

DOTTORATO DI RICERCA IN INGEGNERIA CIVILE

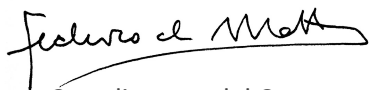
CURRICULUM INGEGNERIA CIVILE

XXXVIII CICLO

TESI DI DOTTORATO IN

A novel BIM opensource platform to support design and maintenance of maritime structures

SSD: CEAR-01/B



Coordinatore del Corso
Prof. Federico De Matteis

Dottorando
Valerio Gianforte

Tutor
Prof. Marcello Di Risio





UNIVERSITÀ DEGLI STUDI DELL'AQUILA

Department of Civil, Construction-Architectural and
Environmental Engineering

DOCTORAL THESIS

**A novel BIM open source
platform to support
design and maintenance
of maritime structures**

Ph.D Course in Civil,
Construction-Architectural and
Environmental Engineering
XXXVIII cycle

Candidate
Eng. Valerio Gianforte

SSD
CEAR-01/B

Course Coordinator
Prof. Federico De Matteis

Thesis Tutor
Prof. Eng. Marcello Di Risio

Co-Tutor
Eng. Nicola Bernabeo



A NOVEL BIM OPEN SOURCE
PLATFORM TO SUPPORT
DESIGN AND MAINTENANCE
OF MARITIME STRUCTURES

Eng. Valerio Gianforte

Prof. Eng. Marcello Di Risio

**A novel BIM open source
platform to support
design and maintenance
of maritime structures**

Eng. Valerio Gianforte
Candidate ID number: 289598

Department of Civil, Construction-Architectural and Environmental Engineering-
DICEAA
University of L'Aquila

Copyright © 2025, Eng. Valerio Gianforte. All rights reserved.

Material for which the author is the copyright owner cannot be used without the written permission of the author. The permission to reproduce copyright protected material does not extend to any material that is copyright of a third party; authorization to reproduce such material must be obtained from the copyright owners concerned. This thesis has been typeset by $\text{\LaTeX}$ and phdiceaa class.

Website: <http://diceaa.univaq.it/>

[Blank page]

ACKNOWLEDGEMENTS

I would like to thank...

[Blank page]

ABSTRACT

This research work aims to extend the application of the Building Information Modeling methodology (hereinafter referred to as BIM) to the design and management of maritime structures. To date, BIM has been usually and widely adopted for the design, construction, and maintenance management of buildings and civil infrastructures, such as bridges and roads. Accordingly, the associated information layers and classification systems (e.g., Industry Foundation Classes, IFC) are well established and are suitable mainly for these types of structures.

Indeed, the same classes cannot be directly applied to maritime structures, such as vertical or rubble-mound breakwaters. Existing classes are not able to describe specific properties such as the inherent geometric complexity of maritime structures, nor do they allow for the representation of the interaction between maritime structures and meteocean forcing (e.g., stability number, overtopping safety, etc.).

Therefore, this work aims to provide the technical and scientific community with a new tool, hereinafter referred to as "BIM for maritime structures" (BIMMs), which is based on a specific geometrical engine and a companion BIM information system developed for maritime structures. The proposed tool defines the information that must be assigned to each component of maritime structures. Its applicability is demonstrated through two real case studies, highlighting its feasibility and reliability in supporting both the design and maintenance of maritime structures.

[Blank page]

[Blank page]

CONTENTS

1	Introduction	1
1.1	General remarks	1
1.2	State of the art	2
1.3	Aims	4
1.4	Outcomes	5
1.5	Structure of the thesis	6
2	Overview of Building Information Modeling approach	7
2.1	General remarks	7
2.2	Geometric Modeling	8
2.3	Industry Foundation Classes	8
2.4	BIM Project Management	12
2.5	Common Data Environment (CDE)	14
2.6	Actors involved in the BIM methodology	15
3	Overview of Maritime Structure design and maintenance	18
3.1	General remarks	18
3.2	Breakwaters	20
3.2.1	Classification	20
3.2.2	Rubble mound breakwaters	23
3.2.3	Vertical Breakwaters	25
3.3	Wave loads and hydraulic response	27
3.4	Stability verification of crown walls	31
3.4.1	Bradbury formulation	32
3.4.2	Pedersen formulation	32
3.4.3	Martin formulation	34
3.5	Stability analysis	35
3.6	The design of the armor layer	42
3.7	Management and maintenance	43
4	The proposed tool	47
4.1	General remarks	47
4.2	Maritime modeling tool	48
4.2.1	General overview	48

4.2.2	Export STL	50
4.2.3	Create bottom	54
4.2.4	Modeling Tools	55
4.2.5	Linking Tools	57
4.2.6	Create Collections	58
4.2.7	Boolean Tools	58
4.2.8	Positioning Tools	61
4.2.9	Vertices Tools	61
4.2.10	Head Building Tool	63
4.2.11	Set Origin	69
4.2.12	BIM Tools	69
4.3	Maritime deployment tool	71
4.3.1	Export BW	71
4.3.2	Hide Section	72
4.3.3	Create Grid	72
4.3.4	R-Body Properties	76
4.3.5	D-Simulation	79
4.3.6	Stability and overtopping	82
4.4	BIM Modeling	85
4.4.1	General aspects	85
4.4.2	Preliminary Steps	86
4.4.3	Construction of the 4D Model	90
4.4.4	Construction of the 5D Model	93
5	Practical applications	98
5.1	General Remarks	98
5.2	Rubble Mound Breakwaters: The South Quay of Ortona Port case	98
5.3	Composite Breakwaters: The Civitavecchia Port case	105
6	Concluding remarks	110
	References	112

LIST OF FIGURES

2.1	Inheritance hierarchy of IFC schema (e.g., Borrmann et al., 2018)	10
2.2	Structure of the information model (e.g., Borrmann et al., 2018)	13
2.3	Workflow for the creation of a federated model (e.g., Borrmann et al., 2018)	14
2.4	Hierarchical organization of the actors involved in the BIM process	15
3.1	Basic scheme of assessment of rubble mound structure responses	19
3.2	Failure modes affecting rubble mound breakwater structures	23
3.3	Failure modes affecting caisson breakwater structures	24
3.4	Typical cross-section of a rubble mound breakwater structure	24
3.5	Typical cross-section of a caisson breakwater structure	26
3.6	Sketches of wave breaking types	29
3.7	Schematic representation of pressure distribution and geometric parameters according to Pedersen (1996).	33
3.8	Schematic pressure distribution and definition of geometric and hydraulic parameters according to Martin et al. (1999). .	35
3.9	Governing parameters related to the breakwater cross-section	37
3.10	Tetrapod concrete armor unit (Photo of the author)	43
3.11	Workflow of a management plan for maritime structures . .	45
4.1	Workflow of the proposed tool	48
4.2	User interface of the proposed tool for modeling maritime structures	49
4.3	Core element modeled as a cross-section in the Blender user interface	50
4.4	Object library for rubble mound breakwaters developed as plans in the Blender user interface	52
4.5	Object library of the vertical breakwaters structure developed as plans in the Blender user interface	52

4.6	Caisson modeled as a three-dimensional object in the Blender user interface	53
4.7	Head core component modeled as truncated conical section	53
4.8	Structure of the bathymetry shapefile in the GIS environment, showing contour line attributes including the mandatory elevation field <i>ELEV</i>	54
4.9	Bottom surface mesh generated via Delaunay triangulation using Blender GIS and integrated within the <i>Create Bottom</i> tool	55
4.10	Development line imported into the Blender scene.	56
4.11	Core components imported along the selected development line in the Blender scene.	57
4.12	Functionality of the <i>Linking Tools</i> in connecting cross-sectional elements.	58
4.13	Linking two sections with differing dimensions using the <i>EX-Vertex</i> and <i>Create Face</i> commands.	59
4.14	Functionality of the collection tool: creation of a new collection and assignment of colors to selected objects.	59
4.15	Application of the <i>Core2Head</i> command provided by the Boolean Tools.	60
4.16	Application of the Bottom Boolean tool, aligning the core model with the seabed.	61
4.17	Application of the <i>F-2-F</i> command: alignment of selected elements with the filter layer.	62
4.18	Operation of the <i>Z-Inshore</i> and <i>Align Armor</i> tools: positioning of armor elements relative to the bedding and filter layers.	62
4.19	Operation of the <i>Z-Inshore</i> and <i>Align Berm</i> tools: correct alignment of the berm relative to the armor bottom.	63
4.20	Operation of the <i>Align F-Verts</i> tool: adjustment of the filter layer vertices above the bedding layer.	64
4.21	Operation of the <i>Align AL-Verts</i> tool: adjustment of the bottom vertices of the armor layer.	64
4.22	Workflow of the <i>Vertex Spin</i> tool.	65
4.23	Operation of the <i>Sep Verts</i> tool.	66
4.24	Surface generated using the <i>Build Surface</i> tool.	66
4.25	Operation of the <i>B-Curve</i> tool.	67
4.26	Generation of a new curve with the <i>New B-Curve</i> tool.	67
4.27	Operation of the <i>Offset Circle</i> tool.	67
4.28	Import of bottom elements using the <i>B-Head</i> tool.	68
4.29	Linking between the body and the head of the structure using <i>L-Head</i> tool.	68
4.30	Operation of the <i>Set Origin</i> tool.	69
4.31	Working of <i>Export BW</i> tool	72

4.32	Hiding objects using <i>Hide OBJs</i> tool	73
4.33	Different steps to follow for importing the breakwater element on specific vertex through the <i>EV-Grid</i> tool	74
4.34	Different steps to follow for importing the breakwater elements along specific edge through the <i>EV-Grid</i> tool	75
4.35	Different steps to follow for importing the breakwater elements along specific face through the <i>F-Grid</i> tool	75
4.36	Different steps to follow for building the rows of the grid through the <i>SL-Grid</i> tool	76
4.37	Different steps to follow for the usage of <i>Apply XYZ-Rotation</i> tool	77
4.38	Different steps to follow for the usage of <i>Apply R-Rotation</i> tool	77
4.39	Assignment of the active rigid body properties to the breakwater units	80
4.40	Assignment of the passive rigid body properties to the breakwater units	80
4.41	Different steps to follow for the usage of <i>B-Walls</i> tool	81
4.42	Different steps to follow for the usage of <i>Run Simulation</i> tool	82
4.43	Dialog window of the <i>Wave Breaking Criteria</i> tool.	83
4.44	Pop-up window displayed when running the <i>Hudson Method</i> command.	83
4.45	Stability check using the Van der Meer formulation in deep-water (left) and shallow-water (right) conditions.	84
4.46	Pop-up window of the overtopping tool based on the empirical formulations (e.g., van der Meer et al., 2016).	85
4.47	Organization of the structural components into different BIM storeys.	88
4.48	Workflow for defining work calendars.	91
4.49	Interface of the Construction and Schedules tool.	92
4.50	Linking work tasks with their corresponding structural components.	93
4.51	User interface of the resources tool.	94
4.52	Computation of work durations based on deployment rates.	95
4.53	Gantt chart and scheduled works generated from Bonsai BIM.	96
4.54	Computation of the equipment operating time.	96
4.55	Calculation of total cost for specific tasks and structural components.	97
4.56	Spreadsheet of project costs generated using the Bonsai BIM cost tool.	97
5.1	Geographical location of Ortona Port	99
5.2	Type sections of the south quay of Ortona Port	99
5.3	Outcomes of <i>Core2Head</i> and <i>FL2Head</i> commands	100

5.4	Building head layers using <i>Vertex Spin</i> and <i>Build Surface</i> . . .	100
5.5	Outcomes of <i>B-Head</i> and <i>L-Head</i> tools	101
5.6	Geometrical model of core, first filter layer, and second filter layer	101
5.7	Outcome of <i>New B-Curve</i> for the armor layer	101
5.8	Final geometrical model of the armor layer	102
5.9	Final geometrical model of section C of the structure	102
5.10	Subtraction outcome (left) and filled mesh (right)	103
5.11	Outcomes of <i>Align Filter</i> tool	103
5.12	Outcome of <i>Align F-Verts</i> for second filter layer	103
5.13	Linking section B and C using vertex extrusion and face creation	103
5.14	Final geometrical model of the south quay of Ortona Port . .	104
5.15	Gantt chart of the construction process	104
5.16	Bill of quantities for the south quay of Ortona Port	104
5.17	Geographical location of the port of Civitavecchia	106
5.18	Geographical detail of the caisson study case	106
5.19	Modeling steps to build the bedding layer	107
5.20	Geometrical model of the caisson breakwater structure . . .	107
5.21	Different views of the complete caisson breakwater model .	108
5.22	Tetrapod condition properties and Gantt chart of maintenance schedule and costs	108

LIST OF TABLES

3.1	Roughness factor values for different armor layer configurations	30
3.2	Parameter ranges for the method by Pedersen (1996).	33
3.3	Empirical coefficients for pulsating pressure calculation (CIRIA, 2007).	34
3.4	Range of validity of parameters in Van der Meer formulae for shallow water conditions	42
4.1	Blender template used to assign the IFC class.	87
4.2	Template of quantity properties for the <i>IfcWall</i> class.	87
4.3	Template of custom properties assigned to each structural component.	89
4.4	Template for Work Plans in Bonsai BIM.	90
4.5	Structure of the cost schedule tree.	94

INTRODUCTION

1.1 General remarks

Building Information Modeling (hereinafter referred to as BIM) is a widely adopted process in the building construction field. The BIM concept was introduced in 1970 and it was used to manage construction projects by architectural, engineering, and construction (AEC) industries (e.g., Biancardo et al., 2020). Over the years, BIM has become the main resource to integrate 3D geometric representation with physical, functional, and semantic characteristics. These *Semantic characteristics* describe the functional role and informational meaning of building elements, enabling their classification, interpretation, and interoperability across different stages of the project lifecycle.

Furthermore, BIM improves the planning process, design, and construction of projects by offering a novel approach to design, construction, and management (e.g., Biancardo et al., 2020).

In general, BIM platforms rely on the parametric definition of objects. They are stored in libraries used to construct the whole 3D geometrical model. This approach opens the door to the use of emerging technologies for the management of infrastructures that could help achieve safer performance of the entire workflow. Moreover, its usage makes it possible to decrease maintenance costs and risk of information loss and design mistakes, and at the same time, to generate considerable technical benefits for all stakeholders involved in the design and maintenance tasks (e.g., Biancardo et al., 2020).

One of the most important features of the BIM methodology is the interactive collaboration among the different actors involved in all of the phases of the project in order to insert, extract, update, and modify information in the model. In this way, a dynamic model is achieved. The model may contain additional information, such as costs, maintenance, and safety instructions.

It should be stressed that current BIM methodologies and standards have been predominantly conceived for buildings and conventional civil infrastructures. Hence, despite the maturity reached by BIM methodologies in the building sector, their applicability to non-conventional infrastructures, such as maritime construction, is still limited and remains a topic of ongoing research that requires further investigation.

All the briefly outlined aspects — from the methodology up to the identification of actors involved in the process, including the model and the sharing of information — are outlined in the following chapters.

1.2 State of the art

Maritime structures are primarily constructed to ensure the operability of port activities by limiting wave penetration within sheltered areas and to provide protection against coastal flooding. Ports play a fundamental role in the economic development of countries, and the serviceability and safety of maritime infrastructures are therefore critical aspects. In this context, the availability of a centralized and structured database containing geometric, structural, operational, and maintenance-related information would represent a significant advantage for the design, management, and maintenance of maritime assets throughout their lifecycle.

Building Information Modeling (BIM), as already outlined, has been widely and successfully applied in the building sector and represents a promising methodology to address these needs. However, despite its maturity in architectural and building applications, BIM remains underdeveloped in the infrastructure domain, particularly for maritime structures, both in design and maintenance processes (e.g., Valdepeñas et al., 2020). The literature addressing BIM applications in this field is still limited, although several studies have investigated its potential use in port facility management.

One of the most relevant contributions is provided by Valdepeñas et al. (2020), who proposed a BIM-based methodology specifically aimed at the maintenance of port infrastructures. Their framework is articulated into seven phases.

- *Phase 1.* Design phase and structures modeling in Autodesk Revit (a widespread commercial BIM software).
- *Phase 2.* "As-built" project and update of the digital model with the data of the built structures.
- *Phase 3.* Implementation of maintenance parameters into the digital model (e.g., date of surveys, defects, date of last maintenance, etc.).

-
- *Phase 4.* Inspections. One of the objectives that the new method aims to achieve is to collect data from inspections directly from the Autodesk Revit model. The 3D model could be accessed from a portable device (e.g., tablet).
 - *Phase 5.* Generation of inspection files. In this phase the inspection sheets in PDF format are generated and entered into the model.
 - *Phase 6.* Planning tables. This phase consists of obtaining data from the model to define medium- and long-term maintenance plans.
 - *Phase 7.* Data extraction from the model for CMMS (a widespread digital tool used to manage maintenance operations).

Overall, the methodology ranges from the design and modeling of structures in commercial BIM software to data extraction for integration with Computerized Maintenance Management Systems (CMMS). The proposed approach demonstrates the effectiveness of BIM as a data repository supporting inspection activities, maintenance planning, and information exchange among stakeholders. Nevertheless, the methodology is mainly focused on post-construction phases and does not explicitly address the integration of BIM within the early design stages, nor its use as a decision-support tool for engineering analyses.

Other studies have explored BIM applications in specific port-related domains. For instance, Zhang and Chen (2018) applied BIM to the design of port handling systems, highlighting its potential to improve coordination and efficiency during the design process. Similarly, Garibin and Ol'khovik (2019) proposed a workflow for monitoring the technical condition of marine quay walls by linking Autodesk Revit with spreadsheet-based tools. Their approach relies on data extracted from technical reports and documentation related to the structures deployment, which are often the only available sources due to the frequent lack of original project documentation. While the proposed framework enables the generation of maintenance plans and supports both instrumental and visual inspections, it remains primarily oriented toward asset management and does not provide a comprehensive integration of design, monitoring, performance evaluation, and maintenance planning within an unified BIM environment.

More recent researches have focused on integrating BIM with advanced surveying technologies. In this context, Khoi et al. (2024) investigated the combined use of Unmanned Aerial Vehicles (UAVs), Terrestrial Laser Scanning (TLS), BIM, and Geographic Information Systems (GIS) to enhance the accuracy and efficiency of port infrastructure management. Their methodology consists of two main phases: data acquisition (based on

UAV-mounted LiDAR and photogrammetry sensors, along with TLS surveys) and the subsequent creation of a detailed BIM model. The resulting model is georeferenced within a GIS environment and deployed on a cloud-based platform, enabling real-time data sharing and collaboration among stakeholders. Although this approach represents a significant advancement in terms of data integration and accessibility, it is mainly conceived for monitoring and management purposes rather than for supporting design activities or engineering decision-making.

Overall, the reviewed literature demonstrates that current BIM applications for maritime infrastructures predominantly focus on management, inspection, and maintenance tasks, often relying on commercial BIM softwares combined with external tools such as CMMS, spreadsheets, GIS platforms, or cloud-based systems. While these approaches have proven to be effective in improving data organization and maintenance planning, they generally lack integration with the early design phases and do not support advanced engineering analyses or performance-based assessments. Consequently, there is a clear need for the development of new BIM-based frameworks capable of supporting both design, lifecycle management, and maintenance planning of maritime structures, bridging the gap between geometric modeling, information management, and engineering analysis.

1.3 Aims

Although BIM methodologies have already been applied to maritime structures, at least in a few cases, their use has so far been largely limited to management and maintenance purposes. In most existing applications, commercial BIM software, such as Autodesk Revit, has been adopted. However, Autodesk Revit has been primarily developed for building-oriented BIM workflows, and its application to maritime infrastructures requires substantial adaptations. In particular, the lack of dedicated object libraries for maritime structures and the limited flexibility of the information layer constrain the development of detailed and infrastructure-specific BIM models.

The main aim of this PhD research is the development of an open-source BIM-based platform capable of supporting both the design and maintenance phases of maritime structures, with a specific focus on rubble mound and caisson-type breakwaters. The proposed framework is intended to overcome the limitations of existing BIM solutions by providing a flexible and extensible environment tailored to the specific characteristics of maritime infrastructures.

More specifically, this work aims to:

- define modeling guidelines for the creation of BIM objects represen-

tative of maritime structures and their components;

- develop simplified and semi-automatic procedures for constructing detailed geometric models suitable for engineering analyses;
- integrate hydraulic verification tools for breakwater units within the BIM environment;
- design and implement an informative layer specifically conceived for maritime infrastructures, supporting lifecycle data management.

Through these objectives, the proposed platform seeks to bridge the gap between geometric modeling, engineering analysis, and information management, providing a unified tool to support decision-making throughout the lifecycle of maritime structures.

1.4 Outcomes

The main outcome of this PhD research is the open-source BIM-based platform "Building Information Modeling for Maritime Structures" (BIMMs). It is conceived as an integrated environment to support the design, modeling, simulation, and maintenance of maritime structures, overcoming the limitations of existing commercial BIM solutions. The platform is implemented within the Blender environment and is articulated into two complementary sub-tools: the Maritime Modeling Tool and the Deployment Simulation Tool.

The Maritime Modeling Tool is designed to support the guided (and semi-automatic) creation of detailed geometric models of maritime infrastructures and the assignment of an information layer specifically defined for this type of structure. By combining Geographic Information System (GIS) data with the Blender GIS add-on, the tool enables the generation of accurate seabed and terrain models using Delaunay triangulation techniques. Leveraging Blender's advanced modeling capabilities, maritime components are constructed in a modular and flexible manner, facilitating the assembly of complex geometries such as rubble mound and caisson breakwaters. Furthermore, the tool allows the export of geometric components in standard formats and the systematic assignment of semantic and technical information to each structural element, thus enabling a BIM-compliant representation tailored to maritime infrastructures.

The Deployment Simulation Tool extends the modeling environment by integrating physics-based simulations and engineering verification procedures, such as, stability check of rubble mound breakwaters with different criteria (e.g., CIRIA, 2007) and overtopping verification (e.g., van der Meer et al., 2016). This tool allows the simulation of breakwater unit placement by exploiting Blender's rigid body dynamics, enabling the analysis

of deployment processes under gravity and contact interactions. Artificial units such as accropodes, tetrapods, or cubic blocks can be parametrically defined and positioned with assigned physical properties, including mass, friction, and damping coefficients. The simulation framework is complemented by stability and hydraulic performance assessments, including classical design formulations such as the Hudson formula and the Van der Meer approach for both deep and shallow water conditions (e.g., CIRIA, 2007). Additionally, the tool provides functionalities to evaluate overtopping-related aspects within the same integrated environment.

Overall, BIMMs represents more than a conventional geometric or BIM model of a maritime structure. It aims to be an unified, open-source framework that integrates geometric modeling, information management, physics-based simulation, and engineering verification. By bridging the gap between design, analysis, and maintenance within a single platform, the proposed tool provides a novel decision-support system for the lifecycle management of maritime infrastructures.

1.5 Structure of the thesis

The thesis is structured as follows.

- **Overview of Building Information Modeling approach** (2) presents the fundamental principles of the BIM methodology, covering geometric modeling, information management, and the roles of the different stakeholders involved in the process.
- **Overview of Maritime Structure design and maintenance** (3) introduces the main typologies of maritime structures and describes their design methodologies. The chapter discusses stability verification of armor units based on different design criteria and concludes with an overview of maintenance and management planning.
- **The proposed tool** (4) describes the newly developed platform, BIMMs (Building Information Modeling for Maritime Structures), detailing its architecture, functionalities, and implementation.
- **Practical applications** (5) illustrates the application of BIMMs through two case studies. The first case study focuses on a rubble mound breakwater, while the second addresses a caisson-type breakwater.
- **Concluding remarks** (6) summarizes the main outcomes of the research and discusses the implications and potential future developments of the proposed approach.

OVERVIEW OF BUILDING INFORMATION MODELING APPROACH

2.1 General remarks

Building Information Modeling (BIM) is based on the continuous use of digital models throughout the entire lifecycle of a built asset (e.g., Borrmann et al., 2018). Digital representations are employed from the early conceptual design stages through construction and extend into the long-term operation and management phases. One of the main advantages of BIM lies in its ability to improve information exchange and coordination among the various stakeholders involved in a project.

More specifically, a Building Information Model represents a digital and information-rich description of a facility. It includes a three-dimensional geometric model defined at a specific level of detail, together with non-physical entities such as spaces, zones, schedules, and a hierarchical project structure. Each object within the model is associated with a well-defined set of semantic attributes, including component type, materials, technical properties, and cost-related information (e.g. Borrmann et al., 2018). The type and structure of this information depend on the object classification, which is typically defined through Industry Foundation Classes (IFC), as discussed in the following chapters.

BIM provides significant advantages during the design development phase. Conventional two-dimensional technical drawings are directly derived from the three-dimensional model, ensuring consistency and automatic updates of plans and sections. Moreover, the use of a digital building model during the tendering process enables a more accurate definition of required services and construction costs, supporting contractors during bid preparation and facilitating precise cost control at later stages. In this context, four-dimensional (4D) BIM links building components to construction scheduling, while five-dimensional (5D) BIM further inte-

grates cost information into the model (e.g., Borrmann et al., 2018). Although beyond the scope of this work, according to current Italian regulations, it is worth mentioning that environmental and sustainability information can be integrated within seven-dimensional (7D) BIM, while six-dimensional (6D) BIM is primarily associated with the management and operation phases of existing structures.

2.2 Geometric Modeling

As already outlined, a Building Information Model contains the information required to support the planning, construction, and operation of an asset. Within the BIM environment, the three-dimensional geometric representation of a structure plays a central role (e.g., Borrmann et al., 2018). The availability of a consistent 3D model provides several advantages over conventional two-dimensional documentation.

- In a BIM-based workflow, technical drawings are directly generated from the three-dimensional model. As a result, plans, sections, and elevations are automatically updated whenever the model is modified, significantly reducing the risk of errors associated with manual revisions of 2D (unlinked) drawings.
- The three-dimensional representation enables the identification of potential spatial conflicts between structural elements and surrounding (existing or to be designed) infrastructures, such as utility networks or transportation systems. Clash detection is a key aspect for coordinating the activities of the different stakeholders involved in the project.
- The 3D model facilitates the automatic computation of quantities, which can be directly derived from the geometric properties of the model elements, such as volumes and surface areas. The type and level of detail of the extracted quantities typically depend on the IFC classification assigned to each component.

Therefore, the digital three-dimensional representation of a structure constitutes one of the fundamental pillars of the BIM methodology.

2.3 Industry Foundation Classes

BIM is based on the exchange of information. Indeed, the costs and the time component are added to the 3D model in order to obtain 4D and 5D models. Information could also regard the work scheduling, materials used to build each component of the structure, or equipment. The data

exchange avoids the need to re-enter data or information already created manually and reduces the risk of errors (e.g., Borrmann et al., 2018).

For this purpose, Industry Foundation Classes (IFC) provide a comprehensive and standardized data format for the vendor-neutral exchange of digital building models (e.g., Borrmann et al., 2018). In other words, IFC standards allow to share building data among different software products. A further important aspect is the detailed description of semantic information, including the classification of building components within a common hierarchy of types (e.g., Borrmann et al., 2018). IFC standards ensure one of the most useful aspects of BIM methodology, i.e. the *Interoperability*: the capability of the BIM model to share, through the IFC classification standard format, the information of the model from one software product to another. The IFC data model is very important for implementing BIM concepts and is the basis of many standardization initiatives at an international level.

The IFC data model is complex (e.g., Borrmann et al., 2018). To improve its maintainability and extensibility, it is structured in different layers.

Core Layer contains the most elementary classes of the data model which define the basic structures, key relationship and general concepts which can be re-used and classified in the upper layers. The core of the IFC comprises basic abstract classes such as *Control Extension*, *Product Extension*, and *Process Extension*.

The *Product Extension* describes the physical and spatial objects of a building and their relationship. It includes the subclasses of *IfcProduct*, such as *IfcBuilding*, *IfcBuildingStorey*, *IfcElement*, and *IfcBuildingElement*.

The *Process Extension* schema comprises the classes to describe processes and operations.

Control Extension defines the classes to control objects through which it is possible to assign them to physical and spatial objects.

Interoperability Layer defines the classes directly derived from classes in the Core Layer and can be used by a range of different application schemes, e.g. important building element classes such as *IfcWall*, *IfcColumn*, *IfcBeam*, *IfcWindow*.

Domain Layer layer contains specialized classes that are applied to specific application domains. These classes represent the leaf nodes of the inheritance hierarchy. Classes defined at this level cannot be referenced by other layers or by other schemas.

It is also worth highlighting the evolution of the IFC schema. Its development began with IFC2 and has progressively evolved to the IFC4 schema. The IFC4 schema defines domain-specific models for architecture, building services, construction management, electrical systems, and structural elements.

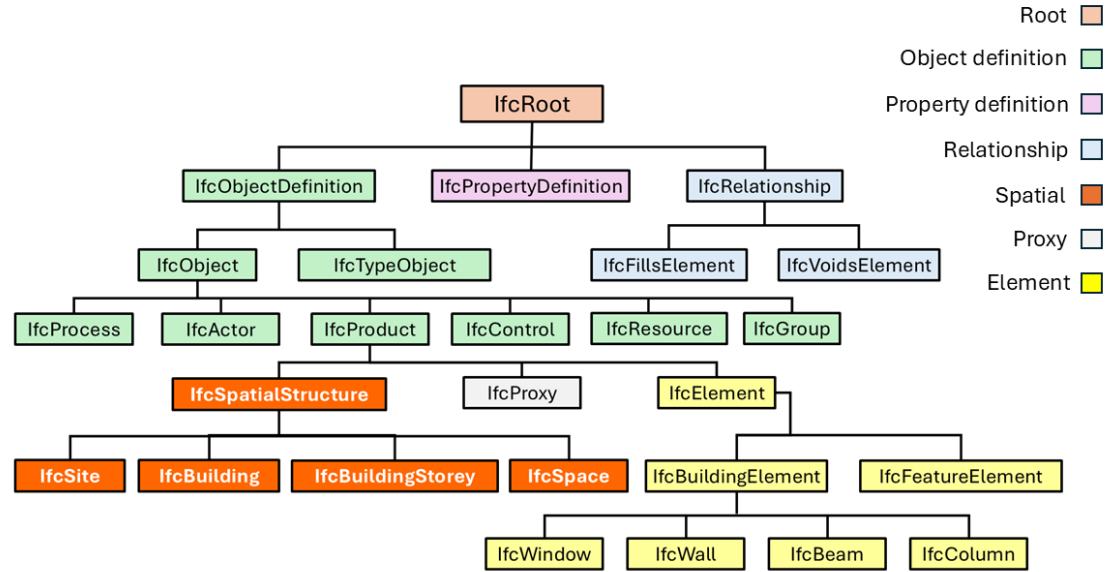


Figure 2.1. Inheritance hierarchy of IFC schema (e.g., Borrmann et al., 2018)

Resource Layer is the lowest layer that provide basic data structures that can be used through the entire IFC data model. The most important resource schemes include:

- Geometry Resource that contains the basic geometric elements such as point, vectors, parametric curves, and surfaces.
- Topology Resource that contains all the classes to represent the topology of a solid.
- Geometric Model Resource contains all classes to describe geometric models such as *IfcCsgSolid*.
- Material Resource contains elements to describe materials.
- Utility Resource provides elements to describe the ownership and version history of IFC objects.

In addition to the resources cited above, there are all of the resources that include the schemes regarding Cost, Measure, DateTime, and Representation.

To better figure out the IFC structure, it is worth pointing out that inheritance hierarchy plays a crucial role in the IFC: it defines specialization and generalization relationships (e.g., Borrmann et al., 2018).

The inheritance hierarchy follows a semantic approach: the meaning of the objects is the basis to model inheritance relationships. The general architecture of the class system is depicted in Figure 2.1.

The starting point is the root with its own class *IfcRoot*. It provides basic functionality to identify an object using a Globally Unique Identifier

(GUID), that allows to describe ownership and the origin of the object.

IfcObjectDefinition, *IfcPropertyDefinition*, and *IfcRelationship* are directly derived from the root (e.g., Borrmann et al., 2018).

IfcObjectDefinition is a superclass that represents physical objects (e.g. building elements), spatial objects (e.g. openings and spaces), and conceptual objects such as processes, costs, and time. The *IfcObjectDefinition* contains:

- *IfcObject* describes all the individual objects in the building project. Its subclasses can be described as follows.
 - *IfcProduct* can be assigned to geometric representation and are positioned within the project coordinate system.
 - *IfcProcess* is a process that occurs during the building project (e.g. planning, construction, operation). Processes have a temporal dimension.
 - *IfcControl* describes an object that controls or limits another object. Controls can be laws, guidelines, specifications, boundary conditions or other requirements.
 - *IfcResource* represents the use of an object as a part of a process.
 - *IfcActor* is a human participant involved in the building project.
 - *IfcGroup* is an aggregation of objects.
- *IfcTypeObject* contains the type of each element.
- *IfcContext* describes the generical information of the project.

IfcRelationship describes the relationships between the objects. The *IfcPropertyDefinition* defines those properties that are not part of the IFC model.

Going deeper into the IFC schema, the *IfcProduct* is an abstract representation of all objects. It has different subclasses.

- *IfcElement* is the superclass for a whole series of important basic classes including *IfcBuildingElement*, which is the superclass for all building elements such as *IfcWall*, *IfcColumn*, etc. Each class has its own property template, for instance, *IfcWall*, among the computed properties has *NetVolume* and *NetSideArea*.
- *IfcSpatialStructure* class is used to describe non-physical spatial objects. Its subclasses include *IfcSite*, *IfcBuilding*, *IfcBuildingStorey*, and *IfcSpace*.
- *IfcProxy* serves as a placeholder for representation objects that do not correspond to any of the semantic types so that they can still be defined in the IFC model, and if necessary be assigned a geometric representation.

IfcProduct has further subclasses to describe objects that are embedded within a spatial context such as *IfcAnnotation*, *IfcGrid*, and *IfcPort* (e.g. Borrmann et al., 2018). The semantic classification that IFC elements follow, joined with the inheritance hierarchy structure of the IFC, explains the relationships between the objects. This property is the most important part of the IFC data model.

2.4 BIM Project Management

Building Information Modeling is characterized by the structured creation of three-dimensional models and by the systematic exchange of information throughout the project lifecycle. While the geometric design focuses on the consistent representation of physical components, as discussed in Section 2.2, information exchange relies on standardized data structures and workflows, typically implemented through the Industry Foundation Classes (IFC) framework.

The level of geometric detail and the scope of information exchange vary according to the different project phases and are driven by the client's information requirements. These requirements define the type, quality, and amount of information to be produced, ensuring consistency with the project specifications and objectives.

In a building project, the content and structure of information address different aspects of each project phase. Typically, an information model includes three-dimensional models, equipment schedules, technical specifications, inspection records, and test certificates. Since BIM covers the entire lifecycle of a built asset, information exchange processes are structured by distinguishing between the project delivery phase and the asset management phase (e.g. Borrmann et al., 2018). The overall structure of the information flow is illustrated in Figure 2.2.

Referring to Figure 2.2, the Organizational Information Requirements (OIR) define the high-level data and information needs of stakeholders and directly influence the Asset Information Requirements (AIR).

The Project Information Requirements (PIR) translate organizational objectives into project-specific information needs and support decision-making processes at a strategic level within the organizations involved (e.g., Borrmann et al., 2018). PIR are defined with reference to a specific built asset and guide information production during the project delivery phase.

The Project Information Model (PIM) supports the project delivery phase and represents a primary source of information for the subsequent development of the Asset Information Model (AIM). It is commonly used for activities such as clash detection, construction scheduling, and cost estimation, providing geometric data, spatial relationships, and equipment-

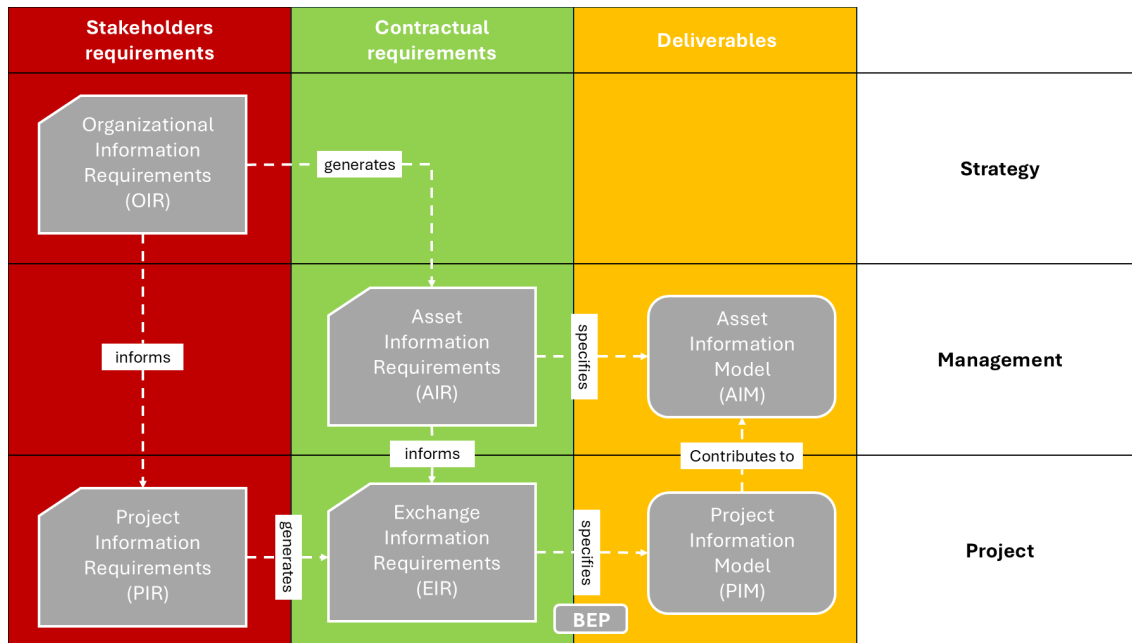


Figure 2.2. Structure of the information model (e.g., Borrmann et al., 2018)

related information.

The AIM supports the operational and maintenance phases of the asset. It contains graphical and non-graphical information, including documentation, equipment registers, maintenance records, and cumulative cost data, in accordance with the defined AIR.

Information exchanges between stakeholders are governed by the Exchange Information Requirements (EIR), which specify what information must be delivered, when, and in which format. All information management processes are formalized within the BIM Execution Plan (BEP). Due to the dynamic nature of construction projects, the BEP is continuously updated and refined throughout the project lifecycle. It typically defines management responsibilities, collaboration processes, modeling standards, and the adopted information technology solutions.

Project management therefore plays a crucial role in the BIM process. Given the involvement of multiple actors with different roles, objectives, and perspectives, the successful implementation of BIM relies on the clear definition of responsibilities and workflows. This coordination is commonly achieved through the adoption of a Common Data Environment (CDE), which provides a centralized and controlled platform for information sharing, thereby enhancing collaboration and maximizing the benefits of BIM for all participants.

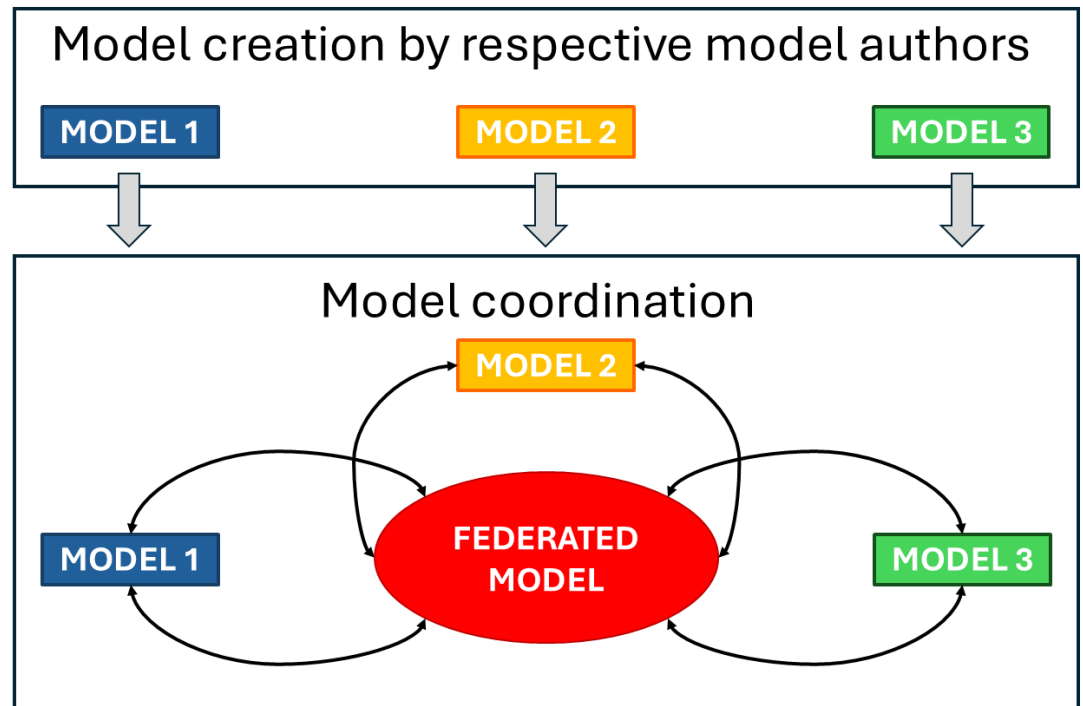


Figure 2.3. Workflow for the creation of a federated model (e.g., Borrmann et al., 2018)

2.5 Common Data Environment (CDE)

The exchange of information in a BIM-based workflow requires a shared digital space, commonly referred to as the Common Data Environment (CDE).

The CDE provides controlled and differentiated access areas for the various project stakeholders, enabling the structured sharing of data, documents, and processes throughout the project lifecycle (e.g., Borrmann et al., 2018). Its primary role is to ensure that all participants operate on consistent, updated, and validated information.

The need for a CDE arises from the fact that each actor involved in a project typically develops their own discipline-specific model using dedicated software tools. For this reason, the use of a single, monolithic model is generally not recommended. Instead, collaborative BIM workflows are based on the integration of multiple discipline-specific models.

Accordingly, several countries have adopted collaborative approaches based on federated models (Figure 2.3). In this approach, each stakeholder retains responsibility for their own sub-model, while coordination and integration are achieved through model federation.

All discipline-specific models and associated documentation are stored within the CDE, which acts as the central repository for project information. This centralized data management reduces information redundancy,

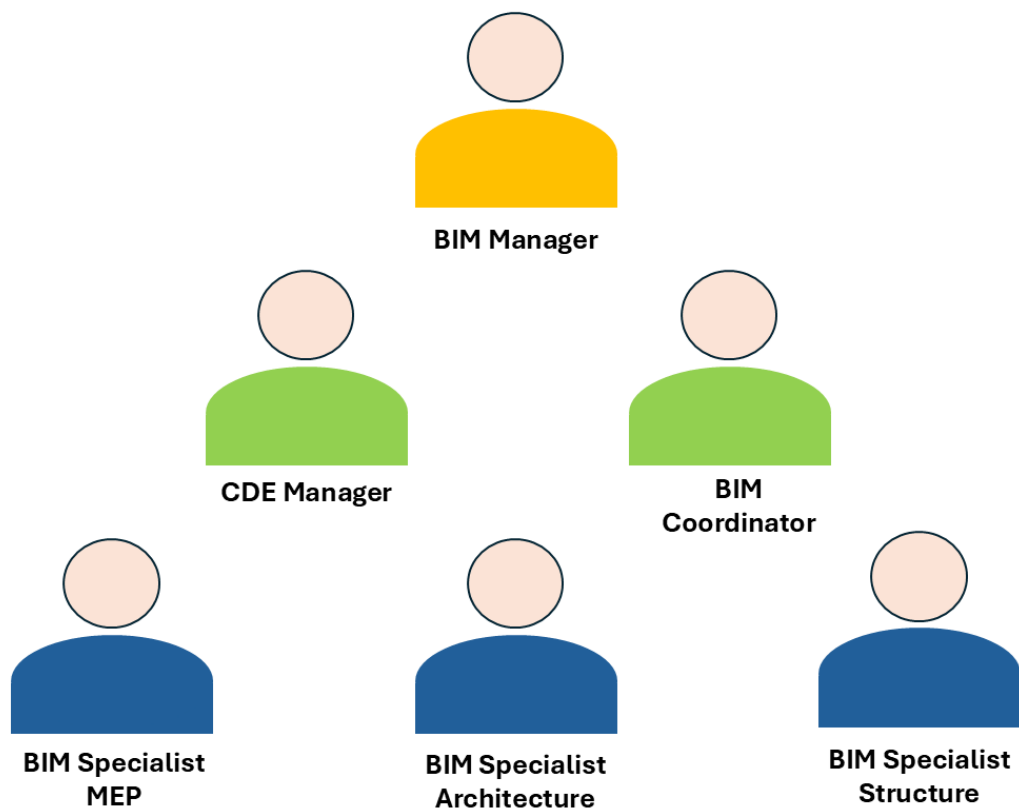


Figure 2.4. Hierarchical organization of the actors involved in the BIM process

minimizes the risk of inconsistencies, and ensures the availability of the most recent and approved data at all stages of the project. Furthermore, the CDE establishes a structured framework for collaboration and coordination among stakeholders, thereby supporting effective information management and interoperability in BIM-based projects (e.g. Borrmann et al., 2018).

2.6 Actors involved in the BIM methodology

The BIM process involves several actors with distinct roles and responsibilities, organized according to a hierarchical structure (Figure 2.4).

The main figures involved in the BIM methodology can be summarized as follows.

- **BIM Manager.** The BIM Manager is responsible for defining and supervising the overall BIM strategy of the project. This role requires a combination of technical, managerial, and IT-related skills. In particular, the BIM Manager:
 - has a background in architecture or civil engineering, with ex-

perience in construction project execution and a thorough understanding of workflows, information requirements, and responsibilities;

- possesses advanced knowledge in the development and use of 3D models, data models, and open data formats;
- has practical experience with IT systems and BIM software, including system configuration and staff training;
- is familiar with international BIM standards, guidelines, and employer's information requirements;
- is capable of developing and delivering training programs and documentation;
- acts as a communicator, team player, and leader, facilitating coordination among stakeholders (e.g., Borrmann et al., 2018).

- **BIM Coordinator.** The BIM Coordinator manages and coordinates information flows among the various disciplines involved in the project. The main responsibilities of this role include:

- supporting the implementation and digitalization of BIM processes;
- contributing to the development of the information management plan;
- translating information requirements into discipline-specific tasks;
- supporting the BIM Manager in operational activities;
- managing clash detection and coordination procedures;
- defining and verifying the required levels of detail and information of models and drawings;
- selecting appropriate tools and supporting team organization.

- **CDE Manager.** The CDE Manager is responsible for the efficient management of the Common Data Environment, ensuring secure access, version control, and compliance with agreed workflows. This role contributes to improving collaboration efficiency and overall project quality.

- **BIM Specialist.** The BIM Specialist is responsible for discipline-specific modeling activities and information production. Depending on the project scope, this role may focus on buildings or infrastructure works. The main tasks of the BIM Specialist include:

- creation and maintenance of 3D models and derived 2D drawings;

-
- implementation and use of object libraries required for project development;
 - execution of structural, facilities, or energy-related analyses, where applicable;
 - extraction and export of data required for quantity take-offs and cost estimation.

In summary, BIM actors play a central role in the success of a BIM-based project. Clear definition of responsibilities, effective coordination, and appropriate skill sets are essential to fully exploit the potential benefits of the BIM methodology.

OVERVIEW OF MARITIME STRUCTURE DESIGN AND MAINTENANCE

3.1 General remarks

Maritime structures are typically needed to create sheltered areas for port operations or to mitigate coastal flooding risks. These structures can take various forms, depending on water depth, environmental conditions, hydraulic forces, geotechnical characteristics, and structural requirements.

Understanding these factors is essential for defining the design, construction, and maintenance processes, as well as for establishing the information content that must be incorporated into a BIM-based workflow.

The key parameters considered during the design process can be summarized as follows (e.g., CIRIA, 2007):

1. Environmental boundary conditions.
2. Hydraulic parameters.
3. Geotechnical parameters.
4. Structural parameters.

Environmental boundary conditions, including wave climate, currents, water levels, foreshore geometry, and seabed characteristics, are largely independent of the structure itself (e.g., Van der Meer, 1995). Designers typically cannot influence these parameters; however, they are critical for determining the loads acting on the structure and to select the most appropriate configuration of the structure. Hydraulic responses include wave run-up, run-down, overtopping, transmission, and reflection. Geotechnical parameters may include liquefaction potential, pore water pressure, and hydraulic gradients. Structural characteristics comprise slope geometry, rock mass properties, density, cohesion, porosity, permeability, and

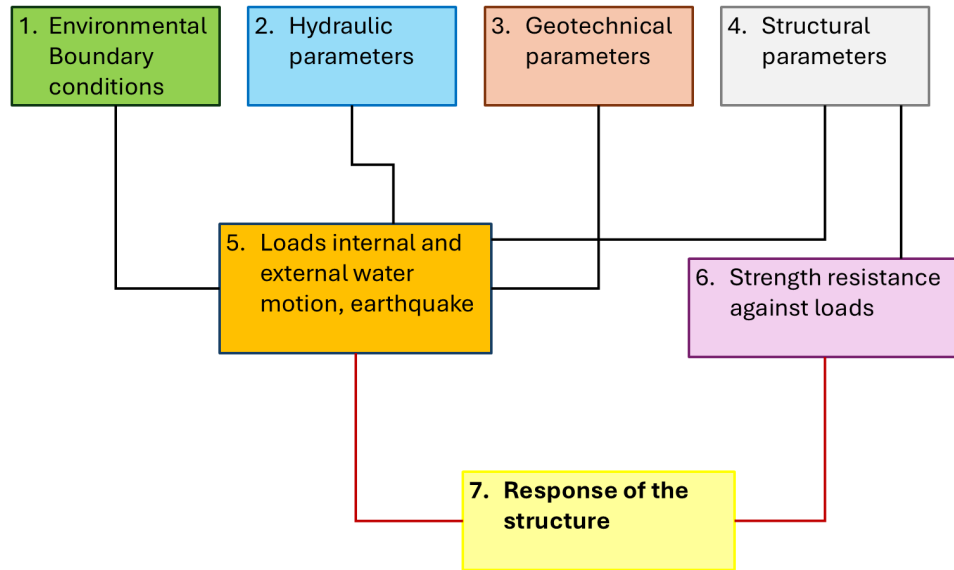


Figure 3.1. Basic scheme of assessment of rubble mound structure responses

cross-sectional dimensions, all of which are directly related to the stability of both vertical and rubble-mound breakwater structures.

These parameters determine both external and internal loads (Figure 3.1). External loads are associated with water motion over the structure, such as wave impact, run-up, run-down, and overtopping, whereas internal loads, for rubble mound breakwaters, describe groundwater flow within the structure, pore pressure variations, and changes in the phreatic line. The resistance of the structure to these loads determines its hydraulic and structural performance, assessed through the stability of the entire caisson for vertical breakwaters and through the armor and filter layers, crest walls, toe berms, and dynamically stable slopes for rubble mound breakwaters (e.g., Van der Meer, 1995).

A thorough understanding of these factors is essential to develop accurate digital representations of maritime structures. By incorporating this information into a BIM environment, it is possible to support both the design phase, including geometric modeling, verification of armor unit stability for rubble mound breakwaters, and simulation of hydraulic loads, and the maintenance phase, ensuring that all relevant data are consistently captured and accessible throughout the structure's life cycle.

This chapter aims to provide to the readers with a brief overview of the most useful aspects that are directly linked to the proposed BIM-based tool.

3.2 Breakwaters

3.2.1 Classification

The classification of breakwaters is commonly based on the dimensionless parameter $H/(\Delta D)$, where H denotes the incident wave height, Δ is the relative mass density of the material, and D represents a characteristic diameter of the structural element, such as armor units, stones, gravel, or sand (e.g., Van der Meer, 1995). This parameter, usually referred to as *the stability number*, expresses the relative intensity of wave loading with respect to the resisting capacity of the material and provides a unified framework for comparing different types of maritime structures.

Based on the value of $H/(\Delta D)$, breakwater structures can be roughly classified into three main categories: *stable structures*, *statically stable structures* and *dynamically stable structures*. The fundamental distinction between these categories lies in the level of damage that is considered acceptable under design conditions. In stable structures, no displacement is allowed (i.e. caisson breakwater). In statically stable structures, no damage or only negligible displacement of armor units is allowed, whereas dynamically stable structures are designed to accommodate controlled material movement without compromising overall structural integrity.

Stable structures are characterized by very low values of $H/(\Delta D)$ (i.e. lower than 1).

Statically stable structures are characterized by relatively low values of $H/(\Delta D)$, typically in the range $1 \leq H/(\Delta D) \leq 4$. Under these conditions, armor units are required to remain essentially immobile during design storm events. Structural safety is ensured by selecting sufficiently large and heavy units, often artificial blocks or large natural rocks, arranged on uniform slopes. Damage, when allowed, is limited to minor local displacements (i.e. rocking) that do not affect the global performance of the structure.

Dynamically stable structures, by contrast, correspond to higher values of $H/(\Delta D)$, generally exceeding 6. In this case, the structural response is governed by profile reshaping under wave action. Individual elements such as stones, gravel, or sand are mobilized during wave run-up and run-down phases, and the structure evolves until an equilibrium profile is reached. This equilibrium is attained when the net cross-shore sediment transport over successive wave cycles becomes negligible, resulting in a stable configuration that can sustain further wave loading without progressive degradation.

A more detailed classification of maritime structures as a function of $H/(\Delta D)$ is summarized below (e.g., Van der Meer, 1995).

- For $H/(\Delta D) < 1$, caissons and seawalls. These structures are de-

signed to remain fully intact under design conditions, and no damage is tolerated. In this case, the characteristic dimension D may represent the height or width of the structure rather than a particle or unit diameter.

- For $1 \leq H/(\Delta D) \leq 4$, statically stable rubble mound breakwaters. Limited damage may be allowed under extreme conditions, while the overall geometry and functionality must be preserved. The armor layer generally consists of heavy artificial units or large natural rocks, with D defined as the nominal diameter of the armor units.
- For $3 \leq H/(\Delta D) \leq 6$, S-shaped and berm breakwaters. These structures feature steep slopes above and below the still water level and a gentler slope in between, aimed at reducing wave forces on the armor layer. The initial profile evolves during early storm events until a dynamically stable configuration is achieved.
- For $6 \leq H/(\Delta D) \leq 20$, rock slopes and beaches. In this range, the rock size is relatively small and cannot withstand severe wave attack without displacement. Consequently, the equilibrium profile becomes a primary design parameter.
- For $15 \leq H/(\Delta D) \leq 500$, gravel beaches. They are characterized by continuous profile adjustment under varying wave and water level conditions. Profile development plays a central role in the design process.
- For $H/(\Delta D) > 500$, sand beaches. These structures consist of very fine material that is highly susceptible to erosion during storm surges, and dune erosion as well as profile evolution represent key design considerations.

It should be noted that the ranges of the stability number may partially overlap, reflecting transitional structural behaviors and different design philosophies.

The selection of the most appropriate breakwater typology depends on several factors, including construction costs, technical feasibility, availability of materials, and owner preferences (e.g., CIRIA, 2007). Water depth plays a particularly important role in this choice. Caisson breakwaters are often preferred in deep-water conditions, where the volume of quarried rock required for rubble mound structures increases significantly with depth. Conversely, rubble mound breakwaters are typically favored in shallower waters, as they offer superior wave energy dissipation and reduced wave reflection compared to vertical structures.

The choice of the breakwater cross-section is generally guided by a combination of functional requirements, boundary conditions, material

availability, construction considerations, and long-term maintenance aspects. These design choices directly affect the geometric configuration, material properties, and performance indicators that must be explicitly represented within a BIM-based information model. Functional requirements primarily concern harbor protection and operability, including the minimization of wave energy within the harbor basin, the reduction of wave disturbance at berths, and the navigability of access channels and entrance areas. Boundary conditions needed at the design phase encompass environmental parameters such as water depth, tides, currents, and bathymetry, as well as construction-stage constraints related to meteorological conditions, environmental regulations, and logistical limitations. Material availability is governed by local quarry characteristics, which determine the maximum size and shape of armor stones or units. Construction considerations include access to the site, availability of equipment and labour, and overall technical feasibility. Finally, maintenance requirements must be carefully assessed, as rubble mound structures are often partially submerged or difficult to access, leading to potentially significant long-term maintenance costs. In some cases, larger armor sizes may be selected to reduce maintenance demands over the structure's operational lifetime, despite higher initial construction costs.

It should be noted that the present study focuses specifically on conventional rubble mound breakwaters and vertical (composite) breakwaters. Dynamic stable structures, such as berm breakwaters, which may experience reshaping processes and longshore displacement of armor units under wave action, fall outside the scope of this research. Consequently, maintenance considerations related to long-term dynamic instability of reshaping structures are not addressed in the current framework.

The final design solution is typically obtained through an optimization process that balances construction and maintenance costs while accounting for feasible construction methods (e.g., CIRIA, 2007). In this context, water depth and material availability often represent the dominant cost drivers.

The design of breakwater structures requires integrated hydraulic, structural, and geotechnical analyses that address all relevant failure modes. Structural performances are evaluated with reference to both the **Serviceability Limit State (SLS)** and the **Ultimate Limit State (ULS)** (e.g., CIRIA, 2007). The SLS describes the ability of the structure to fulfil its intended function under normal operating conditions, while the ULS refers to the capacity of the structure to withstand extreme loading scenarios without catastrophic failure.

For rubble mound breakwaters, failure modes are primarily associated with wave action and geotechnical instability (Figure 3.2).

For caisson breakwaters, failure mechanisms are mainly related to the

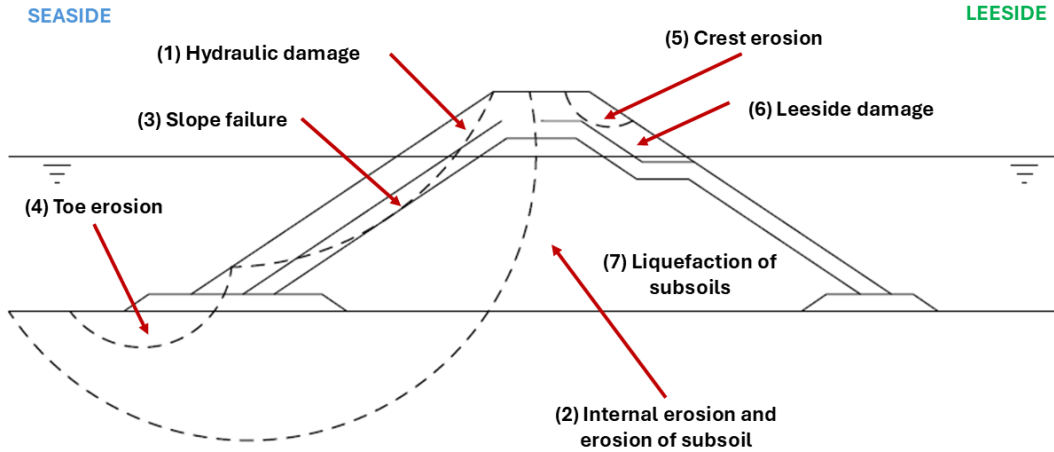


Figure 3.2. Failure modes affecting rubble mound breakwater structures

high impact forces generated by breaking waves, which may induce sliding, overturning, or bearing capacity failure of the caisson on its rubble foundation (Figure 3.3).

3.2.2 Rubble mound breakwaters

Rubble mound breakwaters are multi-layered coastal structures designed to dissipate wave energy through their geometric configuration and porous features that enhances wave breaking. They typically consist of a core made of relatively small quarry stones, protected by one or more armor layers placed on the seaward slope, crest, and leeward slope. Between the core and the armor layer, one or more filter layers are usually introduced in order to prevent the loss of finer core material under wave action. In addition, a toe berm is often deployed at the base of the seaward slope to provide structural support to the armor layer and to improve overall stability (Figure 3.4).

The main parameters governing the design of rubble mound breakwaters can be summarized as follows (e.g., CIRIA, 2007).

- **Crest freeboard, R_c (m).** The crest elevation is generally dictated by acceptable overtopping discharge or wave transmission levels, in accordance with the functional requirements defined for the structure and for the activities to be performed on the lee side. In addition, overtopping rates can be assessed through experimental investigations in order to obtain more accurate estimates for the design of the crest freeboard R_c (e.g., Beltrami et al., 2005).
- **Crest width, B (m).** The crest width should be sufficient to allow the placement of at least three natural rocks or artificial armor units. This requirement becomes particularly important when significant overtopping is expected.

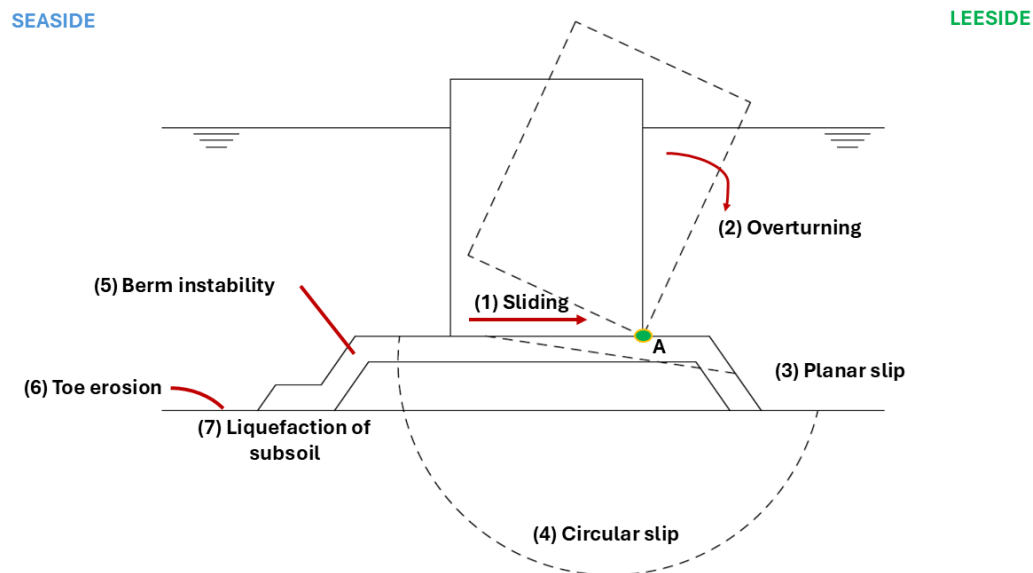


Figure 3.3. Failure modes affecting caisson breakwater structures

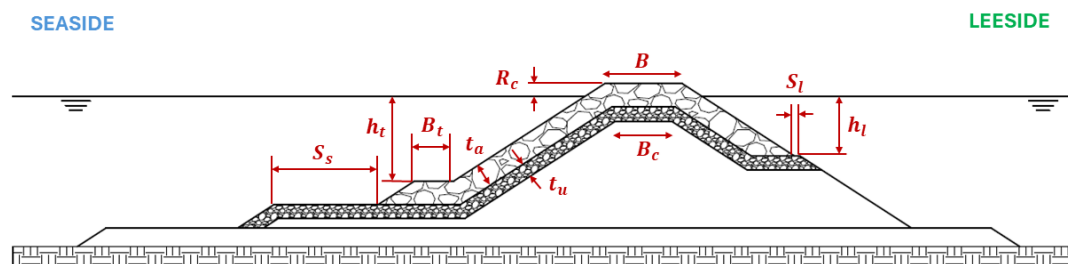


Figure 3.4. Typical cross-section of a rubble mound breakwater structure

- **Slope angle, α (deg).** The slope should be as steep as practicable in order to minimize the overall volume of the structure, while satisfying hydraulic and geotechnical stability criteria. For conventional rubble mound breakwaters, slopes are generally not steeper than 1:1.5 (V:H). For artificial armor units, steeper slopes may be adopted, depending on the guidance provided by the unit developer, with values as steep as 1:1.33 commonly used.
- **Layer thickness, t_a and t_u (m).** The thickness of armor (t_a) and underlayer layers t_u is typically determined using the following relationship:

$$t_a, t_u = 2 k_t D_{n50}, \quad (3.1)$$

where k_t is the layer thickness coefficient accounting for packing density effects, and D_{n50} is the nominal diameter of the units. For artificial armor units, recommended values of k_t are usually provided by the unit developers. In general, the layer thickness can be expressed as $n k_t D_n$, where $D_n = k_s^{1/3} D$, D is the characteristic dimension of the unit, and k_s is the shape coefficient.

- **Seaward toe level, h_t (m).** The water depth at the seaward toe typically ranges between $1.0H_s$ and $1.5H_s$ and strongly influences the required stone size for the toe berm.
- **Leeward berm or shoulder level, h_l (m).** This parameter depends on wave attack from the lee side and on the expected overtopping discharge. As reported in CIRIA (2007), a depth of approximately 3 m can be considered acceptable in many practical applications.
- **Toe width, B_t (m).** The toe width should allow the placement of at least three armor units. The thickness of the toe berm is generally governed by the same criteria adopted for the armor layer thickness.
- **Bedding layer width, S_s and S_l (m).** Unless specific erosion or scour conditions are anticipated, the seaward bedding layer width is typically not less than $S_s = 2$ m. The corresponding leeward bedding layer width is often computed as $S_l = 0.5 t_u$. When significant scour is expected, the bedding layer may act as an erosion control measure, and its width should not be less than 6 m.

3.2.3 Vertical Breakwaters

Vertical breakwaters, sometimes referred to as caisson breakwaters, are generally considered more economical, if compared to rubble mound breakwaters, in relatively deep water conditions, typically for water depths of approximately 15 m or greater (e.g., CIRIA, 2007). A sufficient water

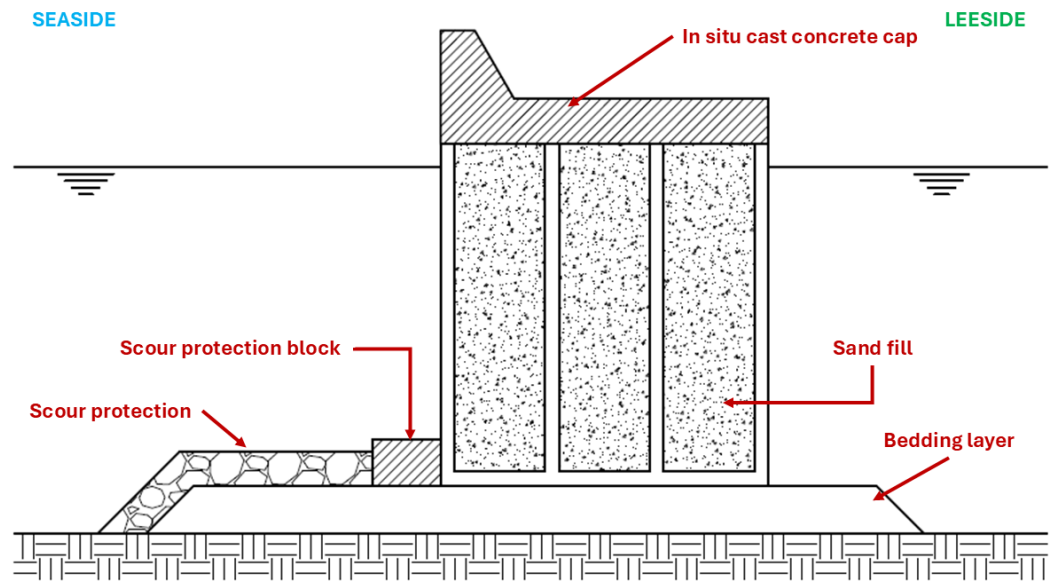


Figure 3.5. Typical cross-section of a caisson breakwater structure

depth is required to allow the placement and installation of the caisson units, which are usually prefabricated concrete elements positioned on a rubble foundation (Figure 3.5).

As water depth increases, the width of the caisson generally increases in order to ensure adequate stability against wave-induced loads, resulting in a composite breakwater configuration. The design of caisson structures is governed by the potential failure modes illustrated in Figure 3.3, which can be summarized as follows.

- **Horizontal sliding** (1), which occurs when the total horizontal wave force exceeds the frictional resistance at the interface between the caisson and its foundation.
- **Overturning** (2), involving rotation of the caisson around the lee-side edge of the concrete structure.
- **Geotechnical instability** (4), which may develop along a circular slip surface under unfavorable subsoil conditions.
- **Toe damage and seabed erosion** (5–6), resulting from wave action in front of the caisson, potentially leading to instability of the rubble foundation or erosion of the seabed adjacent to the toe.
- **Subsoil liquefaction** (7), which can be induced by wave impact forces when the foundation consists of loosely packed sandy materials.

The design of caisson stability, associated with failure mechanisms (1) to (4), is typically governed by extreme combinations of wave height and

wave period. In contrast, instability of the toe berm (5) is generally linked to severe storm conditions characterized by high significant wave heights, often combined with low water levels. This distinction reflects the fact that caisson failure may be triggered by a single extreme wave event (fragile behavior), whereas damage to rubble foundations and toe structures usually develops through more gradual processes (ductile behavior).

Accordingly, different probabilities of exceedance are adopted in the determination of design loads. The resulting design wave parameters include $H_{d,c}$, representing the design wave height relevant for caisson stability, and H_s , corresponding to the significant wave height used for the design of the toe and foundation. It is worth noting that the primary caisson failure mechanisms, namely sliding and overturning (1-2), are not directly influenced by the properties of the rubble mound foundation, which mainly affects toe stability and seabed response.

Last but not least, wave overtopping represents a further critical issue for this type of structure. In order to optimize the design of the crown wall, experimental campaigns are often carried out (e.g., Di Risio et al., 2007).

3.3 Wave loads and hydraulic response

To properly frame the design phase of maritime structures within a BIM-based workflow, it is useful to provide a synthetic description of the wave-related parameters that govern hydraulic loading and structural response.

Wave conditions are commonly characterized by the following parameters (e.g., Van der Meer, 1995).

- **Wave height (H).** The most widely adopted descriptor is the significant wave height, H_s , traditionally defined as the average height of the highest one-third waves ($H_{1/3}$). Under the assumption of a Rayleigh distribution of wave heights, $H_s \approx H_{1/3}$ and is commonly considered equivalent to the spectral significant wave height $H_{m0} = 4\sqrt{m_0}$, derived from the wave energy spectrum (where m_0 is the zeroth spectral moment).
- **Wave period (T).** Each value of H_s is typically associated with a peak wave period, T_p . In some applications, the mean wave period T_m is adopted, which can be approximated as $T_m = 0.9 T_p$.
- **Angle of wave attack (β)** defined as the angle between the wave propagation direction and the normal to the structure alignment.
- **Water depth (h).**

Depending on the water depth, two limiting conditions can be identified: *deep water* and *shallow water*. In deep water conditions, the wave

height distribution follows a Rayleigh distribution, making H_s a suitable representative parameter. In shallow water conditions, however, the highest waves in the wave train break, and the wave height distribution deviates from Rayleigh. In such cases, alternative characteristic wave heights are commonly adopted, such as $H_{2\%}$ (the wave height exceeded by 2% of individual waves) or $H_{1/10}$ (the mean height of the highest 10% of individual waves). For Rayleigh-distributed waves, these quantities can be approximated as:

$$H_{2\%} = 1.4 H_s, \quad H_{1/10} = 1.27 H_s. \quad (3.2)$$

The influence of the wave period is expressed through the wave length. Under deep water conditions, the wave length can be computed as $L_0 = gT^2/(2\pi)$, where g denotes gravitational acceleration. In practical coastal engineering applications, however, deep water conditions are rarely met at the structure location, and offshore wave characteristics may differ significantly from those acting on the structure.

To account for wave transformation on slopes and the associated breaking behavior, the *Iribarren number*, also known as the *surf similarity parameter*, is commonly introduced:

$$\xi = \frac{\tan(\alpha)}{\sqrt{s_0}}, \quad (3.3)$$

where $\tan(\alpha)$ is the slope of the structure and s_0 is the wave steepness, defined as $s_0 = H_b/L_0$, with H_b denoting the wave breaking height (e.g., CIRIA, 2007). Different empirical formulations exist for the estimation of wave steepness and breaking height.

The surf similarity parameter can be used to provide a useful classification of wave breaking types (Figure 3.6). In particular, spilling waves occur for $\xi < 0.4$, plunging waves for $0.4 < \xi < 2$, and collapsing or surging waves for $\xi > 2$.

When waves interact with a structure, extreme vertical oscillations may develop along the slope. These oscillations are referred to as *wave run-up*, R_u , and *wave run-down*, R_d . Run-up is defined as the maximum vertical level reached by water on the slope of a structure due to wave action (e.g., CIRIA, 2007). In design practice, the value $R_{u2\%}$ is commonly adopted, representing the run-up height exceeded by only 2% of incoming individual waves (e.g., van der Meer et al., 2016).

As already outlined, rubble mound breakwaters basically consist of a permeable mound protected by an armor layer composed of large quarry stones or concrete units (e.g., van der Meer et al., 2016). The inherent porosity and roughness of these structures significantly influence wave run-up, overtopping, transmission, and reflection processes. Similar ar-

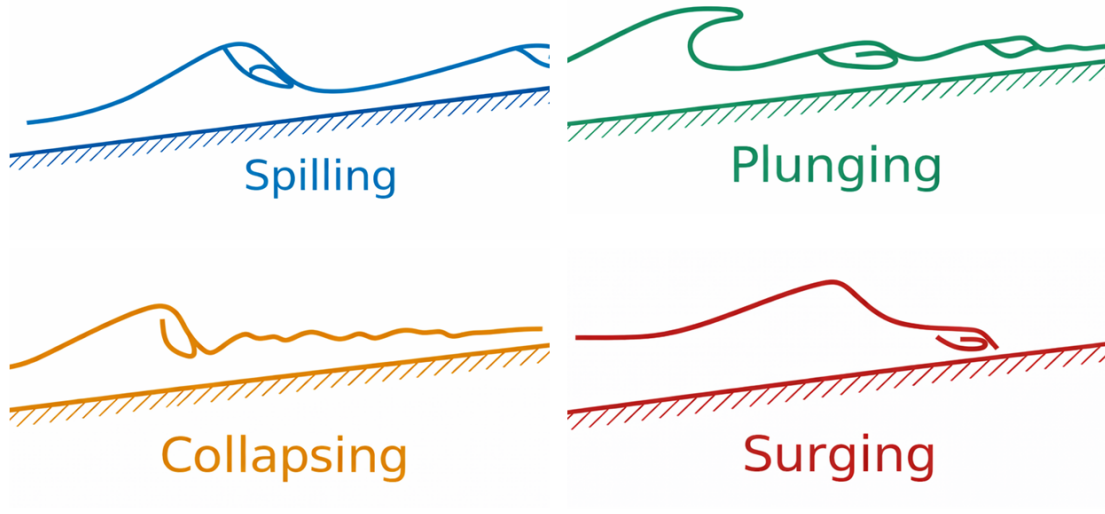


Figure 3.6. Sketches of wave breaking types

mor units may also be employed in vertical breakwaters to protect the concrete structure from direct wave impact.

Overtopping assessment can be carried out using two alternative methodologies: the *Mean Value Approach* and the *Design and Assessment Approach* (e.g., van der Meer et al., 2016). For rubble mound structures, the mean value formulation for wave run-up is expressed as:

$$\frac{R_{u2\%}}{H_{m0}} = 1.65 \gamma_b \gamma_f \gamma_\beta \xi_{m-1,0}, \quad (3.4)$$

with an upper bound given by:

$$\frac{R_{u2\%}}{H_{m0}} = \gamma_{f,surging} \gamma_\beta \left(4.0 - \frac{1.5}{\sqrt{\gamma_b \xi_{m-1,0}}} \right). \quad (3.5)$$

For $\xi_{m-1,0} \geq 1.8$, the roughness factor $\gamma_{f,surging}$ increases linearly up to unity at $\xi_{m-1,0} = 10$:

$$\gamma_{f,surging} = \gamma_f + (\xi_{m-1,0} - 1.8) \frac{1 - \gamma_f}{8.2}. \quad (3.6)$$

In the *Design and Assessment Approach*, the coefficients in Equations 3.4 and 3.5 are modified as follows:

$$\frac{R_{u2\%}}{H_{m0}} = 1.75 \gamma_b \gamma_f \gamma_\beta \xi_{m-1,0}, \quad (3.7)$$

$$\frac{R_{u2\%}}{H_{m0}} = 1.07 \gamma_{f,surging} \gamma_\beta \left(4.0 - \frac{1.5}{\sqrt{\gamma_b \xi_{m-1,0}}} \right). \quad (3.8)$$

Table 3.1. Roughness factor values for different armor layer configurations

Armor type	γ_f
Smooth impermeable surface	1.00
Rocks, 1 layer (impermeable core)	0.60
Rocks, 1 layer (permeable core)	0.45
Rocks, 2 layers (impermeable core)	0.55
Rocks, 2 layers (permeable core)	0.40
Tetrapods	0.38
Dolosse	0.43
Accropode TM I	0.46
Accropode TM II, Xbloc [®] , CORE-LOC [®]	0.44
Cubipods, one layer	0.49
Cubipods, two layers	0.47

Once $R_{u2\%}$ is known, the probability of overtopping can be estimated as:

$$P_{ov} = \exp \left[- \left(\sqrt{-\ln(0.02)} \frac{R_c}{R_{u2\%}} \right)^2 \right], \quad (3.9)$$

where R_c denotes the crest freeboard. The above formulations tend to provide conservative estimates of overtopping occurrence; therefore, P_{ov} represents an allowable exceedance probability (e.g., van der Meer et al., 2016).

In design practice, overtopping is primarily quantified in terms of the mean overtopping discharge q . For rubble mound breakwaters with steep slopes (1:2 to 1:4/3), the mean overtopping discharge according to the Mean Value Approach is given by:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 0.09 \exp \left[- \left(1.5 \frac{R_c}{H_{m0}\gamma_f\gamma_\beta} \right)^{1.3} \right]. \quad (3.10)$$

For the Design and Assessment Approach, the corresponding expression becomes:

$$\frac{q}{\sqrt{gH_{m0}^3}} = 1.35 \exp \left[- \left(1.35 \frac{R_c}{H_{m0}\gamma_f\gamma_\beta} \right)^{1.3} \right]. \quad (3.11)$$

Representative values of the roughness factor γ_f for different armor types and layer configurations are reported in Table 3.1 (e.g., van der Meer et al., 2016).

Table 3.1 reports representative values of the roughness factor γ_f for

various armor types and layer configurations (van der Meer et al., 2016, e.g.,). It should be noted that γ_f calibration depends not only on the armor unit type but also on the selected calibration dataset, following the methodology proposed by Molines and Medina (2015).

As shown in Equations (3.4)–(3.8), the influence of oblique wave attack is accounted for through the factor γ_β . The β parameter is defined as the angle between the wave direction and the normal to the structure (e.g., van der Meer et al., 2016). The reduction factor is computed as:

$$\gamma_\beta = 1 - 0.0063 |\beta|, \quad 0^\circ < |\beta| < 80^\circ. \quad (3.12)$$

For $|\beta| \geq 80^\circ$, the value at $|\beta| = 80^\circ$ is adopted. Wave height and period are assumed to decrease linearly to zero for $80^\circ \leq |\beta| \leq 90^\circ$, and wave overtopping is neglected for $|\beta| > 110^\circ$ (e.g., van der Meer et al., 2016).

Finally, *wave transmission* and *wave reflection* represent additional parameters of interest. Transmission is quantified by the transmission coefficient:

$$C_t = \frac{H_t}{H_i} = \sqrt{\frac{E_t}{E_i}}, \quad (3.13)$$

where H_t and H_i denote transmitted and incident wave heights, respectively, and E_t and E_i are the corresponding wave energies.

Wave reflection, which may lead to hazardous sea states in front of the structure, is described by the reflection coefficient:

$$C_r = \frac{H_r}{H_i} = \sqrt{\frac{E_r}{E_i}}, \quad (3.14)$$

where H_r is the reflected wave height and E_r is the reflected wave energy.

3.4 Stability verification of crown walls

Crown walls represent a fundamental component of both vertical and rubble mound breakwaters (Figure 3.9). They improve overtopping performance and contribute to structural stability at crest level. Under severe wave attack, crown walls are subjected to significant horizontal impact forces and uplift pressures that may govern their structural design.

The stability verification is generally performed with reference to the ultimate limit states of sliding and overturning (e.g., CIRIA, 2007).

Stability against sliding requires:

$$f(F_G - F_U) \geq F_H \quad (3.15)$$

while stability against overturning requires:

$$M_G - M_U \geq M_H \quad (3.16)$$

where F_G is the self-weight of the crown wall, F_U the uplift force, F_H the horizontal wave force, and f the friction coefficient, commonly taken equal to 0.5 for concrete elements resting on rubble foundations. M_G , M_U , and M_H denote the corresponding moments computed about the relevant rotation point.

No universal method exists to predict wave loads on crown walls for all geometric and hydraulic configurations. Among the formulations most commonly adopted in practice are those proposed by Bradbury et al. (1988), Pedersen (1996), and Martin et al. (1999). These approaches differ in their physical assumptions and in the representation of the design sea state.

3.4.1 Bradbury formulation

The approach proposed by Bradbury et al. (1988) expresses the maximum horizontal force as:

$$F_H = (\rho_w g d_c L_{op}) \left(a \frac{H_s}{R_{ca}} - b \right) \quad (3.17)$$

where H_s is the significant wave height, L_{op} the deep-water wavelength corresponding to the peak period, d_c the height of the crown wall face, R_{ca} the armour crest level, and a, b empirical coefficients.

Due to limited data on uplift pressures, simplified pressure distributions are assumed. The horizontal pressure is taken as rectangular ($p_H = F_H/d_c$), while the uplift pressure is assumed to decrease linearly from the front edge to zero at the rear. The uplift force is therefore estimated as:

$$F_U = \left(\frac{\rho_w g B_c L_{op}}{2} \right) \left(a \frac{H_s}{R_{ca}} - b \right) \quad (3.18)$$

where B_c is the base width of the crown wall.

3.4.2 Pedersen formulation

The formulation proposed by Pedersen (1996) relates the impact pressure to extreme run-up levels. The horizontal impact pressure component is defined as:

$$p_i = \rho_w g (R_{u,0.1\%} - R_{ca}) \quad (3.19)$$

where $R_{u,0.1\%}$ is the run-up level with 0.1% exceedance probability and R_{ca} is the vertical distance between SWL and the armour crest.

The corresponding horizontal force is:

$$F_{H,0.1\%} = 0.21 \sqrt{\frac{L_{om}}{B_a}} \left(1.6 p_i y_{eff} + V \frac{p_i}{2} d_{c,prot} \right) \quad (3.20)$$

where

$$y_{eff} = \min \left\{ \frac{y}{2}, d_{ca} \right\} \quad (3.21)$$

and

$$V = \min \left\{ \frac{V_2}{V_1}, 1 \right\} \quad (3.22)$$

The parameters involved in the formulation are illustrated in Figure 3.7.

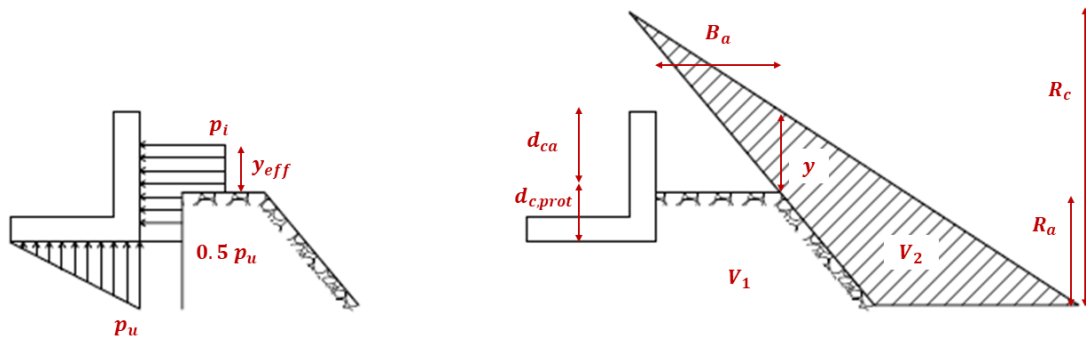


Figure 3.7. Schematic representation of pressure distribution and geometric parameters according to Pedersen (1996).

The associated overturning moment is:

$$M_{H,0.1\%} = 0.55(d_{c,prot} + y_{eff})F_{H,0.1\%} \quad (3.23)$$

while the uplift pressure is:

$$p_{U,0.1\%} = V p_i \quad (3.24)$$

The validity of the formulation is limited to the parametric ranges reported in Table 3.2.

Table 3.2. Parameter ranges for the method by Pedersen (1996).

Parameter	Symbol	Range
Breaker parameter using T_m	ξ_m	1.1–4.2
Relative wave height	H_s/R_{ca}	0.5–1.5
Relative run-up level	R_c/R_{ca}	1–2.6
Relative berm width	R_{ca}/B_a	0.3–1
Front side slope	$\cot \alpha$	1.5–3.5

3.4.3 Martin formulation

The methodology proposed by Martin et al. (1999) is formulated for broken waves impacting the crown wall and distinguishes between impact and pulsating pressure components.

3.4.3.0.1 IMPACT PRESSURE

$$p_i = c_{wl} \rho_w g S_o \quad (3.25)$$

$$S_o = H \left(1 - \frac{R_{ca}}{R_u} \right) \quad (3.26)$$

$$c_{wl} = 2.9 \left[\left(\frac{R_u}{H} \right) \cos \alpha \right]^2 \quad (3.27)$$

For the protected portion:

$$p_i = c_{w2} c_{wl} \rho_w g S_o \quad (3.28)$$

$$c_{w2} = 0.8 \exp \left(-10.9 \frac{B_a}{L_p} \right) \quad (3.29)$$

3.4.3.0.2 PULSATING PRESSURE

$$p_p(z) = c_{w3} \rho_w g (S_o + R_{ca} - z) \quad (3.30)$$

$$c_{w3} = a \exp(c_o) \quad (3.31)$$

$$c_o = c \left(\frac{H}{L_p} - b \right)^2 \quad (3.32)$$

The empirical coefficients a , b , and c depend on berm width and armour size, as summarized in Table 3.3.

Table 3.3. Empirical coefficients for pulsating pressure calculation (CIRIA, 2007).

B_u/D_{n50}	a	b	c
1	0.446	0.068	259.0
2	0.362	0.069	357.1
3	0.296	0.073	383.1

Uplift pressures are derived consistently with the horizontal pressure distribution at the base of the front face, with impact contribution vanishing at the heel.

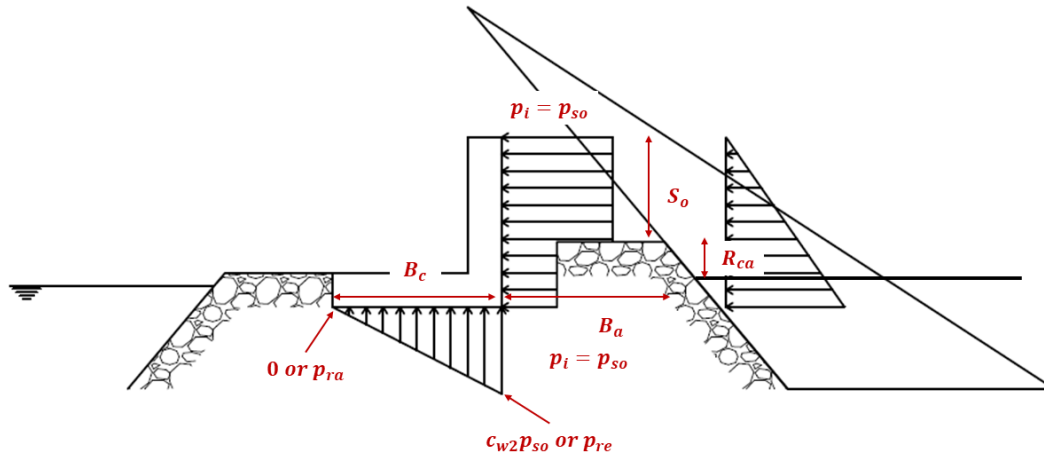


Figure 3.8. Schematic pressure distribution and definition of geometric and hydraulic parameters according to Martin et al. (1999).

Figure 3.8 provides a schematic overview of the pressure distribution and the parameters governing the Martin formulation.

The verification methods for crown walls are not implemented in the tool developed in the present work, whose current scope is limited to geometric and BIM modelling and deployment simulation. The integration of structural verification procedures represents a natural extension of the framework and constitutes part of ongoing research.

3.5 Stability analysis

Once the main design parameters and related hydraulic response have been defined, the hydraulic stability assessment can be introduced.

Different approaches must be used depending on the type of structure considered. For rubble mound breakwaters, the stability of the armor layer is typically evaluated using empirical formulae derived from physical model tests or field observations. In contrast, for caisson breakwaters, stability is assessed through limit state analyses that consider sliding, overturning, and bearing capacity failure modes.

The evaluation of the hydraulic stability of rock-armored coastal structures relies on a combination of hydraulic loading parameters, material characteristics, and structural configuration (e.g., CIRIA, 2007). For clarity, the governing parameters can be grouped into four categories:

- wave and current attack;
- characterization of armorstone;

- cross-sectional geometry of the structure;
- structural response.

A key non-dimensional parameter summarizing the interaction between wave loading and material resistance is the **stability number**, which relates the characteristic wave height to the size and density of the protective material. The stability number N_s is defined as:

$$N_s = \frac{H}{\Delta D}, \quad (3.33)$$

where:

H = wave height (m), typically taken as the significant wave height H_s or the spectral significant wave height H_{m0} . Under deep-water conditions, $H_s \approx H_{m0}$;

Δ = relative buoyant density (-);

D = characteristic diameter (m), depending on the structure type. For armorstone, D is commonly the median nominal diameter D_{n50} , defined as the median equivalent cube size. For concrete armor units, the nominal diameter D_n is used, which depends on unit geometry.

The relative buoyant density is computed as:

$$\Delta = \frac{\rho_r - \rho_w}{\rho_w} = \frac{\rho_r}{\rho_w} - 1, \quad (3.34)$$

where ρ_r is the apparent mass density of the rock (kg/m^3) and ρ_w is the density of water (kg/m^3). For concrete armor units, ρ_c is used in place of ρ_r .

Another crucial parameter controlling wave–structure interaction is the **surf similarity parameter** (Iribarren number), ξ (see Eq. 3.3). Its computation requires an estimate of the wave steepness and, consequently, of the breaking wave height H_b . Several approaches are available in the literature. For instance, Goda proposed an expression for surf-zone steepness (e.g., Goda, 2010):

$$\frac{H_b}{L_0} = A \left\{ 1 - \exp \left[-1.5 \frac{\pi h}{L_0} \left(1 + 15 \tan^{4/3} \theta \right) \right] \right\}, \quad (3.35)$$

where L_0 is the deep-water wave length, θ denotes the seabed slope angle (so that $\tan \theta$ is the bottom slope), and A is an empirical coefficient (for regular waves, $A = 0.17$).

To estimate the breaking wave height, Kamphuis proposed alternative

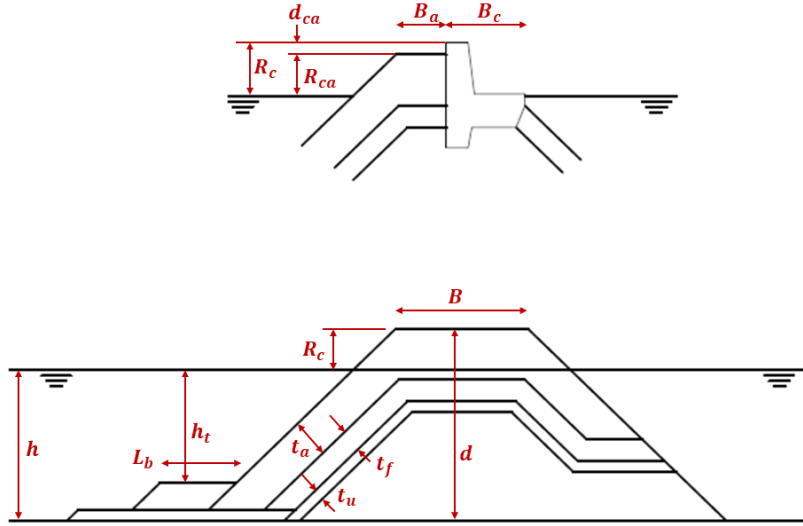


Figure 3.9. Governing parameters related to the breakwater cross-section

formulations (e.g., Kamphuis, 1991). The first expression is:

$$H_b = 0.0955 \exp(4m) L_b \tanh\left(\frac{2\pi h}{L_b}\right), \quad (3.36)$$

where:

- m = bottom slope ($\tan \alpha$);
- L_b = breaking wave length (m);
- T_p = peak wave period (s);
- h = breaking water depth (m).

A second formulation reads as:

$$H_b = 0.56 \exp(3.5m) h. \quad (3.37)$$

In practical applications, the first Kamphuis formulation is often preferred because it accounts for wave period (or wave length) in addition to slope and depth (e.g., Kamphuis, 1991).

Once an appropriate breaking criterion is selected, the wave steepness s_0 and the corresponding ξ can be evaluated.

Beyond hydraulic loading, cross-section geometry significantly affects stability. As discussed in (e.g., CIRIA, 2007), structural parameters can be grouped into (i) geometric parameters defining the cross-section and (ii) parameters associated with construction and placement conditions. Figure 3.9 provides an overview of the principal geometric descriptors.

The main geometric parameters include:

- crest freeboard relative to the still water level (SWL), R_c ;
- armor crest freeboard relative to SWL, R_{ca} ;
- difference between crown wall and armor crest, d_{ca} ;
- structure height relative to the seabed, d ;
- structure width, B ;
- width of the armor berm at the crest, B_a ;
- thickness of armor, underlayer, and filter, t_a, t_u, t_f ;
- seaward slope angle, α (deg);
- depth of the toe below SWL, h_t ;
- length of the berm, L_b .

Among these, R_c and B are primarily governed by allowable overtopping, while crest width can also be influenced by construction constraints (e.g., CIRIA, 2007).

As with the previously cited parameters, the berm configuration—expressed through its length L_b —also plays a crucial role in the stability of rubble mound breakwater structures. A submerged berm can significantly influence the seabed soil response and the occurrence of momentary liquefaction phenomena around and beneath the breakwater foundation under dynamic wave loading (e.g., Celli et al., 2019, 2020). Furthermore, a submerged berm with a length greater than usual enhances the overall stability of the armor layer (e.g., Celli et al., 2018), as it reduces the wave loads acting on the upper slope of the armor layer.

Additional parameters describing construction-induced conditions include:

- porosity of the armor layer;
- permeability of the armor, filter, and core;
- packing density (placement density) of the armor layer.

Armor layer porosity depends on unit shape and grading as well as on placement method (e.g., CIRIA, 2007). For concrete armor units, an expression for layer porosity is:

$$n_v = \left[1 - \frac{N}{n k_t} \left(\frac{M}{\rho_c} \right)^{2/3} \right] = \left[1 - \frac{N}{n k_t} \frac{V}{D_n^3} \right], \quad (3.38)$$

where:

N = number of armor units per unit area (m^{-2});

n = number of armor layers (-);

k_t = layer thickness coefficient (-);

M = mass of a concrete armor unit (kg);

ρ_c = mass density of concrete (kg/m^3);

V = volume of the armor unit (m^3);

D_n = nominal diameter of the armor unit (m), $D_n = k_s^{1/3} D$,
where k_s is the shape coefficient and D is a characteristic
unit dimension (e.g., block height).

Permeability is not typically expressed through a conventional Darcy formulation at the scale of these structures; instead, a *notional permeability* factor P is commonly adopted (e.g., van der Meer, 1988). A simplified alternative is to use ratios between characteristic diameters of core and armor materials (e.g., CIRIA, 2007).

The **packing density** provides information on the placement pattern and can be used to estimate the number of armor units per unit area:

$$N = \frac{t_a(1 - n_v)}{V} = \frac{n k_t(1 - n_v)}{D_{n50}^3}, \quad (3.39)$$

where t_a is the armor layer thickness, commonly expressed as $t_a = n k_t D_{n50}$.

Hydraulic stability is ultimately assessed by relating wave loading to acceptable levels of structural response. One widely used approach is based on **damage level** indicators, which quantify armor unit displacement within a reference area and are often associated with *no-damage* or *limited-damage* criteria. A classical formulation in this context is the Hudson formula, derived from model tests under regular wave conditions for non-overtopped rock structures with permeable cores (CIRIA, 2007):

$$W_{50} = \frac{\rho_r g H^3}{K_D \Delta^3 \cot(\alpha)}, \quad (3.40)$$

where W_{50} is the median armorstone weight, H is the design wave height at the toe (typically H_s), K_D is a stability coefficient (-), ρ_r is the apparent rock density (kg/m^3), Δ is the relative buoyant density, and α is the slope angle. For design purposes, a limited displacement of armor stones (approximately 0–5%) is often considered acceptable (e.g., CIRIA, 2007). Under a no-damage criterion, the Shore Protection Manual (SPM) suggests $K_D = 3.5$ for breaking waves and $K_D = 4.0$ for non-breaking waves on the foreshore (e.g., US).

The Hudson formula is attractive due to its simplicity; however, it ex-

hibits important limitations:

- it is based on experimental tests performed with regular waves only;
- it does not explicitly account for wave period or storm duration;
- it does not provide a description of damage progression;
- it is applicable to non-overtopped structures and specific permeability conditions.

Expressed in terms of the stability number and adopting $H_{1/10}$, the Hudson relationship can be written as (e.g., CIRIA, 2007):

$$\frac{H_s}{\Delta D_{n50}} = \frac{(K_D \cot \alpha)^{1/3}}{1.27}. \quad (3.41)$$

For this formulation, typical values are $K_D = 2.0$ for breaking waves and $K_D = 4.0$ for non-breaking waves.

While Eq. (3.41) corresponds to a fixed damage level, it can be extended by introducing a damage parameter S_d (e.g., van der Meer, 1988):

$$\frac{H_s}{\Delta D_{n50}} = 0.7 (K_D \cot \alpha)^{1/3} S_d^{0.15}, \quad (3.42)$$

where $S_d = A_e/D_{n50}^2$ and A_e denotes the eroded cross-section area (m^2). In this formulation strongly K_D also reflects permeability effects, with representative values of $K_D = 1.0$ for impermeable cores and $K_D = 4.0$ for permeable cores (e.g., van der Meer, 1988).

A more comprehensive stability framework was developed by Van der Meer (1995), explicitly accounting for storm duration (through the number of individual waves), damage level, wave breaking type, wave period, and structure permeability. For deep-water wave conditions, separate expressions are provided for plunging and surging waves:

- **Plunging waves** ($\xi_m < \xi_{cr}$):

$$\frac{H_s}{\Delta D_{n50}} = C_{pl} P^{0.18} \left(\frac{S_d}{\sqrt{N}} \right)^{0.2} \xi_m^{-0.5}, \quad (3.43)$$

- **Surging waves** ($\xi_m \geq \xi_{cr}$):

$$\frac{H_s}{\Delta D_{n50}} = C_s P^{0.13} \left(\frac{S_d}{\sqrt{N}} \right)^{0.2} \xi_m^P, \quad (3.44)$$

where N is the number of incident waves at the toe (-), ξ_m is the surf similarity parameter computed using the mean wave period T_m , P is the notional permeability factor, typically $0.1 \leq P \leq 0.6$ (e.g., CIRIA, 2007), and the coefficients are commonly taken as $C_{pl} = 6.2$ and $C_s = 1.0$.

The transition between plunging and surging regimes is governed by a critical surf similarity parameter:

$$\xi_{cr} = \left[\frac{C_{pl}}{C_s} P^{0.31} \sqrt{\tan \alpha} \right]^{\frac{1}{P+0.5}}. \quad (3.45)$$

For relatively gentle slopes ($\cot \alpha \geq 4$), only the plunging formulation is typically applied (e.g., CIRIA, 2007).

For shallow water conditions, wave loading and wave height distributions deviate from Rayleigh behavior, and stability is better described using higher-percentile wave heights (e.g., $H_{2\%}$). Furthermore, the surf similarity parameter is often computed using the energy period $T_{m-1,0}$, extending the applicability of the method to intermediate and shallow water conditions (e.g., Van Gent et al., 2003). In this context, the Van der Meer expressions can be rewritten as:

- **Plunging conditions** ($\xi_{s-1,0} < \xi_{cr}$):

$$\frac{H_s}{\Delta D_{n50}} = C_{pl} P^{0.18} \left(\frac{S_d}{\sqrt{N}} \right)^{0.2} \left(\frac{H_s}{H_{2\%}} \right) \xi_{s-1,0}^{-0.5}, \quad (3.46)$$

- **Surging conditions** ($\xi_{s-1,0} \geq \xi_{cr}$):

$$\frac{H_s}{\Delta D_{n50}} = C_s P^{-0.13} \left(\frac{S_d}{\sqrt{N}} \right)^{0.2} \left(\frac{H_s}{H_{2\%}} \right) \sqrt{\cot \alpha} (\xi_{s-1,0})^P, \quad (3.47)$$

where $H_{2\%}$ is the wave height exceeded by 2% of the incident waves at the toe, $\xi_{s-1,0}$ is computed using the energy wave period $T_{m-1,0}$, and $T_{m-1,0} = m_{-1}/m_0$. Based on regression analyses of shallow-water tests (e.g., Van Gent et al., 2003), typical coefficients are $C_{pl} = 8.4$ (standard deviation $\sigma = 0.7$) and $C_s = 1.3$ (standard deviation $\sigma = 0.15$). The validity range of the shallow-water formulation is reported in Table 3.4.

In practical stability checks, useful within the frame of a BIM workflow, the wave conditions are first established (using the preferred wave breaking and transformation criteria) and the armor unit characteristics are defined during the design stage. Given the limitations of the Hudson approach, the Van der Meer formulations provide a more complete basis for stability assessment under both deep- and shallow-water conditions. In the present work, stability is considered satisfied when the design median nominal diameter of the armor layer is greater than or equal to the diameter required by the selected stability formulation:

$$D_{n50,design} \geq D_{n50,method}. \quad (3.48)$$

Table 3.4. Range of validity of parameters in Van der Meer formulae for shallow water conditions

Parameter	Symbol	Range
Slope angle	$\tan \alpha$	1:4 – 1:2
Number of waves	N	< 3000
Wave steepness (based on T_m)	s_{0m}	0.01 – 0.06
Surf similarity (using T_m)	ξ_m	1 – 5
Surf similarity (using $T_{m-1,0}$)	$\xi_{s-1,0}$	1.3 – 6.5
Wave height ratio	$H_{2\%}/H_s$	1.2 – 1.4
Deep-water wave height over toe depth	H_{s0}/h	0.25 – 1.5
Armorstone gradation	D_{n85}/D_{n15}	1.4 – 2.0
Core–armor ratio	$D_{n50,core}/D_{n50}$	0.0 – 0.3
Stability number	$H_s/(\Delta D_{n50})$	0.5 – 4.5
Damage level	S_d	< 30

3.6 The design of the armor layer

The design of the armor layer depends on the typology of the protective units adopted, as different armor units require specific placement and deployment strategies.

Natural rocks and simple concrete units, such as cubes, are generally placed using a random placement technique. In these cases, stability is mainly ensured by unit mass, layer thickness, and overall porosity, rather than by controlled interlocking.

By contrast, complex-shaped concrete armor units, such as AccropodesTM, require a specific design phase for their placement and deployment. These units are specifically shaped to promote interlocking and stability through controlled positioning, rather than relying solely on self-mass.

Just for instance, AccropodesTM are single-layer concrete armor units designed to provide high hydraulic stability with reduced material volume. They are precast in concrete using specialized moulds and are placed on the breakwater slope following a specific placement pattern. A detailed placement plan must be then defined during the design phase to ensure correct orientation, contact points, and interlocking between adjacent units.

Tetrapods are another type of artificial concrete armor unit, characterized by a four-legged geometry that enhances interlocking and energy dissipation. Like AccropodesTM, Tetrapods are prefabricated using dedicated moulds (Figure 3.10).

Unlike AccropodesTM, Tetrapods are typically placed in two layers us-



Figure 3.10. Tetrapod concrete armor unit (Photo of the author)

ing a random or semi-random placement technique. Stability is achieved through mutual interlocking between units, combined with adequate layer thickness and porosity.

It is worth to be highlighted that differences in placement philosophy may have direct implications for BIM-based modeling, as they require different levels of geometric detail and information granularity depending on the armor unit typology.

3.7 Management and maintenance

One of the key aspects influencing the design of both rubble mound and vertical breakwaters is the long-term management and maintenance.

Maintenance activities should be planned within a structured management strategy developed during the design stage, taking into account the entire service life of the hydraulic structure, including performance requirements and life-cycle costs (e.g., CIRIA, 2007).

The relationship between initial investment, maintenance actions, and failure risk can be expressed through the minimization of the following objective function:

$$\min \{I + PV(M) + PV(R) + PV(P_F C_F)\}, \quad (3.49)$$

where:

I	initial investment cost of the structure,
M	cost of monitoring and routine maintenance,
R	cost of repair or replacement,
P_F	probability of failure,
C_F	consequences (costs) associated with failure,
$PV(\cdot)$	present value operator.

This formulation highlights the strong relationship between design decisions, inspection strategies, maintenance planning, and acceptable levels of risk.

Reliable methods are therefore required to evaluate the condition of the structure in order to:

- assess damage caused by specific events;
- predict the remaining service life of the structure;
- plan maintenance, rehabilitation, or replacement interventions.

In general, management and maintenance strategies for maritime structures (e.g., CIRIA, 2007) can be classified as follows:

- **Failure-based maintenance**, where intervention occurs only after failure. This strategy is acceptable only when the consequences of failure are minimal.
- **Periodic maintenance**, based on inspections or interventions performed at predefined time intervals.
- **Use-based maintenance**, where maintenance is scheduled after a certain number of operational cycles.
- **Load-based maintenance**, where deterioration is related to the occurrence of heavy loading events, which must be monitored.
- **Condition-based maintenance**, which relies on systematic inspections and monitoring of the physical condition of the structure.

To ensure that the selected maintenance strategy remains effective, a comprehensive management plan must be implemented and maintained throughout the entire life cycle of the structure (Figure 3.11).

An effective management strategy aims to guarantee structural functionality while meeting end-user requirements in a cost-effective manner. In particular, a management plan should:

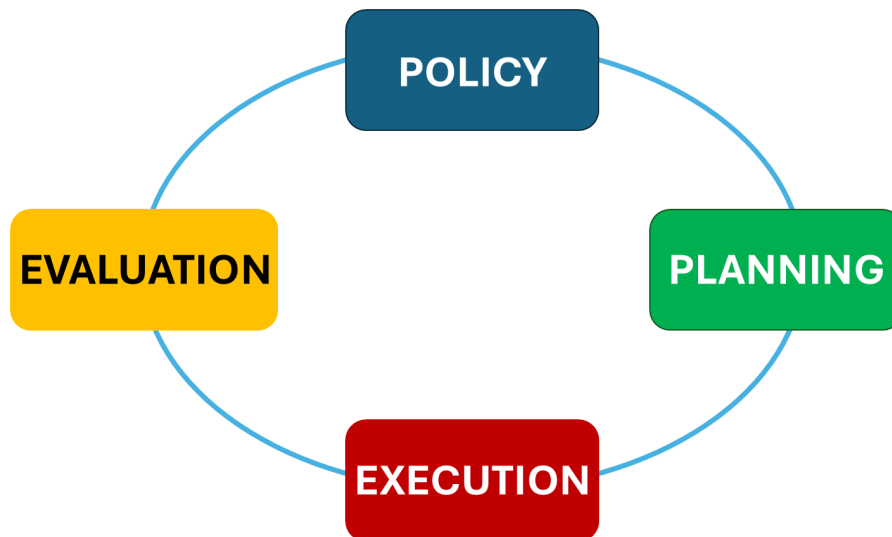


Figure 3.11. Workflow of a management plan for maritime structures

- maximize structural performance while minimizing total life-cycle costs;
- identify required maintenance and monitoring measures and their objectives;
- schedule maintenance and inspection activities;
- assess the current service level and physical condition of all components within the system;
- adapt to changes in policy, budget constraints, and operational priorities;
- preserve knowledge and experience to prevent loss of information over time.

Management plans can be conceptually divided into a static and a dynamic component (e.g., CIRIA, 2007):

Static component	Dynamic component
Introduction	Evaluation of past performance
Description of the infrastructure system and its subdivision into management units	Medium-term planning (e.g. five-year horizon): measures and costs
Policy framework, target conditions, and functional requirements	Long-term strategic planning
Management philosophy	

The static component is periodically reviewed to account for changes in policies, user requirements, or unexpected structural performance (e.g., CIRIA, 2007). The dynamic component defines the operational measures required to manage the system, including inspection activities, maintenance actions, and associated costs.

In summary, a comprehensive management plan for maritime structures should include the following essential elements:

- periodic inspection of the structure and monitoring of environmental conditions and structural response;
- evaluation of inspection and monitoring data to assess physical condition and performance relative to design assumptions and predefined service levels;
- definition of appropriate responses based on evaluation results, including:
 - no action,
 - repair of localized damage,
 - rehabilitation of part or all of the structure,
 - replacement of components whose estimated service life is shorter than that of the overall structure.

Within this context, BIM represents a powerful tool not only for design but also for long-term management and maintenance. By relating an up-to-date information layer with each structural component inspection unit, by continuously updating it through inspection and survey activities, BIM enables efficient data management, supports decision-making processes, and minimizes the risk of information loss throughout the structure's life cycle.

THE PROPOSED TOOL

4.1 General remarks

This chapter introduces BIMMs (Building Information Modeling for Maritime Structures), a novel tool developed to support the design, modeling, maintenance, and analysis of maritime infrastructures. BIMMs is developed within the framework of Blender and integrates two complementary sub-tools, each addressing a specific phase of the design and verification process:

1. **Maritime modeling tool.** This module, in combination with the add-ons Blender GIS and Bonsai BIM, enables the creation of detailed and semantically enriched BIM models of maritime structures. It allows users to generate accurate geometric representations of breakwaters including, for rubble mound breakwaters, cross-sections, armor layers, and filter layers, while ensuring interoperability with standard BIM formats.
2. **Maritime deployment tool.** This module, for rubble mound, leverages Blender's built-in rigid body physics engine to simulate the deployment and placement of breakwater armor units. In addition, it supports the assessment of armor unit stability and the calculation of wave overtopping discharge, thereby establishing a direct link between the geometric model and hydraulic performance analyses.

The workflow relies on some pre-processing steps. GIS software is employed to obtain site-specific bottom contour lines and the alignment of the structure to be reproduced within the BIM workflow. These data are then used to construct the cross-section geometry of the maritime structure using Blender's modeling tools. The resulting objects are exported as STL files and imported into BIMMs to generate a detailed seabed model. Subsequently, the complete geometric model of the breakwater is assembled, and the BIM model is created by integrating geometric and informational

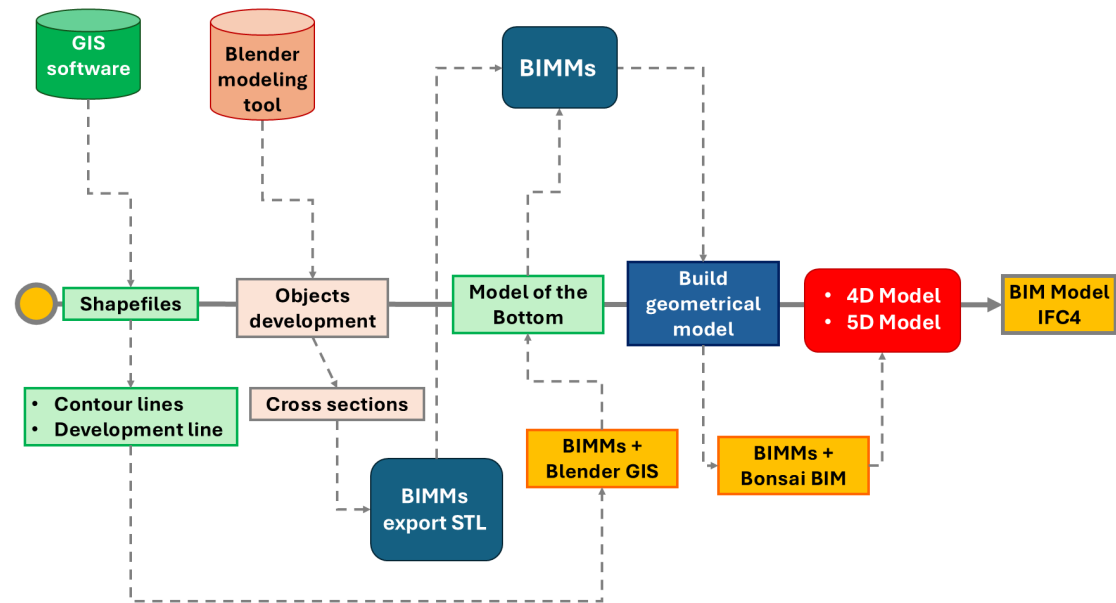


Figure 4.1. Workflow of the proposed tool

layers through Bonsai BIM (Figure 4.1).

By combining GIS data, advanced 3D modeling, and physics-based simulation, BIMMs enables a seamless transition from design to analysis, providing a comprehensive platform that supports both conceptual and detailed design stages of maritime infrastructure projects. Unlike conventional BIM tools, BIMMs explicitly embeds maritime engineering knowledge into both the geometric modeling process and the associated information structure. This integrated approach facilitates the concurrent consideration of design, structural stability verification, and hydraulic performance assessment within a single interoperable BIM environment, effectively bridging the gap between traditional maritime engineering practice and modern digital design methodologies and digital tools for long term maintenance planning.

4.2 Maritime modeling tool

4.2.1 General overview

Maritime Modeling Tool: enables the design of a detailed geometric model of maritime structures. Before explaining how the tool is organized, it is worth noting that the modeling process begins with the use of GIS software to define the longitudinal development of the structure (*development line*, i.e., the line that runs along the center of the structure) and the bathymetric contour lines used to create the seabed model.

Within the Blender user interface, the tool is organized into a set of sub-menus (Figure 4.2):

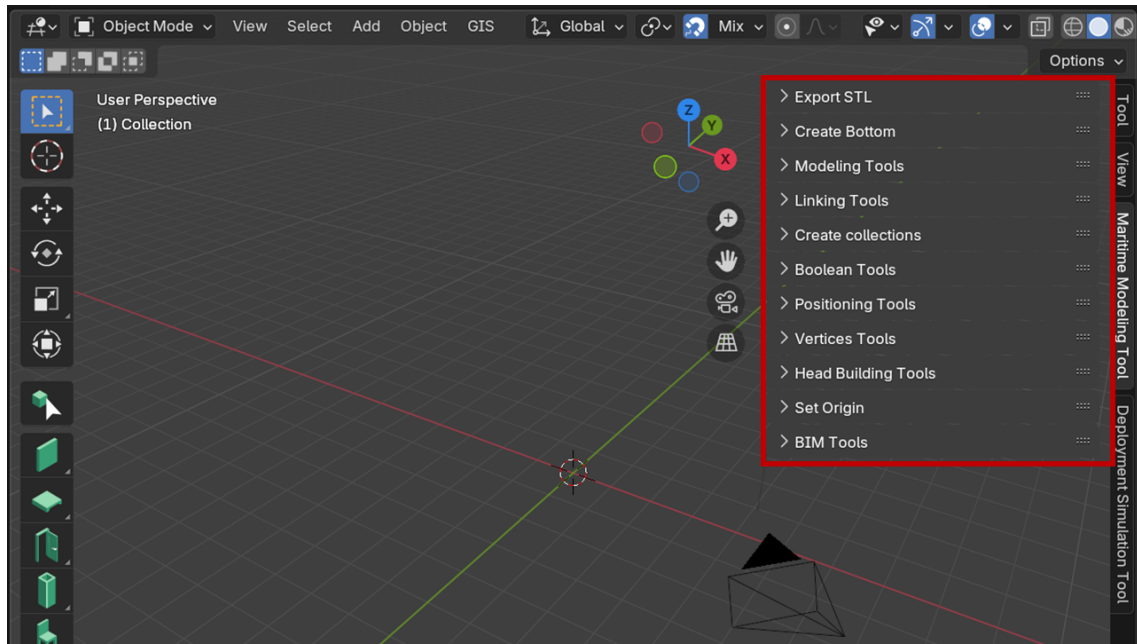


Figure 4.2. User interface of the proposed tool for modeling maritime structures

1. *Export STL*: allows the export of the various library elements used in the construction of the geometric model, such as the cross-sections of the different layers of a rubble-mound breakwater or the caisson of a vertical breakwater structure.
2. *Create Bottom*: generates the seabed model starting from bottom contour lines obtained using GIS software.
3. *Modeling Tools*: provides a set of commands to import the longitudinal alignment (*Development Line*) of the structure and the corresponding cross-sections along it.
4. *Linking Tools*: enables the connection of the different cross-sections of the structure.
5. *Create Collections*: allows the organization of the working environment by grouping elements into dedicated containers.
6. *Boolean Tools*: applies Boolean operations to the selected elements.
7. *Positioning Tools*: places the selected elements in their correct spatial position.
8. *Vertices Tools*: adjusts and corrects the position of the vertices of the selected objects.
9. *Head Building Tools*: supports the modeling of the head section of the structure.
10. *Set Origin*: enables modification of the object origin.

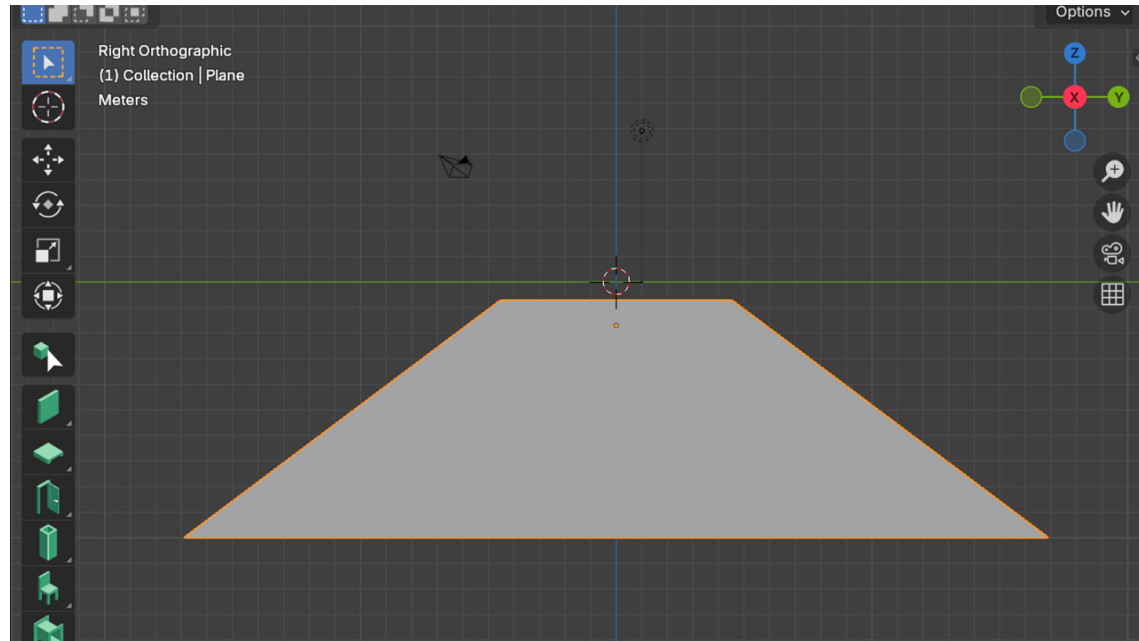


Figure 4.3. Core element modeled as a cross-section in the Blender user interface

11. *BIM Tools*: allows the creation of BIM storeys and the assignment of (specific) IFC properties.

Each sub-menu is described in detail in the following sections.

4.2.2 Export STL

Each object modeled within the Blender user interface is exported through a specific command, which automatically saves it as an STL file in a directory created by the tool. This approach ensures a streamlined workflow by reducing the risk of errors during the preparation of geometric models for subsequent BIM-based processes thanks to the minimization of manual operations.

For rubble mound breakwaters, each structural component is represented by a cross-section (Figure 4.3). Once modeled, each cross-section is positioned at its design elevation, in accordance with the corresponding hydraulic and geotechnical requirements. Similarly, vertical breakwaters are modeled using cross-sections for all constituent layers, with the exception of the caisson, which is represented as a fully three-dimensional object (Figures 4.5 and 4.6).

To enable automated STL export and to ensure consistency across the different structural components, each modeled element is related to a specific identification name according to the conventions defined within BIMMs. For rubble mound breakwaters, the adopted naming convention is as follows:

- *00_core*: core elements

-
- *01_filter_firstLayer*: first filter layer
 - *01_filter_inshore*: inshore boundary of the first filter layer
 - *01_filter_offshore*: offshore boundary of the first filter layer
 - *02_filter_layer_inshore*: second filter layer, inshore side
 - *02_filter_layer_offshore*: second filter layer, offshore side
 - *03_berm_inshore*: berm, inshore side
 - *03_berm_offshore*: berm, offshore side
 - *04_armor_bottom_inshore*: bottom armor layer, inshore side
 - *04_armor_bottom_offshore*: bottom armor layer, offshore side
 - *04_armor_layer_inshore*: main armor layer, inshore side
 - *04_armor_layer_offshore*: main armor layer, offshore side

For vertical breakwaters, objects are renamed according to the stratification of layers (Figure 4.5):

- *00_core*
- *01_filterLayer*
- *02_secondFilterLayer*
- *03_crown_wall*
- *04_caisson*

Figure 4.4 presents the complete library of objects used to build the structural model, with each component consistently named according to the established conventions. By activating the *Export STL* function, the tool automatically exports all selected objects to the correct directory, ensuring seamless integration with subsequent stages of the BIM workflow.

It is worth noting that the roundhead components are modeled differently from the body elements. Instead of cross-sections, the head is represented by a truncated conical geometry (Figure 4.7). This representation allows for a more accurate description of the geometric and hydraulic behavior at the boundary of the structure.

The naming convention adopted for the head elements follows the same logical structure as that used for the body elements:

- *head_core*
- *head_filter_firstLayer*

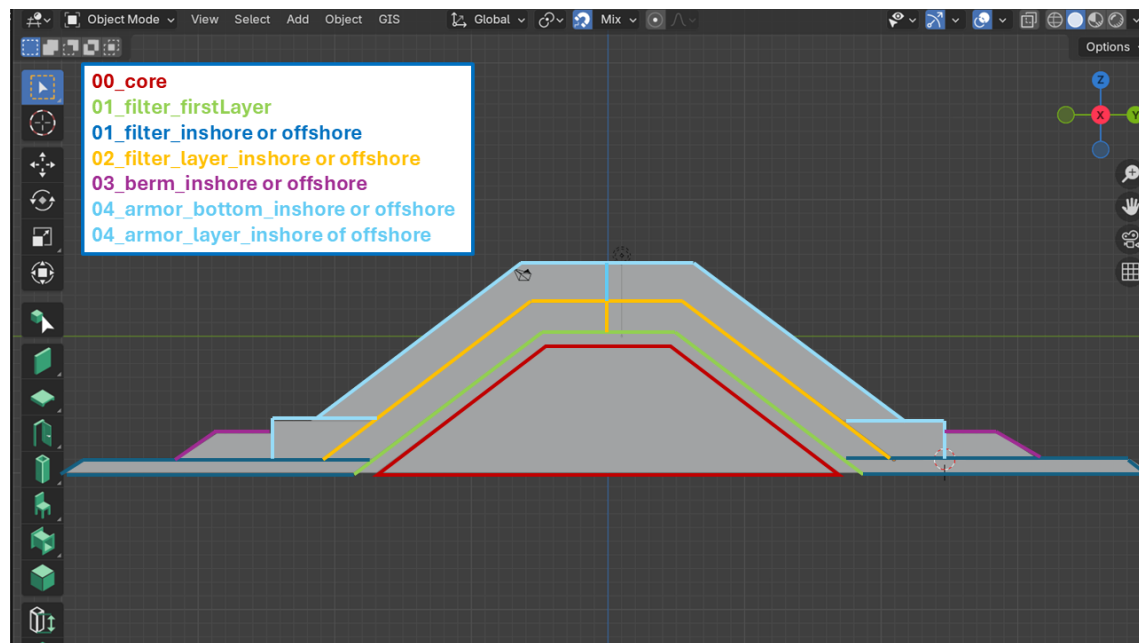


Figure 4.4. Object library for rubble mound breakwaters developed as plans in the Blender user interface

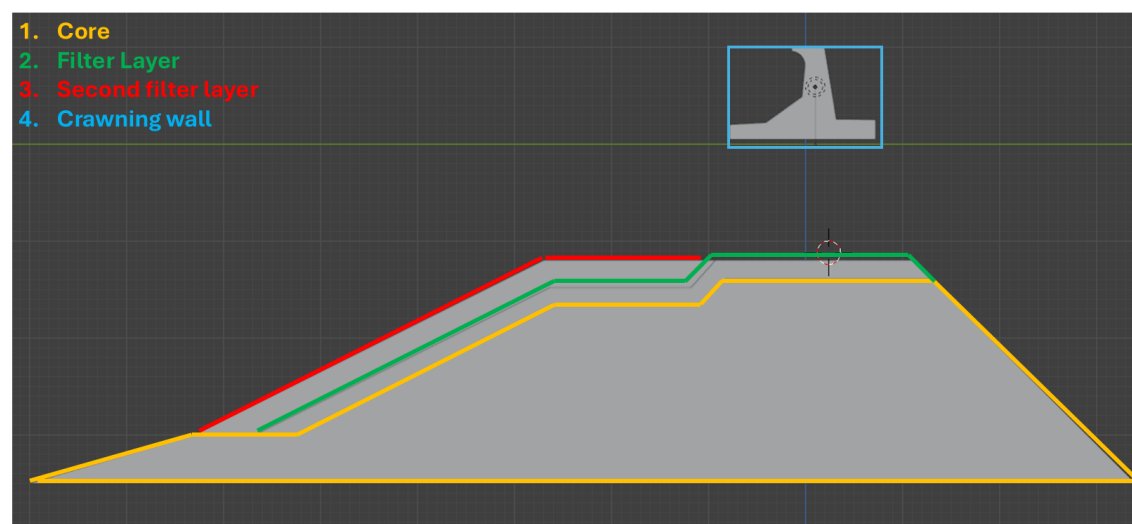


Figure 4.5. Object library of the vertical breakwaters structure developed as plans in the Blender user interface

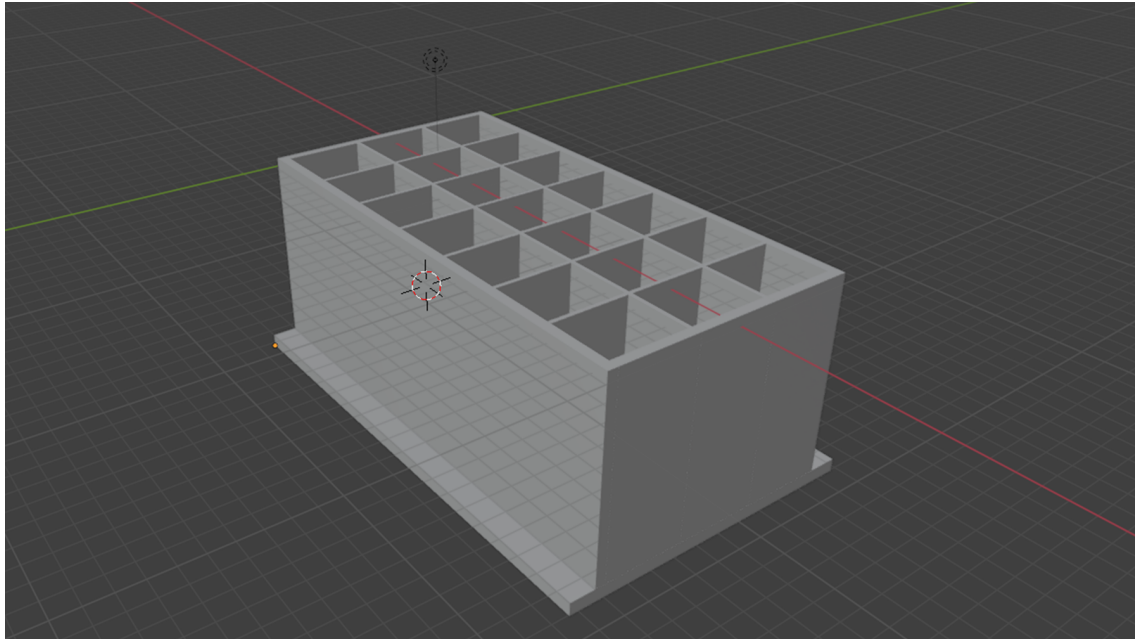


Figure 4.6. Caisson modeled as a three-dimensional object in the Blender user interface

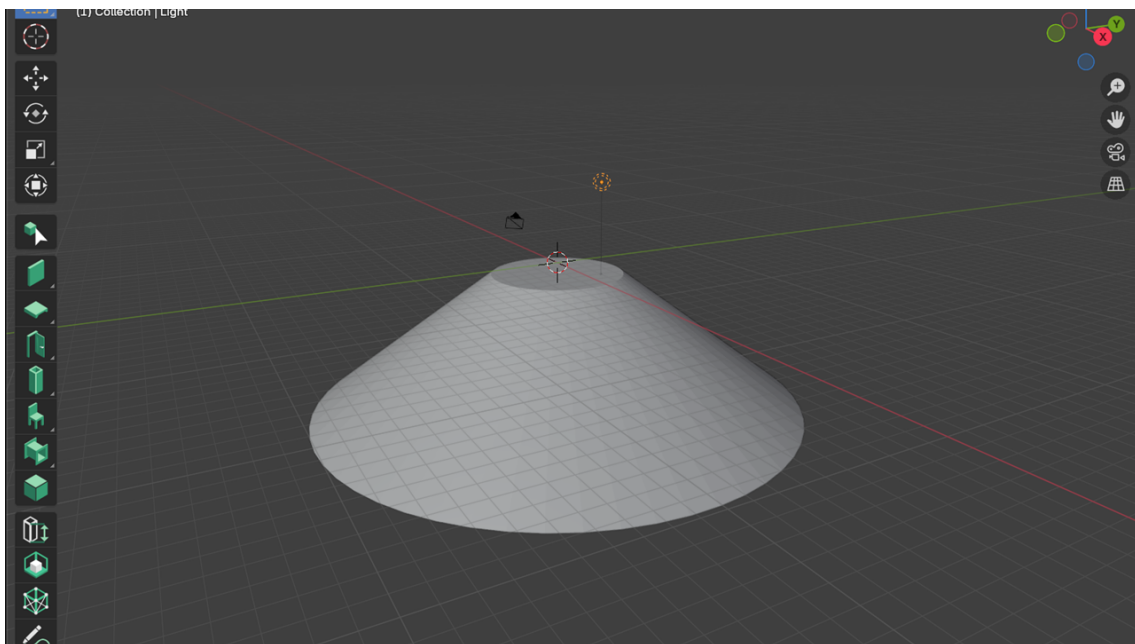


Figure 4.7. Head core component modeled as truncated conical section

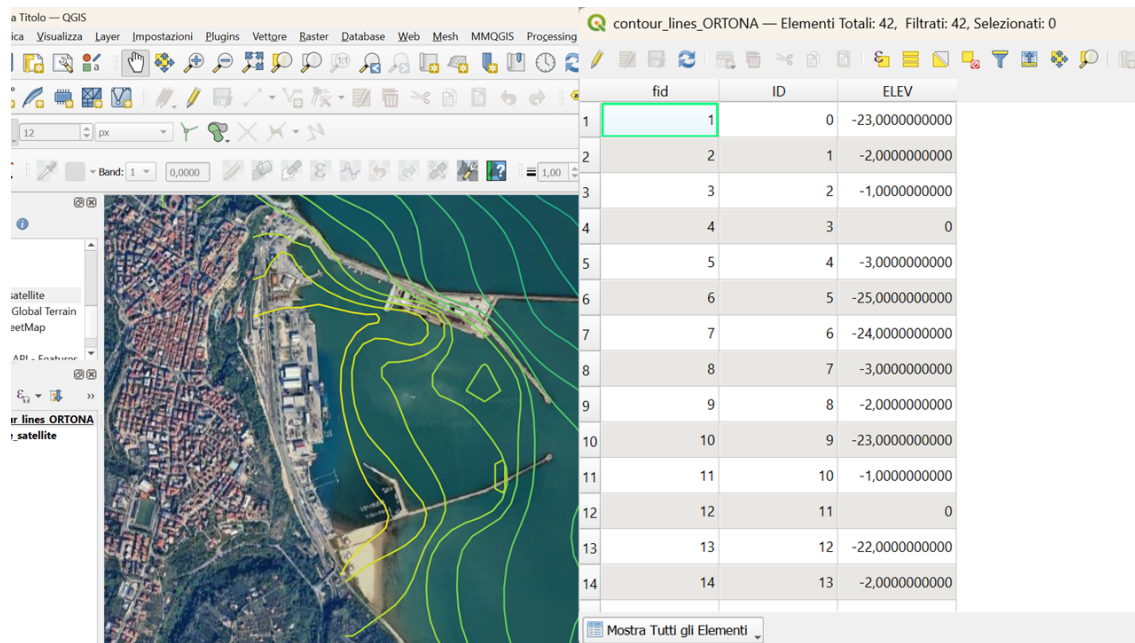


Figure 4.8. Structure of the bathymetry shapefile in the GIS environment, showing contour line attributes including the mandatory elevation field ELEV

- *head_filter_SL*
- *head_armor_layer*

Through this structured approach to modeling, naming, and exporting, BIMMs ensures that all maritime structure components are consistently defined and fully compatible with subsequent simulation and analysis modules, including the deployment simulation and stability verification of armor units.

4.2.3 Create bottom

The *Create Bottom* sub-menu consists of a single button with the same name. This functionality operates in conjunction with the Blender GIS add-on, enabling the direct integration of geospatial data into the three-dimensional modeling workflow.

To generate a detailed bathymetric representation of the site, including contour lines and the development line of the structure, GIS software is first employed at the pre-processing stage. The resulting shapefile must contain all relevant elevation data and must be structured as outlined in Figure 4.8. The figure shows the attribute table of the contour line file, in which elevation values are stored in the field labeled ELEV (the name of this field is mandatory for correct processing by the tool).

Upon activation of the *Create Bottom* function, a Delaunay triangulation is performed to generate a detailed seabed surface model from the

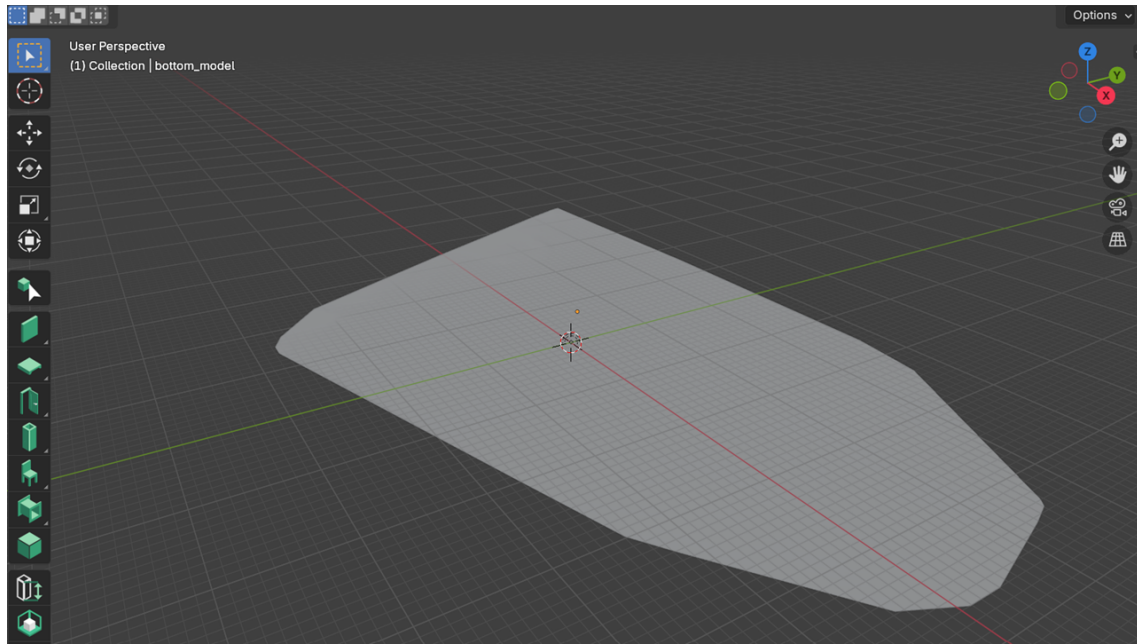


Figure 4.9. Bottom surface mesh generated via Delaunay triangulation using Blender GIS and integrated within the *Create Bottom* tool

input contour line shapefile (Figure 4.9). This triangulation procedure ensures that the resulting mesh accurately captures the (geo)spatial variability of the bathymetry, thereby providing a reliable geometric representation of the sea bottom for the subsequent modeling of the maritime structure.

Similarly, the shapefile corresponding to the development line must include an elevation field labeled `ELEV` to ensure consistent vertical alignment with the bottom model. This structured and standardized approach guarantees that all geospatial and elevation data are coherently incorporated into the BIM-based modeling workflow, providing an accurate geometric reference for subsequent design, simulation, and analysis phases.

4.2.4 Modeling Tools

The *Modeling Tools* sub-menu comprises five core functionalities designed to support the structured import, placement, and replication of breakwater components within the Blender environment.

- *D-Line*: enables the import of the development line of the structure directly from its directory into the Blender scene. The imported line serves as the primary geometric reference for positioning all subsequent structural elements.
- *Body*: allows the import of cross-sectional elements along the development line. The tool also provides the option to define the spacing

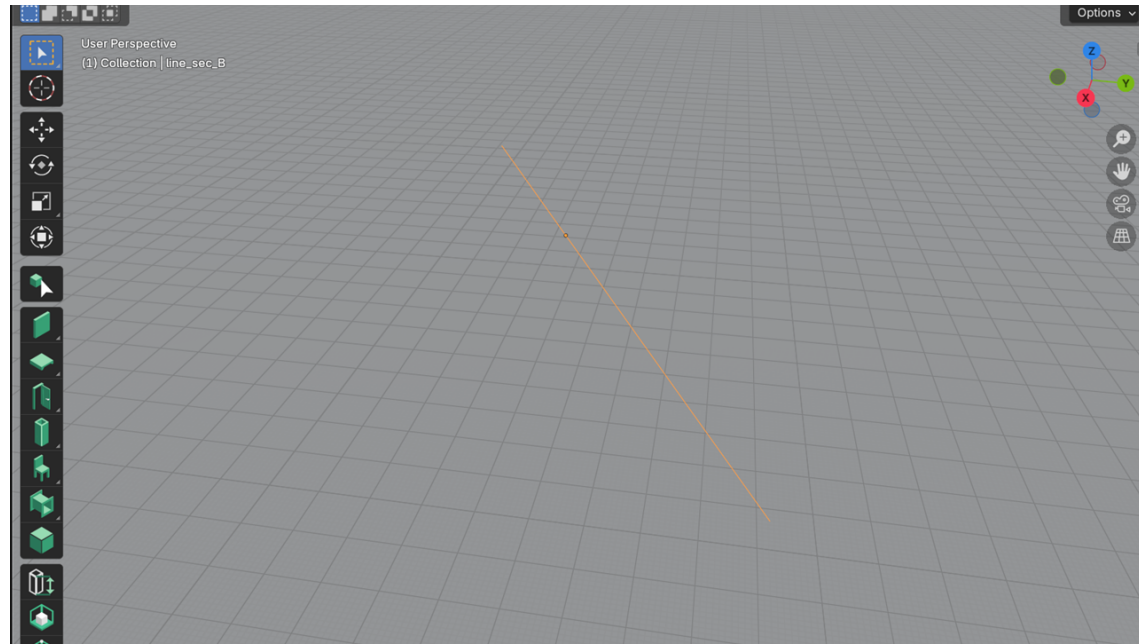


Figure 4.10. Development line imported into the Blender scene.

between consecutive cross-sections through a specific dialog window.

- *Simulated*: imports the simulated breakwater units into the scene, enabling further visualization and post-processing analyses.
- *Head*: facilitates the placement of head components at the endpoint of the development line.
- *Duplicate along the curve*: by selecting both the development line and the simulated objects, this function automatically replicates the objects along the entire curve, ensuring consistent alignment and spacing.

The development line is typically imported into the Blender scene after the bottom model has been generated (Figure 4.10).

More specifically, the *D-Line* tool converts the input shapefile into a curve object, which is subsequently used as a geometric reference for the placement of all structural components.

To import the body components, the development line must first be selected. Upon executing the *Body* command, a directory containing the available cross-sectional elements modeled before are displayed. The selected element is then imported and distributed along the curve (Figure 4.11). This procedure is repeated for each structural component, ensuring accurate spatial alignment along the development line.

Finally, the head components are imported at the endpoint of the development line, ensuring a geometrically consistent transition between the

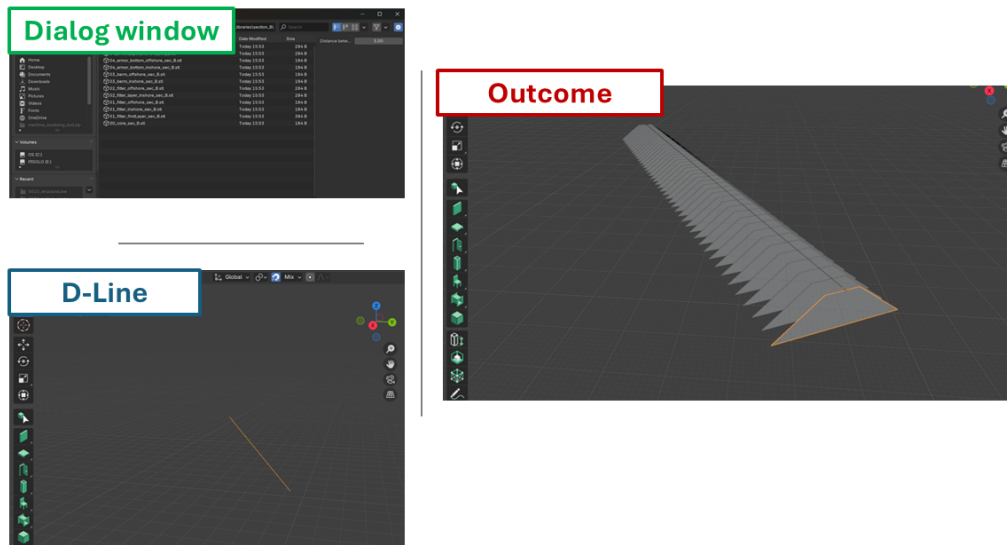


Figure 4.11. Core components imported along the selected development line in the Blender scene.

main body and the head of the breakwater within the 3D model.

4.2.5 Linking Tools

The *Linking Tools* are designed to establish geometric connections between cross-sectional elements, ensuring continuity and structural coherence along the breakwater body. Connections must be performed exclusively between sections of the same type. The toolset comprises six distinct commands:

- *Link Sections*: by selecting a reference cross-section, this command automatically links all sections sharing the same name (Figure 4.12).
- *Link 1by1*: enables manual linking of cross-sections on a one-by-one basis, providing increased control when dealing with complex or irregular geometries.
- *Fill Mesh*: fills gaps in the mesh by closing empty faces or holes that may remain between connected sections.
- *EX-Vertex*: particularly useful at junctions where consecutive sections have differing dimensions. This command projects the selected vertex onto the closest vertex of the subsequent section (Figure 4.13).
- *Create Face*: allows the creation of faces by selecting edges generated through the *EX-Vertex* command (Figure 4.13).

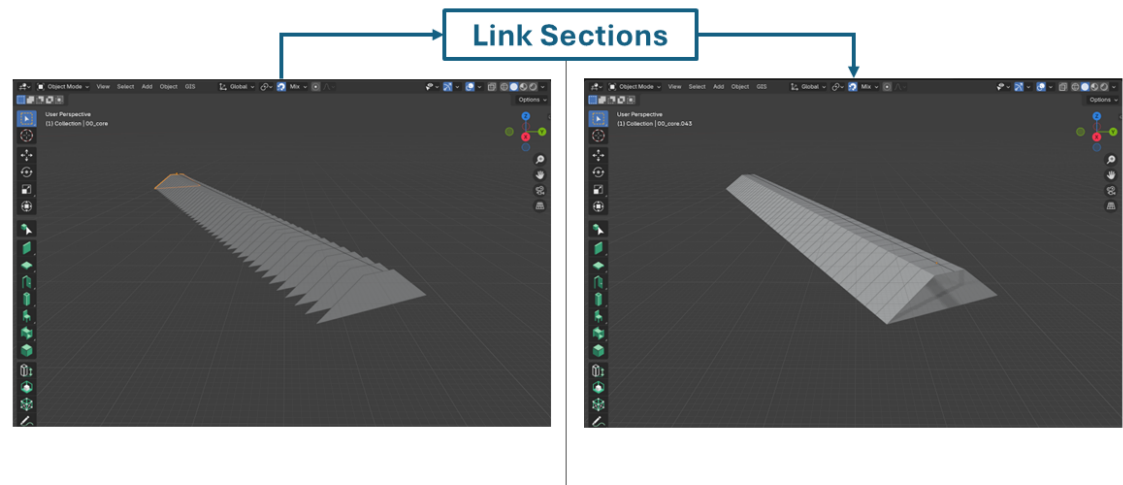


Figure 4.12. Functionality of the *Linking Tools* in connecting cross-sectional elements.

- *Join AL-AB*: connects the component named *04_armor_layer* with its corresponding element *04_armor_bottom*, ensuring a seamless transition between the armor layer and the armor bottom.

4.2.6 Create Collections

The *Create Collections* tool provides functionalities aimed at improving the organization and visual clarity of the Blender workspace (Figure 4.14). The available commands are:

- *New Collection*: enables the creation of a new collection within the Blender environment, facilitating a more structured organization of the scene. The tool also allows the assignment of different colors to the selected objects grouped within the newly created collection.
- *Move Objects*: allows selected objects to be transferred to an existing collection, preserving a clear and hierarchical organization of the project elements.

Through this tool, selected objects can be assigned individual colors and grouped into newly created collections, which may be renamed according to project-specific requirements. This approach enhances both organizational efficiency and visual readability within the modeling environment.

4.2.7 Boolean Tools

This sub-menu provides a set of commands designed to apply Boolean subtraction operations between different objects in a structured and auto-

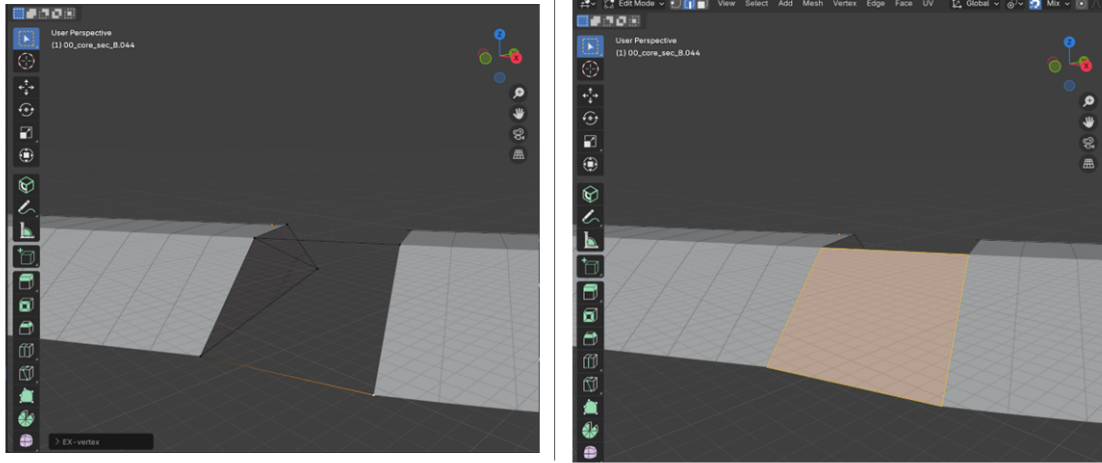


Figure 4.13. Linking two sections with differing dimensions using the *EX-Vertex* and *Create Face* commands.

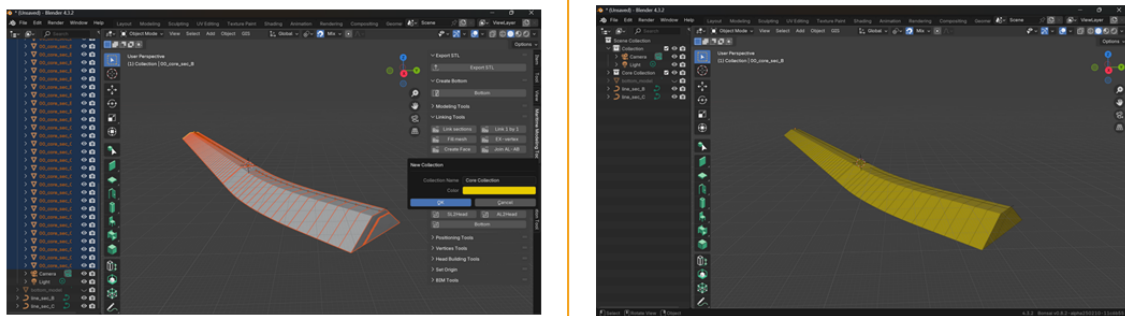


Figure 4.14. Functionality of the collection tool: creation of a new collection and assignment of colors to selected objects.

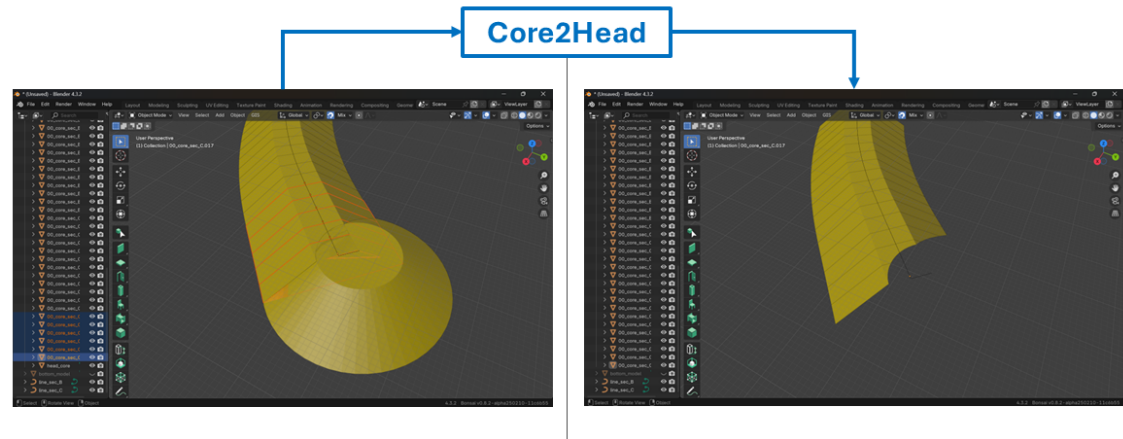


Figure 4.15. Application of the *Core2Head* command provided by the Boolean Tools.

ated manner. The *Boolean Tools* sub-menu includes the following functionalities:

- *Core2Head*: performs the Boolean subtraction between elements whose names start with *00_core* and the head component named *head_core*. To execute this operation, the core objects must be selected, as illustrated in Figure 4.15.
- *FL2Head*: performs the Boolean subtraction between elements whose names start with *01_filter_firstLayer* and the head component named *head_filter_firstLayer*. The corresponding filter objects must be selected before running the tool.
- *SL2Head*: performs the Boolean subtraction between elements whose names start with *02_filter_layer* and the head component named *head_filter_SL*. The corresponding filter layer objects must be selected.
- *AL2Head*: performs the Boolean subtraction between elements whose names start with *04_armor_layer* and the head component named *head_armor_layer*. The appropriate armor layer objects must be selected.
- *Bottom*: performs the Boolean subtraction between the selected objects and the bottom model. This command is particularly relevant for maritime structures, as it ensures that the modeled elements conform to the seabed topography.

The operational workflow is identical for all head-related commands, producing consistent results across the different structural components. The *Bottom* command differs as it aligns the modeled elements with the seabed profile (Figure 4.16).

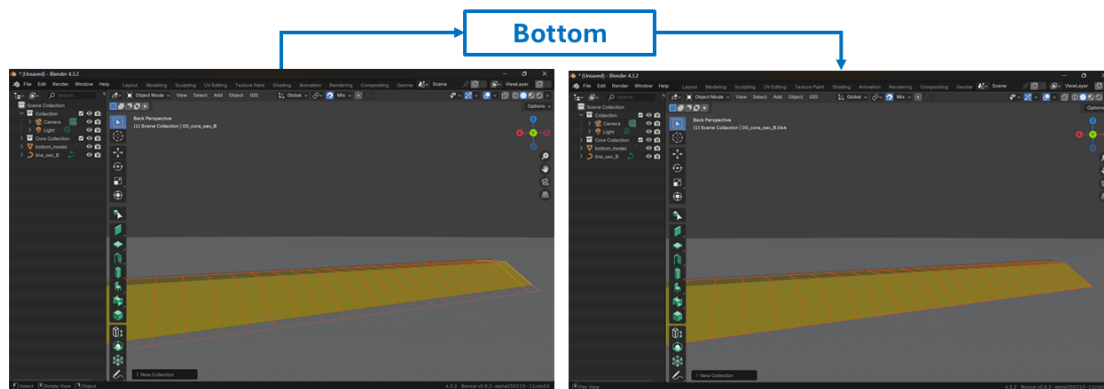


Figure 4.16. Application of the Bottom Boolean tool, aligning the core model with the seabed.

4.2.8 Positioning Tools

The *Positioning Tools* sub-menu is designed to accurately place the various structural components after the Boolean subtraction operations have been completed. The available commands are described as follows:

- *Z-Inshore*: when a bedding layer is present, this layer defines the reference bottom. This command positions all selected elements on the inshore side above the bedding layer (Figure 4.18).
- *Z-Offshore*: positions the selected elements above the bedding layer on the offshore side (Figure 4.18).
- *Align Armor*: the armor layer is divided into two components, namely the bottom and the upper layer, for both the inshore and offshore sides. This tool aligns the bottom part of the armor layer with the underlying filter layer (Figure 4.18).
- *Align Berm*: aligns the berm with the armor bottom, ensuring correct positioning relative to the underlying layers (Figure 4.19).
- *F-2-F*: aligns the selected objects with the filter layer (Figure 4.17).
- *F-2-C*: aligns the selected objects with the core layer, ensuring both vertical and horizontal consistency along the structure.

4.2.9 Vertices Tools

The tools within this sub-menu are designed to adjust and correct the positions of vertices associated with the different structural components. The available commands are:

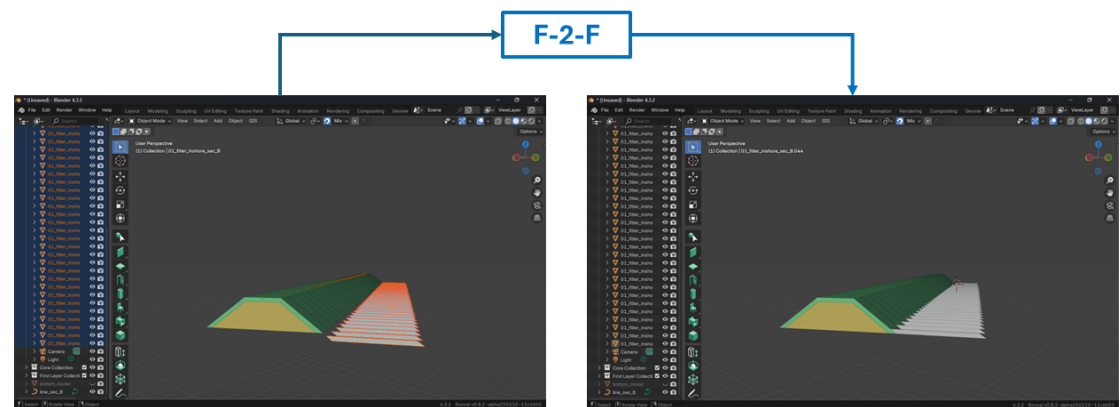


Figure 4.17. Application of the *F-2-F* command: alignment of selected elements with the filter layer.

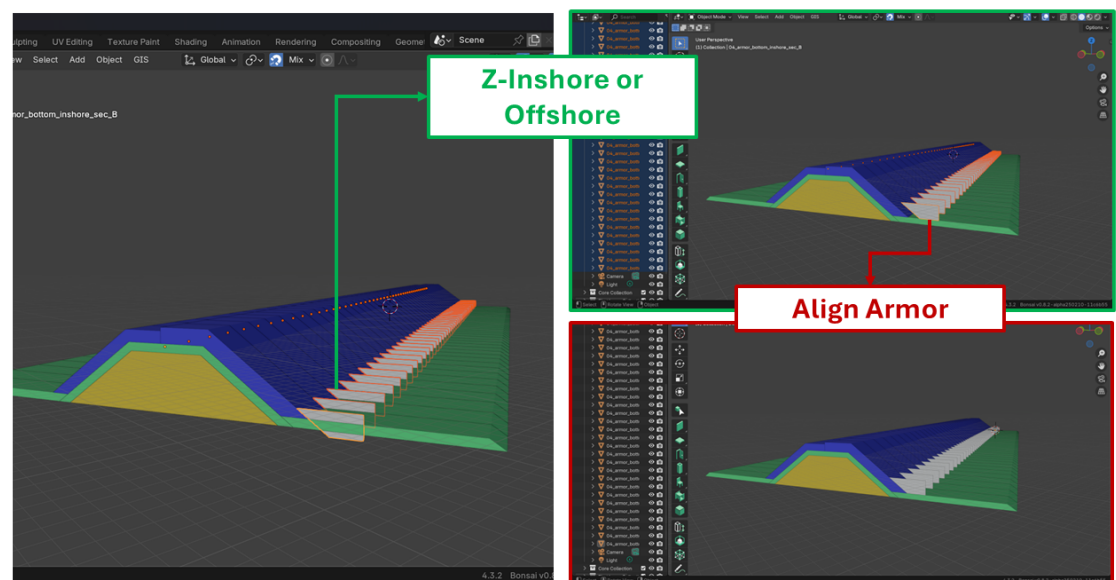


Figure 4.18. Operation of the *Z-Inshore* and *Align Armor* tools: positioning of armor elements relative to the bedding and filter layers.

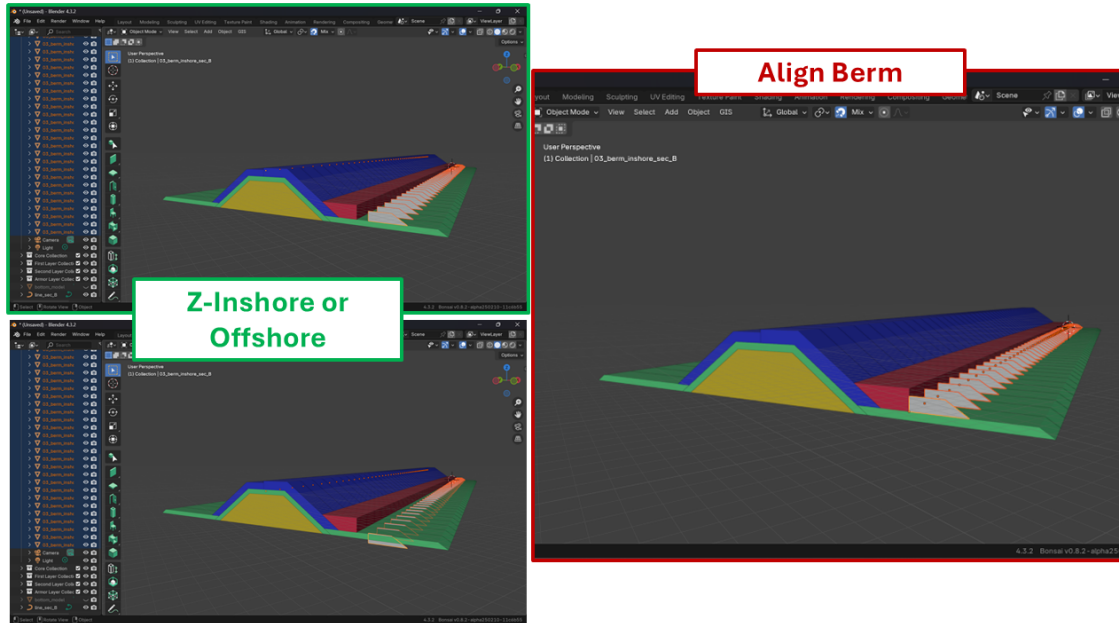


Figure 4.19. Operation of the *Z-Inshore* and *Align Berm* tools: correct alignment of the berm relative to the armor bottom.

- *Align F-Verts*: aligns the bottom vertices of the filter layer to their correct positions above the bedding layer (Figure 4.20). To apply this command, the relevant objects must be selected. The tool allows the user to specify either the *inshore* or *offshore* side.
- *Align AL-Verts*: adjusts the positions of the bottom vertices of the armor layer. The selected objects are aligned with their corresponding targets, with the option to choose either the *inshore* or *offshore* side (Figure 4.21).
- *Align AL-Filter*: aligns the bottom vertices of the selected armor layer elements with the underlying filter layer. As with the other commands, the user can select the *inshore* or *offshore* option (Figure 4.20).

4.2.10 Head Building Tool

The *Head Building Tool* is the most advanced sub-menu developed within the proposed tool, and operates in combination with the *Boolean Tools*. Its primary function is to create the head model by extracting and spinning vertices generated through the boolean subtraction operations. From the resulting vertex circles, truncated cone solids are generated for each structural component, from the core to the armor layer. Particular attention is paid to the junction points between the head and the body of the structure.

It is important to note that all commands within this sub-menu must be applied after performing the corresponding boolean subtraction. For

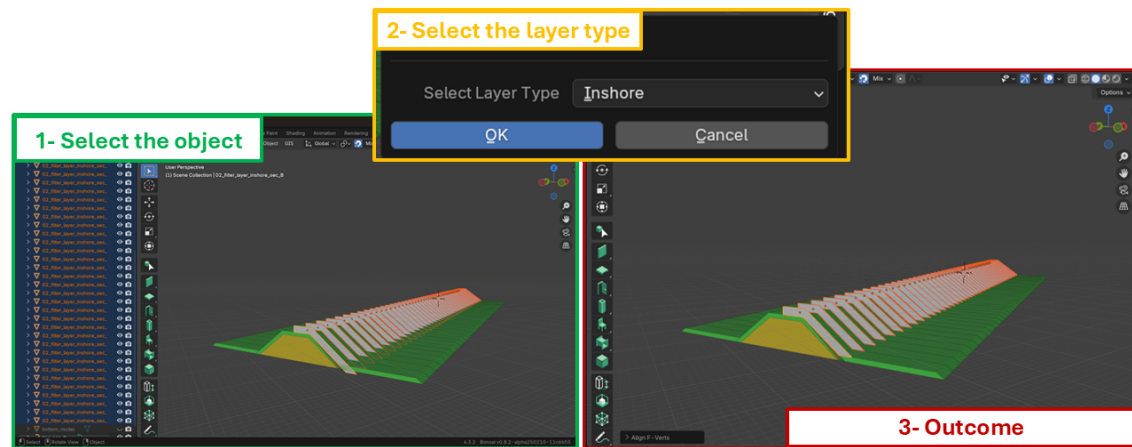


Figure 4.20. Operation of the *Align F-Verts* tool: adjustment of the filter layer vertices above the bedding layer.

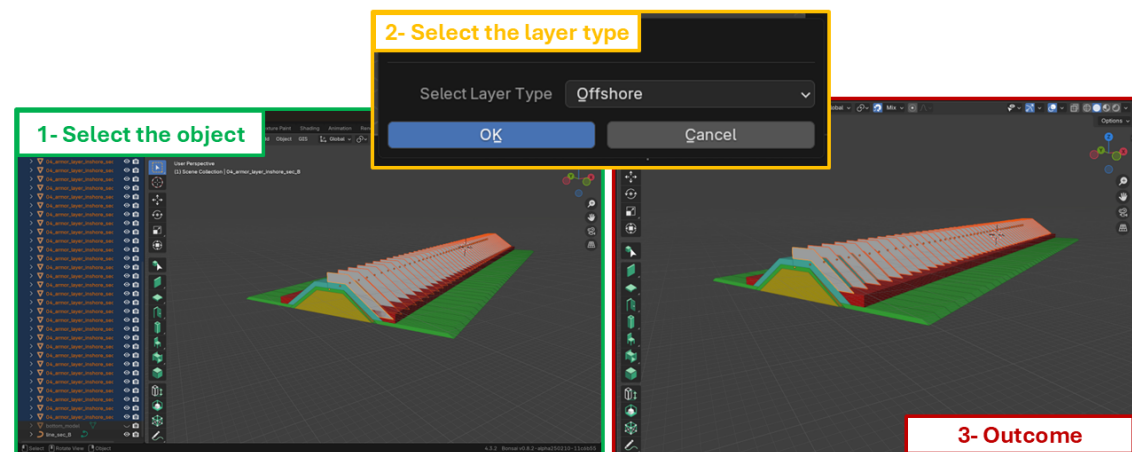


Figure 4.21. Operation of the *Align AL-Verts* tool: adjustment of the bottom vertices of the armor layer.

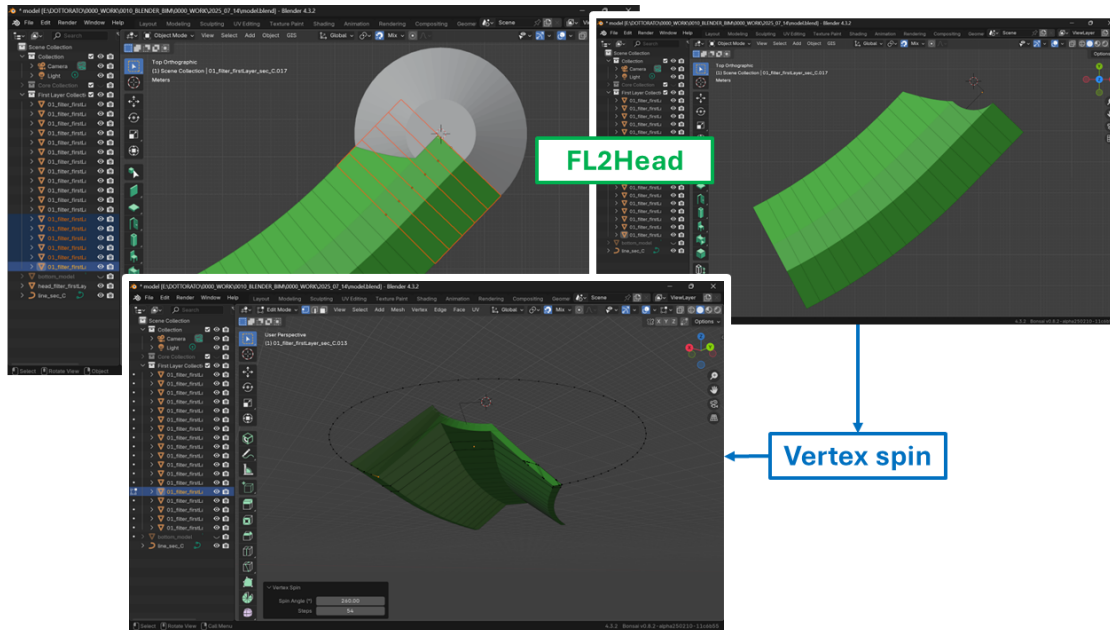


Figure 4.22. Workflow of the *Vertex Spin* tool.

instance, *head_core* must first be subtracted from *00_core* (Figure 4.15). The sub-menu consists of the following commands:

- *Vertex Spin*: extrudes and rotates a selected vertex around a specified rotation center. The rotation angle can be defined via a pop-up menu. The procedure requires the following steps:
 1. Perform the boolean subtraction between the selected objects and the corresponding head component (e.g. *01_filter_firstLayer* with *head_filter_firstLayer*, see Figure 4.22).
 2. Switch the Blender scene into *edit mode* (press TAB from *object mode*).
 3. Define the rotation center, typically located along the development line. Select the development line, switch to *edit mode*, select the end point, press *Shift+S+2*, and return to *object mode*.
 4. Select the element containing the target vertex, enter *edit mode*, choose the vertex to rotate, and run the command. Set the rotation angle so that the final vertex aligns closely with the element edge.

The tool also allows the user to specify the number of vertices to extrude from the selected one; the number must be consistent across all generated curves.

- *Sep Verts*: separates the generated vertex curve from the original element. Running the command creates a new mesh. This operation is

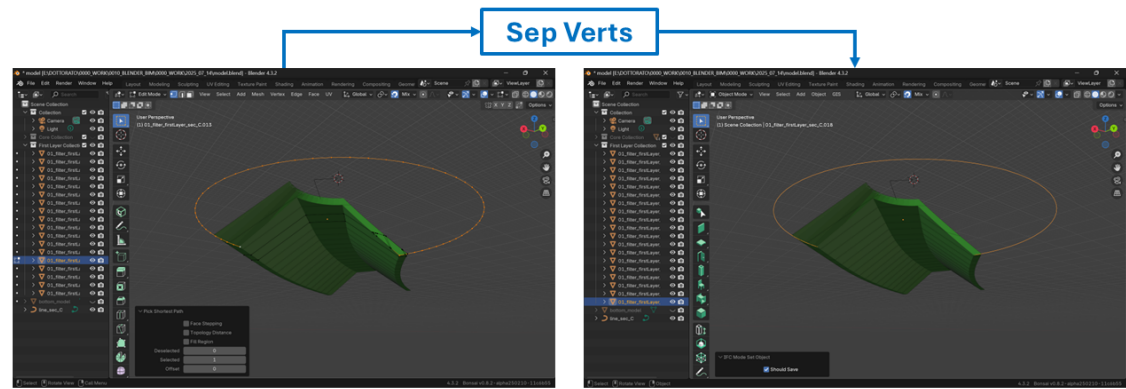


Figure 4.23. Operation of the *Sep Verts* tool.

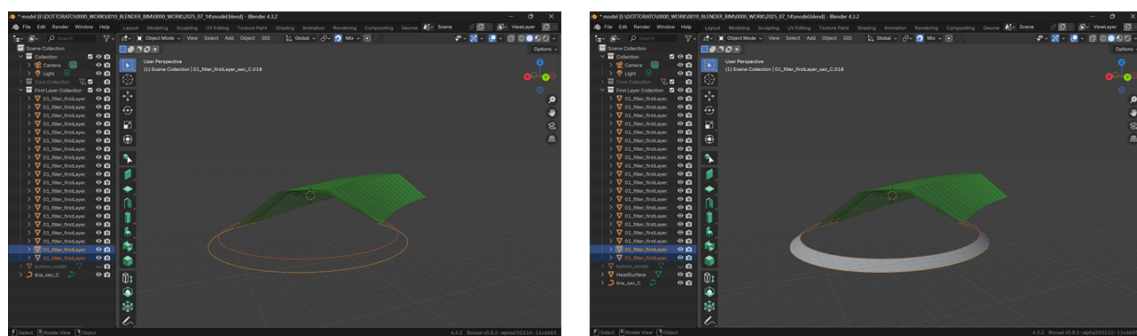


Figure 4.24. Surface generated using the *Build Surface* tool.

repeated for multiple vertices to generate a detailed surface (Figure 4.23).

- *Build Surface*: generates a surface between two curves created with *Vertex Spin* and *Sep Verts*. Both curves must have the same number of vertices and identical orientation. Selecting the curves and executing the tool produces a surface named *HeadSurface* (Figure 4.24).
- *B-Curve*: creates a curve that follows the bottom profile by applying an *Intersect* boolean operation between the surface and the bottom. The surface *HeadSurface* must be selected (Figure 4.25).
- *New B-Curve*: generates a new curve from selected vertices of imported elements. Using the *B-Head* command, vertices from the bottom components are selected in *edit mode*. The tool creates two objects: a *curve* for importing other elements along it, and a *mesh* for building surfaces using *Build Surface* (Figure 4.26).
- *Offset Circle*: creates an offset of the selected circle. The user sets the rotation center, selects the circle, runs the command, and specifies the offset distance in a pop-up menu (Figure 4.27).

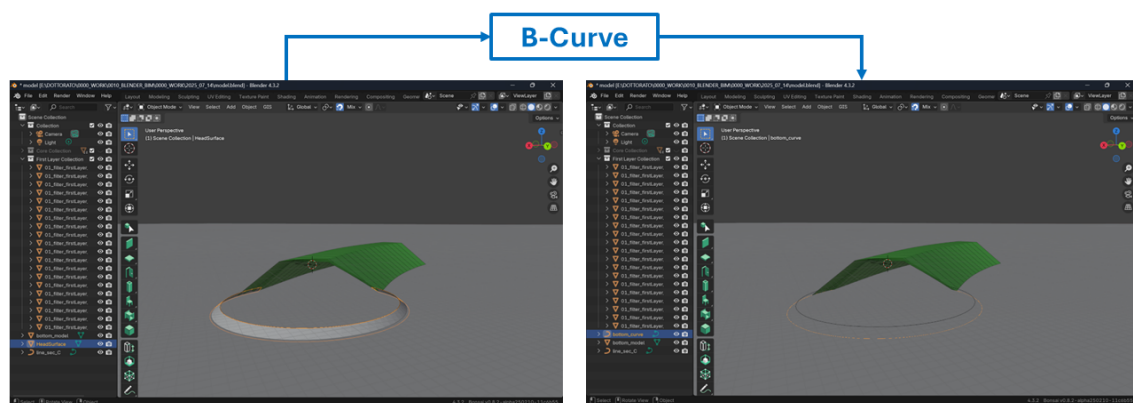


Figure 4.25. Operation of the *B-Curve* tool.

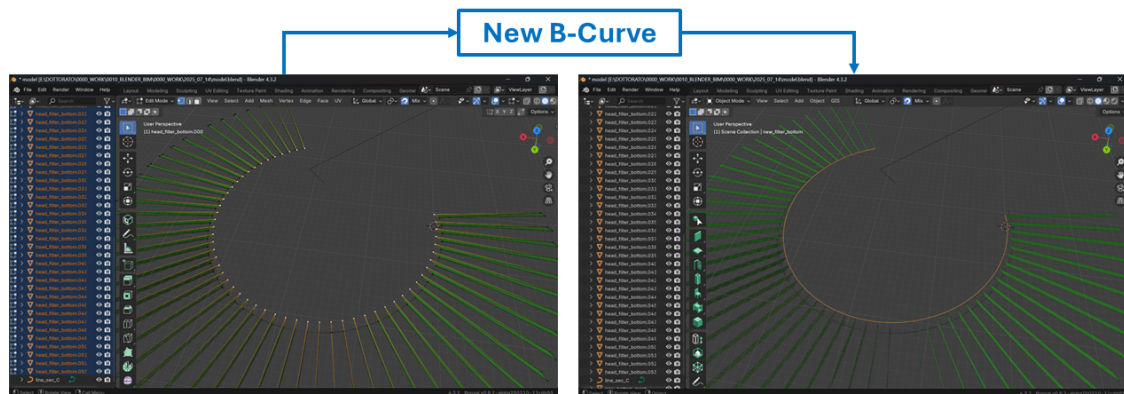


Figure 4.26. Generation of a new curve with the *New B-Curve* tool.

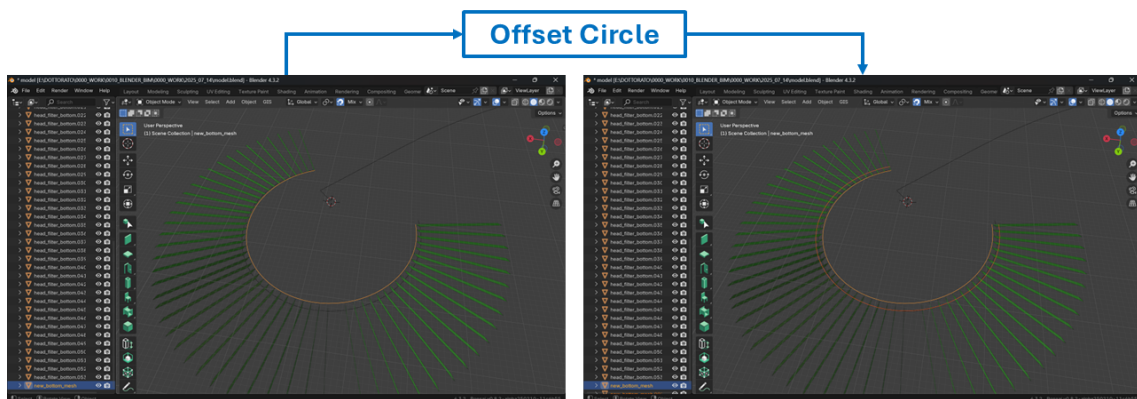


Figure 4.27. Operation of the *Offset Circle* tool.

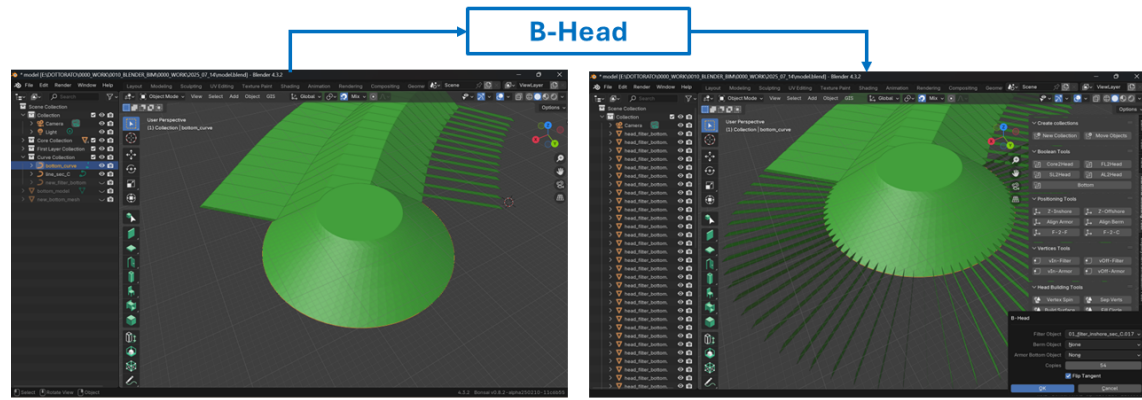


Figure 4.28. Import of bottom elements using the *B-Head* tool.

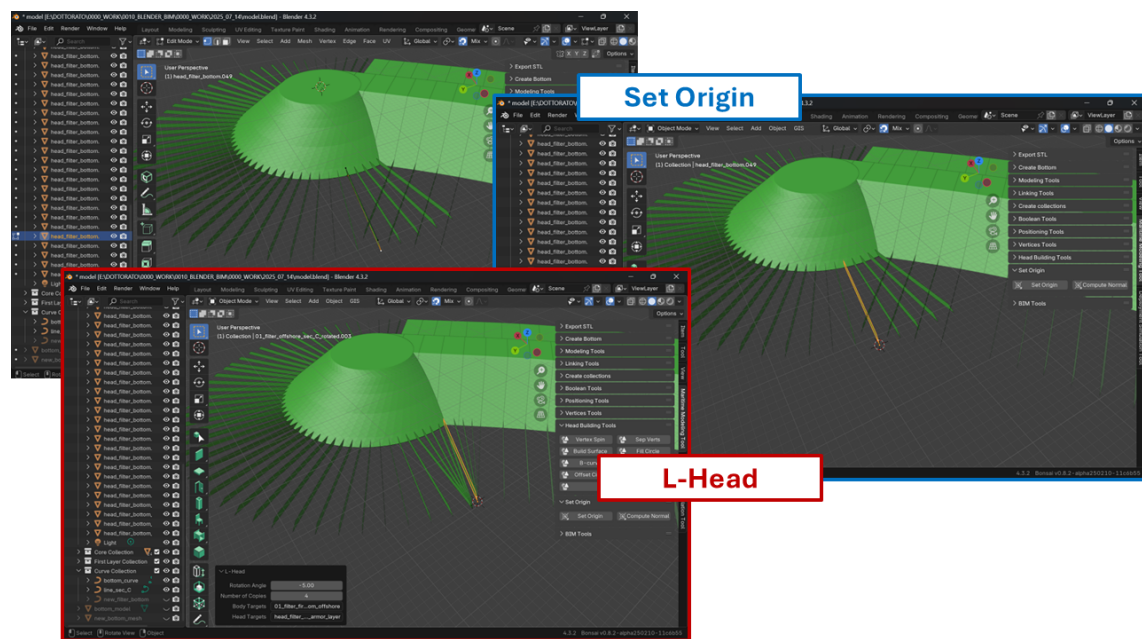


Figure 4.29. Linking between the body and the head of the structure using *L-Head* tool.

- *B-Head*: imports bottom elements along a selected curve. A pop-up menu allows choosing among three element types: *01_filter_inshore/offshore*, *03_berm_inshore/offshore*, and *04_armor_bottom_inshore/offshore*. The number of copies and the tangent direction along the curve can be adjusted (Figure 4.28).
- *L-Head*: links the bottom elements of the head to the corresponding bottom elements of the body. The user selects an element, enters *edit mode*, selects a vertex, and sets it as the new object origin and rotation center using *Set Origin*. The tool allows specifying the number of copies and the rotation angle between them. All objects must share the same origin to correctly link the rotated copies (Figure 4.29).

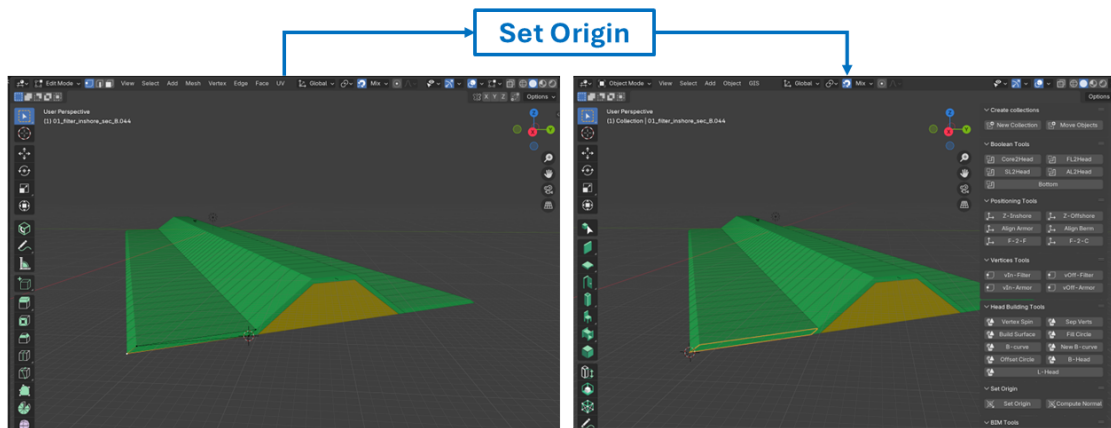


Figure 4.30. Operation of the *Set Origin* tool.

In summary, the commands described above are used to generate the different layers of the head model. Not all commands are required in every case; their usage depends on the complexity of the head geometry and design requirements.

4.2.11 Set Origin

The *Set Origin* sub-menu provides functionality to define the origin point of an object and to correct potential geometry issues related to normals. It consists of the following commands:

- *Set Origin*: this command allows the user to set the origin of a selected object at a specific vertex. To use the tool, the object must be selected and switched to *edit mode*. Then, the desired vertex is selected and the command executed (Figure 4.30).
- *Compute Normal*: when objects are built through extrusion, Blender may encounter issues in computing the correct volume due to inconsistent normals. This command recomputes the normals for all selected objects, ensuring that subsequent operations, such as boolean subtraction and surface generation, function correctly.

This sub-menu is particularly important for ensuring accurate alignment, rotation, and volume computation when constructing complex components, such as head elements and armor layers, in the modeling workflow.

4.2.12 BIM Tools

The *BIM* sub-menu provides commands to manage and assign BIM-related data to the modeled elements. The available tools are as follows:

- *BIM Storey*: this command moves all selected elements into a storey collection created in *Bonsai BIM*. The original collection from which the elements were moved is automatically deleted.
- *My Data*: this tool enables the user to assign custom properties to each object. For maritime structures, the following attributes have been defined:
 - Design return period, T_R
 - Significant wave height, H_s
 - Significant wave height at the toe of the structure, H_{st}
 - Peak period correlated to significant wave height, T_p
 - Peak period at the toe of the structure, T_{p-toe}
 - Rock density, ρ_s
 - Rock porosity, p
 - Nominal diameter, D_{n50}
 - Slope, $\tan \alpha$
 - Minimum sea level, h_{min}
 - Maximum sea level, h_{max}
 - Depth, h
 - Damage parameter, S_d
 - No-damage parameter, K_d

When the command is executed, a template containing these properties is opened. The user sets the values manually, which are then stored as custom quantity (QTO) properties of the selected element.

It is important to highlight that the model parameters — including rock and armor porosity — can be dynamically updated, enabling the analysis to reflect temporal variations and different construction stages.

Within this parametric framework, recent studies have demonstrated the effectiveness of Blender for the accurate placement and arrangement of armor units in breakwater modeling. In particular, the works Molines et al. (2021) and Munoz-Palao et al. (2024) present practical workflows that enhance both precision and efficiency in positioning individual units. These contributions provide a methodological reference for the modeling strategy adopted in this research.

To integrate this modeling approach within a BIM-oriented environment, a BIM project must first be created using the Bonsai BIM add-on for Blender.

4.3 Maritime deployment tool

The Maritime Deployment Tool has been developed to simulate the placement of armor units within the digital model. The tool allows the user to isolate a specific portion of the structure by temporarily hiding all non-selected objects. The isolated section may correspond to critical areas, such as geometric transitions, slope variations, or the head of the breakwater, where a detailed evaluation of unit arrangement and spatial configuration is required.

Rigid body properties can be assigned to the selected elements, enabling the execution of deployment simulations based on Blender's built-in physics engine. In addition, the tool implements several design and verification methods, including the Van der Meer and Hudson formulations (e.g., CIRIA, 2007) and the overtopping discharge formula (e.g., van der Meer et al., 2016).

The tool is organised into a set of sub-menus, listed as follows:

- *Export BW*: exports the armor units to a dedicated directory automatically created by the tool;
- *Hide Section*: hides all non-selected objects, allowing the user to focus on a specific portion of the structure;
- *Create Grid*: generates a regular grid of armor units;
- *R-Body Properties*: assigns rigid body properties to the selected objects;
- *D-Simulation*: performs the armor unit deployment simulation;
- *Stability & Overtopping*: carries out stability checks using different methods and computes the overtopping discharge.

Each sub-menu is described as follows.

4.3.1 Export BW

This tool enables the export of armor unit models. To use it, the `.blend` file must first be saved; subsequently, the user selects the object to be exported and executes the command. The tool automatically creates a dedicated directory in which the exported object is stored.

Several types of breakwater armor units can be modelled and exported using this functionality, including:

- Cubes;
- Cubipods®;

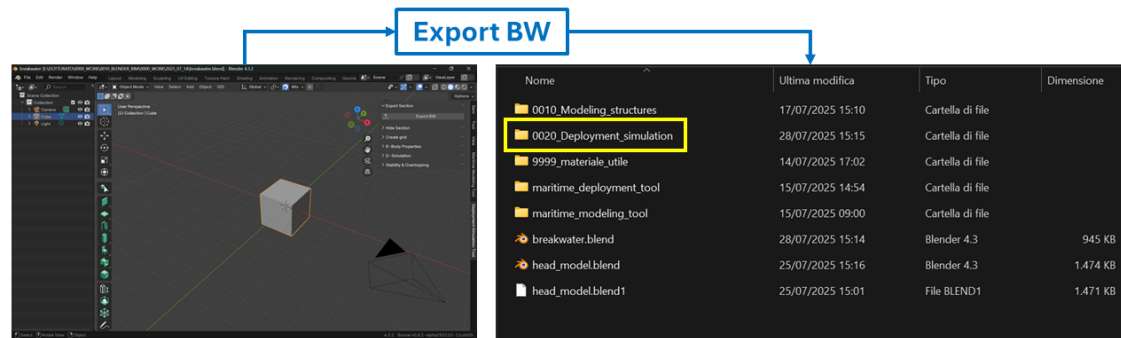


Figure 4.31. Working of *Export BW* tool

- AccropodesTM;
- Tetrapods.

Figure 4.31 illustrates the operation of the command. The left-hand image shows an example of a cube-shaped armor unit modelled in Blender, while the right-hand image displays the directory structure automatically generated by the tool for storing the exported geometry.

4.3.2 Hide Section

Maritime structures typically extend over large distances. For both dimensional and computational reasons, the simulation of armor unit deployment is therefore carried out on selected portions of the structure rather than on the entire model. These portions generally correspond to critical areas, such as zones where the cross-section changes or the head of the structure.

This sub-menu provides tools to isolate specific sections of the model by controlling object visibility within the Blender scene. It consists of the following commands:

- *Hide OBJS* hides all objects that are not currently selected in the Blender scene. To execute this command, the objects of interest must be selected beforehand.
- *Unhide OBJS* performs the opposite operation of the *Hide OBJS* command, restoring the visibility of all previously hidden objects in the scene.

Figure 4.32 illustrates the use of the *Hide OBJS* tool to isolate a specific section of the structure for deployment simulation.

4.3.3 Create Grid

This tool enables the generation of a structured grid of armor units, which represents the starting configuration for the deployment simulation. The

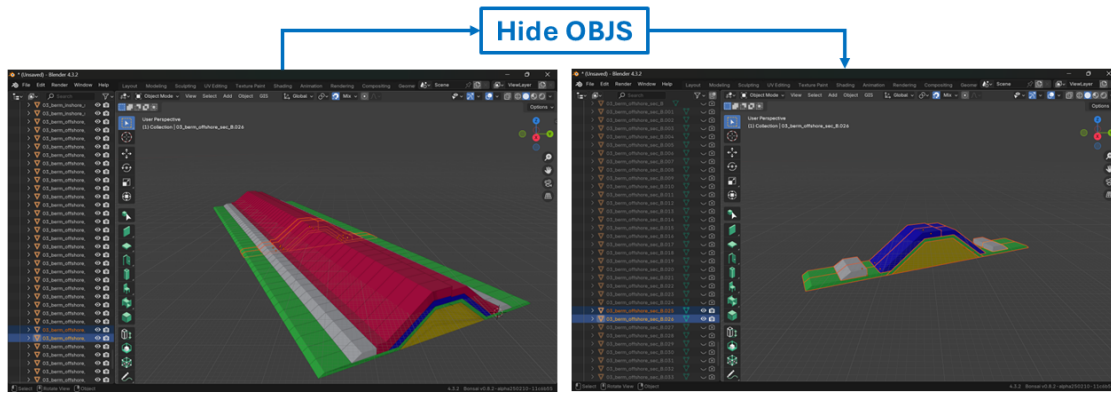


Figure 4.32. Hiding objects using *Hide OBJS* tool

grid is built by duplicating a reference armor unit and positioning its copies according to geometrical entities selected by the user (vertices, edges, faces, or curves). The procedure is fully parametric and ensures repeatability of the armor layout.

The sub-menu includes the following commands:

- **Create EV-Grid** operator allows the generation of armor unit grids starting from either a vertex or an edge. Internally, the tool retrieves the spatial coordinates of the selected geometrical entity and uses them as reference points for instantiating the armor units. Translation vectors are computed according to user-defined offsets along the global Cartesian axes.

The tool can be used in two different modes:

1. **Vertex-based grid:** the user selects a single vertex in *Edit Mode* and runs the command. The algorithm extracts the global coordinates of the selected vertex and imports a single copy of the reference armor unit at that location. Through the pop-up dialog, the user defines the translation offsets along the x, y, and z axes, which are directly applied to the imported object.

Figure 4.33 illustrates the complete workflow: selection of the reference armor unit, identification of the target vertex, definition of the placement parameters, and final positioning of the element. This approach is particularly useful when a precise initial placement of the first armor unit is required, for instance in geometrically complex areas of the structure.

2. **Edge-based grid:** the grid is generated along a selected edge. Once the edge is identified in *Edit Mode*, the tool computes its direction vector and length. The reference armor unit is then duplicated multiple times, and each copy is translated along the edge direction using a step size defined by the user.

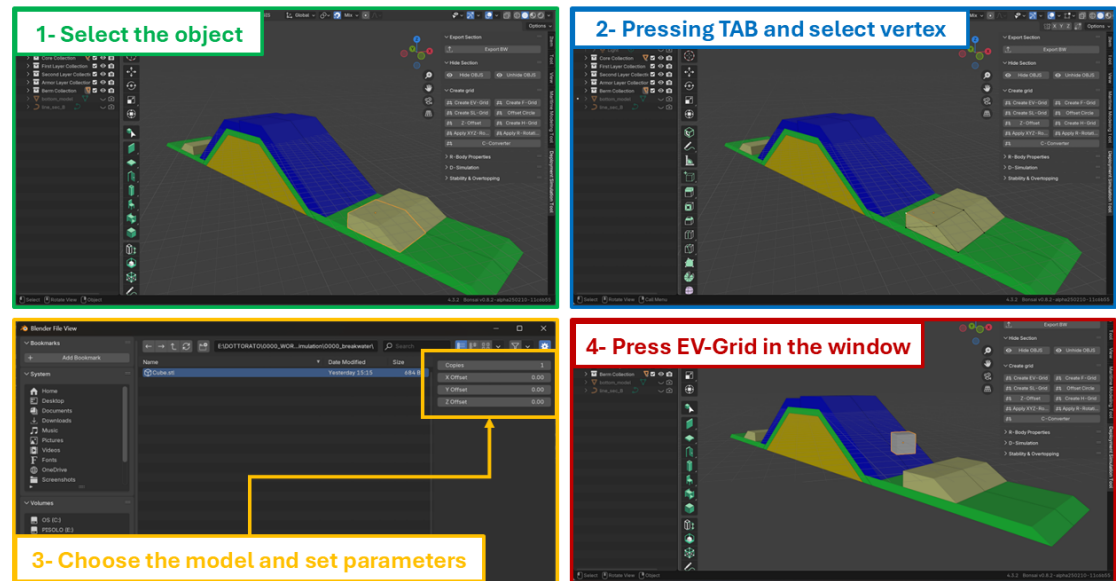


Figure 4.33. Different steps to follow for importing the breakwater element on specific vertex through the *EV-Grid* tool

The number of instances and the offsets along the x , y , and z axes are assigned through the pop-up window. The resulting grid follows the geometrical alignment of the selected edge (Figure 4.34). This mode is typically employed to generate the first row of armor units along the slope of the structure.

- **Create F-Grid:** extends the grid generation to a surface. Its usage requires the prior placement of the first row of armor units. After selecting a face in *Edit Mode*, the tool evaluates the face normal and generates multiple rows of duplicated elements by applying a translation along the normal direction.

The number of rows and the vertical offset along the z -axis are specified by the user (Figure 4.35).

- **Create SL-Grid** enables the generation of additional rows of armor units between two existing ones. The user selects two reference objects, and the tool computes the intermediate positions by interpolating their spatial coordinates.

A user-defined number of copies is then distributed between the selected units, with an optional vertical offset applied along the z -axis (Figure 4.36).

Additional commands are provided to refine the spatial arrangement of the grid:

- **Offset Circle** applies a vertical offset to a selected curve object. The offset value can be specified through a dialog window.

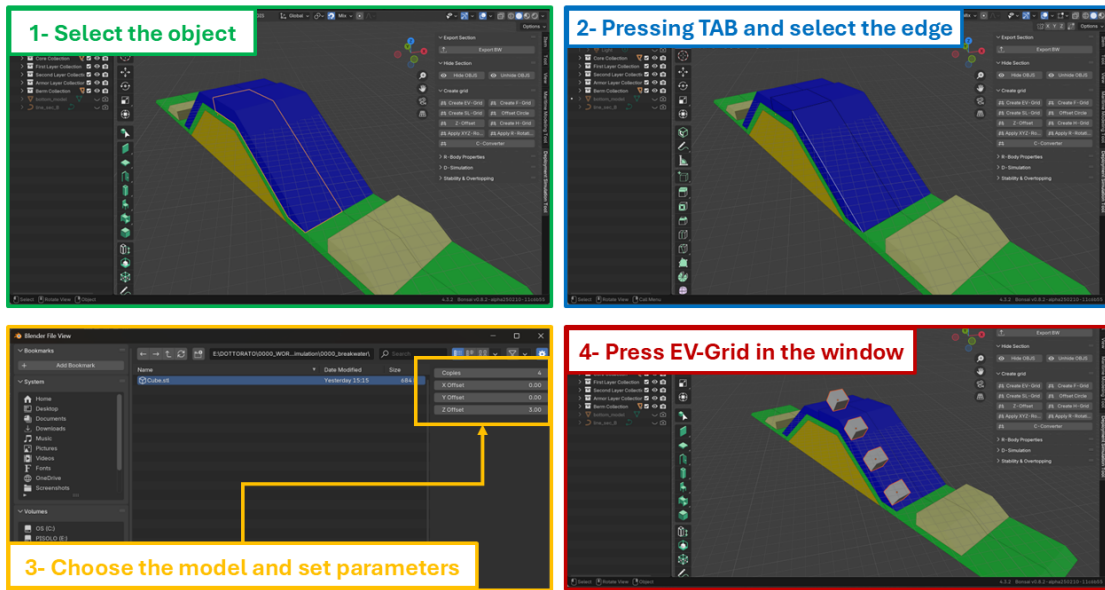


Figure 4.34. Different steps to follow for importing the breakwater elements along specific edge through the *EV-Grid* tool

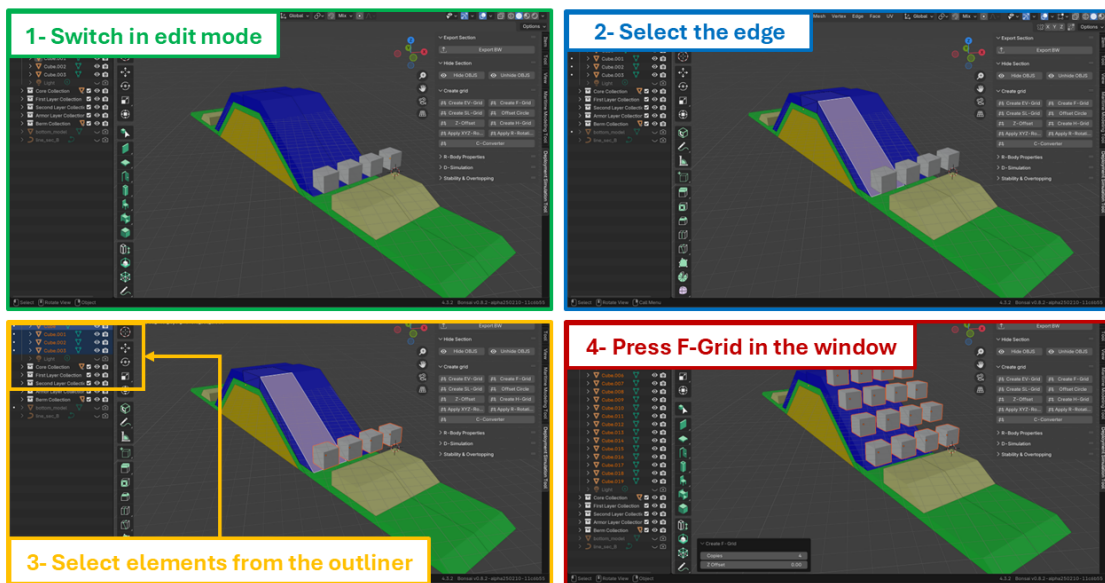


Figure 4.35. Different steps to follow for importing the breakwater elements along specific face through the *F-Grid* tool

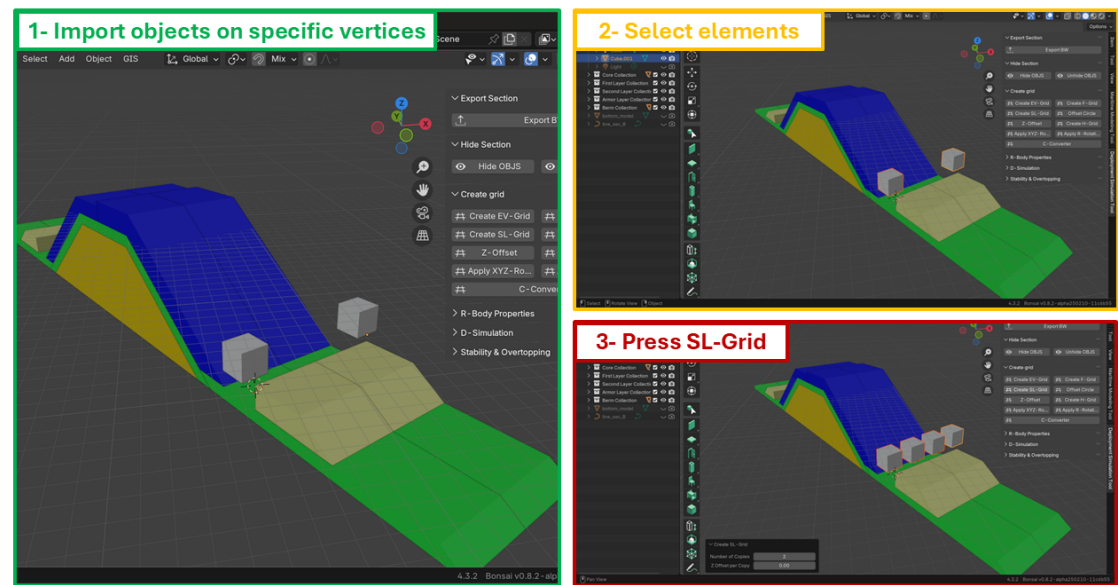


Figure 4.36. Different steps to follow for building the rows of the grid through the *SL-Grid* tool

- **Z-Offset** translates selected objects along the vertical axis by a user-defined amount.
- **Create H-Grid** generates a grid of armor units distributed along a circular path, typically used for the head of rubble mound breakwaters.
- **Apply XYZ-Rotation** applies deterministic rotations to selected objects around the global x, y, and z axes (Figure 4.37).
- **Apply R-Rotation** enables to apply a random rotation to selected objects. Objects must be selected to perform the tool (Figure 4.38).
- **C-Converter** converts mesh objects into curve representations, facilitating the generation of the first armor row along curved geometries, especially in head sections of rubble mound breakwaters.

4.3.4 R-Body Properties

The sub-menu has been developed by integrating a reduced version of Blender's Rigid Body panel directly into the add-on user interface. This integration simplifies the workflow and enhances usability, allowing users to access the most relevant parameters without interacting with Blender's default physics panels.

Rigid body simulations are employed to reproduce the motion and interaction of solid objects under physical laws. In Blender, the rigid body

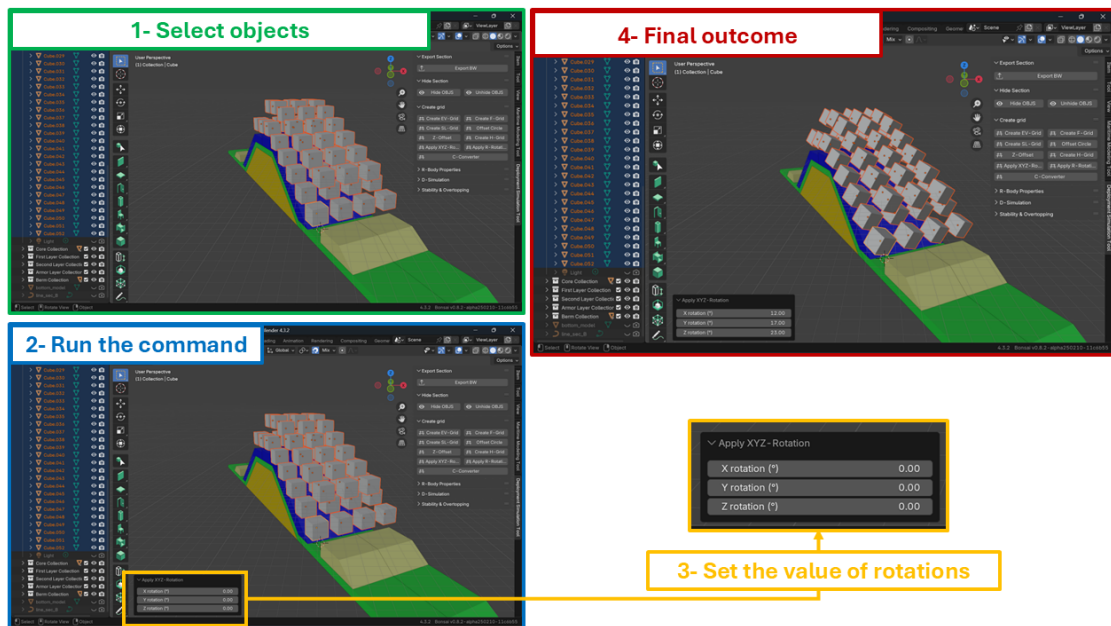


Figure 4.37. Different steps to follow for the usage of *Apply XYZ-Rotation* tool

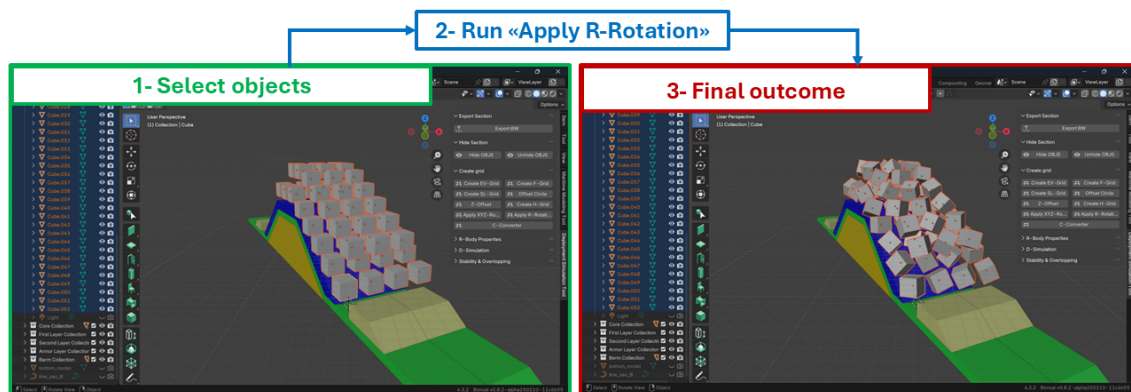


Figure 4.38. Different steps to follow for the usage of *Apply R-Rotation* tool

engine is tightly integrated with the animation system, allowing physical simulations to coexist with keyframe-based transformations.

Two distinct types of rigid bodies are defined. Active bodies are dynamically simulated and respond to forces, collisions, and constraints, whereas passive bodies remain static during the simulation and are directly controlled by the animation system (e.g., Blender Foundation, 2025).

Once the distinction between active and passive rigid bodies is established, the parameters governing the rigid body simulation can be introduced and discussed in detail.

- **Shape** defines the collision representation adopted by the rigid body solver. Collision shapes can be grouped into two main categories: *primitive shapes* and *mesh-based shapes*.

Primitive shapes (box, sphere, capsule, cylinder, and cone) (e.g., Blender Foundation, 2025), offer the best performance in terms of computational cost and memory usage. However, they provide only a simplified approximation of the actual geometry. In this case, the object dimensions are derived from its bounding box, and the centre of mass is always assumed to coincide with the geometric centre of the primitive.

Mesh-based shapes are computed directly from the object geometry and therefore provide a more accurate representation of complex elements. Among them, the *Convex Hull* shape is particularly relevant: it consists of a convex envelope surrounding the object geometry, representing a compromise between geometric fidelity, numerical stability, and computational efficiency.

- **Mass** represents the weight of the armor unit and directly affects its dynamic response during collisions and deployment.
- **Friction** defines the resistance to relative motion between contacting bodies and controls the amount of velocity dissipated during collisions.
- **Collision Margin** is introduced to improve numerical stability and performance by defining a tolerance distance near the object surface within which collisions are still detected. Its behaviour depends on the selected collision shape. For some shapes, the margin is embedded within the collision representation, whereas for others it introduces a visible gap between colliding objects.

The margin is embedded for the following shapes:

- Sphere
- Box

-
- Capsule
 - Cylinder
 - Convex Hull

The margin is not embedded for the following shapes:

- Cone
- Active Triangle Mesh
- Passive Triangle Mesh

In general, better numerical results are obtained when the collision margin is set to a non-zero value.

- **Linear Damping** controls the gradual loss of linear velocity over time, simulating energy dissipation mechanisms such as hydrodynamic resistance.
- **Deactivation** improves both performance and numerical stability by allowing rigid bodies to enter a sleep state when they are not involved in significant interactions (e.g., Blender Foundation, 2025). Rigid bodies are initially deactivated and become active only when they are within the proximity of a moving active rigid body. The proximity check is based on the object bounding box.

The values of the model parameters, including linear damping, collision margin, and others, are selected following the methodology presented by Molines et al. (2021).

In the native Blender rigid body panel, several additional parameters are available. However, the subset described above is sufficient to realistically simulate the deployment of armor layer units in rubble mound breakwater structures.

Two distinct cases must be considered when using the tool: *active* and *passive* rigid bodies. In rubble mound structures, armor units are treated as active bodies, while all underlying components (e.g. filter layers, core, and seabed) are defined as passive bodies. The workflow is identical in both cases: first, the relevant objects are selected, the parameters are assigned, and finally the *Assign Rigid Properties* command is executed. The only difference lies in the activation of the corresponding *Active* (Figure 4.39) or *Passive* option (Figure 4.40).

4.3.5 D-Simulation

This sub-menu enables the execution of the *placement simulation* of breakwater armor units. As previously discussed, numerical simulations are performed only on selected portions of the structure—namely, representative trunk sections or the head, rather than on the entire breakwater. This

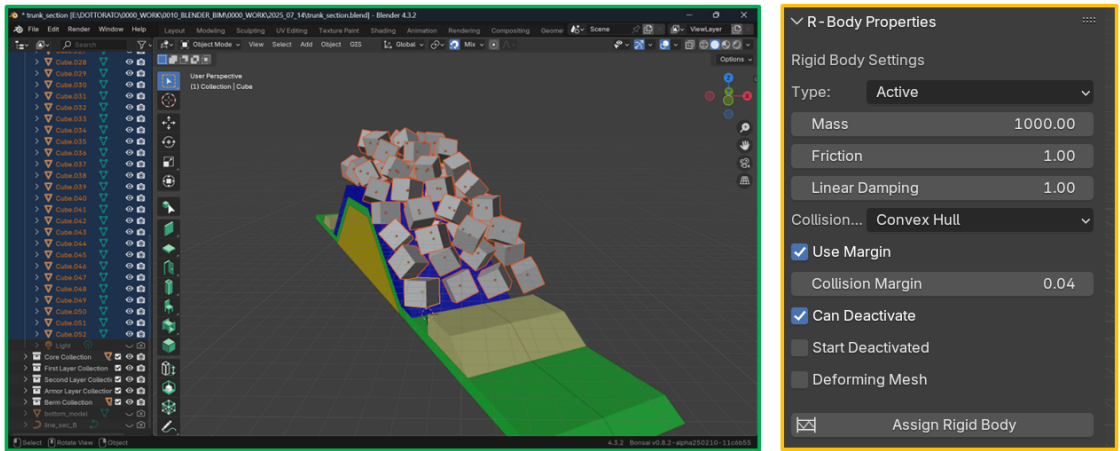


Figure 4.39. Assignment of the active rigid body properties to the breakwater units

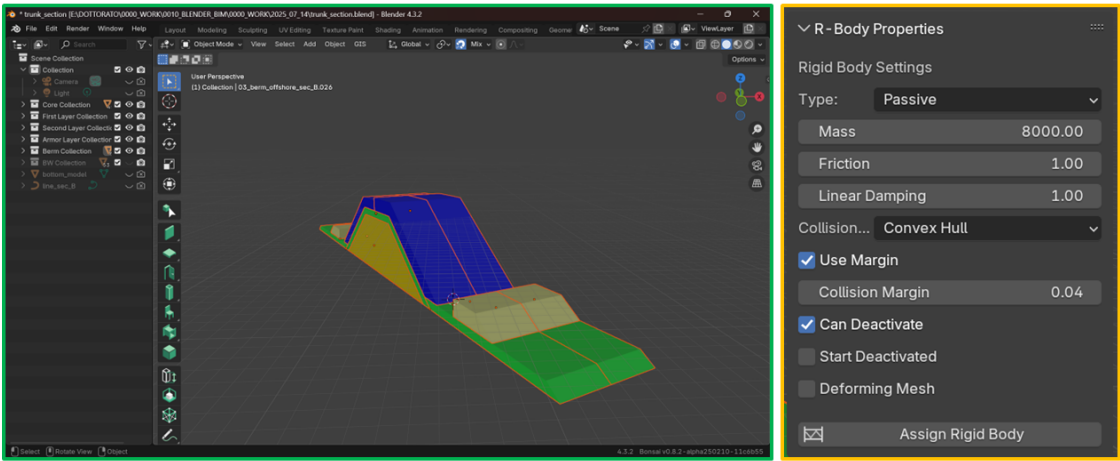


Figure 4.40. Assignment of the passive rigid body properties to the breakwater units

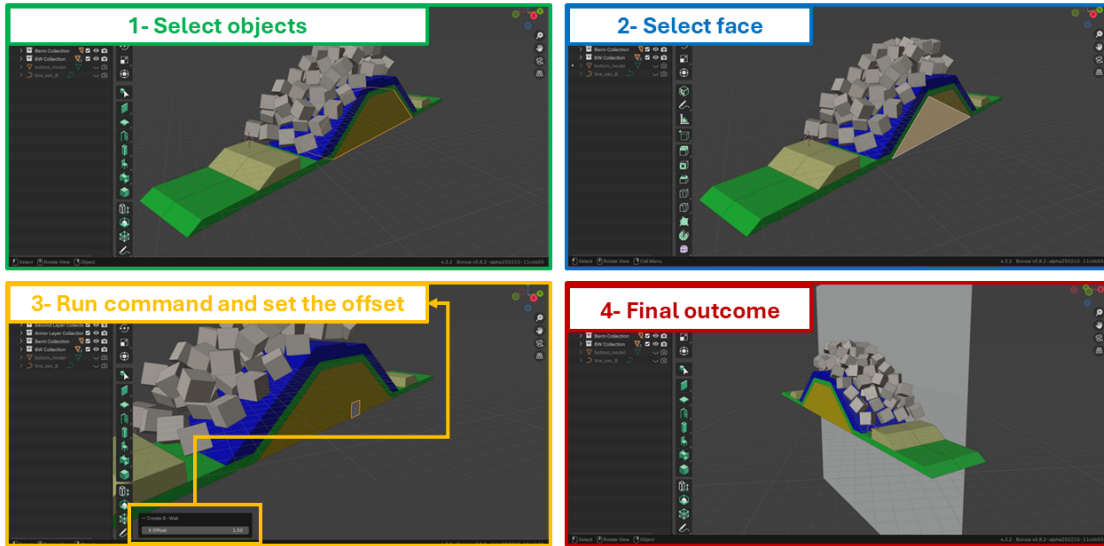


Figure 4.41. Different steps to follow for the usage of *B-Walls* tool

choice is motivated by both computational efficiency and the localized nature of the phenomena of interest.

To correctly perform the simulation, artificial boundary walls must be introduced to bound the analyzed domain. These boundaries prevent armor units from escaping the selected section during the simulation and ensure physically meaningful results. Once the boundary geometry has been properly defined, the deployment simulation can be executed.

In summary, the sub-menu is composed of the following tools:

- **Create B-Wall** enables the creation of boundary walls as planar surfaces. Each wall must be assigned the rigid body properties prior to the simulation. To use the tool, first select the reference object—typically a core element—then switch the scene to *edit mode* and select the relevant face. Running the command, it imports a plane at the center of the selected face. A pop-up window allows the user to define an offset along the x-axis for the plane's position. Once imported, standard Blender modeling tools can be used to scale and adjust the plane to match the desired boundary dimensions (Figure 4.41).
- **Run Simulation** executes the numerical deployment simulation of the breakwater units (Figure 4.42). To perform the simulation, the relevant objects must be selected. The tool allows the user to define key parameters such as the time delay between successive unit drops, the starting time, and the duration of the falling process. These parameters help to reproduce a deployment behavior as close as possible to real-world conditions. Finally, the simulation can be baked to store the computed motion for subsequent analysis or visualization.

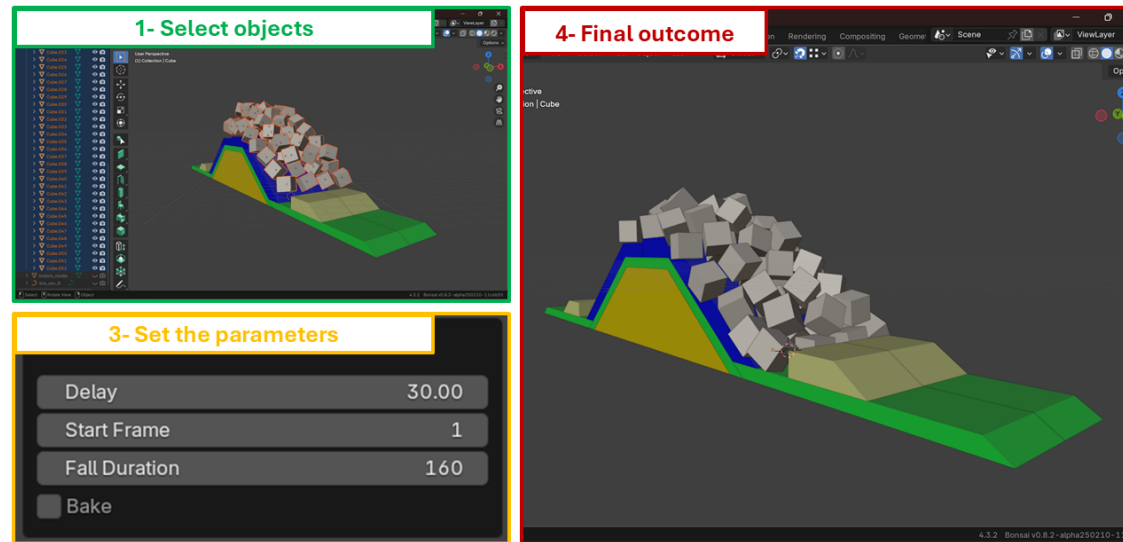


Figure 4.42. Different steps to follow for the usage of *Run Simulation* tool

4.3.6 Stability and overtopping

This sub-menu allows the verification of breakwater stability through different design methods, as well as the computation of wave overtopping discharge (Chapter 3, see Sections 3.5 and 3.3).

The *Stability & Overtopping* sub-menu includes the following functionalities:

- **Wave Breaking Criteria:** applies different wave breaking criteria (Chapter 3, see Section 3.5). In particular, this tool computes the wave breaking height and identifies the wave breaking type according to Goda's criteria (Goda, 2010, e.g.,) and the Kamphuis formulations (Kamphuis, 1991, e.g.,).

After running the command, a dialog window opens (Figure 4.43), allowing the user to set the parameters required by the selected method. Once the computation is completed, the tool exports a CSV file reporting the adopted method, the wave breaking height H_b , the significant wave height, and the corresponding wave period.

- **Hudson Method:** applies the Hudson formula to assess the stability of breakwater units (e.g., CIRIA, 2007).

When the command is executed, a pop-up window opens (Figure 4.44), allowing the user to define the parameters required for the stability check.

- **Van der Meer DW:** performs the stability check using the Van der Meer formulation under deep-water conditions (e.g., CIRIA, 2007). Running the command opens a dialog window for parameter definition (Figure 4.45). The tool allows exporting a CSV file containing

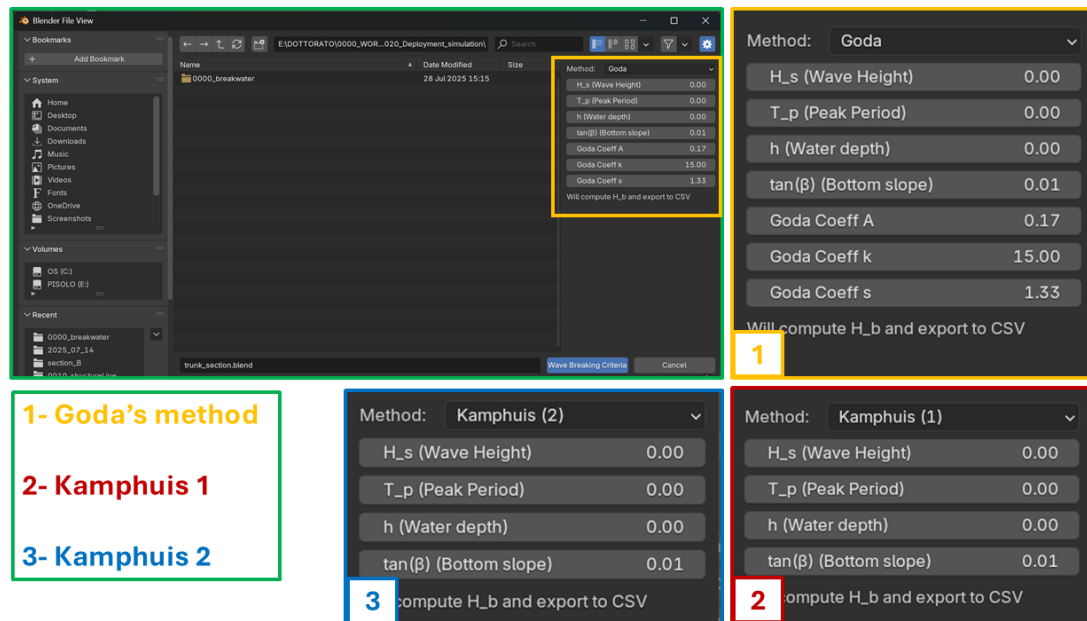


Figure 4.43. Dialog window of the *Wave Breaking Criteria* tool.

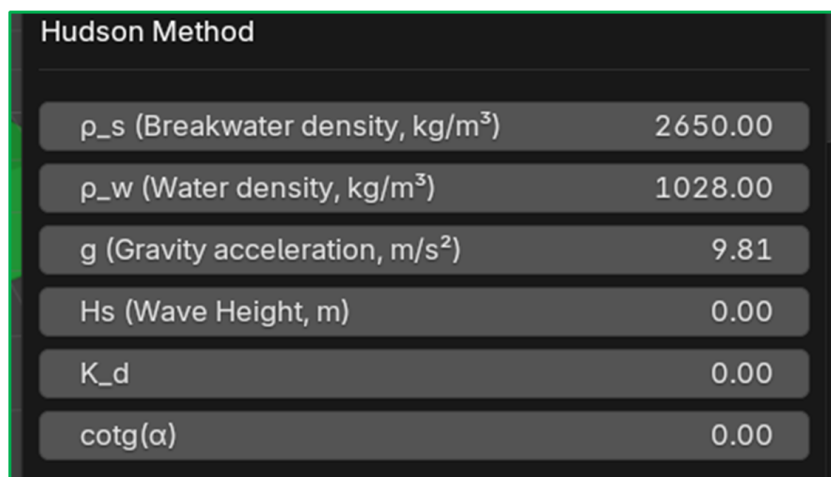


Figure 4.44. Pop-up window displayed when running the *Hudson Method* command.

Van der Meer offshore		Van der Meer SW	
H _b (Breaking Wave Height, m)	0.00	H _s (Wave Height at toe, m)	0.00
H _s (Offshore Wave Height, m)	0.00	T _p (Peak Period at toe, s)	0.00
T _p (Offshore Peak Period, s)	0.00	ρ _s (Breakwaters density, kg/m ³)	2650.00
ρ _s (Breakwaters density, kg/m ³)	2650.00	ρ _w (Water Density, kg/m ³)	1028.00
ρ _w (Water density, kg/m ³)	1028.00	g (Gravity acceleration, m/s ²)	9.81
g (Gravity acceleration, m/s ²)	9.81	F _s (Shape factor)	0.00
F _s (Shape factor)	0.00	C _{pl} (Plunging Coeff.)	8.40
C _{pl} (Plunging Coeff.)	6.20	C _s (Surging Coeff.)	1.30
C _s (Surging Coeff.)	1.00	P (Permeability)	0.60
P (Permeability)	0.60	cotg(α)	0.00
cotg(α)	0.00	S _d (Damage Level)	2.00
S _d (Damage Level)	2.00	N (Number of Waves)	1000.00
N (Number of Waves)	1000.00		
OK	Cancel	OK	Cancel

Figure 4.45. Stability check using the Van der Meer formulation in deep-water (left) and shallow-water (right) conditions.

the parameters and results of the stability analysis, including:

- wave breaking type;
 - ξ_s , surf similarity parameter computed according to the Iribarren formulation;
 - ξ_{cr} , critical value of the surf similarity parameter according to the Van der Meer formulation;
 - N_s , stability number;
 - D_{n50} , nominal diameter [m];
 - V_{50} , unit volume [m³];
 - M_{50} , unit mass [t];
 - stability check result (*Satisfied* or *Not satisfied*).
- **Van der Meer SW:** performs the stability check using the Van der Meer formulation under shallow-water conditions (e.g., CIRIA, 2007).
The command opens a dialog window for parameter input (Figure 4.45). Similarly to the offshore formulation, the tool exports a CSV file reporting all quantities required for the stability assessment.
 - **q-Overtopping:** computes the overtopping discharge using empirical formulations (e.g., van der Meer et al., 2016).

When the command is executed, a pop-up window opens (Figure 4.46), allowing the user to set the required parameters and to select

q - Overtopping	
Hm0 (Spectral wave height, m)	1.00
Tp (Peak period, s)	1.00
g (Gravity acceleration, m/s ²)	9.81
Rc (Freeboard, m)	1.00
β (Incident wave angle, deg)	0.00
γ _f (Roughness factor)	1.00
γ _b (Berm factor)	1.00
γ _β (Wave angle factor)	1.00
cotan(α)	1.50
tan(α) (Structure slope)	0.67
Structure T...	Rubble Mound
Filepath:	//overtopping_results.csv
OK Cancel	

Figure 4.46. Pop-up window of the overtopping tool based on the empirical formulations (e.g., van der Meer et al., 2016).

the structure type (rubble mound or vertical wall). The tool exports a CSV file containing the following information:

- q_{mean} , mean overtopping discharge [$m^3/s/m$];
- q_{max} , maximum overtopping discharge [$m^3/s/m$];
- P_{ov} , overtopping probability;
- ξ_m , surf similarity parameter;
- structure type.

4.4 BIM Modeling

4.4.1 General aspects

This section describes the different steps required to build a detailed BIM model.

A BIM model is a geometric model in which additional information layers, namely *time* and *economic* aspects, are associated with the 3D representation. In this way, the model evolves from a traditional 3D parametric model into a 5D model. More specifically, the *time* dimension refers to the duration required to complete the scheduled construction or maintenance activities, while the *economic* dimension includes all costs associated with the planned works. Furthermore, each structural element is assigned a specific IFC class according to its component type.

The BIM modeling process follows a defined sequence, summarized as follows:

- creation of the 3D geometric model;
- assignment of a specific IFC class to each structural component;
- grouping of components into their respective containers using the *BIM Storey* command provided by the Maritime Modeling Tool;
- creation and assignment of materials to each structural component;
- definition of the time dimension by creating work tasks and work schedules;
- association of each structural element with the corresponding work item in order to compute its cost.

4.4.2 Preliminary Steps

This section summarizes all the operations required to complete the 3D geometric model and to generate an IFC model enriched with its corresponding properties. In order to obtain a detailed BIM model of a maritime structure, it is important to underline that specific IFC classes for this type of infrastructure do not currently exist. To overcome this limitation, a dedicated *informative layer* has been developed and integrated with the automatically computed properties of the *IfcWall* class.

Starting from the geometric model shown in Figure 5.14, the following steps are performed to generate the IFC model:

1. selection of all elements sharing the same name;
2. assignment of the appropriate IFC class to the selected elements;
3. assignment of custom properties through the *My Data* command, which writes a predefined informative layer;
4. creation and assignment of IFC materials for each structural component.

To obtain a consistent and structured IFC model, the steps described above must be followed in sequence. In particular, the most suitable IFC class for maritime structural components is *IfcWall*, as rubble mound and caisson breakwater structures can be semantically interpreted as wall-like elements. This choice offers significant advantages in terms of property management, since several geometric and quantitative attributes can be computed automatically (Table 4.2).

The IFC class assignment can be further customized according to the specific role of each structural component (Table 4.1).

Products	IfcElement
Class	IfcWall
Predefined Type	USERDEFINED
UserDefined Type	CORE
Contexts	Model / Body / MODEL_VIEW

Table 4.1. Blender template used to assign the IFC class.

This approach allows the *UserDefinedType* field to be freely specified by the user. In addition, all components are grouped under specific *IfcBuildingStorey* entities (Figure 4.47), enabling a hierarchical organization of the project and facilitating model management.

The main quantity properties associated with the *IfcWall* class are reported in Table 4.2.

Property	Type
Height	float
Length	float
Width	float
NetVolume	float

Table 4.2. Template of quantity properties for the *IfcWall* class.

In addition to standard IFC quantities, custom properties are assigned to each structural component. These properties are predefined and listed in Table 4.3.

It should be emphasized that environmental variables such as significant wave height (H_s), peak period (T_p), and wave direction are intrinsically probabilistic and are typically associated with specific return periods for a given site. In the present framework, the wave parameters reported in the informative layer (Table 4.3) are introduced as input values derived

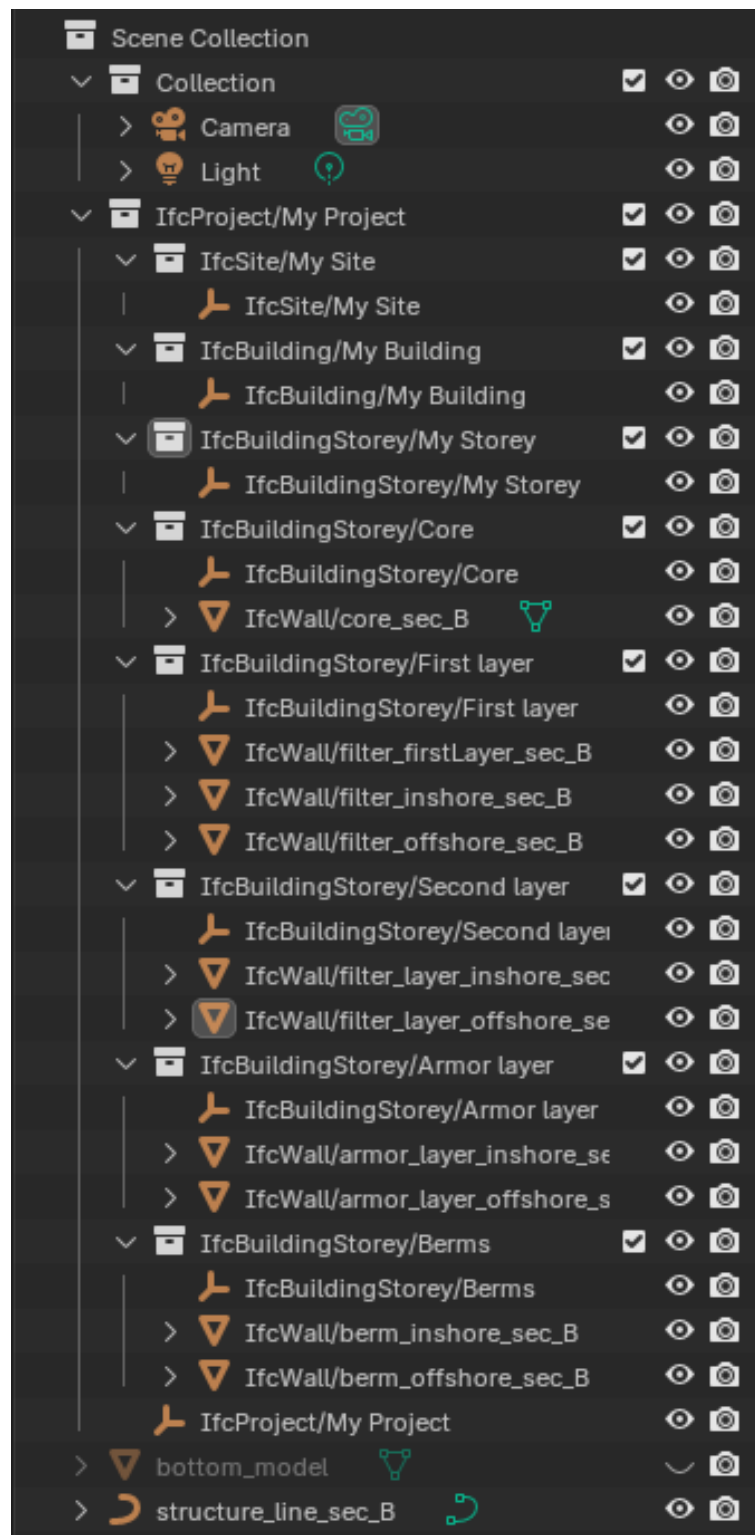


Figure 4.47. Organization of the structural components into different BIM storeys.

Property	Type
D_{n50}	float
H_s	float
T_p	float
$H_{s,toe}$	float
$T_{p,toe}$	float
ξ_{max}	float
ξ_{min}	float
h	float
$\tan \alpha$	float
S_d	float
K_d	float
NetMass	float

Table 4.3. Template of custom properties assigned to each structural component.

from preliminary design conditions corresponding to selected return periods. The probabilistic characterization of environmental variables remains outside the scope of the proposed BIM-based modeling approach.

All property fields are filled manually, with the exception of *NetMass*, which is computed automatically according to the following expression:

$$m = \left(\frac{V \cdot \rho_s}{1000} \right) (1 - p) \quad (4.1)$$

where V is the volume obtained from the *IfcWall* quantity properties, ρ_s is the rock density, and p is the porosity.

Finally, materials are associated with each IFC component. Rubble mound breakwater structures are composed of two main material types: concrete, used for armor units, and natural rock, used for the remaining structural components. Natural rock materials are further subdivided according to stone size categories. Specifically, the core is composed of *tout venant* material; the first filter layer, its bedding layer, and the offshore part of the second filter layer are composed of *Category 1* stones; the berms and the inshore part of the second filter layer are composed of *Category 2* stones. The armor layer consists of concrete breakwater units, such as accropodes. Stone categories are defined based on rock weight.

Accordingly, multiple *IfcMaterial* entities are created: one for concrete and several for natural rocks, namely *Tout Venant*, *Category 1*, and *Category 2*. In the case of caisson breakwater structures, natural rocks are used

for the bedding layer, while concrete is used for both the caisson and the crown wall, with rock categories defined in the same manner as for rubble mound structures.

4.4.3 Construction of the 4D Model

A 4D model extends a 3D geometric representation by integrating a temporal component. In this work, the 4D model incorporates scheduled construction activities along with their corresponding durations. The development is carried out using the *Construction Scheduling* tool provided by Bonsai BIM. The tool is organized into the following sub-menus:

- Work Plans
- Work Schedules
- Work Calendars
- Animation Color Scheme
- 4D Tools

The *Work Plans* sub-menu allows the creation of a work plan by filling in the corresponding template (Table 4.4). The *Work Schedules* sub-menu enables the generation of scheduled works directly associated with the work plans and allows the selection of type options: PLANNED, ACTUAL, USERDEFINED, and NOTDEFINED. *Work Calendars* define work-days and holidays, while the *Animation Color Scheme* and *4D Tools* sub-menus generate visualizations and animations of the construction phases.

Name	string
Description	string
ObjectType	string
Identification	string
CreationDate	automatically filled
Purpose	string
Duration	string
StartTime	automatically filled
FinishTime	string
PredefinedType	string

Table 4.4. Template for Work Plans in Bonsai BIM.

The 4D modeling process follows a specific sequence. First, the work calendar is defined by specifying workdays and holidays. To build the calendar, the user sets its name, defines work and exception times, and enables the *Edit Work Calendar* option (Figure 4.48).

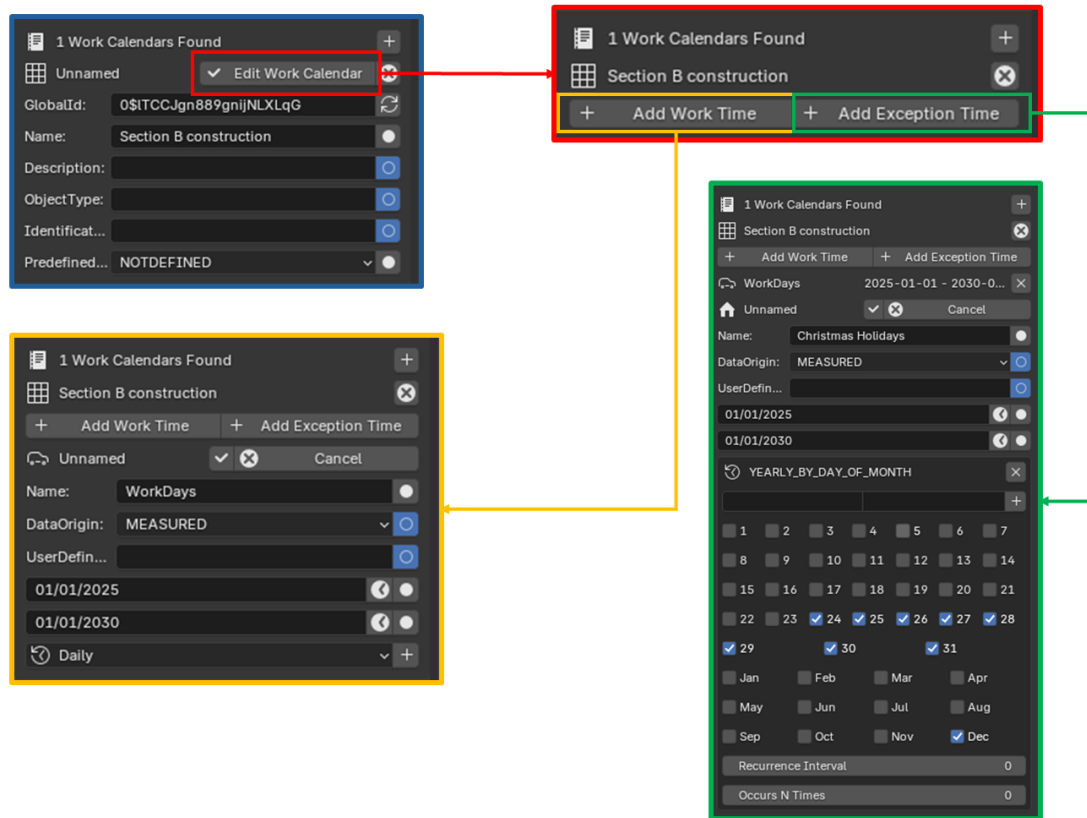


Figure 4.48. Workflow for defining work calendars.

The second step is the design of a detailed work schedule. Based on the structural components, the schedule is organized as follows:

- Core deployment
- First layer deployment
 - Core covering
 - Inshore bedding layer
 - Offshore bedding layer
- Second layer deployment
 - Inshore elements
 - Offshore elements
- Berm deployment
 - Inshore

- Offshore
- Armor layer deployment
 - Inshore
 - Offshore

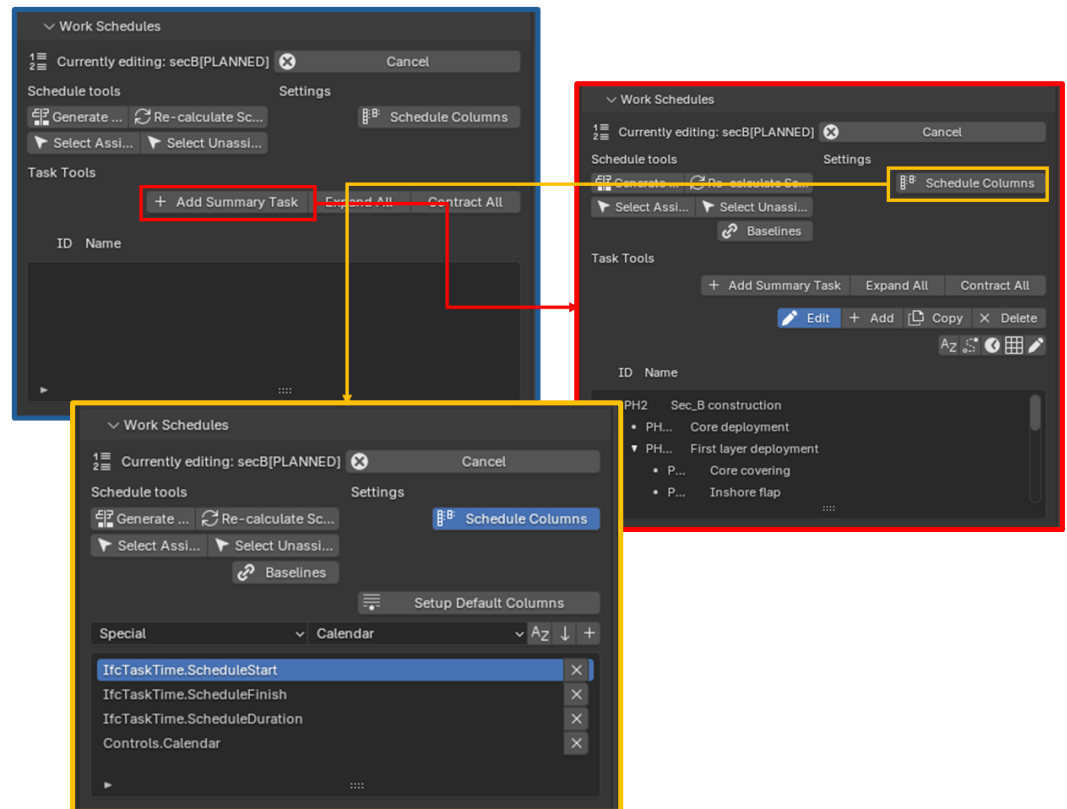


Figure 4.49. Interface of the Construction and Schedules tool.

To create the work schedule (Figure 4.49), the user clicks the *Add Summary Task* button to define work tasks, then links each task to its corresponding *IfcTaskTime* and calendar. Using the *Task ICOM* tool, each structural component is associated with its respective task (Figure 4.50). The duration and end date of each task are computed by defining and linking work resources through the same tool.

The resource hierarchy is structured as follows:

- Crew
 - Labor
 - * Equipment
 - * Material
 - * Product

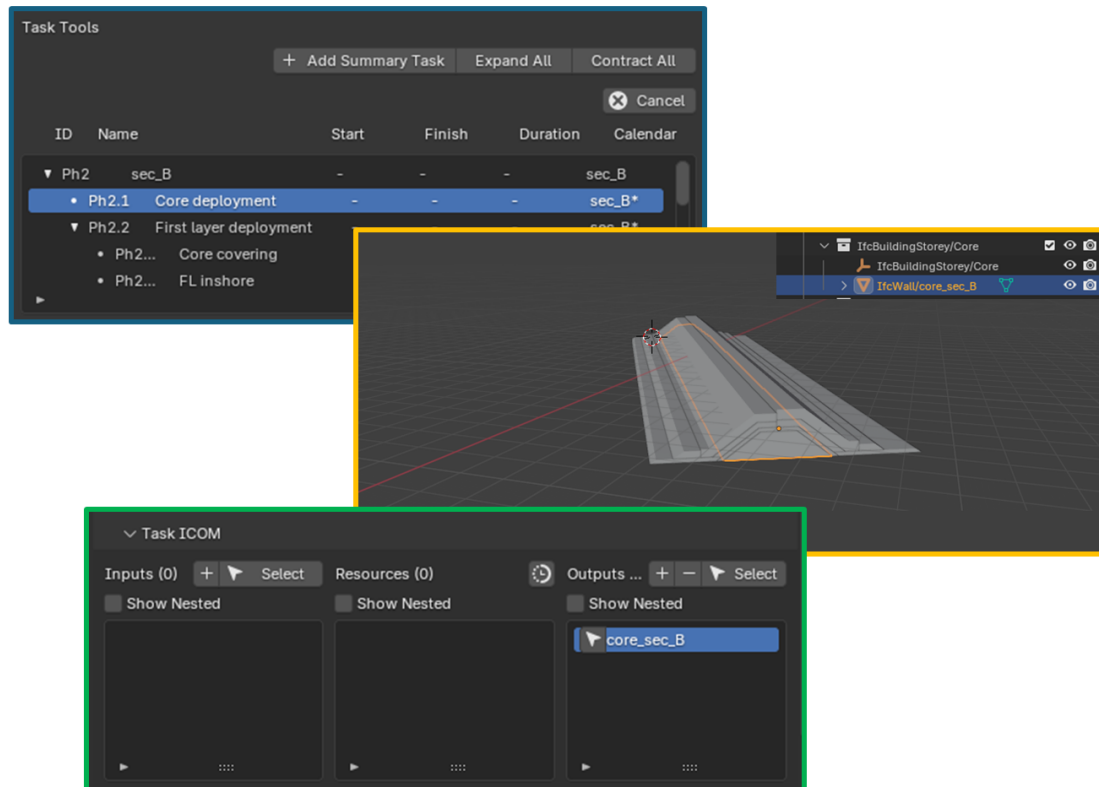


Figure 4.50. Linking work tasks with their corresponding structural components.

For instance, the *SecB construction* represents a crew, while the labor corresponds to the realization of individual structural components, such as the core (Figure 4.51). Each labor is associated with equipment and assigned a *Productivity Rate*, representing the material mass deployed per day. Using *Task ICOM*, this information enables the calculation of task durations and end dates (Figure 4.52).

Repeating the described procedure for all components yields the final 4D model, including a detailed Gantt chart and scheduled works (Figure 4.53).

4.4.4 Construction of the 5D Model

The 5D model extends the 4D model by integrating cost information, taking advantage of the 5D functionalities provided by Bonsai BIM. This allows associating each cost item with its corresponding unit of measurement. For instance, material costs are linked to quantities expressed in *tons*, while equipment-related costs are referenced to time units. This association is possible because the 5D tools are directly integrated with the project's resources and work plans.

The creation of a detailed 5D model involves the following steps:

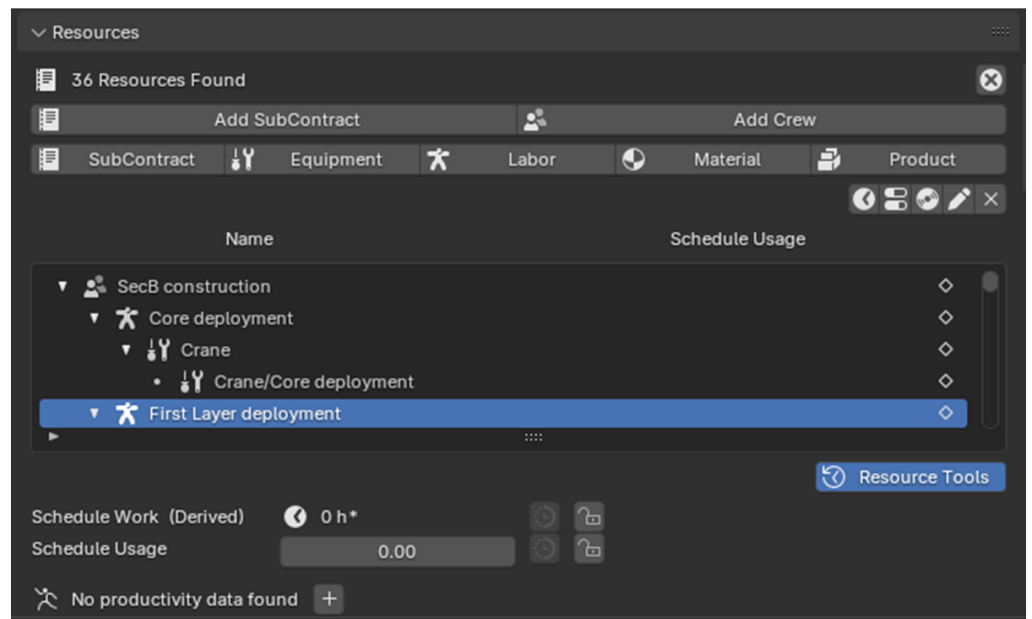


Figure 4.51. User interface of the resources tool.

1. Compute the usage time of each equipment during each construction phase.
2. Create a cost schedule tree.
3. Link each cost item to its corresponding work task, Ifc component, and unit of measurement.

The *Usage Time* is calculated (Figure 4.54).

The 5D model is then developed using the *Cost* tool provided by Bonsai BIM. First, the project currency is selected. The cost structure is organized (Table 4.5).

Name	Quantity	Unit Value	Total Cost
Core deployment	-	-	-
Materials	tons	currency	tons × currency
Equipment	Work hours	currency	Hours × currency

Table 4.5. Structure of the cost schedule tree.

The material quantity is directly linked to the Ifc model, while the work hours correspond to the *Usage Time* computed previously through the *Re-*

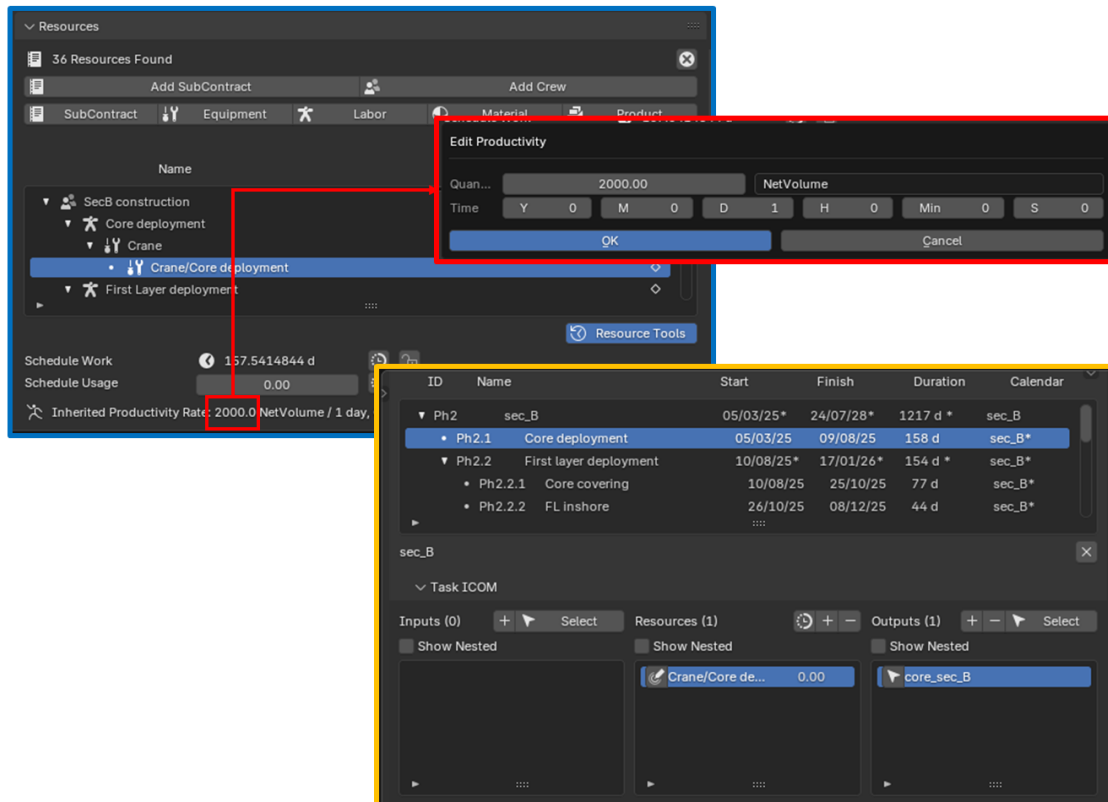


Figure 4.52. Computation of work durations based on deployment rates.

sources Tool (Table 4.5). The total cost is calculated automatically based on the linked quantity and unit value (Figure 4.55).

Following this workflow, the 5D model is complete. Bonsai BIM allows exporting a detailed spreadsheet containing all costs (Figure 4.56).

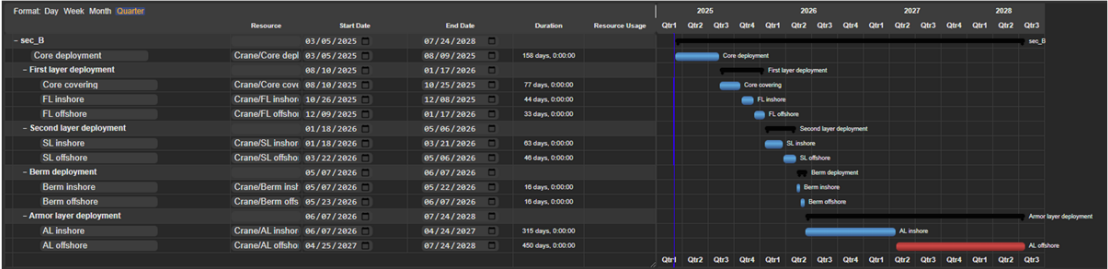


Figure 4.53. Gantt chart and scheduled works generated from Bonsai BIM.

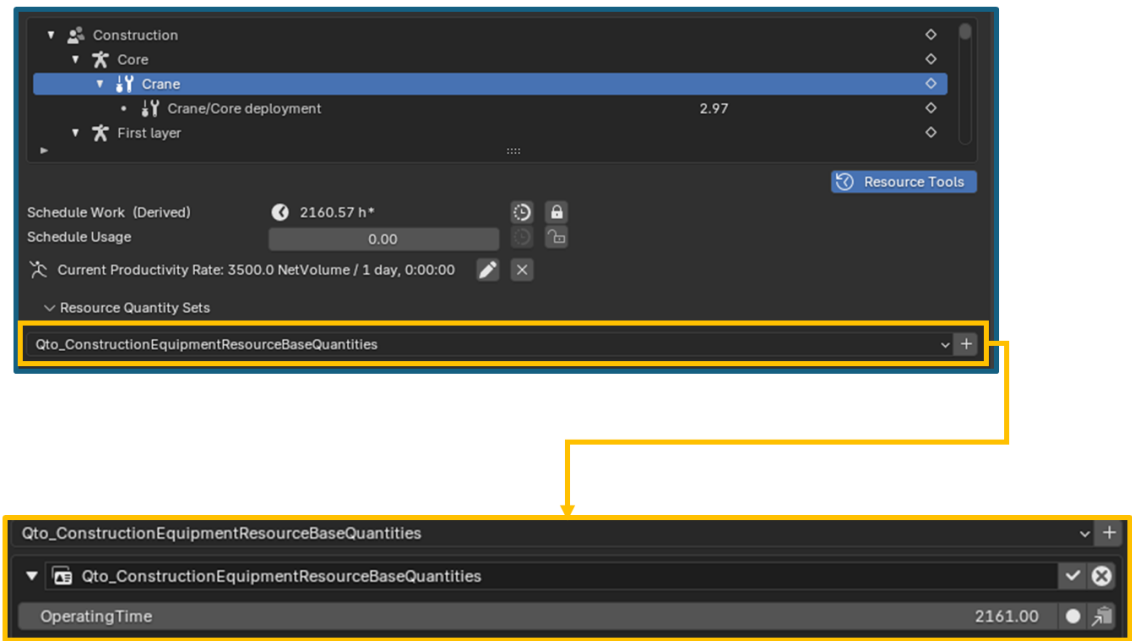


Figure 4.54. Computation of the equipment operating time.

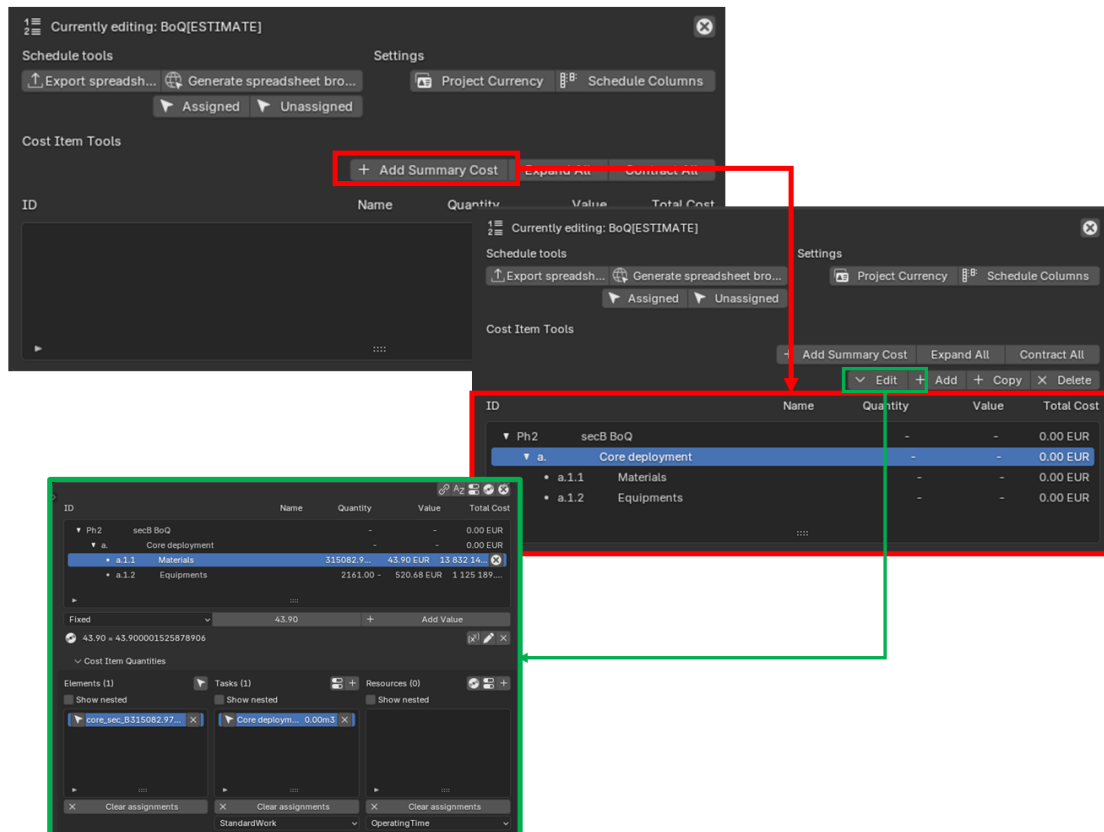


Figure 4.55. Calculation of total cost for specific tasks and structural components.

BoQ					
Identification	Name		Quantity	Unit	Cost (EUR)
Ph2	South quay sec B construction		-	U	-
XXX	Core deployment		-	U	-
XXX	Materials		315 082.97	m3	48.20
XXX	Equipment		2 161.00	U	520.68
XXX	First layer deployment		-	U	-
XXX	Materials		76 745.70	m3	48.20
XXX	Equipment		1 535.00	U	520.68

A	B	C	D	E	F	G	H	I	J
1	Id	Hierarchy	Index	Identification	Description	Quantity	Unit	* Cost	Rate Subtotal
2	26680	1	0	Ph2	South quay sec B construction			0,00	20.810.232,74 €
3	26682	11	1		Core deployment			0,00	
4	26684	111	2		Materials	315082,00	48,20	15.186.952,40 €	
5	26686	112	2		Equipment	2161,00	520,60	1.125.016,60 €	
6	26687	12	1		First layer deployment			0,00	
7	26688	121	2		Materials	76745,70	48,20	3.699.142,74 €	
8	26690	122	2		Equipment	1535,00	520,60	799.121,00 €	

Figure 4.56. Spreadsheet of project costs generated using the Bonsai BIM cost tool.

PRACTICAL APPLICATIONS

5.1 General Remarks

This chapter presents two practical applications of BIM modeling. The first application focuses on rubble mound breakwater structures, while the second concerns caisson breakwater structures.

Both models are developed using the newly implemented BIMMs tool, demonstrating its capabilities in creating detailed, structured, and semantically enriched BIM representations of maritime infrastructure.

In particular, the two applications are intended to demonstrate the flexibility of BIMMs in addressing both rubble mound and vertical breakwater typologies, as well as new design and existing infrastructure management scenarios. The Ortona case (rubble mound breakwater) highlights the capability of the tool to handle complex geometries and construction planning, while the Civitavecchia application (composite breakwater) shows its potential for maintenance-oriented BIM workflows. These applications allow to highlight how BIMMs is a comprehensive framework for the digital modeling, analysis, and life-cycle management of maritime structures.

5.2 Rubble Mound Breakwaters: The South Quay of Ortona Port case

This section presents a practical application of geometric and BIM-based modeling for a rubble mound breakwater structure. The case study considered is the south quay of Ortona Port, located in the Abruzzo region of southern Italy (Figure 5.1).

The structure is of rubble mound type, with two changes in cross-section along the body and a distinct head section. Figure 5.2 shows the type sections of the south quay, from section A to section C.

Sections are detailed as follows:

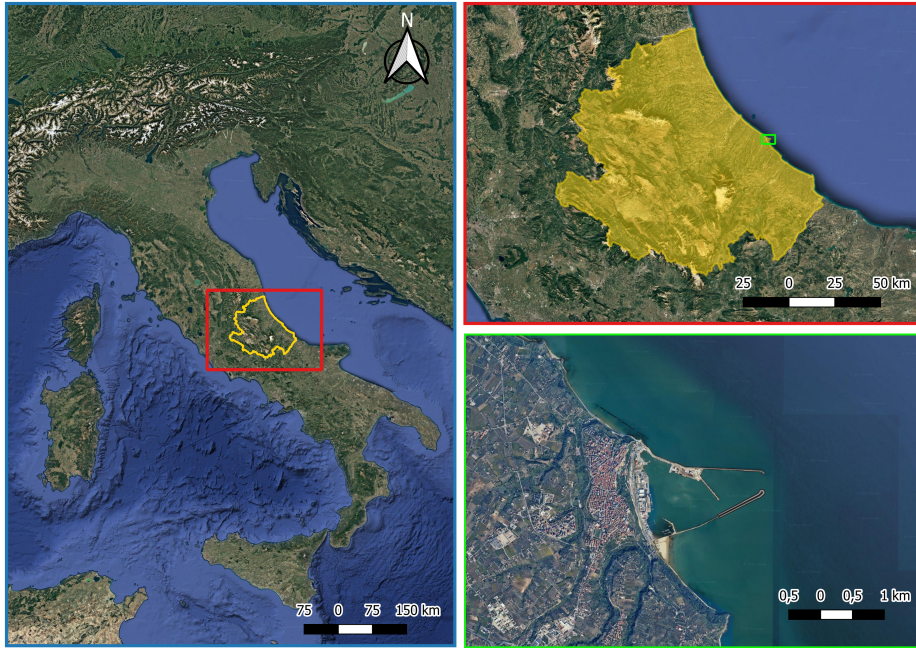


Figure 5.1. Geographical location of Ortona Port

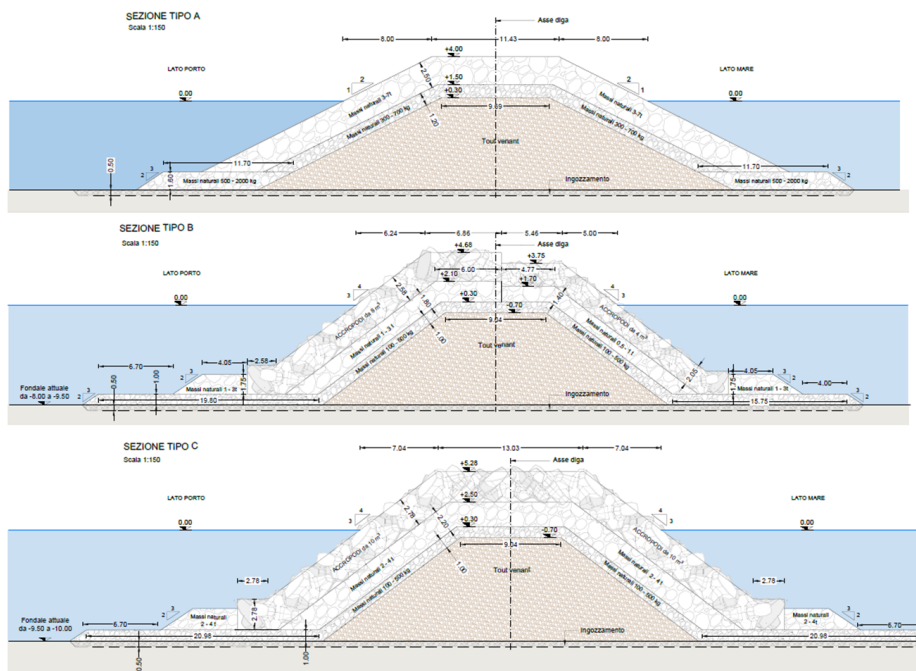


Figure 5.2. Type sections of the south quay of Ortona Port

- **Section A** includes core, filter layer (300–700 kg rocks), and armor layer (3–7 t rocks).
- **Section B** is the most complex, with different inshore and offshore sides: core, first filter layer (100–500 kg rocks), second filter layer (1–3 t inshore, 0.5–1 t offshore), berm (1–3 t rocks), and armor layer

of Accropodes™(8 m³ inshore, 4 m³ offshore).

- **Section C** has similar inshore/offshore sides: core, first filter layer (100–500 kg), second filter layer (2–4 t), berm (2–4 t), and armor layer of Accropodes™(10 m³ both sides).
- **Section D** (head) follows Section C: core, first filter layer (100–500 kg), second filter layer (2–4 t), berm (2–4 t), armor layer of Accropodes™(10 m³ both sides).

Modeling starts from the most complex head section (Section D). First, the bottom model is generated using the *Bottom* command, then development line for Section C is imported. Objects intersecting the bottom (00_core_sec_C and 01_filter_firstLayer_sec_C) are imported first, and sections are linked with *Link Sections*. Collections are created to keep the workspace organized.

Head and body elements are processed with boolean operators *Core2Head* and *FL2Head*, as shown in Figure 5.3.

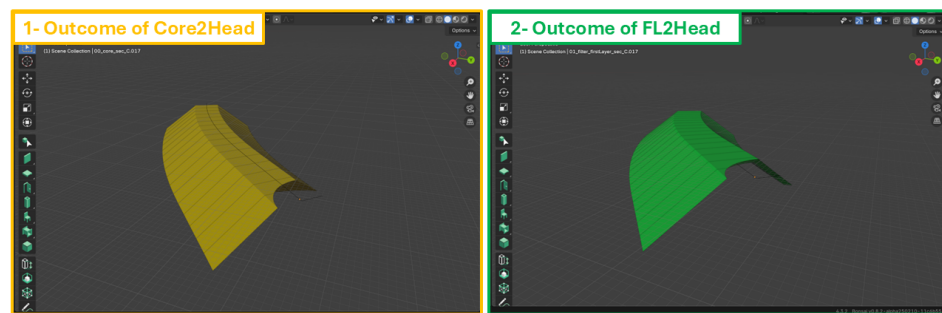


Figure 5.3. Outcomes of *Core2Head* and *FL2Head* commands

The head solid is built using *Vertex Spin* to generate vertex circles, separated with *Sep Verts*, and surfaces created with *Build Surface* (Figure 5.4).

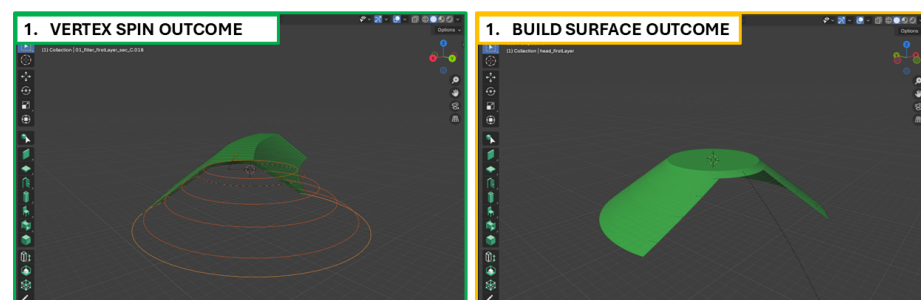


Figure 5.4. Building head layers using *Vertex Spin* and *Build Surface*

Bedding layers and berm are modeled with *B-Head* and *L-Head* tools (Figure 5.5).

The second filter layer is modeled similarly, using *Vertex Spin* and *New B-Curve* for bottom alignment (Figure 5.6).

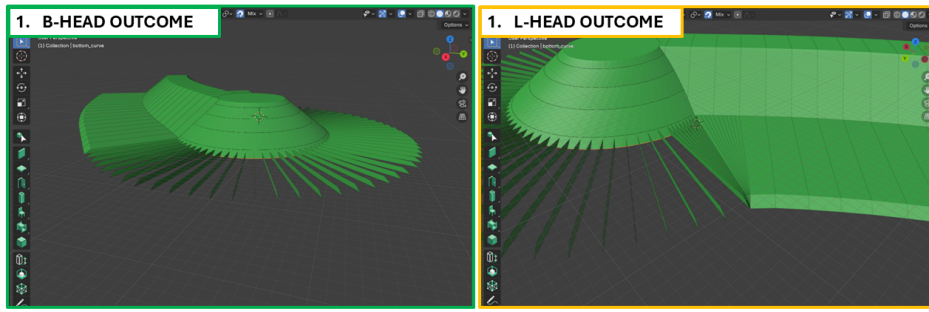


Figure 5.5. Outcomes of *B-Head* and *L-Head* tools

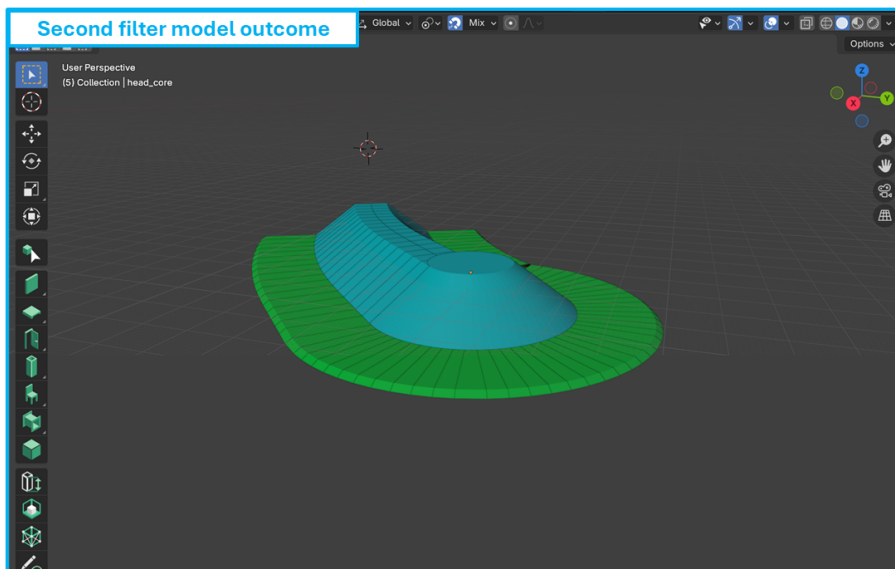


Figure 5.6. Geometrical model of core, first filter layer, and second filter layer

The armor layer is split into bottom and body. Bottom curve is created using *New B-Curve* (Figure 5.7) and surfaces are generated along the curve. Alignment is performed using *Z-Inshore*, *Z-Offshore*, *Align Armor*, and *Align AL-Verts*.

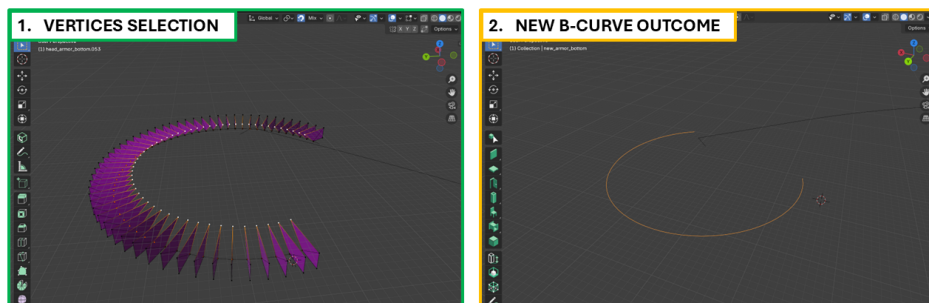


Figure 5.7. Outcome of *New B-Curve* for the armor layer

Final geometrical model of the armor layer is shown in Figure 5.8. Berm and bedding layers are linked with the body using *B-Head* and

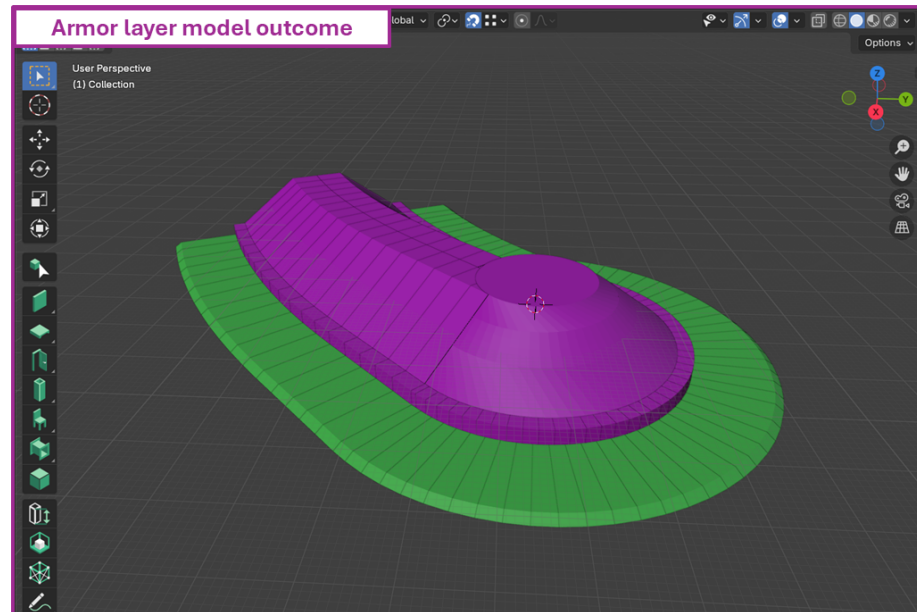


Figure 5.8. Final geometrical model of the armor layer

L-Head (Figure 5.9).

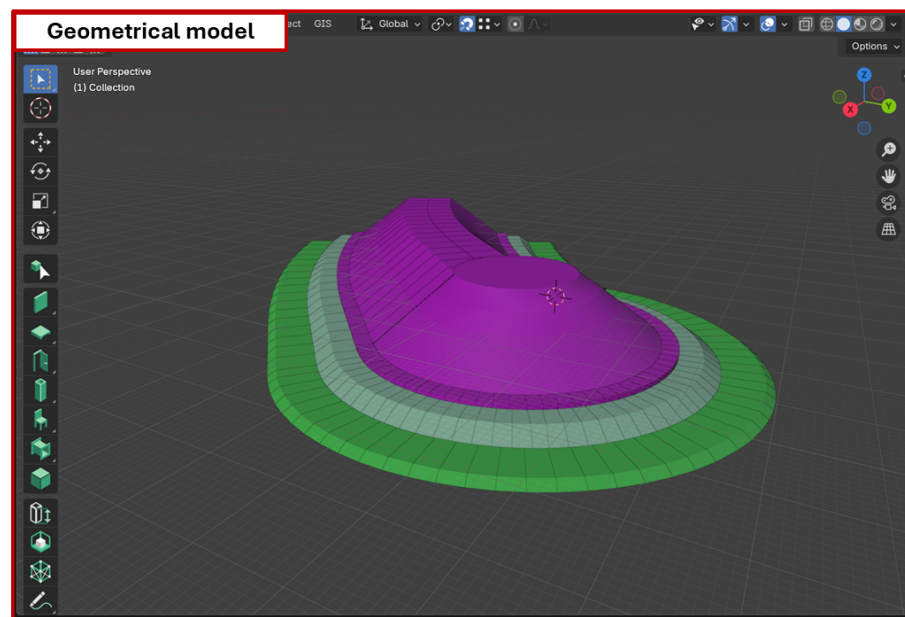


Figure 5.9. Final geometrical model of section C of the structure

Sections B and A are modeled following similar steps, including boolean subtraction with the bottom, mesh filling using *Fill Mesh* (Figure 5.10), and alignment of filter layers with *Align Filter* and *Align F-Verts* (Figures 5.11, 5.12).

Transition zones between sections B and C are modeled using *Ex-Vertex* and *Create Face* (Figure 5.13).

Regarding the armor layer, it is important to note that the placement

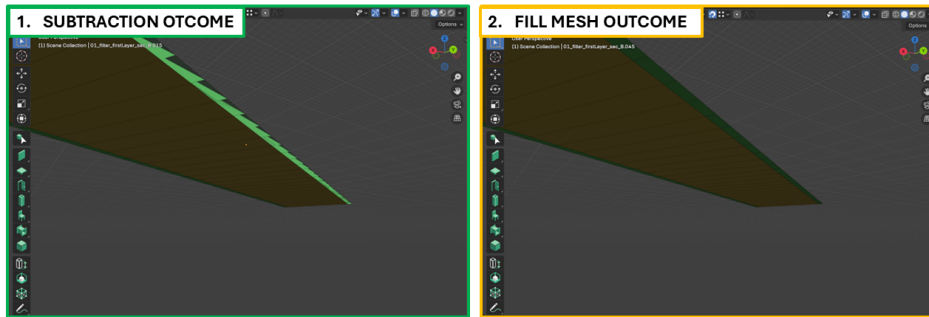


Figure 5.10. Subtraction outcome (left) and filled mesh (right)

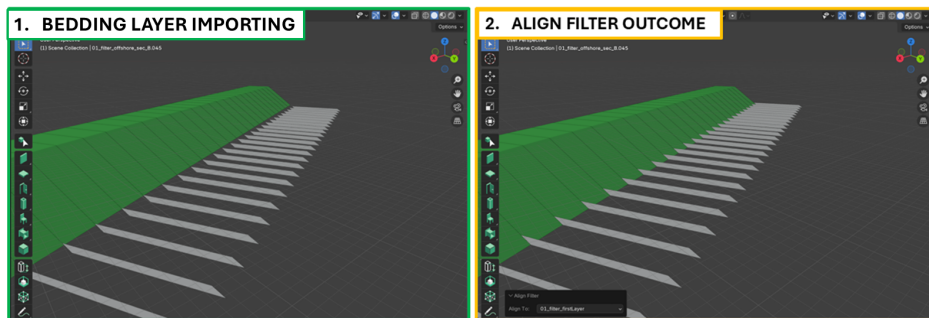


Figure 5.11. Outcomes of *Align Filter* tool

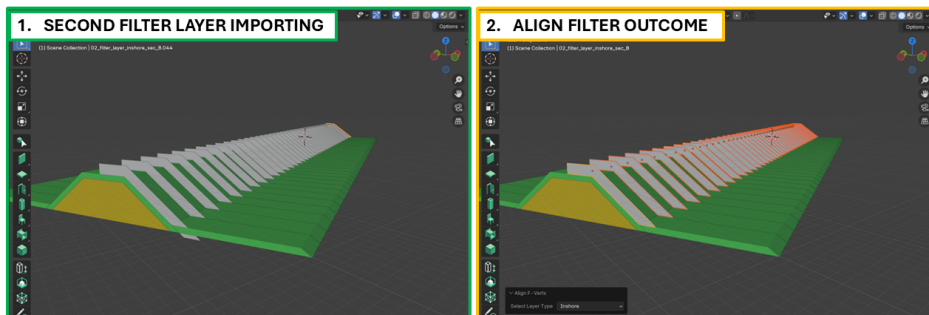


Figure 5.12. Outcome of *Align F-Verts* for second filter layer

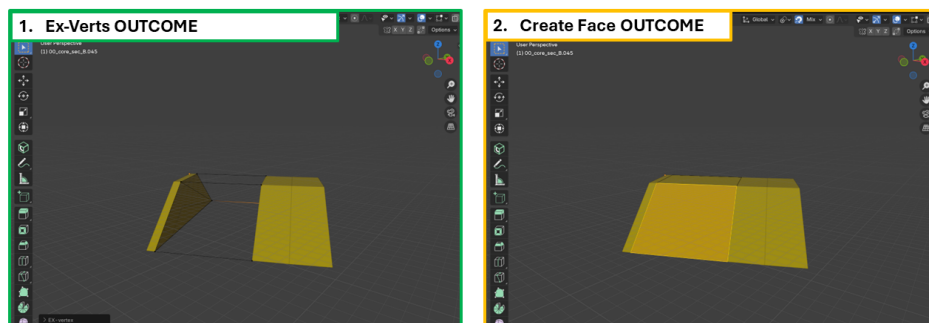


Figure 5.13. Linking section B and C using vertex extrusion and face creation

of Accropode™ armor units follows predefined installation patterns and controlled orientation criteria to achieve adequate interlocking and hy-

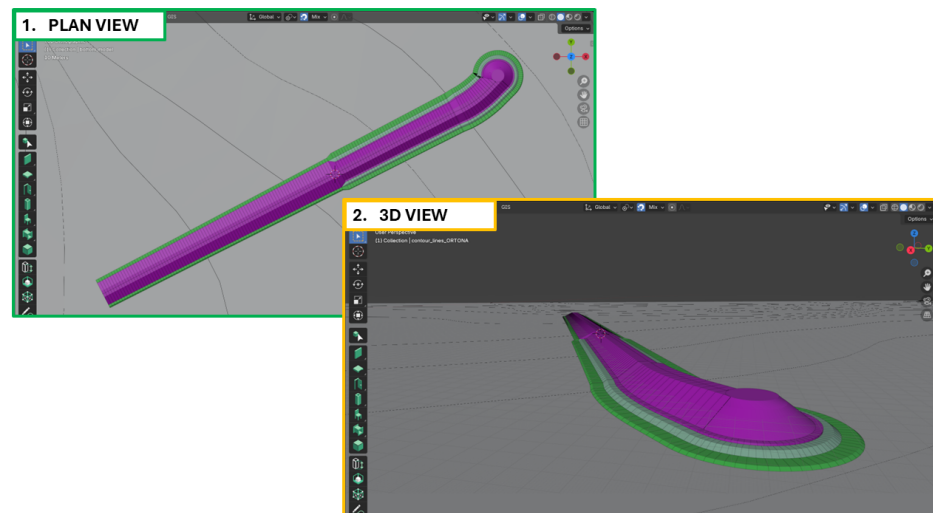


Figure 5.14. Final geometrical model of the south quay of Ortona Port

draulic performance. The proposed BIM framework does not simulate the physical placement process nor analyze feasible placement grids. The digital representation is therefore intended as a parametric modeling approach rather than a construction simulation tool.

The BIM model extends the 3D model to 4D and 5D, with Gantt chart for construction scheduling (Figure 5.15) and a bill of quantities summarizing costs (Figure 5.16).

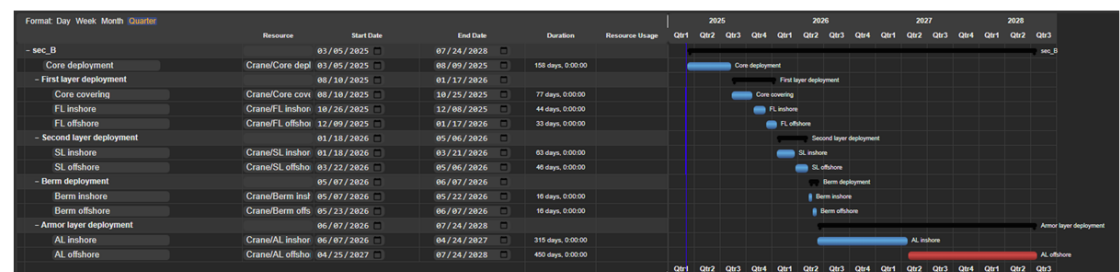


Figure 5.15. Gantt chart of the construction process

Id	Hierarchy	Index	Identification	Description	Quantity	Unit	* Cost	Rate Subtotal	Total Price
26680	1	0	Ph2	South quay sec B construction	0,00				20.810.232,74 €
26682	11	1		Core deployment	0,00				
26684	111	2		Materials	315082,00		48,20	15.186.952,40 €	
26686	112	2		Equipment	2161,00		520,60	1.125.016,60 €	
26687	12	1		First layer deployment	0,00				
26688	121	2		Materials	76745,70		48,20	3.699.142,74 €	
26690	122	2		Equipment	1535,00		520,60	799.121,00 €	

Figure 5.16. Bill of quantities for the south quay of Ortona Port

The application of the proposed BIM-based platform to the rubble mound breakwater of the South Quay of Ortona Port demonstrates clear advantages compared to conventional design workflows. Traditionally, rub-

ble mound structures are designed through fragmented processes, where cross-sections are drafted in 2D CAD environments and hydraulic stability verifications (e.g., Hudson or Van der Meer formulations) are performed independently using spreadsheets or external calculation tools. This separation may lead to information loss and inconsistencies between geometric assumptions and verification parameters. In the proposed framework, geometric modeling, hydraulic stability checks, and structured information management are integrated within a unified BIM environment. Armor layers, filter layers, core materials, and toe berms are defined as parametric objects enriched with structured attributes, enabling coherence between geometry and engineering verification procedures. If the configuration must be changed during the design phase, the updating of the model (and the inherited information) is quick and efficient. The automatic derivation of 2D drawings and sections directly from the 3D model ensures consistency between design documentation and the actual structural configuration, significantly reducing the risk of drafting errors and misalignment typical of conventional CAD-based approaches. It should be noted that the modeled distribution of armor units represents a design configuration in particular for single layer armours. The actual post-construction arrangement can only be accurately determined through dedicated field surveys (e.g., bathymetric surveys or photogrammetric techniques). Within the proposed BIM environment, survey-derived geometries can be incorporated into the digital model, enabling alignment between theoretical design assumptions and real conditions. The IFC-based classification of structural components further guarantees interoperability and long-term accessibility of information, supporting traceability of inspections, interventions, and performance indicators throughout the lifecycle of the breakwater.

5.3 Composite Breakwaters: The Civitavecchia Port case

The adopted case study is the caisson breakwater in front of "Terminal Bramante" in the port of Civitavecchia, Lazio region (Figure 5.17).

Figure 5.18 highlights the specific study area of the caisson structure. The structure consists of:

- *Bedding layer* composed of:
 - Tout-venant layer
 - First filter layer with natural rocks (1–3 t)
 - Second filter layer with natural rocks (3–7 t)
- *Caissons*



Figure 5.17. Geographical location of the port of Civitavecchia



Figure 5.18. Geographical detail of the caisson study case

- *Curved crowning wall*
- *Tetrapods* placed as guardian stones to protect the caisson toe

The first step is to model all the objects. As done for the rubble mound breakwater, the bottom model is created with the *Bottom* command. Next, the development line of the structure is imported, allowing upload of all components from the bedding layers to the caissons. Plane objects are imported with a step equal to the caisson length and linked using *Link Sections*. Objects intersecting the bottom are subtracted to follow the bottom trend. The *Collection Tool* groups objects of the same type into collections

(Figure 5.19).

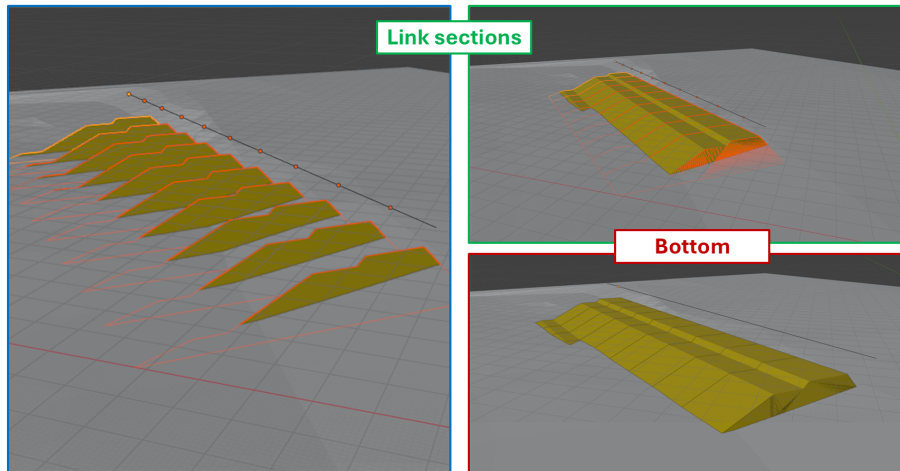


Figure 5.19. Modeling steps to build the bedding layer

To complete the bedding layers and construct the caissons and crawling wall, the same workflow is applied (Figure 5.20).

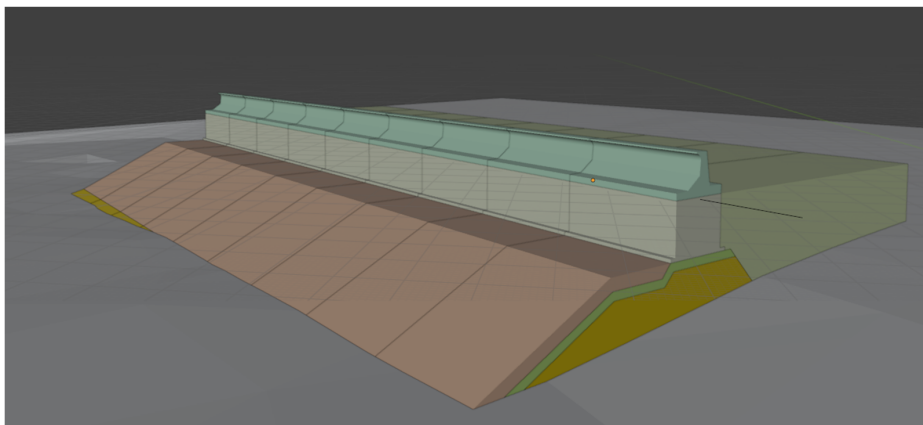


Figure 5.20. Geometrical model of the caisson breakwater structure

Regarding the placement of the armor units, it is important to underline that their actual position is derived from detailed field survey data. Taking this aspect into account, the units are deployed within the model using the *Deployment Simulation Tool*.

To enhance computational efficiency while maintaining modeling consistency, the deployment procedure is first carried out for a single caisson. The resulting configuration is then replicated along the alignment of the structure using the *Duplicate Along Curve* command, with the offset set equal to the caisson length (Figure 5.21).

Since the structure already exists, a management and maintenance plan can be created (Chapter 4, see Section 4.4). Each object can be assigned an

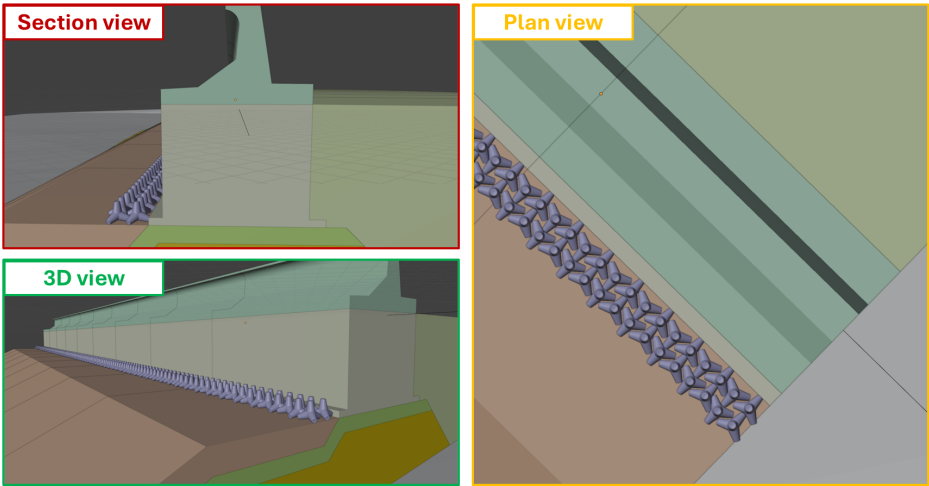


Figure 5.21. Different views of the complete caisson breakwater model

“EXISTING” condition, including tetrapods, with the following properties:

- Displacement
- Scour Depth
- Structural Condition
- Replacement Needed

These properties enable detailed monitoring and planning of maintenance work (Figure 5.22).

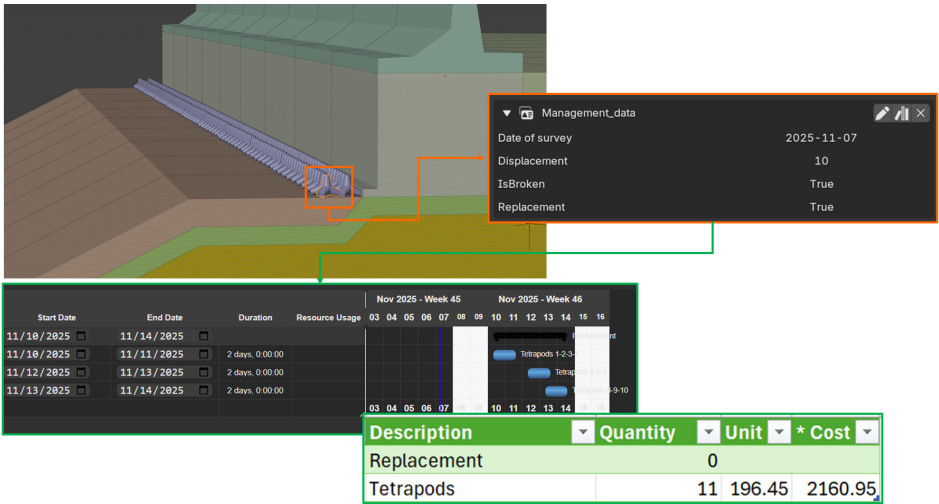


Figure 5.22. Tetrapod condition properties and Gantt chart of maintenance schedule and costs

The composite breakwater case study at Civitavecchia Port further confirms the advantages of the proposed open-source BIM framework over

traditional methodologies. In conventional practice, geometric drawings of caissons and rubble foundations are typically managed in 2D CAD systems less often in 3D CAD systems, while stability verifications of armor unit and hydraulic assessments are performed separately through independent calculation tools. This fragmented workflow limits data consistency and traceability and may lead to information loss. In contrast, the proposed platform integrates caisson geometry, foundation layers, and associated structural and hydraulic parameters within a single parametric digital model. This integration ensures coherence between geometric configuration and stability verification processes, reducing the likelihood of inconsistencies between design assumptions and structural checks. As in the rubble mound case, 2D drawings are automatically generated from the 3D model, guaranteeing consistency between documentation and structural configuration while improving efficiency during design modifications (e.g., crest elevation changes or caisson dimension updates). With specific reference to armor units such as tetrapods, the BIM model provides a parametric and geometrically coherent representation of their design distribution. However, the actual in-situ position of these elements can only be accurately determined through dedicated survey campaigns. The integration of survey data into the BIM environment enables the updating of the digital model, effectively supporting the development of a digital twin aligned with real structural conditions useful during the lifetime of the structure. The adoption of IFC-based classes ensures semantic interoperability and facilitates structured maintenance planning, improving long-term management of caisson elements and associated rubble foundations.

CONCLUDING REMARKS

BIM methodology is widely applied to the building sector and in the last years it is spreaded in civil infrastructures such as bridges and roads. Applications to ports and, maritime structures in general, are still limited to management support and maintenance planning starting from the design phase. Nevertheless, regulatory frameworks have progressively indicated the road to digitizing the whole lifecycle of maritime structures, even by indicating that BIM approach must be adopted mandatory. Despite this evolution, BIM methodologies specifically tailored to maritime structures is still challenging. Indeed, the lack of object libraries specific for maritime structures and the limited flexibility of the information layer constrain the development of detailed and maritime structures-specific BIM models.

This work is an attempt to address this gap by developing a specific tool (Building Information Modeling for Maritime Structures, BIMMs) for the geometric modeling and BIM-based representation of rubble mound breakwaters and vertical breakwaters. The intrinsic complexity of these structures is not related only to construction techniques, but also to the environmental context, to the design challenges associated with wave–structure interaction, variable bathymetric configuration, and irregular geometries. Hence, the aim of this work is to provide the technical and scientific community with a comprehensive (and practical) tool that enables the creation of detailed geometric models and their extension into BIM models. Basically, it allows the creation of detailed three-dimensional geometric models and their extension into enriched BIM models through the definition of a structured informative layer associated with each structural component.

The core of this work is then the development of an open-source BIM-based platform capable of supporting both the design and maintenance phases of maritime structures. The proposed framework is intended to overcome the limitations of existing commercial BIM solutions by providing a flexible and extensible environment tailored to the specific characteristics of maritime structures.

BIMMs is basically composed by three main parts: the (geometrical) modeling tool, the deployment tool and the informative layer definition. Each component plays a crucial role in ensuring that the BIM model is both geometrically accurate and rich in information.

BIMMs is described in detail through the thesis. Two practical applications are presented, one for a rubble mound breakwater and one for a vertical breakwater. The two applications are intended to demonstrate the flexibility of BIMMs in addressing both rubble mound and vertical breakwater typologies, as well as new design and existing infrastructure management scenarios. The rubble mound breakwater case highlights the capability of the tool to handle complex geometries and construction planning, while the composite breakwater case shows its potential for maintenance-oriented BIM workflows.

The two case studies — the rubble mound breakwater of Ortona Port and the composite caisson breakwater of Civitavecchia Port — demonstrate that the proposed open-source BIM platform provides measurable procedural advantages over conventional design and maintenance methods. Unlike traditional workflows, typically characterized by fragmented tools (2D CAD drafting, spreadsheet-based calculations, and external maintenance records), the proposed framework centralizes geometric modeling, hydraulic verification, scheduling (4D), cost estimation (5D), and maintenance-related information within a unified environment. The adoption of IFC-based classes ensures semantic interoperability and long-term sustainability of data, while the automatic linkage between 3D models and 2D documentation reduces the risk of human error and information loss and improves revision efficiency. Overall, the platform contributes to workflow optimization, improved traceability of structural components, and enhanced decision-making capabilities throughout the lifecycle of maritime infrastructures.

Overall, this work demonstrates that BIM methodology can be effectively applied to maritime structures by providing a specific tool that is made available to the scientific community within the frame of an open-source approach. Future developments may include the integration of additional analysis tools, such as structural analysis and hydrodynamic simulations, to further enhance the capabilities of the BIM platform for maritime structures.

[Blank page]

BIBLIOGRAPHY

- Beltrami, G.-M., Di-Risio, M., De-Girolamo, P., and Noli, A. (2005). Laboratory investigation on wave overtopping of rubble mound breakwaters: The port of civitavecchia case. In *International Conference on Coastlines, structures and breakwaters 2005*, pages 211–220. Thomas Telford Publishing.
- Biancardo, S. A., Viscione, N., Cerbone, A., and Dessì Jr, E. (2020). Bim-based design for road infrastructure: a critical focus on modeling guardrails and retaining walls. *Infrastructures*, 5(7):59.
- Blender Foundation (2025). Blender manual. Accessed July 30, 2025.
- Borrmann, A., König, M., Koch, C., and Beetz, J. (2018). *Building information modeling: Why? what? how?* Springer.
- Bradbury, A., Allsop, W., and Stephens, R. (1988). Hydraulics performance of breakwater crown walls.
- Celli, D., Li, Y., Ong, M. C., and Di Risio, M. (2019). The role of submerged berms on the momentary liquefaction around conventional rubble mound breakwaters. *Applied Ocean Research*, 85:1–11.
- Celli, D., Li, Y., Ong, M. C., and Di Risio, M. (2020). Random wave-induced momentary liquefaction around rubble mound breakwaters with submerged berms. *Journal of Marine Science and Engineering*, 8(5):338.
- Celli, D., Pasquali, D., De Girolamo, P., and Di Risio, M. (2018). Effects of submerged berms on the stability of conventional rubble mound breakwaters. *Coastal Engineering*, 136:16–25.
- CIRIA, CUR, C. (2007). *Physical processes and design tools*. CIRIA.
- Di Risio, M., Beltrami, G., and De Girolamo, P. (2007). Laboratory investigation on wave overtopping of composite breakwaters: The port of civitavecchia case. In *Coastal Engineering 2006: (In 5 Volumes)*, pages 4616–4627. World Scientific.

- Garibin, P. and Ol'khovik, E. (2019). Application of bim technology in operation of port marine structures. In *E3S Web of Conferences*, volume 135, page 01022. EDP Sciences.
- Goda, Y. (2010). *Random seas and design of maritime structures*, volume 33. World Scientific Publishing Company.
- Kamphuis, J. (1991). Incipient wave breaking. *Coastal Engineering*, 15(3):185–203.
- Khoi, T. P. M., Chung, B. M., Phuoc, L. N. T., Van Tan, N., Le Vin, T., Van Do, T., and Thao, N. D. (2024). Integration of advanced surveying technologies into bim-gis systems of port infrastructure. In *International Conference on Civil Engineering and Architecture*, pages 178–191. Springer.
- Martin, F. L., Losada, M. A., and Medina, R. (1999). Wave loads on rubble mound breakwater crown walls. *Coastal Engineering*, 37(2):149–174.
- Molines, J., Centi, R., Di Risio, M., and Medina, J. R. (2021). Estimation of layer coefficients of cubipod homogeneous low-crested structures using physical and numerical model placement tests. *Coastal Engineering*, 168:103901.
- Molines, J. and Medina, J. R. (2015). Calibration of overtopping roughness factors for concrete armor units in non-breaking conditions using the clash database. *Coastal Engineering*, 96:62–70.
- Munoz-Palao, S., Diaz-Carrasco, P., Molines, J., Gómez-Martín, M. E., and Medina, J. R. (2024). Numerical construction tests to assess the feasibility of placement grids for cubipod homogeneous low-crested structures. *Coastal Engineering*, 188:104455.
- Pedersen, J. (1996). Wave forces and overtopping on crown walls of rubble mound breakwaters: an experimental study.
- (US), C. E. R. C. (1984). *Shore protection manual*, volume 1. Department of the Army, Waterways Experiment Station, Corps of Engineers . . .
- Valdepeñas, P., Esteban Pérez, M. D., Henche, C., Rodríguez-Escribano, R., Fernández, G., and López-Gutiérrez, J.-S. (2020). Application of the bim method in the management of the maintenance in port infrastructures. *Journal of Marine Science and Engineering*, 8(12):981.
- van der Meer, J., Allsop, W., Bruce, T., Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P., and Zanuttigh, B. (2016). *EurOtop: Manual on wave overtopping of sea defences and related structures - An overtopping manual largely based on European research, but for worldwide application (2nd edition)*.

-
- van der Meer, J. W. (1988). Deterministic and probabilistic design of break-water armor layers. *Journal of waterway, port, coastal, and ocean engineering*, 114(1):66–80.
- Van der Meer, J. W. (1995). Conceptual design of rubble mound breakwaters. In *Advances In Coastal And Ocean Engineering: (Volume 1)*, pages 221–315. World Scientific.
- Van Gent, M. R., Smale, A. J., and Kuiper, C. (2003). Stability of rock slopes with shallow foreshores. In *Coastal structures 2003*, pages 100–112.
- Zhang, P. and Chen, Q. (2018). Application research of bim technology used in port handling system design. In *IOP Conference Series: Materials Science and Engineering*, volume 452, page 042012. IOP Publishing.

ETHICAL DECLARATION

The author declares that artificial intelligence–based tools were used solely for language editing purposes, including grammar and stylistic improvements. No content generation, data analysis, or scientific interpretation was performed using artificial intelligence tools.

The author takes full responsibility for the originality, accuracy, and scientific validity of the thesis.

Tesi redatta con il cofinanziamento dell'Unione europea-*NextGeneration EU*
Piano Nazionale di Ripresa e Resilienza Missione 4, Componente 2 –
Investimento 3.3. del PNRR – “Dottorati innovativi che rispondono ai fabbisogni di innovazione delle
imprese” – CUP E11I22000190001



Finanziato
dall'Unione europea
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



UNIVERSITÀ
DEGLI STUDI
DELL'AQUILA