OSOM-VR: Virtual Breakwater Exploration

PIC2 - Master in Computer Science and Engineering
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Abstract Breakwater inspection and maintenance are traditionally based on on-site observations and 2D data visualization platforms, such as LNEC's OSOM system, which can limit spatial understanding of complex 3D structures and their evolution over time. This work presents OSOM-VR, a prototype that extends the existing OSOM platform with an immersive 3D visualization environment for breakwater inspection data, aiming to support engineers in exploring structural conditions and historical inspection information more intuitively than with conventional desktop-based tools.

The prototype is designed to complement the existing OSOM workflow, maintaining compatibility with established inspection practices while taking advantage of the immersive environments' benefits. An evaluation methodology is proposed to assess the system's effectiveness, usability, and usefulness. The results of this work aim to contribute to the adoption of immersive technologies in coastal infrastructure monitoring, offering a more intuitive and efficient framework for breakwater inspection and analysis.

Keywords — virtual reality, breakwater, inspection, maintenance, immersion

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1 Introduction

1.1 Context

Breakwaters are coastal defense structures built to promote sheltered areas for people, ships, and harbor activities. [1] They are designed to intercept and dissipate wave energy before it reaches the shoreline, protecting coastal areas from erosion and damage. These structures are typically built using large rocks, concrete units, or other engineered materials specifically designed to withstand severe marine conditions.

Given their continuous exposure to harsh environments, breakwaters naturally deteriorate over time. As a result, regular inspection, maintenance, and repair are essential to ensure their effectiveness. In Portugal, Laboratório Nacional de Engenharia Civil (LNEC) is responsible for the maintenance of some breakwaters. To support this activity, LNEC developed OSOM (Observação Sistemática de Obras Marítimas), which contains, as part of the methodology, a web-based platform created to document inspection data, evaluate structural conditions, and support maintenance planning.

Although OSOM provides an approach for collecting, storing, and analyzing inspection data, it is predominantly based on traditional 2D visualizations, which, although effective, can limit the spatial perception of large-scale maritime infrastructures. This limitation creates an opportunity to explore alternative visualization approaches that could improve the way engineers interact with inspection data and understand the physical configuration of these structures. To address these limitations, we propose OSOM-VR (Observação Sistemática de Obras Marítimas com Realidade Virtual), an immersive virtual reality prototype for breakwater maintenance.

Virtual Reality (VR) is a technology that combines specialized hardware, such as head-mounted displays, with software to create immersive three-dimensional environments in which users can interact. As described by Wohlgenannt et al. [2], VR leverages immersive technologies to simulate interactive virtual environments or virtual worlds in which users become subjectively involved and experience a sense of physical presence. In the context of this work, the focus is placed on the maintenance and visualization of breakwaters. By developing a VR application capable of simulating a breakwater and its surrounding environment with a high degree of realism, we aim to evaluate the usefulness of this technology as a support tool for inspection and monitoring tasks.

1.2 Motivation

The web-based monitoring application OSOM makes the inspection of breakwaters heavily dependent on on-site observations and 2D data visualization. Although adequate, this method has some limitations, such as difficulties in visualizing structural evolution over time and limited interactivity when analyzing complex geometries.

In collaboration with LNEC, this work aims to explore a more interactive approach to the visualization and analysis of breakwaters. The proposed OSOM-VR prototype integrates data from OSOM into an immersive 3D environment. The goal is not to replace the existing system, but to complement it, allowing engineers to navigate, explore, and analyze virtual models of breakwaters remotely. Throughout this work, we aim to evaluate the potential of VR as a support tool within LNEC's workflows, assessing its effectiveness in enhancing the visualization of breakwaters, improving accessibility to inspection data, and ultimately contributing to more efficient monitoring and maintenance practices.

1.3 Problem Description

The focus of this work is to evaluate the potential benefits of using a VR application compared to a traditional 2D web interface. If proven effective, such an application could serve as a more intuitive entry point for engineers who are less familiar with OSOM, since the prototype aims to replicate a realistic environment that is often easier to navigate than a 2D interface.

The problem addressed by this project lies in understanding whether a VR application can serve as a good substitute or complement to the existing OSOM solution. This requires examining whether an interactive 3D environment can effectively support the same tasks, such as visualizing breakwaters and accessing inspection data. Unlike 2D systems, VR depends on specialized hardware and interaction methods, which can influence both practicality and accessibility. The main focus of this work is therefore to evaluate whether integrating VR into LNEC's workflow can make these tasks easier and more intuitive.

To ensure a fair comparison, the prototype will allow the execution of equivalent tasks within an immersive 3D environment to determine whether these tasks can be carried out more naturally and efficiently in OSOM-VR. The evaluation will be conducted through user testing with LNEC engineers experienced in the use of OSOM. These tests will assess whether the prototype meets their requirements and if it provides measurable advantages over the existing 2D solution.

1.4 Objectives

Based on the motivation and problem definition presented in the previous sections, this section defines the main objectives of the proposed work. These objectives are divided into two complementary areas: the broader societal goals aligned with the United Nations Sustainable Development Goals and the technical objectives related to the development and evaluation of the proposed prototype.

1.4.1 UN Sustainable Development Goals

The 17 United Nations Sustainable Development Goals [1] provide a global framework adopted by member states to promote sustainable development, resilience, and well-being. This work contributes to these goals by seeking to improve the efficiency, accessibility, and effectiveness of breakwater inspection and maintenance processes. This work supports Goal 9: Industry, Innovation and Infrastructure, by promoting more resilient and sustainable coastal infrastructure, and Goal 11: Sustainable Cities and Communities, by contributing to the safety and protection of coastal urban areas.

1.4.2 Prototype Objectives

This work aims to explore how a VR solution can be used in the context of breakwater inspections. The goal is to assess whether a 3D environment can improve the accessibility and ease of use compared to the existing 2D visualization. Our work seeks to help create a more immersive environment to facilitate the inspection workflow. To achieve this goal, we established the following objectives:

Develop a VR prototype in Unity for breakwater inspections. Design and implement a VR system implemented in Unity that enables the comprehensive visualization of breakwaters and their surroundings. The system will also provide a natural exploration of photos and other data regarding the breakwater. The prototype will incorporate a realistic 3D model of a specific breakwater to be determined, with its surrounding landscapes and pertinent features, offering an interactive and visually rich experience.

Evaluate the usefulness of the prototype. The objective of this prototype is to assess the potential benefits of using a VR application in comparison to the existing 2D solution. If the evaluation shows added value, the prototype may serve as a foundation for the development of a practical tool to support LNEC engineers in the monitoring and maintenance of breakwaters.

Integrate the prototype into the existing application OSOM. As a starting point, the prototype will be developed to support multiple models of VR headsets, ensuring that it remains VR-headset agnostic. As a final objective, the prototype will then be integrated into the OSOM web platform, enhancing accessibility and facilitating its adoption within existing workflows.

[1]"The 17 goals | sustainable development." [Online]. Available: `Available:https://sdgs.un.org/goals`. Accessed: Nov. 20, 2025

2 Background

This section presents the fundamental concepts required to understand this work. We begin by describing the role and structural composition of breakwaters, which constitute the physical focus of this study. We then introduce OSOM, the systematic methodology developed by LNEC for monitoring and managing the condition of maritime structures, outlining its inspection processes and data management workflow. Together, these topics establish the technical and conceptual foundation required to understand the design and objectives of the proposed OSOM-VR prototype.

2.1 Breakwaters

As introduced earlier, breakwaters' primary purpose is to protect the coast by reducing incoming wave energy, creating a sheltered area for the operations of ships, boats, and other vessels, while also enabling port operations.

Breakwaters can be classified into natural and artificial. These two classes differ in the fact that one is of natural origin and the other man-made (this work focuses exclusively on artificial breakwaters). Both natural and artificial breakwaters can be further categorized by their position relative to the shoreline. When connected to the coast, they are referred to as attached breakwaters, while those built outside of the coast are known as detached breakwaters. [3]

Artificial breakwaters are divided into two main groups: conventional and non-conventional. Conventional breakwaters include rubble-mound, vertical, and composite. Non-conventional breakwaters comprise submerged, floating, and pneumatic (air-cushion) structures.

Among these, the rubble-mound breakwater is the most common type in Portugal, and will be the main focus of this work.

Rubble-mound breakwaters [4] are made of five main components:

1. **Core:** The innermost section of the breakwater, generally of prismatic shape, composed of rock material of varied sizes, commonly referred to as T.O.T. (all sizes). Its main functions are to attenuate wave propagation and to provide structural support for both the underlayer and the armor layer.

2. **Underlayer:** A zone consisting of one or more layers of selected rock, which may have uniform or varying weights. It acts as a filter between the core and the armor layer, preventing the migration of fine material from the core, increasing the porosity of the slope, and contributing to the overall stability of the structure.

3. **Armor Layer:** The outer layer of the slope, directly exposed to wave action. It typically consists of layers of natural or artificial blocks arranged to dissipate wave energy and prevent erosion of the underlayer and core caused by wave impact. It can be subdivided into two zones, the resistant armor layer and the interior armor layer (tardoz).

4. **Superstructure:** Usually a massive concrete or masonry blocks located at the crest of the breakwater. It facilitates vehicle and people access, and may also accommodate infrastructure installations. In some cases, it includes a wave wall designed to improve safety by reducing overtopping.

5. **Toe Berm:** Located at the base of the slope, this section consists of rock or concrete blocks. Its main function is to support and stabilize the armor layer, preventing its displacement due to wave action.

Initially, the armor layer of rubble-mound breakwaters was constructed using natural rock-fill due to the lack of other options, but over time, artificial blocks have been used more, starting with tetrapods, designed to dissipate wave energy efficiently and interlock to enhance structural stability. After that, other types were also developed to take advantage of the same characteristic. Today, the choice of materials largely depends on local availability, but it is common to use a combination of artificial units and natural rock fill. [4]

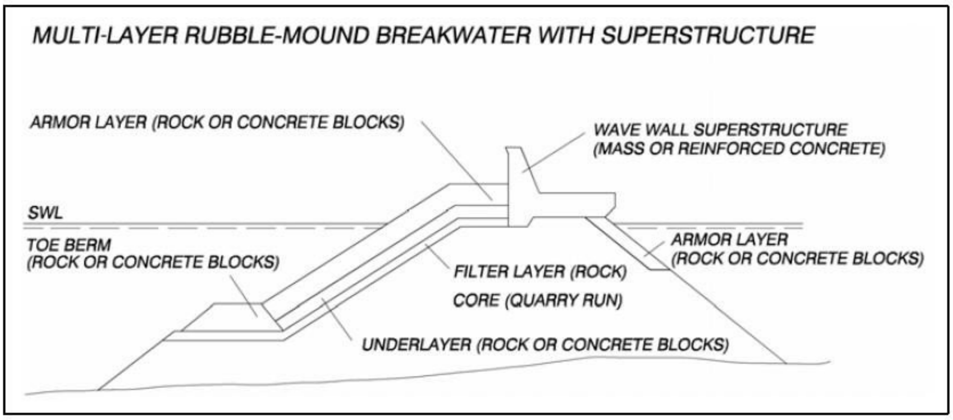

Figure 1: Cross section of rubble mound breakwaters with superstructure [5]

2.2 OSOM

OSOM is a methodology developed by LNEC since 1986 to monitor the condition of breakwaters and recommend timely interventions for their maintenance and repair. It integrates several components to ensure accurate, systematic, and continuous monitoring of these structures. [6]

OSOM enables the execution of systematic visual and aerial inspections to track the evolution of damage and determine the need for interventions, preventing future structural problems. Each monitored breakwater is inspected annually, as well as after major storm events, to ensure that the conditions and damage progression are well understood.

The OSOM methodology comprises four main components:

1. Periodic visual inspections carried out by trained technicians;
2. Periodic aerial inspections conducted using drones;
3. Storage and management of all collected information within the ANOSOM database;
4. A web application that enables real-time input, visualization, and analysis of the data.

The inspection process aims to characterize the current condition of the structure. To achieve this objective, each breakwater is divided into sections, with the head always considered a distinct section. Within each section, a set of reference points is established where photographs and/or videos are taken during each inspection campaign, maintaining consistent viewpoint parameters to ensure reliable comparisons over time. These reference points are also physically marked on the breakwater to ensure consistency in subsequent inspections.

Visual Inspections: These inspections are conducted by a specialist while walking along the breakwater. During the inspection, they observe at least the three main components of the structure: the armor layer, superstructure, and tardoz. Photographs and georeferenced videos are taken to compare the evolution of the structure when compared with that of previous campaigns. These photos are uploaded to the platform OSOM-WEB for later analysis.

Aerial Inspections: These inspections are done with the use of a UAV (Unmanned Aerial Vehicle). The information gathered using drones provides a much higher level of detail and precise information about the condition of the structure, allowing for visualization of zones that were otherwise inaccessible. This inspection provides individual aerial photographs, orthomosaics, cloud points, and numerical models to identify areas of deformation or damage. These observations must be conducted under favorable atmospheric conditions and preferably at low tide to maximize the visible area.

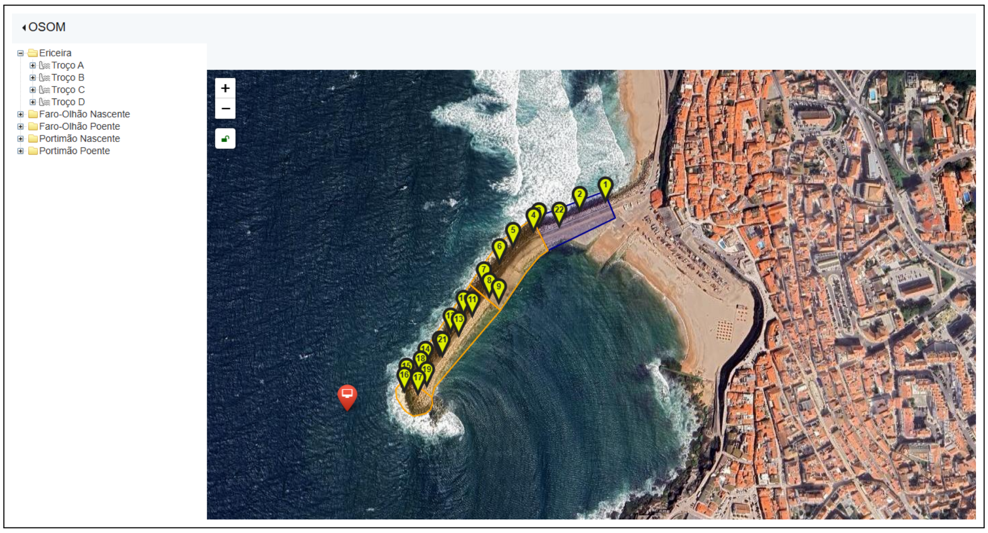

Figure 2: OSOM-WEB: General view of the Ericeira breakwater [2]

OSOM-WEB is an online database and interface used to store, analyze, and visualize all collected information. In it, it's possible to: Store and analyze the data from both aerial and visual inspections; Diagnose the structure to determine the levels for the structural condition, evolution, and risk of each zone or component of the breakwater; Visualize the historical inspection records of the structure; Observe the physical characteristics of the zones, including their physical limits, geometry, materials used, and standard profiles.

The platform performs calculations based on the information gathered during the inspections to calculate the damage index for each zone, dividing it into three components: The overall score, on a scale of 0 to 5, where 0 indicates the structure is in good condition and 5 indicates severe degradation; The evolution level, describing how the structure's condition has changed over time; The current risk level, reflecting the urgency for interventions.

In Figure 2 and Figure 3, we can see some screenshots from the OSOM-WEB platform. In them, it's possible to see some of the information shown for the *Ericeira* breakwater. Starting with Figure 2, we can see the whole breakwater divided into its different zones, each with a color associated with its risk level, blue being the lowest and orange moderate. It's also possible to see the different hotspots in the breakwater, where the inspection campaign's photos are taken from. In Figure 3, we can see general information about the breakwater in zone A, the selected zone. Our objective is to take what the current application can do and replicate it in a more immersive 3D environment with new functionalities to take advantage of VR.

3 Related Work

In this section, we review the existing research and projects related to the topic of our study, to identify what has already been achieved and what gaps remain. Given the limited amount of literature found specifically addressing the use of VR in the inspection and maintenance of breakwaters, our review adopts a progressively focused approach. We begin by examining the broader use of VR in civil engineering to understand how immersive technologies have been applied in areas related to bridge inspection, construction, and teleoperation. We then narrow our focus to coastal and dam engineering, where VR applications are more closely aligned with our domain of interest. Following that, we explore research involving 3D modeling and visualization techniques for the analysis and study of breakwaters, since these share relevant aspects with our proposed work. Finally, we examine the few existing studies

[2] "Osom." [Online]. Available: https://osom.lnec.pt/. Accessed: Nov. 26, 2025

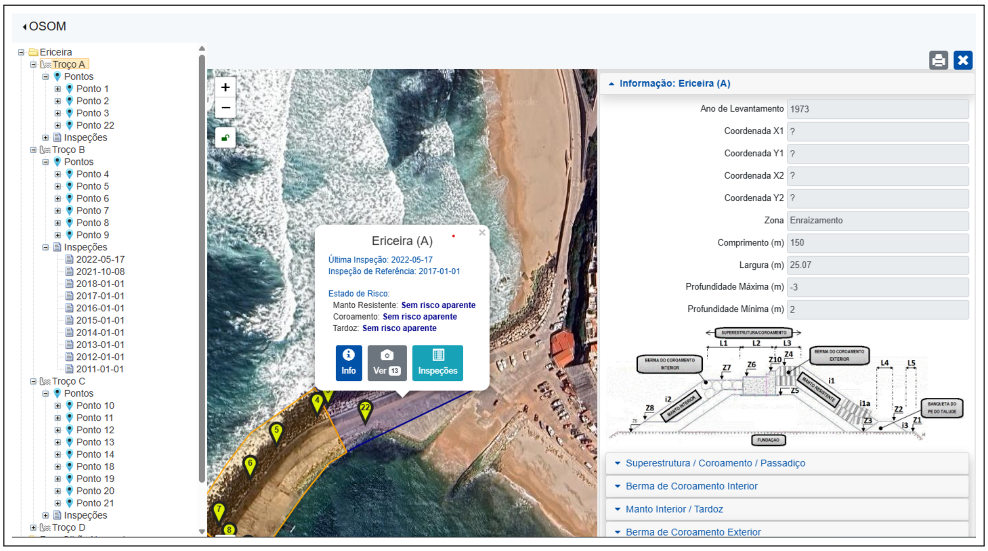

Figure 3: OSOM-WEB: Details from the Ericeira breakwater section[2]

and projects that directly involve VR applications for breakwaters. At the end of this section, we present a comparative analysis summarizing the strengths and limitations of the reviewed works. This highlights the existing gaps and motivates the requirements that guide the development of our proposed work.

3.1 VR in civil engineering

VR has emerged as a promising tool in the field of civil engineering, supporting design visualization, training, and inspection processes. In this section, we will look at some of its applications and their conclusions.

To start, a notable application of VR in infrastructure management is its use for bridge inspection, as demonstrated in the study by Omer et al. [7], which showed that this approach enables inspectors to examine bridge digital twins in a virtual environment, eliminating many of the challenges associated with traditional inspections. Specifically, the VR environment enables teleportation-based navigation, providing access to previously inaccessible or hazardous locations without the need for scaffolding or cranes. This can be observed in the Figure 4, which represents a hard-to-access zone of the bridge, now easier to visualize using the 3D model. Artificial lighting within the VR model ensures consistent visibility across all structural elements, overcoming issues related to poor illumination in real-world inspections. The study highlighted that data collection could be outsourced and analyzed remotely, reducing travel time and inspection costs. The authors concluded that VR-based inspections are likely to be more consistent and repeatable than those from conventional in-situ inspections, where conditions may vary due to weather, fatigue, or infrastructure accessibility constraints.

In the same field, Yigit et al. [8] describe an integrated methodology combining unmanned aerial vehicle (UAV) photogrammetry, digital twin modeling, and VR for automated bridge inspection. Their study focused on the Elvanlı Bridge in Mersin, Turkey, where UAV imagery was processed to generate a high-resolution 3D model. Advanced machine learning and deep learning algorithms were then employed to automatically detect surface cracks from the photogrammetric data. The detected cracks were incorporated into the 3D model to create a damage-augmented digital twin (DADT), enabling detailed visualization of both the bridge geometry and its damage condition. The DADT was subsequently rendered in a VR environment as seen in Figure 5, allowing remote, interactive inspection and analysis of the bridge. This approach significantly enhances inspection objectivity, reduces fieldwork and operational costs, and facilitates collaboration among experts without requiring on-site presence. The findings emphasize the potential of integrating UAV-based photogrammetry, AI-driven damage detec-

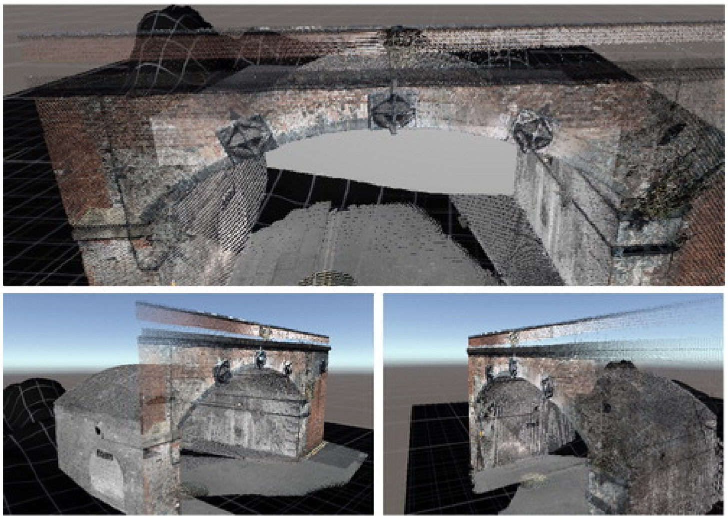

Figure 4: 3D model visualization in VR of bridge arch ring, the most critical element of masonry bridges that is not easily accessible in real life [7]

tion, and VR visualization as a comprehensive, non-invasive solution for structural health monitoring and infrastructure management.

A notable contribution to the integration of immersive technologies in structural monitoring is the VR application developed by Luleci et al. [9], which focuses on structural health monitoring (SHM) and inspection of a steel truss footbridge. Their work addresses the challenges of traditional bridge inspections, such as traffic closures, inaccessible areas, high costs from timely operations, and the usage of expensive special equipment, heavy machinery, or safety gear, by creating a virtual environment that allows engineers and inspectors to access structural data and 3D reconstructions remotely. The VR application offers multiple forms of interaction: users can switch between different 3D models, inspect analysis panels, manipulate models in space (see Figure 6), and enter immersive scenes aligned with the real-world environment reconstructed through photogrammetry. A multi-user networking feature allows up to 20 participants to join the same session, using avatars and voice communication to collaborate remotely on inspection and decision-making tasks, Figure 6. In their conclusions, the authors emphasize that their VR application significantly enhanced accessibility to structural data and reduced the reliance on field visits, lowering costs and improving safety. They highlight the potential to develop it into a real-time digital twin once a permanent SHM system and automated data transfer pipeline are implemented.

In another field of study, Sampaio et al. [10] present a series of VR-based prototypes designed to

Figure 5: Measuring of bridge crack on Digital Twin using VR [8]

Figure 6: Left: Dynamic monitoring of all the nodes of the bridge with VR controller in immersive view, Right: The VR decision-making room for the inspection of a footbridge [9]

enhance collaborative decision-making in the construction and maintenance of buildings. Their work focused on developing interactive 3D models integrated with databases containing detailed information about construction materials, common anomalies, inspection procedures, and repair techniques. Their VR maintenance model allows users to visually inspect building facades and interior walls, identify anomalies such as cracks or detachment, and explore corresponding repair methodologies directly within the virtual environment. It also incorporates preventive maintenance scheduling through periodic inspection data, offering a dynamic and interactive approach to maintenance management as seen on Figure 7. The authors extended their approach to construction management by integrating 3D geometric data with project schedules, producing a 4D VR model that links spatial and temporal information. This prototype enables visualization of construction progress according to the planned timeline.

Another interesting study was the proposed framework for intuitive robot teleoperation in civil engineering operations by Zhou et al. [11], which combines virtual reality, deep learning, and 3D scene reconstruction, to address the limitations of conventional teleoperation interfaces that rely on 2D camera feeds and lack depth perception or spatial awareness. The integration of the Robot Operating System (ROS) with the Unity game engine allowed real-time synchronization between the physical robot and its virtual representation, Figure 8. Through the VR interface, operators could intuitively control a dual-arm robot within a physically simulated environment. This setup provided a more immersive and responsive teleoperation experience, improving situational awareness and control precision.

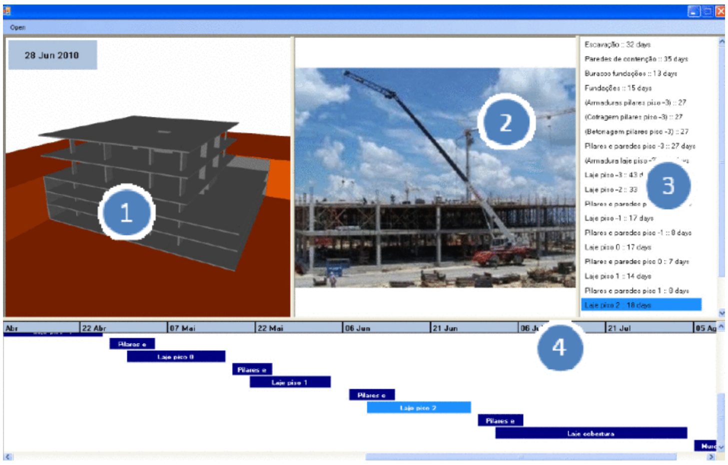

Figure 7: Construction process visualization: Virtual model (1); Pictures of the construction site (2); Planning task list (3); and Gantt map (4) [10]

Figure 8: Robot teleoperation in a pipe operation task [11]

3.2 VR in dam engineering

In this section, we will narrow the area of study from VR in civil engineering to specifically VR in dam engineering, since, despite it not being in the same field of study, the methods used in the works are very similar to what we'll have to do, so they prove to be relevant materials to analyze.

Starting with the projects related to dam engineering, CabrilDamVR is a project developed by Chin [12], which focused on creating a VR application designed for the photorealistic visualization of the Cabril Dam and its surroundings. The work combined photorealistic rendering (PR) techniques with VR to produce a 3D environment that allows users to explore and visualize the dam in detail. The creation of the Cabril Dam model was a central part of the project: the 3D mesh was reconstructed and refined in Blender based on engineering and topographic data, while surface textures were generated from high-resolution photographs taken on-site to ensure realism. Developed in the Unity engine, the prototype integrates several advanced features to enhance realism and usability, including a dynamic day/night cycle, realistic water simulation, interactive data exploration tools for viewing images from specific points of the dam, and a proof of concept for real-time sensor data visualization. The author concluded that CabrilDamVr achieved its main objective of creating a high-fidelity 3D model of the Cabril Dam in VR, and laid the foundations for a complete digital twin of the dam, as well as proving its potential as a practical means of conducting virtual visits to real-world locations.

Another relevant contribution in the same field is the work ImmersiVizDam by Sequeira [13]. His work explores the use of VR for monitoring and inspection tasks in dam infrastructures. The study also focuses on the Cabril Dam and presents the development of a VR prototype in Unity that enables users to visualize and interact with dam data in an immersive 3D environment. The prototype integrates data derived from sensors in the dam and numerical models. It was concluded that this work demonstrated the potential of immersive environments in dam health monitoring and that users could perform tasks of dam analysis and dam safety control through the use of VR faster when compared to traditional methods. It was also concluded that the use of immersive analytics tools could enhance structural health monitoring workflows, providing a more intuitive, engaging, and efficient way to interpret complex engineering data and contributing to the future implementation of digital twins in dam management.

While the previously presented works were very useful in testing and proving the worth of using VR for the visualization and monitoring of dam infrastructures, both of them serve as a prototype for a final work; it's also relevant to look into finished applications to see what they were able to accomplish. For

Figure 9: CabrilDamVR: user interacting with time interface [12]

that, we have IndustrialVR - Hoover Dam [3] , a deployed educational VR experience built with Unreal Engine. It provides a highly detailed virtual reconstruction of the Hoover Dam in the United States, and its surroundings, such as the power plant facilities and the adjacent bridge, as seen in Figure 11. The primary goal of the application is to teach about the dam and its operation, with a particular focus on how hydroelectric energy is generated. The experience includes multiple animations that illustrate the functioning of key components, making the underlying engineering principles easier to understand. The combination of exploration, visualization, and guided explanations makes the experience an effective learning tool for understanding large-scale infrastructures.

For the visualization, Spero et al. [14] presented a work on a VR application built in Unity for the visualization of the Teton Dam disaster, Figure 12. The dam was modeled in two states, intact and fractured, allowing the simulation to depict its failure dynamically. Since they were using Oculus Quest 2, they ran into some problems because of its limitations in computing power, so to keep the computational cost low, the authors implemented custom shaders to represent the post-breach flood. This approach avoided the higher performance cost associated with particle-based water simulation.

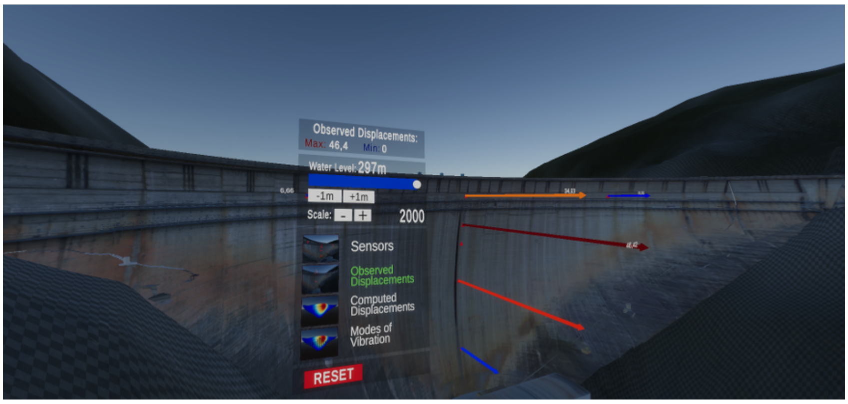

Figure 10: Observed Displacements User Interface in ImmersivizDam [13]

[3]"IndustrialVR" [Online]. Available: https://store.steampowered.com/app/768770/IndustrialVR__Hoover_Dam/. Accessed: Nov. 26, 2025.

Figure 11: IndustrialVR dam model visualization 3

They created a pipeline that takes historical images and terrain data as input to build a low-cost VR environment that could convey the events of the Teton Dam failure. Iterative evaluations showed that realism can be enhanced through high-resolution terrain, soundscapes, user locomotion, multiple viewing positions, selective use of particle effects, and optimized water textures. User feedback highlighted that the soundscape, in particular, elicited strong emotional responses and contributed significantly to the perceived realism of the dam-failure experience.

3.3 3D in coastal engineering

In this section, we narrow our research even further into the study of works focusing on coastal engineering, namely on breakwaters. Since there is a lot of research on the use of 3D models for breakwaters, we will study those first without focusing on VR yet.

In the testing of breakwaters, physical models are an effective solution for validating designs before construction. In these experiments, a series of waves is generated and directed toward a scale model of the breakwater. These models are built using miniature concrete blocks that replicate the real construction materials, carefully placed by hand to represent the structure at a reduced scale. These reduced models, which are as faithful as possible to reality, allow validation of the general design parameters of the breakwater. Since the comparison of the photos is done by eye, it can only be an estimation of the

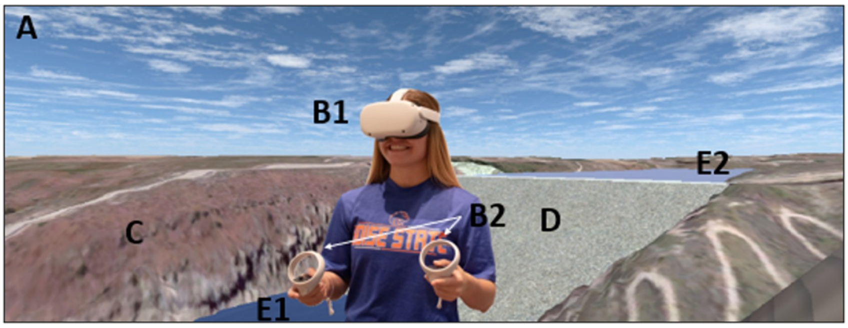

Figure 12: Sketch with Oculus Quest 2 headset and hand controllers in the Teton Dam environment. (A) VR scene or VR environment, (B) Oculus Quest 2 VR Headset where (B1) is the Head Mounted Display (HMD) and (B2) denotes the Oculus Quest 2 controllers, (C) VR terrain, (D) VR Teton Dam, (E) Cloth Textures simulating water where (E1) is downstream and (E2) is the reservoir volume. [14]

movement of the blocks.

SEABIM [4] is a patented scan-to-BIM (Building Information Model) process that generates 3D models of rubble-mound breakwaters. Using computer vision techniques, the 3D shape of the concrete armor units is detected in the point cloud, and the relative orientation and position of each unit is calculated. By superimposing the 3D models produced from different moments, the movement of each block is quantified and represented as a vector, monitoring the movement between each scan. SEABIM is a product that was designed to eliminate the need for manual photo comparisons before and after wave tests. Instead, a 3D model of the structure is created from a scan of the physical model, Figure 13, and after each wave, a new scan is performed to update the 3D model with the latest point cloud data. Using this information, SEABIM's software automatically calculates the displacement of individual blocks, providing a precise and efficient way to analyze the model's behavior under wave action.

In the area of maintenance, Valdepeñas et al. describe in their paper [15] the development of a new conservation management method in which the BIM method is applied as the main tool, serving as a database for the maintenance of port infrastructures. The study presents a workflow for implementing BIM in port environments, combining traditional inspection procedures with digital 3D modeling. The authors developed a 3D model of the sections of the outer port of LA Coruña, Figure 14, including the main rubble mound breakwater and the vertical spur breakwater, which function as inventory databases that store information such as inspection records, photographs, detected pathologies, and repair histories for each structural element. By parameterizing the model elements, maintenance data can be updated directly within the model, allowing for the automatic generation of inspection files and maintenance planning tables. The study demonstrates that applying BIM in this way facilitates more efficient information management, provides clearer visualization of the structures and their condition, and improves the organization of maintenance activities throughout the life cycle of port infrastructures.

Also focusing on BIM development, Kesdech et al. in their paper [16] do a study of the development of 3D models using the BIM technique to create models of important structures having physical impacts on coastal areas, such as wharves, breakwaters, and buildings. Field surveys provided positional and structural data, complemented by multi-source geospatial datasets such as digital elevation models and high-resolution satellite imagery. The researchers developed detailed 3D BIM models of coastal structures to represent their geometry, dimensions, and placement within the environment, Figure 15. The 3D models helped visualize how man-made structures interact with natural processes and how shoreline shifts correlate with coastal engineering interventions. In their conclusions, the authors emphasize that combining BIM and geo-informatics improves the accuracy, clarity, and efficiency of coastal management workflows. The integration enables transmission of virtual physical characteristics of coastal zones, enhances understanding of terrain and infrastructure, and supports planning decisions with more reliable spatial information.

Another relevant work is the one proposed by Musumeci et al. [17], a 3D laboratory technique based on RGB-D (Red-Green-Blue and Depth) cameras to measure rubble-mound breakwater damage above and below sea water level. The developed methodology is based on the fully automatic analysis of

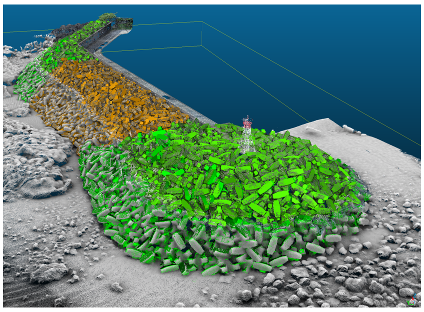

Figure 13: SEABIM model of breakwater 4

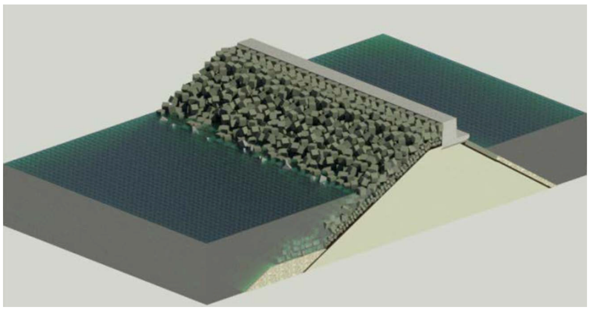

Figure 14: Revit model of the BIM breakwater [15]

[4]"Seabim - homepage." [Online]. Available: https://seabim-breakwater.com/. Accessed: Nov. 03, 2025

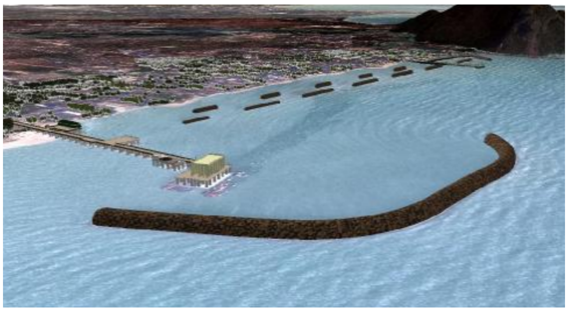

Figure 15: 3D Map Model designed by implementing the geo-informatic programs [16]

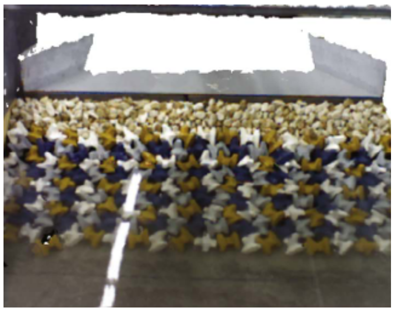

Figure 16: 3D point clouds of rubble mound breakwater configuration during tests [17]

3D point clouds of the armor layers subject to sequences of wave attack. The captured images were processed into 3D point clouds, Figure 16, which were automatically aligned and compared over time to detect movements and rotations of individual armor units. This made it possible to observe how damage developed and spread throughout the structure during testing. The experiments showed that the method could accurately track even small displacements and provide a clear picture of how the breakwater's stability changed under different wave conditions. They demonstrated that affordable 3D imaging can be an effective tool for monitoring and analyzing breakwater damage, providing detailed information on structural changes without interrupting laboratory tests.

3.4 VR in coastal engineering

Following the discussion on the use of 3D models in coastal engineering, this section focuses on the application of VR to support the visualization and understanding of coastal processes and infrastructures. A broad example of the use of VR in coastal engineering is presented by Zhou [18], who describes a web-based VR application for the visualization of global tsunami simulations and coastal hazard education. Unlike traditional VR systems that require dedicated software and hardware installations, WebVR-tsunami uses the web to simplify the process, making it more accessible. The platform allows users to explore 3D global tsunami events directly through web browsers on computers, mobile devices, or in VR headsets. The system integrated numerical tsunami simulations, including events such as the 2022 Hunga Tonga tsunami. The data was processed into 3D globe visualizations with interactive controls for rotating, zooming, and time-stepping, enabling learners and researchers to analyze wave dynamics at a global scale intuitively. We can see in Figure 17 the simulation running. It was concluded that the result was more appealing compared to traditional visualizations for global tsunamis or traditional VR and showed promising results for fast scientific communication and education.

Despite these advances, the application of VR in coastal engineering remains limited when focusing on specific structures such as breakwaters. Through our research, we were unable to identify any existing project that closely matches the prototype proposed in this work. While VR has been adopted in civil engineering contexts more broadly, there is a lack of VR applications dedicated to the visualization or analysis of breakwaters. The closest example found were virtual tours of existing breakwaters, such as the 360-degree panoramic visualization available online [6]. These applications allow users to explore pre-recorded viewpoints along a breakwater, as shown in Figure 18. While such solutions can be accessed via desktop or VR headsets, user interaction is limited to looking around fixed locations, without the ability to move freely, manipulate the environment, or analyze structural behavior.

[5] "Lynett group tonga 3d simulation." [Online]. Available: https://zilizhou.com/lynett. Accessed: Nov. 03, 2025

[6] "Sitges, breakwater 360 panorama | 360cities." [Online]. Available: https://www.360cities.net/image/sitges-breakwater. Accessed: Nov. 03, 2025

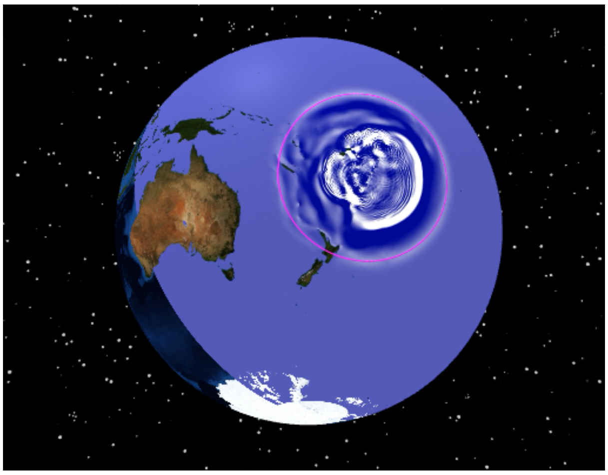

Figure 17: WebVR-tsunami: tsunami simulation[5]

3.5 Discussion

The reviewed literature demonstrates that VR and 3D models have been successfully applied across multiple areas of civil engineering, particularly in dam inspection, structural monitoring, education, and coastal hazard communication. For this work, a focused comparison was conducted on studies related to dams, coastal engineering, and breakwater structures. Table 1 summarizes the key characteristics and contributions of the selected studies.

The comparative analysis of existing VR and 3D visualization approaches highlights the gap for projects related to the monitoring of breakwaters. Existing VR applications such as *CabrilDamVR* and *ImmersiVizDam* show how immersive environments can support virtual inspection, user-centered analytics, and, in some cases, real-time sensor integration. Educational platforms like *WebVR-Tsunami* and *IndustrialVR* emphasize intuitive visualization of complex phenomena and structures. In the domain of breakwater monitoring, tools such as SEABIM, 3D monitoring, and BIM-based systems provide accurate structural modeling, damage tracking, and maintenance planning. However, they offer limited or no immersive interaction. Across all surveyed work, no existing solution combines high-fidelity 3D modeling, structural monitoring features, and fully immersive VR interaction specifically for breakwaters. This gap

Figure 18: 360 cities virtual tour of breakwater 6

is reinforced by the comparison done in Table 2, which shows that current breakwater-focused systems deliver strong analytical or modeling capabilities but do not extend these into immersive environments.

The proposed OSOM-VR prototype aims to address this gap in research by developing a VR application for breakwater monitoring that integrates 3D modeling and interactive exploration within an immersive environment. This approach aims to enhance the efficiency and intuitiveness of breakwater inspection and analysis, effectively bridging the gap between traditional 3D monitoring techniques and immersive virtual inspection methods. This approach leverages the proven benefits of dam-oriented VR systems while bringing them into a domain where immersive solutions are largely absent. In doing so, OSOM-VR combines traditional 3D monitoring tools and modern virtual inspection methods, offering a more intuitive, efficient, and interactive framework for breakwater visualization and analysis.

Work	**Domain**	**Objective**	**Visualization**	**Analysis / Notes**
CabrilDamVR [12]	Dam Visualization	Photorealistic VR exploration of Cabril Dam	VR, Unity	High-fidelity visualization; virtual inspection
ImmersiVizDam [13]	Dam Monitoring	Immersive analytics for dam health	VR, Unity	Accelerates analysis tasks; structural health monitoring; user-centered design
IndustrialVR 3	Dam Visualization	Educational study of Hoover Dam	VR, Unreal Engine	High-fidelity visualization
Teton Dam [14]	Dam Visualization	Educational study of Teton Dam disaster	VR, Unity	Simulation
WebVR-tsunami [18]	Coastal Education	Visualization of global tsunami simulations	VR, Web	Educational tool; accessible without dedicated software
SEABIM 4	Breakwater Monitoring	3D scan-to-BIM of rubble-mound breakwaters	3D BIM	Tracks block movements; eliminates need for manual photo comparison; precise and efficient
BIM for Port Maintenance [15]	Breakwater/Port Management	Maintenance database for port infrastructures	3D BIM	Facilitates maintenance planning; integrates inspection and repair information
3D Monitoring of Rubble-Mound Breakwaters [17]	Breakwater Lab Tests	Track breakwater damage above/below water	3D BIM	Detects small displacements and rotations; cost-effective; structural monitoring
3D BIM for Coastal Zone Management [16]	Coastal Management	3D BIM models of coastal structures	3D BIM	3D BIM; supports planning and coastal management decisions
360° Breakwater Tours 6	Breakwater Visualization	Virtual exploration of breakwaters	VR, Web	Limited interaction; no real-time data; primarily for visualization

Table 1: Summary of VR and 3D visualization works for dam and coastal engineering

Work	Immersive	High-Fidelity	Sensor Data	3D Modelling	Damage / Movement Tracking	Interactive Analytics	Web-Based
CabrilDamVR [12]	✓	✓	–	✓	–	✓	–
ImmersiVizDam [13]	✓	✓	✓	✓	–	✓	–
IndustrialVR (Hoover Dam) 3	✓	✓	–	✓	–	✓	–
Teton Dam VR [14]	✓	✓	–	✓	–	–	–
WebVR-Tsunami [18]	–	–	–	–	–	–	✓
SEABIM 4	–	–	–	✓	✓	–	–
BIM for Port Maintenance [15]	–	–	–	✓	✓	–	–
3D Breakwater Monitoring [17]	–	–	–	✓	✓	–	–
3D BIM Coastal Zone [16]	–	✓	–	✓	✓	–	–
360° Breakwater Tours 6	–	–	–	–	–	–	✓
OSOM-VR	✓	✓	–	✓	–	✓	✓

Table 2: Comparison of VR and 3D visualization works in dam and coastal engineering.

4 Proposed Solution

Building upon the comparative analysis presented in the last section, we will now introduce the proposed solution developed to address the identified gap found in research associated with the use of VR in the study and inspections of breakwaters. This section outlines the prototype's concept, main features, and technologies that will be used.

4.1 Solution Overview

The proposed system is designed to support monitoring and inspection methodologies while complementing OSOM by providing an immersive VR extension to it. To maintain compatibility with current inspection practices, the core functionalities of OSOM-WEB were used as a basis for the features implemented in our application, as well as feedback from civil engineers experienced with OSOM.

Our prototype, OSOM-VR, will be a 3D application developed in Unity that will function as an immersive counterpart to OSOM-WEB. It provides the same core features, such as visualizing data from inspection campaigns and examining photos on the different spots of the breakwater where they were taken. To take advantage of the capabilities of VR, the system will also introduce some functionalities such as the ability to compare multiple pieces of information at the same time, something not possible in OSOM. The virtual environment will be designed to be realistic to reinforce user immersion and intuitive spatial understanding. In Figure 19, a mockup of what the prototype will be like is represented, showing a user interacting with a hotspot in the 3D model of the breakwater.

4.2 Requirements

The requirement definition process involved hands-on experimentation with the OSOM-WEB platform, study of the OSOM methodology, and the complete workflow for the inspection and maintenance of the breakwaters, as well as consultation with LNEC engineers experienced in the OSOM system and a field visit to a breakwater to better understand how the inspection process works. This process was essential for identifying not only the key functionalities for the OSOM-VR prototype, but also additional features that could provide value through VR capabilities beyond what is currently possible. A Software Requirement Specification (SRS) document was created after the initial conversations and experimentation with OSOM-VR, based on the related work research. It contained all the requirements

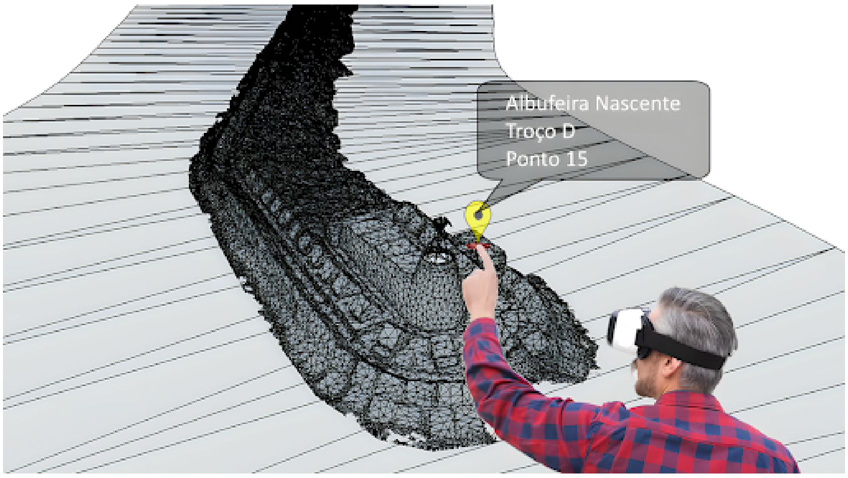

Figure 19: Mockup image of OSOM-VR, showing a user interacting with a hotspot

that had been identified so far, and it was done to more easily show the target users what our idea was, and for them to provide feedback. The final version of this document is provided in the annex.

4.2.1 LNEC Meeting

To validate the requirements for the prototype, a meeting was held at LNEC with three engineers from the Harbors and Maritime Structures Division to present the SRS document to them.

Overall, all previously defined requirements were approved, and no new ones were added. However, the meeting served to clarify several details regarding the use of OSOM, as well as the engineers' preferences and needs. For example, although OSOM technically supports video content, the engineers explained that video formats are difficult to regulate and therefore are not used in practice. Another clarification was that comparing inspection results across different zones of the breakwater is not necessary; instead, comparisons are made only within the same zone across different inspection campaigns. So the document was updated accordingly.

Finally, priorities for the requirements were discussed. It was noted that nearly all requirements related to existing OSOM functionalities are considered high priority. In addition, the ability to zoom into inspection images (FR10) was highlighted as particularly useful and therefore important. Some other requirements were also considered relevant, but not as critical as the previously mentioned ones, such as the tutorial (FR9) and data legends (FR8). These features are not essential for users already familiar with OSOM, but they would be beneficial when presenting the application to people outside the organization.

4.2.2 Site Visit

To better understand breakwater inspections and to support the requirements specification process for OSOM-VR, a site visit was conducted at the Ericeira breakwater on December 4th 2025. The main objective of this visit was to observe and simulate the main aspects of an inspection campaign, document the visual and spatial characteristics of the structure, and identify elements that are critical for a realistic virtual reproduction. The Ericeira structure, as seen in Figure 20, is a rubble-mound breakwater, predominantly composed of natural rock armor units and tetrapodes, and is a potential candidate to serve as the primary case study structure for the OSOM-VR prototype.

At the time of the visit, the sea state was rough, with significant wave agitation and frequent wave overtopping events. Rainy weather conditions further increased the difficulty of the inspection, as several areas of the structure became inaccessible due to wave impact and slippery surfaces. As a result, it was only possible to access less than half of the structure and to inspect three relevant reference points

Figure 20: Photo of Ericeira Breakwater taken during visit

(hotspots) previously marked on the breakwater and in the OSOM system. These constraints highlighted the practical limitations of on-site inspections under adverse environmental conditions and reinforced the relevance of immersive VR-based visits when physical access to the structure is restricted or unsafe.

The observations made during this field survey directly influenced the requirements specification process of the OSOM-VR prototype. One aspect that influenced this was a structural characteristic observed during the visit, the presence of multiple elevation levels along the breakwater that are relevant for the inspection, such as the superstructure, and then a barrier wall and the armor layer on a higher level. So the new requirements added were the need for multiple navigable elevation levels, variable sea states, and wave overtopping phenomena. These requirements have been incorporated into the SRS document in the annex.

4.2.3 Final Requirements

The result of the requirements gathering process is the SRS document, provided as an annex to this work, where all the requirements are described in more detail. In Table 3 and Table 4, we provide an overview of the requirements and their priorities.

For this prototype, all required data will be embedded within the application before building and deployment. The system will not dynamically retrieve data from OSOM or require user authentication. This design choice allows us to focus on the core VR functionality while avoiding dependence on OSOM's backend during development. Although the system is intended to be compatible with multiple VR headsets, development and testing will be performed using one headset model that will serve as the primary reference device. This ensures consistency during evaluation while allowing future adaptation to other platforms. This and the rest of the prototypes' constraints are described in the Table 5

One important aspect to consider is the hardware limitations of the VR headset. Given the objective of maintaining a minimum frame rate of 60 FPS (NFR02), requirements NFR11, NFR13, and NFR14 may need to be implemented using shaders rather than particle-based simulations, which could be too computationally expensive for the target hardware. The performance impacts of these approaches will be assessed during the development phase.

Requirement FR16 may introduce challenges related to motion sickness due to the use of teleportation for navigation between different elevation levels. During development, this issue will be carefully considered, and mitigation techniques will be explored and implemented where possible to reduce discomfort for users.

ID	Requirement	Priority
FR01	3D navigation.	High
FR02	Breakwater section filtering.	High
FR03	Damage levels color overlay.	High
FR04	Access to inspection photos	High
FR05	Structural condition and risk indicators.	High
FR06	Historical comparison	High
FR07	Information panels.	High
FR08	Data legends.	Medium
FR09	Interactive tutorial for new users.	Medium
FR10	Zooming in on inspection photos.	High
FR11	Screenshot tool inside the VR environment.	Low
FR12	Image annotation tools	Low
FR13	Breakwater zone annotation tools.	Low
FR14	Temporal comparison (stage 2)	Medium
FR15	Changing breakwaters (stage 3)	Medium
FR16	Multiple navigable elevation levels	High

Table 3: Functional Requirements

ID	Requirement	Priority
NFR01	System should be easy to use.	High
NFR02	System should run at least at 60 FPS.	High
NFR03	3D models and data should load in less than 1 minute.	High
NFR04	System must be modular to allow new breakwaters.	High
NFR05	Should be compatible with multiple VR headsets.	High
NFR06	3D model should be visually accurate.	High
NFR07	Hotspot interactions should load data within 500 ms.	High
NFR08	Prototype should work on PC (Windows/Mac) and VR headset.	High
NFR09	3D model visualization must be realistic.	High
NFR10	Basic environmental elements should be included.	Medium
NFR11	Realistic water surface included (no dynamic waves).	Medium
NFR12	The prototype should include a menu system.	High
NFR13	System should include multiple selectable sea states	Low
NFR14	Wave overtopping phenomena simulation	Low

Table 4: Non-Functional Requirements

ID	Constraints
C01	Pre-loaded data only. Users cannot upload data in the prototype.
C02	Stages 1 and 2 support only one breakwater.
C03	Users will not be able to create new hotspots.
C04	The inspection photos have to be JPEG, resolution 4032x3025, and less than 25MB.
C05	The breakwater models must be a .fbx

Table 5: Prototype Constraints

4.3 Development Stages

To ensure a structured and manageable development process, the prototype is organized into multiple stages. Each stage introduces new functionalities while building upon the foundations established in previous ones, allowing the system to evolve in a controlled and iterative manner. Based on the prototype's requirements, these are the stages we propose:

Stage 1 – Single Case Study: This stage includes the core functionalities previously described, such as 3D navigation, section filtering, damage visualization, and integration with the OSOM database. It uses a single 3D model of the breakwater, serving as the foundation for all subsequent stages.

Stage 2 – Temporal Analysis: In addition to the features of Stage 1, this stage introduces the possibility of loading and visualizing different 3D models of the same breakwater corresponding to different points in time. Users can select a specific year to visualize the corresponding model, enabling temporal comparison and assessment of structural evolution.

Stage 3 - Multiple Case Study: The final stage extends the application to support the analysis of multiple breakwaters, allowing comparative studies across different structures.

Although the prototype is designed with modularity and extensibility in mind, the implementation of Stage 3 is beyond the scope of the present work. Therefore, the prototype developed in this project covers only Stages 1 and 2, while support for multiple case studies is left for future work.

4.4 Solution Architecture

Based on the previously defined requirements, we will now present the solution architecture we propose for OSOM-VR. The prototype will be developed using the Unity engine with the objective of being hardware-agnostic. In the Figure 21, the architecture of our prototype is presented, following the Model View Component (MVC) design pattern. In this architecture, the View corresponds to all visual output presented to the user, including the 3D environment, UI panels, and the VR or desktop rendering of the breakwater model. The Model contains the prototype's underlying data and logic, such as the 3D representations of the breakwater structures, the inspection imagery, and data. It is responsible for managing and updating the state that the View displays. The Controller handles all user interactions, whether through VR controllers, keyboard, or mouse, translating inputs into actions that modify the Model and trigger updates in the View.

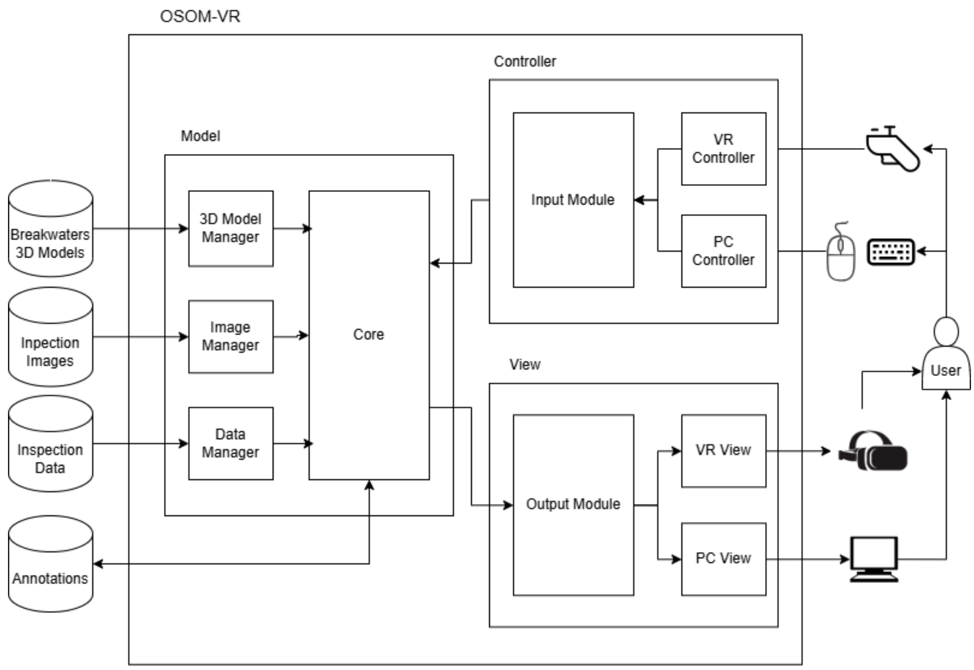

Figure 21: Prototype architecture

A key architectural decision pertains to the availability of both a web-based version and a downloadable version of the prototype. While the web deployment is the final objective, due to its accessibility and integration benefits, maintaining a local build simplifies testing and avoids browser limitations during development.

4.5 User Interfaces

The OSOM-VR prototype provides two interaction modes, desktop and VR, ensuring accessibility across different hardware setups while maintaining a consistent user experience. Both interfaces will provide an intuitive navigation, exploration of the breakwater models, and available inspection data. Although the interaction will differ in some aspects, the underlying structure and presented information will remain the same.

VR Interface: The VR interface provides an immersive design to improve depth perception and spatial understanding of the breakwater structure. Users interact with the prototype using the VR controllers through ray-casting selection for UI interaction. The locomotion within the environment is performed using the controllers' joysticks, enabling smooth navigation around the breakwater model, and for changing elevation, teleportation using the joysticks to point to where the user wants to go. All interface elements are presented as floating 2D panels positioned within the 3D space. These include the main menus, image viewers, and inspection data panels. The images and inspection data appear on movable and resizable world-space panels, allowing users to organize the information around them while maintaining full situational awareness of the environment.

Desktop Interface: For the desktop version, we will create a traditional first-person navigation, allowing the users to explore the breakwater models with keyboard and mouse. In this mode, all interface elements are displayed directly on the screen through standard 2D UI panels. These include the main menu button and the tools for filtering or isolating specific zones of the structure. Interactions with hotspots follow the same logic as in the VR version but are adapted for screen-based visualization. When a hotspot is selected, the corresponding images are displayed as on-screen panels, enabling users to view multiple images simultaneously without obstructing navigation. Similarly, inspection data is presented through dedicated information panels. Users can open several panels at once to compare data from different zones, supporting a flexible and efficient inspection workflow.

4.6 Data Handling

The prototype handles four main categories of data: 3D breakwater models, inspection images, inspection and diagnostic data, and user-generated annotations. For the scope of this work, all data is pre-loaded and embedded within the application, in accordance with the constraints defined. This design choice avoids runtime dependencies on OSOM's backend services, allows the focus to remain on interaction design and immersive visualization, and ensures modularity by decoupling all data from the prototype's core logic, enabling new breakwaters or inspection campaigns to be added simply by supplying new datasets, without requiring changes to the application code.

3D Breakwater Models The geometric representation of the breakwater constitutes the core visual element of the prototype. The models will be provided by LNEC in PLY format and converted to FBX, which is natively supported by Unity. Each model will be structured into semantic subcomponents (e.g., armor layer, superstructure, and core), enabling runtime section filtering, highlighting, and section-specific data visualization. Inspection hotspots are spatially defined using geographic coordinates (latitude and longitude). To integrate these coordinates into the local coordinate system of the 3D model, a reference origin point will be selected on the breakwater. All hotspot positions are then transformed from geographic coordinates into relative coordinates, allowing accurate placement of interactive elements within the Unity scene while preserving spatial relationships. The visual appearance of the breakwater is achieved through the application of textures derived from orthophotomaps. These images provide a high-resolution and geographically accurate representation of the breakwater surface. The orthophotomaps enable realistic texturing that reflects the actual condition of the structure at the time of acquisition.

Inspection Images Inspection photographs collected during OSOM campaigns are stored as JPEG files. These images are imported as textures and linked to their corresponding inspection points through identifiers defined in the inspection data files. At runtime, images are loaded on demand when the user interacts with a hotspot. The images provided by LNEC include the inspection year, hotspot identifier, and camera direction.

Inspection Data Inspection data, such as damage levels, risk indicators, and historical evolution metrics, will be extracted from ANOSOM-WEB and provided by LNEC in .xlsx. Excel will be used as an intermediate data representation due to its widespread adoption and ease of editing, but will then be converted into lightweight structured files (JSON). Each JSON file contains inspection records indexed by breakwater identifier, inspection year, and hotspot or structural section. During the import process, these JSON files are parsed and mapped to predefined Unity prefabs representing breakwater sections and inspection hotspots. This mapping enables inspection information to be dynamically instantiated and visualized within the 3D environment, while maintaining a clear separation between data and visualization logic. The use of JSON also supports extensibility and reuse across different breakwater models and inspection datasets.

Annotations User-generated annotations are treated as an additional data layer linked to the virtual environment. Each annotation is associated with relevant metadata, including the breakwater identifier, structural section or hotspot, inspection year, and author. While the final annotation modalities have not yet been fully defined, current options under consideration include textual notes, audio recordings, and freehand sketches drawn directly in the virtual environment. Annotations are designed to be stored in a structured format compatible with the inspection data model, allowing future integration with backend systems or collaborative workflows. To determine the most appropriate annotation method, a state-of-the-art analysis of text input techniques in VR will be conducted. If multiple suitable approaches are identified, they will be evaluated during the preliminary evaluation to determine the method preferred by users.

4.7 Tech Stack

The OSOM-VR prototype will be developed using the Unity game engine, which provides native support for immersive 3D environments and VR applications. Unity's XR framework will be used to abstract hardware-specific details, offering a unified interface for VR rendering, tracking, and user interaction. This approach ensures that the prototype remains hardware-agnostic and can be executed on different VR headsets without changes to the core application logic. All logic will be implemented using C#, the primary programming language supported by Unity.

For this prototype, data management was designed to be as simple as possible while maintaining modularity and independence from the OSOM backend. For this reason, all data is stored locally and embedded within the application. Inspection data is stored using JSON files. Each breakwater is associated with a set of JSON files organized by structural zones and inspection year. At runtime, these files are parsed and mapped to the corresponding elements of the 3D model, enabling the visualization of damage levels, risk indicators, and historical inspection information. Inspection images are stored locally as JPEG files. Images are loaded on demand when the user interacts with a hotspot in the 3D environment. User-generated annotations are also stored locally in JSON format. Each annotation record includes metadata such as the breakwater identifier, inspection year, spatial reference, and the annotation content.

4.8 Unity Web

One of the objectives of this prototype is its integration with the existing OSOM-WEB solution; therefore, a Unity Web build is required. This choice introduces several specific considerations, most notably the performance limitations associated with web-based deployments. As a result, it is necessary to analyze the advantages and disadvantages of developing the prototype with web compatibility in mind, particularly in terms of performance, scalability, and user experience.

From an accessibility and deployment perspective, Unity Web offers significant advantages. Web-based applications do not require local installation, allowing users to access the prototype directly through a browser. This approach greatly simplifies distribution, ensures platform independence, and facilitates seamless integration with the existing OSOM-WEB. These benefits, however, come at the cost of reduced performance when compared to standalone Unity builds. Unity Web deployments are constrained by the browser environment, including limited memory availability, restricted access to system resources, and reliance on WebGL for rendering. Such constraints can negatively impact rendering performance, increase loading times, and limit the complexity of 3D scenes, all of which are particularly relevant for the proposed prototype.

In contrast, standalone Unity applications provide greater computational flexibility and generally achieve higher performance, as they can fully leverage the underlying hardware and operating system. This allows for smoother interaction, faster data processing, and support for more complex scenes. Nevertheless, standalone deployments require manual installation, making them less suitable for seamless integration with web-based platforms.

As the limitations of a web-based build for a VR application are not yet fully understood, a small Unity Web application with basic VR functionality will be developed and deployed. This prototype will be used to evaluate the practical constraints of a web-based approach, particularly with respect to performance, interaction responsiveness, and VR support. The results of this evaluation will provide the necessary empirical basis for making a final, informed decision between a web-based or standalone Unity implementation.

5 Evaluation

Based on the solution architecture for OSOM-VR defined in the previous section, we will define the evaluation process to be used to validate whether the defined requirements were achieved in the prototype. The evaluation of the OSOM-VR prototype will be carried out in two main phases, aimed at assessing both the usability and the perceived usefulness of the system within the context of the OSOM inspection methodology.

5.1 Preliminary Evaluation

The first evaluation will take place after the completion of the alpha version of the prototype. This preliminary evaluation will be conducted with a small group of professionals, consisting of two engineers from the Computer Science department at IST to validate the user experience and technical aspects, and two engineers from LNEC to validate the requirements. The objective of this phase is to evaluate the overall usability of the system, identify technical issues, interaction problems, and sources of user confusion, as well as to validate the requirements that were achieved so far.

Participants will be asked to perform a set of predefined tasks, including navigation along the breakwater model, interaction with hotspots, and visualization of inspection data. During these sessions, direct observation will be used to identify difficulties, and semi-structured interviews will be conducted to collect feedback at the end of each session to capture participant perceptions and suggestions. Based on the results of this preliminary evaluation, the prototype will be refined and improved before moving to the second phase.

5.2 User Study

The second evaluation will consist of a user study conducted with the target user group. This phase is planned for June and will involve approximately 20 participants who were not part of the prototype's development. The main purpose of this evaluation is to again validate the requirements and determine if the final objectives were achieved. The participant group will include members of the Harbors and Maritime Structures Division who did not take part in the preliminary evaluation, as they represent the primary target users. In addition, other participants will be included to represent potential target users with no prior exposure to the system, such as civil engineering students specializing in hydraulics or clients of LNEC. Their participation is also intended to assess requirements related to ease of learning and usability without prior experience (NFR01).

Participants will be divided into two groups of 10. One group will start by using the desktop version of the system, while the other will begin with the VR version. After completing the assigned tasks, the groups will switch versions. Although this approach is not optimal, as participants may perform tasks more efficiently during the second condition due to prior exposure, it was selected due to the limited number of participants and because it allows for direct comparison between the two versions.

During this phase, user interactions will be observed to assess usability, task efficiency, and intuitiveness. After completing the tasks, participants will be asked to complete three standardized questionnaires. The Igroup Presence Questionnaire (IPQ) will be used to measure the perceived sense of presence in the VR environment. The Interface Consistency Testing Questionnaire (ICTQ) will be used to evaluate interface consistency between the desktop and VR versions. This questionnaire assesses Visual Consistency, Navigation Flow, Content Uniformity, and Interaction Standards. The System Usability Scale (SUS) will be used to measure overall usability and user satisfaction. In addition, this evaluation will include a set of quantitative measures aimed at validating the functional and non-functional requirements defined in Section 4.2. These quantitative measures will be obtained through a set of predefined tasks that participants will perform after completing the tutorial. Task completion time, task success rate, error frequency, and other relevant metrics for validating the requirements will be recorded while users perform these tasks and subsequently analyzed. Semi-structured interviews will also be conducted with each participant to gather any additional feedback they may have. Each test will take around 30 minutes to complete. This combined methodological approach will allow us to compare each of the versions, desktop and VR, to study how the participants perceive the characteristics of each. It will also allow us to assess whether the VR environment provides a practical and effective alternative or complement to the existing OSOM workflow, and whether the objectives of this work have been successfully achieved. All of this will take place according to the timeline better explained in the next section.

6 Work Schedule

The schedule for the development of the prototype is presented in the Gantt chart in Figure 22. The process began with the preparation of this document and the collection of requirements from LNEC. The prototype development started shortly after and will continue until February. This will be followed by a short testing phase. Based on the results of this evaluation, improvements will be implemented by the end of May. Subsequently, the final prototype will be evaluated with the target audience as well as general users who are not familiar with our work. In parallel, the thesis writing process will begin, with completion expected around October, followed by the defense in November.

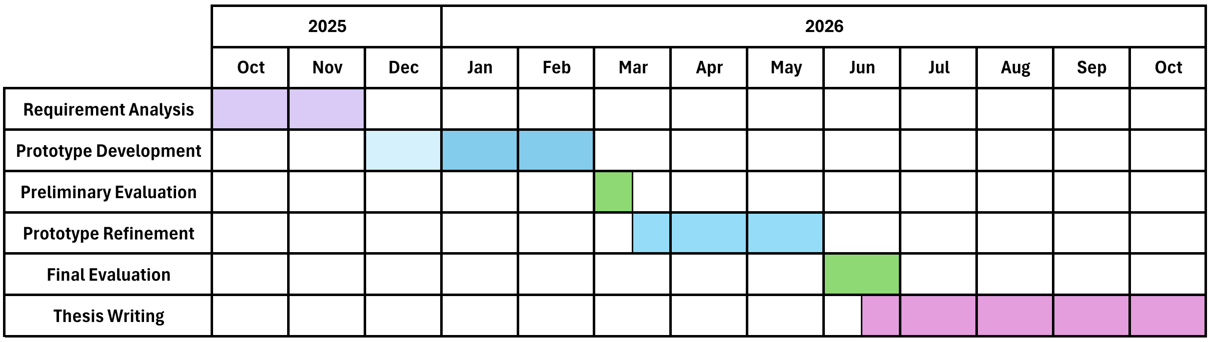

Figure 22: Gantt chart of project timeline.

7 Conclusion

This work explored the potential of VR as a tool for the inspection and monitoring of breakwaters, addressing a gap identified in research. While VR has been successfully applied in several areas of civil engineering, such as dam inspection, structural monitoring, and education for engineering, the literature review revealed a clear lack of immersive solutions specifically dedicated to coastal engineering areas, namely breakwater inspection and maintenance workflows. This observation motivated the development of OSOM-VR, a prototype designed to extend the existing LNEC's OSOM methodology into an immersive 3D environment.

Based on an analysis of the OSOM methodology, hands-on exploration of the OSOM-WEB platform, meetings with LNEC engineers, and a site visit to a breakwater, this work defined a set of functional and non-functional requirements for the proposed prototype. These requirements guided the design of OSOM-VR, ensuring alignment with real inspection workflows while identifying opportunities where VR could add value, particularly in spatial perception, accessibility, and data exploration. This document proposes OSOM-VR as a Unity-based prototype that aims to replicate the core functionalities of OSOM-WEB within an immersive 3D environment, while remaining compatible with desktop interaction, ensuring flexible integration within LNEC's current workflow, and providing a foundation for future scalability.

In addition, a structured evaluation methodology was defined to assess the proposed prototype once implemented. This evaluation plan outlines both preliminary and user study phases, combining observational studies, standardized questionnaires, and user feedback to determine whether OSOM-VR can effectively support inspection tasks and offer advantages over the existing 2D solution.

In conclusion, this work establishes the conceptual and technical groundwork for the future development of OSOM-VR. By clearly defining the problem space, reviewing relevant technologies, and proposing a solution design and evaluation plan, this project lays a foundation for the implementation and assessment of a VR-based breakwater maintenance tool.

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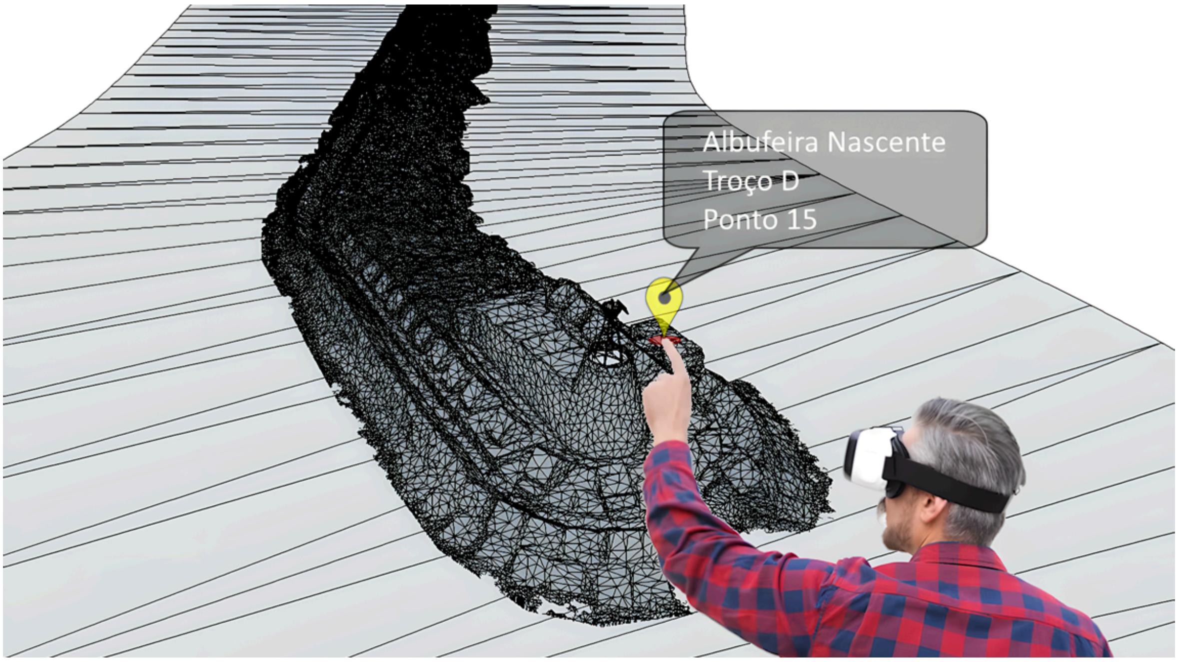
Software Requirement Specification

OSOM-VR - Observação Sistemática de Obras Marítimas com Realidade Virtual

Catarina Costa - INESC/IST/ULisboa & LNEC - December 2025



General Description:

This Software Requirements Specification (SRS) document defines the requirements for OSOM-VR, a Virtual Reality (VR) application developed as part of a Master's thesis. The prototype is designed to visualize, explore, and analyze breakwater structures using data provided by OSOM, with a focus on creating an interactive and immersive user experience. The figure above illustrates a mock-up of the proposed system, demonstrating how users will interact with the virtual breakwater model through hotspots and other interactive elements to access structural and analytical information.

Functional Requirements:

(FR01) 3D Navigation: Users can freely move around and explore a realistic 3D model of a breakwater using a VR headset or a computer (mouse + keyboard).
(FR02) Section Filtering: Users can highlight or isolate specific sections of the breakwater to examine them more clearly. (e.g., *core*, *superstructure*, *armor layer*)
(FR03) Damage Visualisation: The system will display color-coded damage levels based on OSOM indicators. This will be shown as a semi-transparent overlay on the 3D model.
(FR04) Access to Inspection Photos in Interactive Hotspots: The prototype will have interactive markers on the breakwater where users can click to reveal photos taken from that point. They will be shown as a carousel of 2D floating panels and can be zoomed in on and can be repositioned, and scaled by the user. Each image panel includes a navigation button to switch between different photos taken from the same location/campaign. When multiple image panels are open, changing the image on one panel automatically updates all other panels to the corresponding image from that location or campaign (synchronised comparison mode).
(FR05) Structural Condition and Risk Indicators: For each section, users can see condition information, evolution over time, and risk levels
(FR06) Historical Comparison: The prototype can show past inspection results, allowing users to compare the current condition with previous years and observe how the structure has evolved.
(FR07) Information Panels: When a user selects a section, a 2D floating information panel will appear showing the latest inspection results, damage level, and historical data. Multiple inspection panels can be displayed simultaneously, allowing side-by-side comparison of inspection results across different years.
(FR08) Data Legends: The system will display clear legends explaining what each color means, the scale of damage or risk, and any numerical indicators shown
(FR9) Tutorial: The system will include an interactive tutorial to guide new users through the application and its features.
(FR10) Zooming on Inspection Photos: Users will be able to zoom in on inspection photos to examine details more closely.
(FR11) Screenshot Tool: Users can take screenshots inside the VR environment.
(FR12) Image Annotations: Users can create annotations directly on inspection images. Each annotation is automatically associated with the image file, the inspection date, the corresponding breakwater, and the hotspot ID.
(FR13) Breakwater Zone Annotations: Users can create annotations on specific zones of the 3D breakwater model. Each annotation is automatically associated with the zone/section of the breakwater, the inspection date, and the corresponding breakwater.
(FR14) Temporal comparison: In Stage 2, users can interact with a slider to change the model of the breakwater based on the inspection year.
(FR15) Change breakwater: In Stage 3, users can change the breakwater they are visualizing.
(FR16) Multiple navigable elevation levels: The user can teleport to nearby sections at higher elevations while walking along the breakwater.

Non-functional Requirements:

(NFR01) Usability: The system should be easy to use, even for novice users, making it possible to learn how to use it in less than 5 minutes.
(NFR02) Performance: During VR and desktop use, the system should run smoothly (at least 60 frames per second).
(NFR03) Loading Times: 3D models and data should load within a reasonable time so the user's workflow is not interrupted, especially for stage 2/3, where users can change the model shown. The models should load in less than 1 minute.
(NFR04) Modularity: The system should be designed so that new breakwater structures can be added in future stages.
(NFR05) Hardware Compatibility: The application should be compatible with at least the Meta Quest VR headsets.
(NFR06) Visual Accuracy: The 3D representation must maintain realistic scale and proportions, to be tested based on user feedback.
(NFR07) Hotspot Interaction Load Time: When a user interacts with a hotspot, the corresponding data should respond within 500ms.

(NFR08) User Interfaces: The prototype must be accessible both using only a pc (Windows and Mac) with a mouse and keyboard, and a VR headset.

(NFR09) Realistic Visualization: The 3D model should look visually convincing, based on natural lighting, textures, and materials that help users understand the breakwater's physical characteristics, to be tested based on user feedback.
(NFR10) Surrounding Environment: Basic environmental elements (sky, background, vegetation) will be included.
(NFR11) Water Representation: The application will include a realistic-looking water surface, but not simulated waves or water movement, to be tested based on user feedback.
(NFR12) Menu System: A menu system should be accessible, offering options such as changing breakwaters, toggling damage visualization, data legends, and breakwater zone selection.
(NFR13) Variable sea states: It should be possible to change the sea state between calm and agitated.
(NFR14) Wave overtopping phenomena: The application should include a simulation of wave overtopping.

Constraints:

(C01) Pre-loaded Data: All 3D models, media content, and inspection data are pre-loaded. Users cannot upload their own models or data in the prototype.
(C02) Single Breakwater (Stages 1–2): Stages 1 and 2 support only one breakwater. Stage 3 must support multiple breakwaters.
(C03) Hotspot Creation: Users will not be able to create new hotspots.
(C04) Image format: The inspection photos have to be JPEG, the resolution is 4032x3025, and the size must be less than 25MB.
(C05) Breakwater Model: The models must be a .fbx

System Evolution:

Stage 1 – Single Case Study: This stage includes the core functionalities focused on a single breakwater model. Serves as the foundation for later stages.

For the first stage, these are the different requirements:

- One 3D model
- View inspection photos
- Free movement in and around the structure

Stage 2 – Temporal Analysis: This stage adds the ability to load and visualise 3D models from different time periods of the same breakwater, enabling temporal comparisons and assessment of structural evolution.

Stage 3 – Multiple Case Study: This stage expands the system to support multiple breakwater structures, allowing comparative studies across different sites.

Priorities:

FR01	High	FR02	High	FR03	High
FR04	High	FR05	High	FR06	High
FR07	High	FR08	Medium	FR09	Medium
FR10	High	FR11	Low	FR12	Low
FR13	Low	FR14	Medium	FR15	Medium
FR16	High	NFR01	High	NFR02	High
NFR03	High	NFR04	High	NFR05	High
NFR06	High	NFR07	High	NFR08	High
NFR09	High	NFR10	Medium	NFR11	Medium
NFR12	High	NFR13	Low	NFR14	Low

Glossary:

Armor Layer:
The outer layer of the slope is directly exposed to wave action. It typically consists of layers of natural or artificial blocks arranged to dissipate wave energy and prevent erosion of the underlayer and core caused by wave impact. It can be subdivided into two zones, the resistant armor layer (manto resistente) and the interior armor layer (tardoz).

Artificial Concrete Blocks:
Concrete armor units, some with four protruding arms (such as tetrapods), others cubic shaped (such as Antifer or cubes), are commonly used in the armor layer of rubble-mound breakwaters.

BIM: Building Information Modelling

A digital representation of the physical and functional characteristics of a structure.

Core:
The innermost section of the breakwater, generally of prismatic shape, is composed of rock material of varied sizes, commonly referred to as T.O.T. (all sizes). Its main functions are to attenuate wave propagation and to provide structural support for both the underlayer and the armor layers.

Hotspot:
A predefined interactive point on the virtual breakwater model corresponding to a physical inspection reference point. Hotspots enable users to access inspection images and related data during inspections, as well as within the VR or desktop environment.

OSOM: Observação Sistemática de Obras Marítimas

A systematic methodology developed by LNEC for the inspection, monitoring, and maintenance of maritime structures, particularly breakwaters.

OSOM-WEB:
Web-based database used to store, manage, and visualise inspection data collected under the OSOM methodology. It serves as the backend system for breakwater inspection records, photographs, and diagnostic indicators used by LNEC.

Point Cloud:

A set of data points in 3D space representing the external surface of an object or structure.

Rubble-Mound:
A type of breakwater, the most commonly used in Portugal.

SHM: structural health monitoring

Observation and analysis of a system over time using periodically sampled response measurements to monitor changes to the material and geometric properties of engineering structures such as bridges and buildings.

SRS: Software Requirement Specification
A comprehensive document detailing a software's purpose, features, functionality, and constraints, serving as a blueprint for developers and a contract between stakeholders (clients, developers, testers) to ensure everyone shares a unified understanding.

Superstructure:
Usually, a massive concrete or masonry block is located at the crest of the breakwater. It facilitates vehicle and people access, and may also accommodate infrastructure installations. In some cases, it includes a wave wall designed to improve safety by reducing wave overtopping.

Toe Berm:
Located at the base of the slope, this section consists of rock or concrete blocks. Its main function is to support and stabilise the armor layer, preventing its displacement due to wave action.

UAV: Unmanned Aerial Vehicle
Commonly called a drone.

Underlayer:
A zone consisting of one or more layers of selected rock, which may have uniform or varying weights. It acts as a filter between the core and the armor layer, preventing the migration of fine material from the core, increasing the porosity of the slope, and contributing to the overall stability of the structure.

Wave Overtopping

A coastal engineering phenomenon in which waves run up and pass over the crest of a breakwater or coastal defence structure, potentially causing flooding, structural damage, or safety hazards.