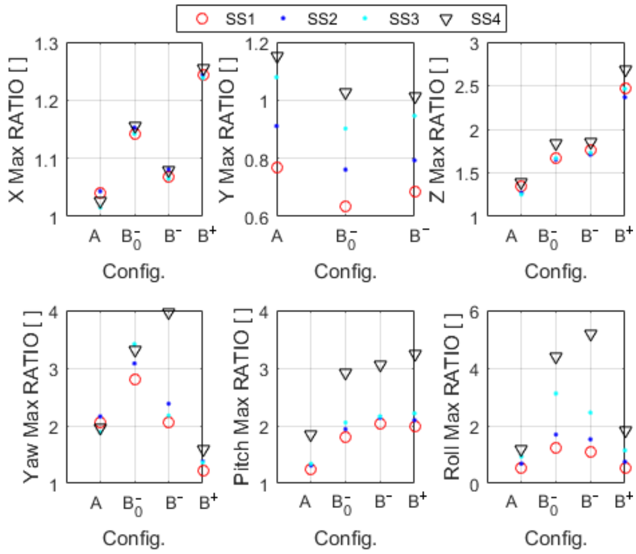


FIG. 6-12 - DEVICE MAXIMUM POSITION FOR THE DIFFERENT MODES AND EACH CONFIGURATION AND EXTREME SEA STATE. THE SEA STATES SS1-SS4 AS IN TABLE 6-6.

From this results an understanding on which configuration might be more suitable for a submerged position can be drawn. It can be seen that although configuration B+ was a lower mean tension in most of the mooring lines (except S3), it has maximum tensions bigger than the reference case (except S4) and therefore making it an inappropriate configuration.

When comparing B-0 and B- it can be seen the added benefit of un-winching some pre-stored cable in mooring line 4 since it yields both lower mean and lower maximum tensions for most mooring lines, especially for S2.

From all the configurations, A is clearly the one that seems more favourable, as it is the one that presented lower mean tension in all the lines (except S4: bottom mooring line 4, but still better than reference case) and on average lower maximum tensions on all the mooring lines. It is also the one that presents smaller mean and maximum motion (when compared to the other configurations) in most of the degree of motion of the device.

The experimental results were also compared with the results from Orcaflex for similar wave conditions (SS1). A comparison of the ratio in relation to the reference case can be seen in Fig. 6-13. The mean and maximum load ratios in relation to the reference case are presented for the different submerged configurations analysed. It is seen that the Orcaflex model in general underestimates the maximum loads ratio andmore precisely estimates the mean loads in the upper moorings but not as precisely the ones in the lower set. This might be due to the fact that the moorings in the lower seat are more tight and subject to snap loads, which the lump-mass mooring model implemented in Orcaflex might not be able so well to estimate. The same is truth for the maximum loads estimation.

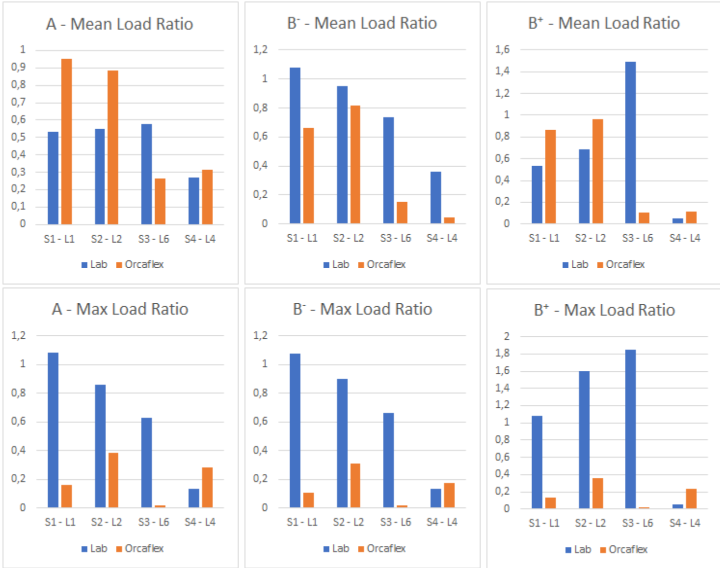


FIG. 6-13 - COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL RESULTS FOR SS1. MEAN AND MAXIMUM LOAD RATIO, FOR DIFFERENT STRATEGIES.

6.5. Conclusions Drawn from the Experimental Work

From both the numerical analysis performed in Orcaflex and consecutively the experimental work performed at the FloWave tank, it was seen that a submergence strategy could be a feasible and valid strategy for a device to survive a storm condition, reducing the loads the mooring lines are subject to and therefore the risk of breaking, representing a possible breakthrough for wave energy devices.

Different strategies, related to the location of the extra added water ballast, were compared, and some, namely using both the top and bottom part of the device, appeared more favourable in terms of mooring dynamic load in extreme events. For this configuration, the results obtained suggested reduction in the maximum dynamic loads in the mooring lines up to around 80% in the upper moorings and up to around 30% in the lower mooring cables. Overall reduction of around 50% in the mean tensions. Cable 1 is the one where the reduction is not seen (although not worsen), indicating that perhaps the cable should have been made even longer.

7. Conclusion

Some floating WECs, such as the OWC spar buoy, are operating on the surface of the ocean and - as a result - are fully exposed to storms. This is a challenge for survivability of wave energy technology (and any surface-floating structure in the ocean). Survivability has an utmost importance in the relatively high upfront capital cost of WEC prototypes deployed offshore. Device submergence is proposed as a breakthrough concept in the WETFEET project.

The objective of this study has been to investigate the submergence of the Spar OWC as survivability strategy. This study has focused on a single device.

First, a functional analysis of the submergence breakthrough has been performed to better understand the main issues related to the Spar OWC design concept, the missing information and the choices to be made. A review of existing submergence process from existing WEC and other industrial process has been realized leading to considerations on potential means to submerge a system and specificities of the Spar OWC system.

The engineering analysis began with a review of potential impacts of the integration of submergence system on the original spar OWC design, and of technical topics to investigate. A FAST diagram has been established to find some solutions on how to submerge the OWC. Risk analysis and experts interview have been performed to complete the investigation and establish the list of topics to investigate. From the solutions identified within the FAST diagram it has been decided to focus on solutions where the Spar is ballasted and the mooring lines are taut to achieve submerged configuration. Then components and technologies have been investigated.

Ballasting needs have been studied with a parametric study aiming at getting some insight on the significant parameters, and defining preliminary values in order to search submerged configurations.

This study also permitted to define submerged configurations (submerged depth, tilt angle and lines configuration) to be further analyzed with a motion analysis in the frequency domain. This motion analysis showed that the configurations had natural frequency within wave frequency range. Further analysis is needed to try to adapt these configurations to reduce loads and motions. Preliminary analysis of impact of the addition of a submergence system on the hull and PTO have been performed, it has been highlighted that pressurizing the air chamber may be a solution to adapt to high hydrostatic pressure during submergence. Solutions to submerge and emerge the Spar have been studied focusing on constructive solutions using pumps, valves and winches. Sequence to submerge / emerge, mooring and cable technologies have also been studied. Mean to have energy available should be further studied.

From the engineering analysis, component and technology which are identified as the most challenging are the tensioning system, the solutions to manage mooring lines during submergence operations, the PTO protection, and the automation of the operations (including SCADA system and sensors) – see components and technology scoring matrix.

- Regarding the tensioning system, at least 4 tensioning systems are needed which need to be powered, and the choice of tensioning systems is depending on the choice of

mooring line type. Subsea winches have been studied. High tensions have been highlighted in the mooring lines, which induce large capacity equipment requirements not available on the market. This equipment also presents some significant challenges of maintenance to be available for service life and are expected to be costly. Subsea additional winches may also be needed to manage some mooring lines during submergence operations to avoid their collision.

- The PTO protection presents also some major challenges if it shall be protected from water during submergence. An alternative may be to develop a PTO designed to allow submergence without specific operations (as activation of mechanisms to close a dedicated dry chamber). This point should be studied in further details.
- Finally, automation of the submergence operation for service life with permanent availability is identified as a major technical challenge which impacts many component of the submergence. High risks have been identified on this topic: repeatability of the process because of changing environment (excitation loads, bio-fouling, corrosion, etc.), high costs.

In parallel to the engineering analysis, a 1:40 tank testing of survival loads and motions under stormy conditions have been performed. Several different configurations were tested, representing different submergence strategies related to the storage position of the ballast water. Conclusion from the experimental work are that from both the numerical analysis performed in Orcaflex and consecutively the experimental work performed at the FloWave tank, it was seen that a submergence strategy could be a feasible and valid strategy for a device to survive a storm condition, reducing the loads the mooring lines are subject to and therefore the risk of breaking, representing a possible breakthrough for wave energy devices.

The engineering analysis and the experimental work has focused on the solution of submergence which considers the use of winches and ballast, with taut mooring lines to achieve submergence (combining these two solutions was intended to decrease necessary pulling force). Other solutions may be studied, as for example laying the Spar on the Seabed (horizontally or vertically), use of surface buoys and neutrally buoyant structure through addition of more ballast.

BIBLIOGRAPHY

[1] R. Alcorn and D. O'Sullivan, "Electrical Design for Ocean Wave and Tidal Energy Systems," *IET- Institution of Engineering and Technolog*y, 2013.
[2] API17-L1, Specification for Flexible Pipe Ancillary Equipment, 2015.
[3] API17-L2, Recommended Practice for Flexible Pipe Ancillary Equipment, 2013.
[4] AWS D11 Structural welding code– steel, 2000.
[5] A. Babarit, G. Delhommeau, "Theoretical and numerical aspects of the open source BEM solver NEMOH". In *Proc. of the 11th European Wave and Tidal Energy Conference*, 2015.
[6] BARLTROP, Nigel DP (ed.). Floating Structures: a guide for design and analysis. Oilfield Pubns Inc, 1998.
[7] C. Barlier, R. Bourgeois, « Mémotech Plus, Conception et dessin, » 2007.
[8] M. Bozorgmehrian et al., "Mooring systems for offshore floating installations Trends & Technology", 2013.
[9] M. Carcas, "The Pelamis Wave Energy Converter – A phased array of heave + surge point absorbers". 2004. http://hydropower.inl.gov/hydrokinetic_wave/pdfs/day1/09_heavesurge_wave_devices.pdf, Accessed 25/04/2017.
[10] S. Chakrabarti, "Handbook of Offshore Engineering (2-volume set)". *Elsevier*, 2005.
[11] R.G. Coe, V.S. Neary, "Review Of Methods For Modeling Wave Energy Converter Survival In Extreme Sea States," in *Proceedings of the 2nd Marine Energy Technology Symposium,* 2014.
[12] G. De Roux, "Projet CLOV", Total – La défense, Coupose, April 8th, 2015.
[13] DNVGL-SE-0163 "Certification of tidal turbines and arrays", October 2015
[14] DNV, "DNV-OS-E301 Position Mooring", May 2014.
[15] DNVGL-OS-E302 Offshore Mooring Chain, DNVGL, July 2015.
[16] DNV, "DNV-RP-C202 Buckling Strength of Shells", January 2013.
[17] DNV, "DNV-RP-C205 Environmental Conditions and Environmental Loads", April 2014.
[18] DTOCEAN Deliverable 3.1 – "State-of-the-art assessment and specification of data requirements for electrical system architectures," 2014.
[19] EN ISO 15641-1 Milling cutters for high speed machining — Safety requirements, 2001.
[20] M. Guerinel, et al. "Submergence Study Technical Note," V2.0, Technical Note, WAVEC, WETFEET project WP2, June 2016.

[21] J. Lucas, "The dynamics of a horizontal cylinder oscillating as a wave energy converter about an off-centred axis," The University of Edinburgh, 2011.
[22] Marintek, "Mimosa 6.3 User Manual", 2010.
[23] L. Marquis, et al., "First Power Production Results from the Wave Star Roshage Wave Energy Converter", 3rd International Conference on Ocean Energy, 2010.
[24] Orcina, "OrcaFlex Documentation - Chain: Mechanical Properties", 2014.
[25] Pelamis Wave Power, "P-750 Wave Energy Converter," [brochure], Pelamis Wave Power, p2. http://ctp.lns.mit.edu/energy/files/pelamisbrochure.pdf, Accessed 25/04/2017
[26] P. C. Vicente, et al., «Moorings for the Negative Spring and Submergence studies," V2 second draft, WAVEC, 2016.
[27] P. C. Vicente, et al., « Submergence parametric study," V1 first draft, WAVEC, 2016.
[28] Vryhof, "Anchor manual", 2010.
[29] WETFEET, Deliverable 2.1, "Designs and specifications of an OWC able to integrate the negative spring," 2016.
[30] WETFEET, Deliverable 2.3, "Engineering challenges related to full scale and large deployment implementation of the proposed breakthroughs," 2016.
[31] http://www.abcosubsea.com/bend-limiters
[32] https://www.arrecifesystems.com/
[33] http://breakingenergy.com/2015/02/26/aussie-wave-energy-deployment-makes-splash-but-next-project-will-be-real-test/
[34] https://www.commonspace.scot/articles/10372/belgian-marine-experts-test-scottish-waters-brexit-storm-approaches
[35] http://www.emec.org.uk/about-us/wave-clients/aquamarine-power/
[36] https://en.wikipedia.org/wiki/RP_FLIP
[37] https://fr.wikipedia.org/wiki/Function_analysis_system_technique
[38] http://www.interoceansystems.com/vps.htm
[39] http://www.laminaria.be/technology.html
[40] http://www.maritimejournal.com/news101/marine-renewable-energy/the-quiet-life-of-a-seabed-oyster
[41] http://www.nemos.org/english/technology/
[42] http://wavestarenergy.com/concept