



## Design of a Virtual Simulation for Tsunami Disaster Education and Mitigation at Teluk Penyul Beach, Cilacap

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### ABSTRACT

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Tsunami disaster mitigation plays a crucial role in minimizing casualties and infrastructure damage, especially in high-risk coastal areas like Cilacap Regency, Indonesia. Current disaster mitigation methods primarily rely on conventional training, which lacks interactivity and fails to accurately simulate real disaster conditions. To address this limitation, this study designs a Virtual Reality (VR)-based disaster mitigation simulation that provides an immersive and interactive experience for users in responding to tsunami threats. The application is developed using the Multimedia Development Life Cycle (MDLC) method and built with Unity3D, utilizing the Oculus Quest 2 as the VR platform. The simulation covers key disaster scenarios, including earthquake tremors, seawater recession, tsunami wave impact, and guided evacuation routes through visual and auditory cues. Unlike traditional drills, the VR system provides an interactive, immersive, and repeatable training environment, enhancing user engagement and preparedness without physical risks. Black-box testing validated system functionality, ensuring reliable performance. By integrating 3D environmental data from prior studies, this cost-effective and scalable solution offers a transformative approach to tsunami preparedness education, significantly improving community awareness and response capabilities in tsunami-prone regions.

## 1. INTRODUCTION

Tsunamis are destructive natural disasters capable of devastating infrastructure and causing significant loss of life. Cilacap, located on the southern coast of Java, faces a high tsunami risk due to subduction activity. A notable example is the 2006 earthquake, which had a magnitude of 7.8 Mw and resulted in 124 deaths and 33 missing persons [1]. Moreover, Indonesia's Meteorology, Climatology, and Geophysics Agency (Badan Meteorologi, Klimatologi dan Geofisika/BMKG) has predicted potential tsunami waves reaching up to 28 meters along Java's southern coast, highlighting the urgency of disaster mitigation efforts in Cilacap [2].

Non-structural mitigation efforts, particularly those focused on educating the public about tsunami preparedness in Cilacap, require further enhancement. A survey conducted by Indonesia's National Disaster Management Agency (BNPB) in 2023 revealed that, although coastal communities are aware of disaster preparedness, the majority have never participated in evacuation training or simulations, with 69% of Cilacap's coastal residents never participating in evacuation drills [2, 3]. This underscores the need for more innovative, interactive, and immersive approaches to improving community preparedness.

Conventional training methods, such as physical drills and text-based education, suffer from several limitations:

- Limited engagement and realism, physical drills and text-based materials often fail to convey the emotional urgency of real disaster scenarios. Field simulations lack sensory immersion, such as the sounds, ground shaking, or environmental destruction associated with actual disasters, causing some participants to lack seriousness and potentially disrupt others who are more engaged [4].

- High costs and logistical complexity, physical drills require substantial resources, including equipment, venues, and coordination, which limit their frequency and accessibility.

Virtual Reality (VR) technology offers an effective solution for disaster simulations by providing realistic experiences without physical risks [5]. VR enables users to recognize early tsunami warning signs, follow evacuation routes, and experience the disaster's impact in a more profound manner compared to traditional methods [5]. Compared to Augmented Reality (AR), VR technology offers superior immersion in virtual disaster simulations by providing a first-person point of view (POV) that places users directly within the disaster scenario. While AR overlays digital elements onto real-world environments, delivering a third-person POV that feels detached [6], VR fully immerses users in a controlled, computer-generated environment, enabling them to experience events like earthquakes or tsunami waves as active participants, enhancing sensory realism and emotional impact.

Previous studies have demonstrated that VR enhances

memory retention, comprehension, and disaster preparedness. Research on flood disaster preparedness [7] and volcanic eruption preparedness [8] supports this claim. Additionally, VR is more cost-effective than physical simulations, as it does not require specialized equipment or additional infrastructure and can be used repeatedly without logistical constraints [5]. Furthermore, as an educational medium, VR supports learning styles that involve physical movement (kinesthetic) [9], and provides an immersive and interactive learning experience proven to enhance understanding, such as in sign language education [10]. This highlights VR's broader potential as a powerful educational tool across various disaster contexts.

It was also concluded that virtual lab applications can help overcome the lack of funding for procuring physical equipment and materials [11]. This finding reinforces the value of VR as a cost-effective educational tool. In the context of tsunami disaster preparedness, VR can similarly reduce the need for expensive physical simulation tools while still offering an immersive and interactive learning experience. By leveraging VR's immersive qualities, the simulation not only delivers practical training but also deepens users' understanding of disaster mitigation strategies.

Given this urgency, this study proposes the development of a VR simulation for tsunami disaster education and mitigation in Cilacap. The simulation will present interactive scenarios, including earthquake tremors, seawater recession, tsunami waves, and evacuation routes that users can follow. Through this approach, it is expected that public understanding and preparedness for tsunami disasters will be significantly improved.

## 2. RESEARCH METHOD

A virtual simulation for tsunami disaster mitigation is designed using the Luther-Sutopo version of the MDLC method, developed in six stages: concept, design, material collecting, assembly, testing, and distribution [12], as illustrated in Figure 1.

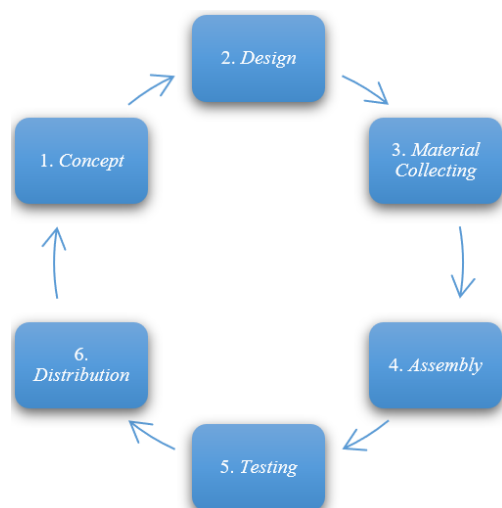


Figure 1. MDLC stages

### 2.1 Concept

The conceptual stage aims to define the objectives and intended users of the program (audience identification). This study involves designing a virtual simulation for tsunami

disaster mitigation in Cilacap, with the goal of developing a VR-based mitigation framework. At this stage, an analysis of the current system is conducted to understand how local institutions manage tsunami disaster mitigation and to identify existing problems that can serve as a foundation for the proposed system design.

Based on reports released by the Cilacap Regional Disaster Management Agency (Badan Penanggulangan Bencana Daerah/BPBD) and the Cilacap Regency Government, BPBD Cilacap has implemented disaster mitigation programs. Two main approaches have been employed: (1) conventional disaster mitigation simulations, where communities are trained in self-evacuation procedures such as taking cover under tables during earthquakes and running toward designated evacuation locations along marked routes, and (2) mitigation education and outreach, which involves the dissemination of disaster risk information and preparedness materials.

However, based on current practices, no interactive and virtual tsunami disaster mitigation system has been identified that aligns with the approach proposed in this study, as highlighted in the research conducted by Anggraheni et al. [13].

Several limitations are associated with the conventional disaster mitigation approach. These include difficulty for the public in understanding real disaster scenarios, lack of mental and emotional adaptation to the stress that may occur during actual events, and limited simulation frequency, which is generally scheduled and not accessible at any time.

One potential solution to mitigate the limitations of conventional methods is the integration of disaster mitigation with Virtual Reality (VR) technology. Through VR, which can replicate realistic conditions such as earthquake visualizations and tsunami effects, communities can gain immersive experiences that help train both mental and emotional preparedness. Additionally, VR simulations can be accessed at any time, offering more flexible and scalable training opportunities.

Based on the analysis of the current system, a proposed system is developed that integrates conventional mitigation methods with VR technology to improve the quality of disaster preparedness training. The proposed system is structured into several menus and features within the VR application. These include a main menu as the access point to other parts of the application, an instruction menu to train users in operating the VR simulation, a settings menu, a developer information menu, and a simulation menu designed to visualize the three main disaster events—earthquake, receding seawater, and tsunami—as shown in Figure 2.

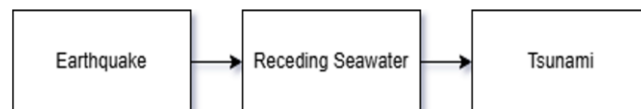


Figure 1. Tsunami disaster scenario

The designed features include an initial VR guide, directional arrows to indicate evacuation routes, tsunami impact visualizations, and environmental monitoring panels to observe conditions at evacuation points.

### 2.2 Design

The design stage involves creating specifications for

program architecture, style, appearance, and material requirements. The VR application will be developed using Unity software, which is primarily object-oriented, making Unified Modeling Language (UML) an essential tool for structuring the VR-based tsunami disaster mitigation simulation.

This study’s design incorporates multiple media, including text, audio, animations, images, and 3D objects, which will be placed across various menus, including the main menu and other interactive menus.

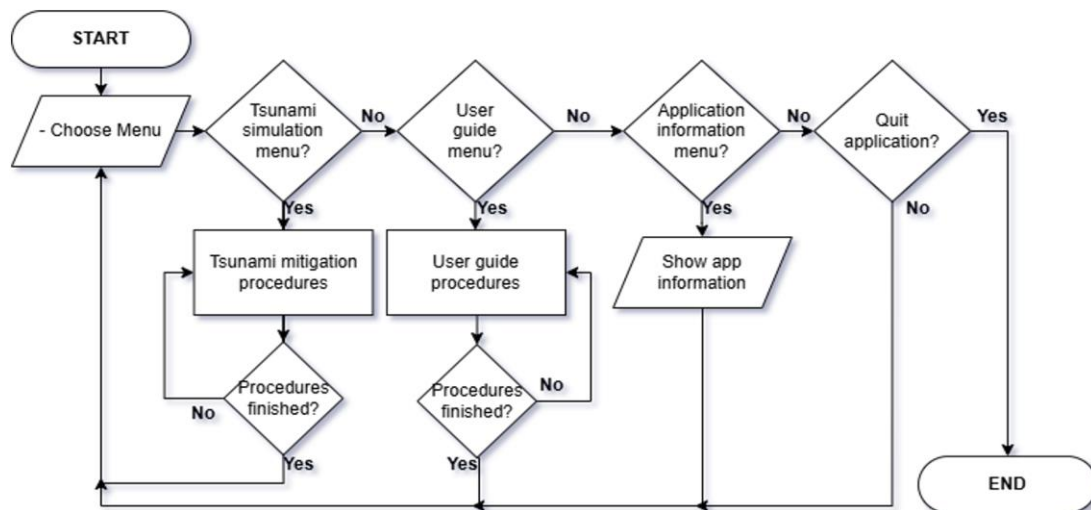
### 2.2.1 Flowchart

Figure 3 illustrates the general application design flowchart for the virtual tsunami disaster mitigation simulation in Cilacap:

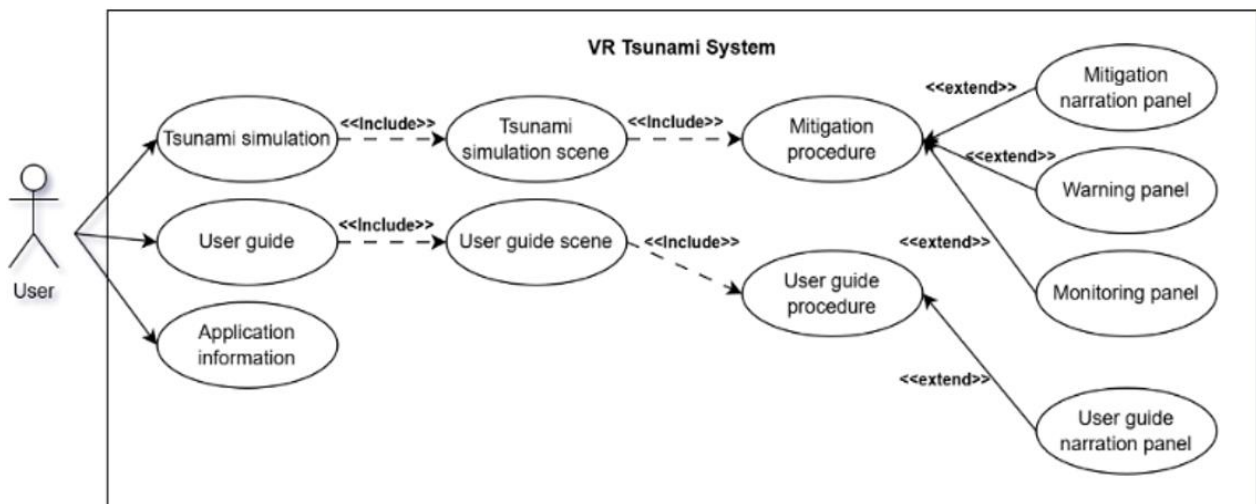
- 1) When users enter the Main Menu, they can choose

among the Tsunami Simulation Menu, User Guide Menu, or Application Info Menu.

- 2) Selecting the Tsunami Simulation Menu directs users to the virtual tsunami simulation environment, where they follow disaster mitigation procedures before returning to the main menu.
- 3) Selecting the User Guide Menu directs users to a virtual training area where they learn how to use the tsunami simulation VR before returning to the main menu.
- 4) Selecting the Application Info Menu displays general information about the simulation application.
- 5) Choosing the Exit Application option closes the application.



**Figure 3.** Main flowchart VR tsunami mitigation



**Figure 4.** VR tsunami system use case

### 2.2.2 Use case diagram

A use case diagram describes the interaction between one or more actors and the system. It outlines system functions and the actors authorized to access them [14]. In the VR tsunami simulation for Cilacap, the use case diagram in Figure 4 illustrates three primary functions accessible to users:

- 1) Tsunami Simulation – Allows users to enter the

virtual tsunami simulation environment. Users follow mitigation procedures such as evacuation route guidance and seeking shelter. During the process, narrative panels provide text and audio guidance. Upon completing the procedure correctly, users receive a monitoring panel displaying affected areas.

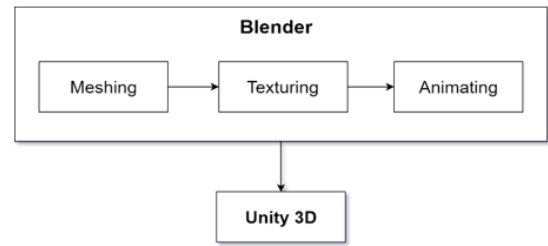
- 2) User Guide – Provides instructions on effectively using the VR tsunami mitigation simulation. Users enter the instructional environment and follow guidance steps, with narrative panels offering text and audio explanations.
- 3) Application Info – Displays general information about the simulation, including its objectives, features, and developer details.

### 2.2.3 3D modeling

The 3D modeling stage involves designing object models to be used in the Virtual Reality tsunami disaster mitigation simulation. This stage not only includes independently creating objects but also utilizes 3D environmental data of Teluk Penyu Beach obtained from Muhammad Yudhi Rezaldi's research on Unmanned Aerial Vehicle (UAV) and Photogrammetric Technique for 3D Tsunami Safety Modeling in Cilacap, Indonesia [15]. Additional independently modeled objects include oceanic conditions before a tsunami, tsunami waves, and post-tsunami flooding. Other disaster indicators such as flocks of birds and stranded fish during tidal shifts are also incorporated. The objects will be modeled using Blender 4.2, which enables a wide range of functionalities, including modeling, animating, rendering, texturing, skinning, rigging, weighting, non-linear editing, scripting, post-production compositing, and much more [16]. Unity3D will be used for compiling and refining all 3D assets. The 3D modeling system follows these phases:

- 1) Meshing: Creating mesh models for objects. Low-poly meshes for animals (e.g., birds and fish) and vehicles optimized performance.
- 2) Texturing: Applying colors and UV map textures to objects to match real-world appearances, such as terrain and water.
- 3) Animating: Developing object animations to simulate specific processes, such as tsunami waves and birds flock.
- 4) Integration into Unity: Transferring finalized

objects into Unity for simulation use. Figure 5 illustrates the 3D modeling process.

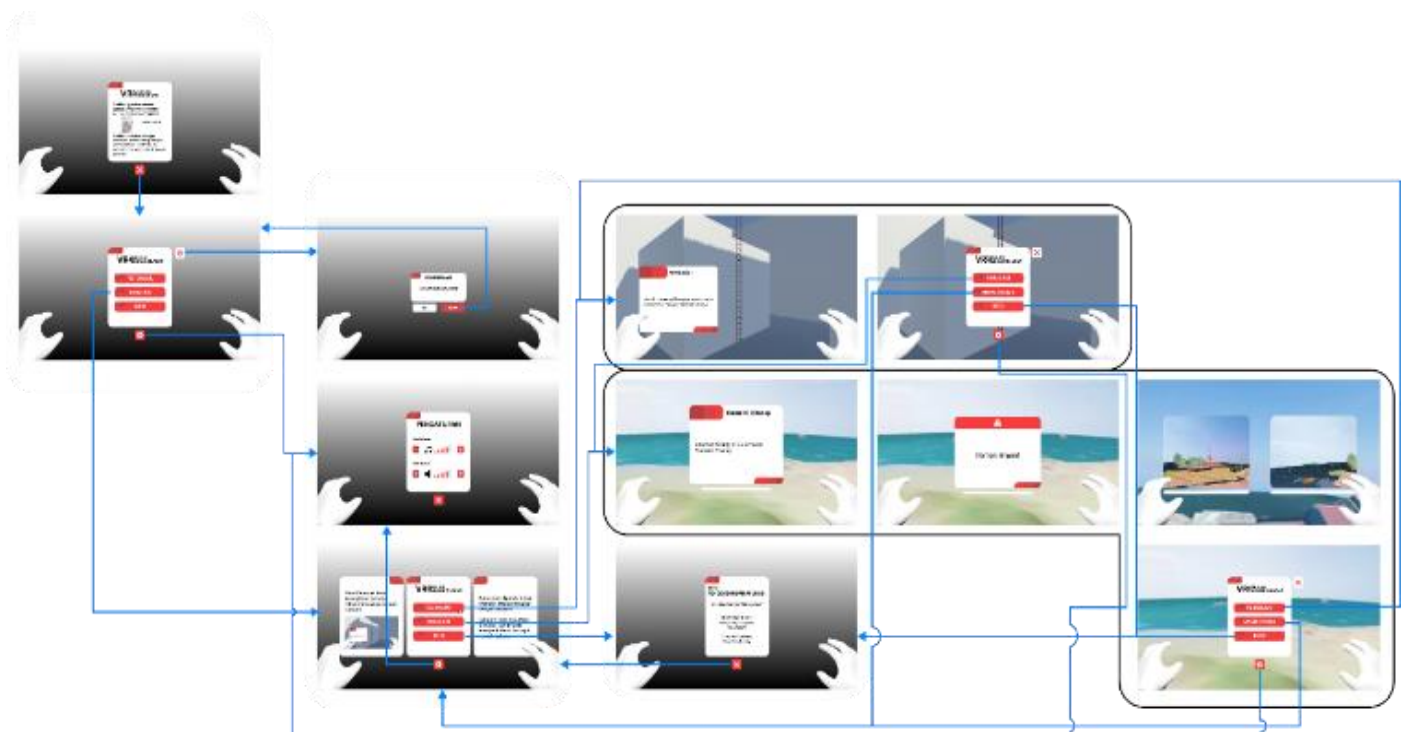


**Figure 5.** 3D modeling process

### 2.2.4 UI/UX Design

The application design adopts a flat design concept that is simple and minimalistic, incorporating Human-Computer Interaction (HCI) principles to ensure the application can be operated comfortably while emphasizing readability, consistency, and ease of interaction, such as high-contrast colors, consistent panel layouts, and visual-audio cues to confirm user actions [17]. This approach ensures accessibility for users across different age groups, particularly adults and older users. Readable typography, clear feedback, and a minimalist layout contribute to an intuitive and comfortable user experience [18, 19]. Flat design features include minimal textures and 3D effects, clear icons and graphical elements, symmetric layout, and intuitive navigation.

The UX design principles applied to VR include User-centered design, Consistency, Hierarchy, Comfort of the users, and Empathy [15]. The UI/UX development stage is based on Applebee's theory [20, 21], which involves several phases: beginning with the wireframe, serving as the foundational layout for the interface design; followed by the visual design, which provides a realistic visual representation based on the wireframe; and concluding with the blueprint, which outlines the flow of user interaction for each UI element, as illustrated in Figure 6.



**Figure 6.** UI blueprint



## 2.3 Material collecting

At this stage, relevant data and materials are collected, including academic literature and input from BRIN researchers. Visual assets such as 3D models, visual effects, and 2D images, along with audio materials like sound effects and instructional voice-overs, are compiled within the Unity application's Assets window.

## 2.4 Assembly

All collected assets are integrated and developed in Unity. A virtual environment is built using OpenXR to support interaction with the Oculus Quest 2. Interactive elements such as navigation and object collision responses are implemented. Audio effects are synchronized with user interactions, and visual enhancements are applied using the Universal Render Pipeline (URP), visual effects (VFX), and post-processing.

## 2.5 Testing

This stage ensures the application functions as designed. Testing is conducted on the Oculus Quest 2, using black-box testing to verify that each feature performs according to its specifications [22].

## 2.6 Distribution

The final application is exported as an APK file for Android and initially distributed via cloud storage (e.g., Google Drive) along with an installation manual for Oculus. For the long term, submission to the Oculus App Store is planned, requiring compliance with Oculus guidelines, including performance optimization and content review. Target users include coastal residents, schools, and BPBD Cilacap staff. Potential collaborators, such as BPBD and local non governmental organizations (NGOs), will facilitate workshops to promote adoption.

# 3. RESULTS AND DISCUSSION

## 3.1 Development result

This In the design of this final project, several stages were carried out in accordance with the MDLC method. During the concept stage, an analysis was conducted on the existing system related to tsunami disaster mitigation in Cilacap. The results of the analysis were developed into several menus or features within the proposed VR system. At this stage, a needs analysis for application development was also performed. Once the analysis stage was completed, the process proceeded to the design stage.

The design stage began with the creation of an overall application flowchart, followed by the development of several UML models, including use-case diagrams, activity diagrams, class diagrams, and object diagrams. Subsequently, the design of 3D models and the required UI/UX was carried out. The 3D models were categorized into several types, including environmental models, organic models supporting simulation, non-organic models supporting simulation, and evacuation support models. The UI/UX design adopted a simple and minimalist flat design concept, incorporating HCI principles such as high-contrast colors (e.g., black text on white

backgrounds), consistent panel layouts, and visual-audio cues. to confirm user actions. These elements enhance readability, consistency, and ease of interaction, ensuring the application is user-friendly for all users as shown in Figure 7. The UI/UX design process started with wireframe creation, followed by visual design, and concluded with the development of a blueprint.

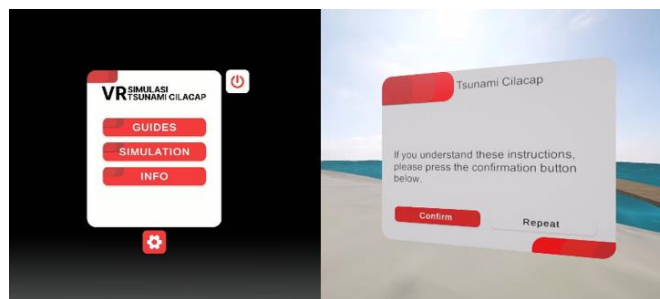


Figure 7. UI/UX design

In the material collection stage, the necessary assets were gathered and created based on the design. The collected or created assets included visual assets, such as 3D models, images, and visual effects, as well as audio assets, comprising sound effects and audio instructions.

All collected and created assets were then integrated during the implementation stage, which utilized Unity3D comprehensively. In this stage, the virtual environment was developed using the OpenXR API. This was followed by the development of interactions, including UI interactions and interactions with triggers on colliders. To achieve more realistic sea waves and tsunami effects, experiments were conducted using water physics simulation programs in Unity. However, these caused lag and performance issues. As an alternative, 3D mesh animations and shader graphs were employed, resulting in visuals closely resembling actual tsunami waves, as shown in Figure 8, while maintaining lightweight program performance.

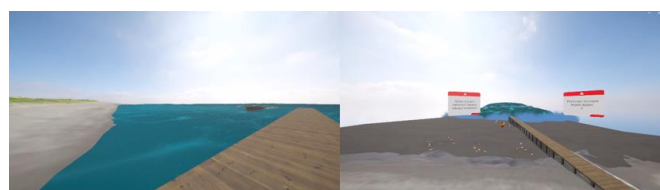


Figure 8. 3D tsunami mesh animation

To create the foam effect of tsunami waves, VFX particles were used, as depicted in Figure 9.



Figure 9. Foam effect

Additionally, post-processing was applied to produce darker and blurrier visuals for users' eyes when struck by the tsunami.

The testing stage was conducted after the implementation stage was completed. The purpose of this stage was to ensure the system functioned as intended according to the design. Testing was performed using an Oculus device directly connected to the project. If errors in the program or system were identified during testing, revisions were made until the system aligned with the design.

Once the project outcomes met the design requirements during the testing stage, the next stage was distribution. To make the application accessible to users, the VR project was built for the Android platform, generating an APK file that

could be installed on Oculus devices. The distribution stage was divided into two schemes: a short-term scheme involving the distribution of the APK and a manual book via Google Drive, and a long-term scheme involving the distribution of the application through the official Oculus App Store.

### 3.2 Test result

The application testing was conducted using the black box method, with the primary focus on ensuring that each feature and function of the application works according to specifications without examining the internal code. Table 1 contains the list of black box testing features.

**Table 1.** The list of black box testing features

| No. | Feature Tested                            | Expected Output  | Test Result |
|-----|---|--|-------------|
| 1.  | VR Navigation                             | The user moves in the virtual space according to the direction provided by the thumbstick. | Success     |
| 2.  | Switch to User Guide Virtual Room         | The user switches from the main menu room to the user guide room.                          | Success     |
| 3.  | Switch to Tsunami Simulation Virtual Room | The user switches from the main menu room to the tsunami simulation room.                  | Success     |
| 4.  | Display Info Panel                        | The Developer Information Panel appears.   | Success     |
| 5.  | Exit Application                          | The Tsunami Simulation VR application is terminated.                                       | Success     |
| 6.  | Display Settings Panel                    | The Settings Panel appears.  | Success     |
| 7.  | Increase and Decrease Sound Effect Volume | The sound effect volume decreases or increases according to the selected button.           | Success     |
| 8.  | Mitigation Procedure Program              | The procedure program aligns with the flow of the tsunami disaster mitigation simulation.  | Success     |
| 9.  | Sound on Simulation Narration Panel       | Voice-over narration sound is heard when the narration panel appears.                      | Success     |
| 10. | Walking Sound Effect                      | Sound effect is heard according to the type of surface the user's character steps on.      | Success     |
| 11. | Wave Crash Foam Effect                    | Visual wave crash foam appears accompanied by crash sound.                                 | Success     |

## 4. CONCLUSION

Based on the design outcomes of the VR application for tsunami disaster education and mitigation at Teluk Penyau Beach, Cilacap, it can be concluded that a VR-based application has been successfully developed for tsunami disaster mitigation at Teluk Penyau Beach, Cilacap. This application serves as an educational medium for learning about tsunamis and their mitigation measures. With a simple UI/UX design, the application is crafted to enhance readability, consistency, and ease of interaction, making it accessible and user-friendly for diverse community groups.

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