Immersive Situated Analysis of Dams' Behavior

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***Abstract*—Dam safety control is a complex and challenging task that involves the analysis, monitoring, and behavior prediction of the various components of dams. Its primary objective is to ensure the safety and optimal performance of these structures. This undertaking involves the abstraction and interpretation of extensive structural, hydraulic, and geotechnical data, typically acquired through sensor networks embedded within the dam. This study introduces 'DamVR', a virtual reality tool for situated dam safety control data visualization. This tool allows dam engineers and other industry professionals to analyze the fluctuation of structural behavior over time. Its immersive environment contains a realistic representation of the dam structure, networks of sensors, and surroundings. It aims to frame the data within the visual context of the object of the analysis. This contextualization is intended to improve analytical reasoning and decision-making. The usability of DamVR was evaluated by a group of domain experts and compared to an existing augmented reality tool in similar tasks. The results indicate that DamVR is a usable and effective dam safety control data visualization tool.**

***Index Terms*—situated analysis, virtual reality, immersive visualization, dam safety control, structural health monitoring**

I. Introduction

Dams are a testament to human engineering prowess. They play a vital role in the management of water resources. These critical structures serve multiple purposes, such as water storage, flood control, and hydroelectric power generation. Concrete dams are a subset of these structures. They are robust and immense engineering constructions designed to withstand high water pressure and ensure long-term stability. Due to their unique structural characteristics, they have exceptional resistance to erosion, corrosion, and seismic forces, ensuring the safety of downstream communities. As such, it is of utmost importance to ensure their integrity and safety.

Dam safety control consists of the analysis, monitoring, and behavior prediction of the different components of dams. It aims to ensure its safety and correct operation by continuously monitoring various parameters. These parameters include water levels, stresses, displacements both in the structure and in the foundation, relative movements in joints and cracks, temperatures of the air, concrete strains, foundation uplift, and dynamic accelerations, among many others [1].

Dam safety control often implies the abstraction and interpretation of vast structural, hydraulic, and geotechnical datasets. These datasets result from the sensor networks installed inside and outside dam structures and surrounding areas. The analysis of idioms representing such data is typically carried out using 2D screens, keyboard, and mouse. These idioms are also isolated, with no visual reference to the area of the dam being analyzed. This lack of contextualization offers limited understandability in a domain where spatial awareness is key.

Using technologies such as virtual reality (VR) for visualizing dam data may have advantages over conventional means, especially when allied with realistic digital models. It can provide an immersive situated analysis, where the data is framed within the visual context of the object being examined (the dam). This contextualized analysis can potentially improve analytical reasoning and decision-making [2].

This work presents DamVR, an interactive proof-of-concept VR prototype tool that takes the first steps to situated data analysis in dam safety control. This tool was developed in cooperation with the Concrete Dams Department (CDD) from the Portuguese National Laboratory for Civil Engineering (LNEC). LNEC is responsible for the safety control of most of the Portuguese concrete dams. One is the Cabril Dam, a double curvature concrete arch dam in the Zêzere River in Portugal. This dam was used as a case study for evaluating DamVR.

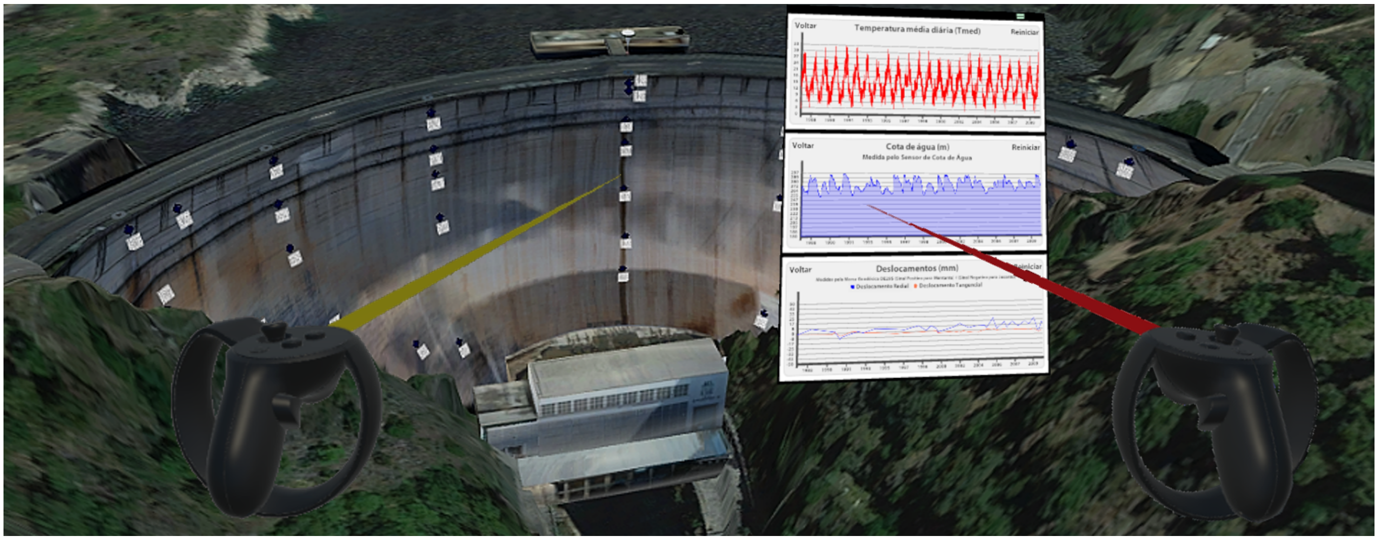

Fig. 1. Overview of DamVRs' immersive environment (mockup). Users can visualize the sensor networks located inside the structure and in the downstream face of the dam. When they selecting a specific device, floating panels with the evolution of measured values over time, together with air temperatures and water levels, are shown.

The tool is specifically aimed at visualizing the evolution of the structural behavior of dams, including seismic events. It is directed at structural engineers and other professionals involved in the dam safety control activity. It provides them with an immersive environment and a natural interface for situated exploration of time-dependent datasets without having to go to the physical location of the dam.

The exploration is carried out in the visual context of the dam, using a realistic 3D digital model of the structure and surrounding terrain. The tool allows users to travel around the structure and explore its interior, including the networks of sensors. They can select specific sensors (e.g., accelerometers or plumblines) and visualize the evolution of the registered data (e.g., horizontal displacements) (Figure 1).

Apart from presenting DamVR, this work addresses the evaluation of the tool's usability by 22 domain experts. It also extends prior research by Verdelho Trindade *et al*. [1], by comparing the performance of DamVR to an augmented reality (AR) tool in similar tasks. As such, the major contribution of this study is **a novel tool that represents a first step towards the development of a fully-fledged immersive situated analysis system for dam safety control**.

II. Related Work

The field of dam engineering has witnessed significant advancements in recent years, driven by the increasing need for reliable safety control systems. A considerable body of research has concentrated on enhancing dam data visualization, abstraction, and analysis with the help of extended reality (XR) technologies [3]. These studies frequently involve the development of realistic dams and hydrographic basins models and simulations. With that objective, many of these models use drones and LiDAR (Light Detection and Ranging) to collect spatial data accurately. They are also often natively integrated with building information modeling (BIM) and heavily use sensor data [4].

A. Engagement and Participation

An example of the use of VR in dam safety control is the work developed by Spero *et al*. [5]. They focused on realistic modeling and simulation of dam failures as a way of communicating the safety risks to the general public and decision-makers. With that objective, they simulated historical dam disasters using accurate hydraulic and structural simulation models combined with spatial data collected using drones. Janovsky *et al*. [6] also addressed the use of VR for demonstrating the dam project landscape impact to the general public. They used historical maps to support the development of an immersive environment representing a 1670 km2 basin and simulated its geomorphic evolution over more than 60 years.

Macchione *et al*. [7] studied the use of VR for risk communication with the players involved in urban flood hazards resulting from dam collapses. They developed a highly accurate simulation of a hydrographic basin based on LiDAR data. This model can be used inside an immersive environment to encourage the active involvement of interested parties in flood management planning.

B. Realistic Modelling and Simulation

Other studies have focused on the efficient transposition of data between engineering design elements and immersive environments. Such is the case of the work by Lin and Chen [8], who developed a process for facilitating the transition between gravity dams' technical CAD drawings and 3D models for VR. Zhao and Zhang [9] focused on developing VR models to simulate dam construction. They also used technical drawings to accurately simulate aspects like the different stages of foundation excavation.

The integration between BIM and 3D models for XR was addressed by Wang *et al*. [10]. They developed a framework for quickly adapting technical drawings into virtual elements for immersive environments. The system was evaluated within the inspection of a steel slit dam located in Taiwan. The visualization of experimental results of groundwater flow in small-scale models of dams was tackled by Marques *et al*. [11]. They used AR to represent, superimposed to real-life models, flow lines, calculated using the finite element method, illustrating the seepage phenomena [12] in embankment dams.

C. Construction Inspection and Management

Lin *et al*. [13] studied the application of XR technologies to the quality control of earth and rockfill dam construction. They developed an AR system that evaluates earth compaction quality during construction. The system relies on real-time data provided by positional sensors installed on compaction roller machines. Likewise, Wang *et al*. [14] focused on the productivity management of cable cranes in dam construction projects. They took an AR vision-based approach to identify and optimize the movement of crane buckets to reduce operational costs.

The use of AR in dam construction inspection was also addressed by Ren *et al*. [15]. They focused on structural feature extraction and matching to identify positional errors during concrete arch dam construction. The system allows an inspector wearing an AR headset to view, superimposed to what is being built, what was envisaged in the project design. Zhong *et al*. [16] used AR for simulating the construction schedule of core rockfill dams. They superimposed the models of the different construction phases foreseen in the design, to reality, to detect non-conformities. Their work was tested on a large hydropower project in southwest China.

D. Safety Control

The monitoring of the safety of dams using XR technologies has also been addressed in recent research. Verdelho Trindade *et al*. [1] focused on on-site visualization of structural health monitoring information superimposed to the actual dam. They used AR technologies to represent the sensor networks on top of the dam face and visualize the evolution of measured structural displacements. A subsequent VR tool with similar functionality was also developed by Leitão [17]. These tools were used as a base for the current study.

Wang *et al*. [18] addressed the use of VR in dam monitoring both during and after construction. They built an immersive environment that allows the user to travel inside the structure of dams. The system displays the location of structural sensor networks and allows users to track the values measured in those sensors. The use of AR in maintaining dam components like pipework, valves, and appurtenant structures was addressed by Goff *et al*. [19]. They developed a mobile AR system that assists inspectors in locating devices and recording values and occurrences.

III. System Overview

The proposed system, DamVR, is a situated immersive data analysis prototype tool for dam safety control. It is aimed at visualizing the evolution of the structural behavior of dams, including seismic events. The prototype was designed for professionals involved in the dam safety control activity, including civil and structural engineers. The prototype focuses on integrating the data with the visual context of the object of analysis.

Inside the virtual environment, the users are initially placed in front of the dam's downstream face. Using the controllers, they can travel around the dam structure and the surrounding landscape. They can turn on or off the visibility of each type of sensors networks, which will be highlighted in the dam structure. They can also use the 'X-ray' tool, which allows the users to point the controller to a specific portion of the structure, which will become semi-transparent with the sensors inside visible.

The range of networks covered by DamVR includes geodetic marks, plumblines (and their respective coordinometer bases), GNSS antennas, uniaxial and triaxial accelerometers, leveling marks, and water elevation sensors [20]. These devices and sensors are represented with accurate geometry, orientation, and positioning in relation to the dam structure. When a sensor is selected, panels with additional information are shown. These panels incorporate idioms that represent the evolution of measured values over time.

In this section, we present the system's general architecture, its implementation, and the characteristics and functionalities of the user interface.

A. Architecture

DamVR was developed using the Unity game engine and the C# programming language. These choices allow maximum compatibility with different VR headsets models. Its architecture is depicted in Figure 2. It is composed of the following parts:

- The immersive environment mimicking the hydrographic basin, where the user can move freely. It is used as a spatial reference during the analysis;
- The dam and surrounding landscape, including the main structure, terrain, and water;
- Sensor networks, composed of models of geodetic marks, plumblines, GNSS equipment, and accelerometers;
- A set of floating panels where the displacements, vibrations, and accelerations charts are represented, but also where the user can get information regarding the selected elements;
- A management module, which is responsible for parsing the data received from a structural health monitoring (SHM) database and translating the positional data from the VR equipment to the immersive environment. This module is also responsible for synchronizing states between the dam models, sensor networks and information panels.

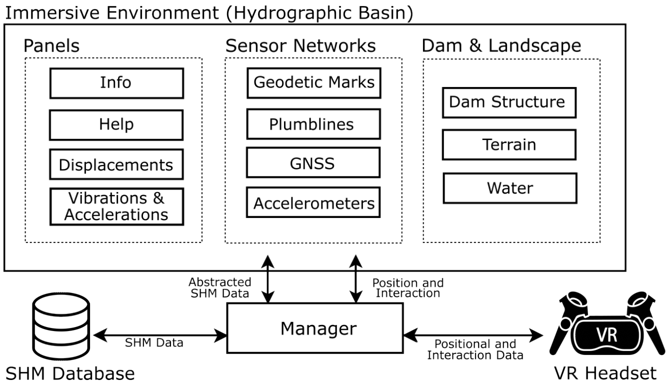

Fig. 2. DamVR system architecture.

As the user interacts with the sensor networks and selects a specific sensor, the management module fetches and parses the necessary data from the SHM database. The abstracted data is then represented in the respective panels, namely charts with the evolution of measured values. As the user interacts with the panels (*e.g.,* selects a specific time frame on the charts), the management module updates the temporal scope by requesting the necessary data subset to the SHM database.

B. User interface

As previously mentioned, the users are placed in a virtual representation of the hydrographic basin where they can interact with the sensors inside and outside the dam structure (Figure 3). They can move around freely using controller-based locomotion [21]. However, if they want to move to a spot furthest from their current position, DamVR also supports teleportation-based locomotion.

The selection within the immersive environment is carried out using raycasting [22]. This technique is applied through the representation of visible beams emanating from both VR controllers. The users can point these beams to the interface component they want to select and interact with. For example, for teleportation, the users can direct the beam associated with the right controller to the spot on the model where they want to be transported.

The user interface is formed by the following components: model, sensor networks, floating panels, and idioms. The complete set of interface components inside the immersive environment is described below.

1) Model: The model is generally made up of three parts: the dam, terrain, and water. The first, the dam structure, is where most user interaction occurs. As such, its representation in the immersive environment needed to be as accurate as possible. The virtual model of the structure was executed from a point cloud resulting from 3D scanning field campaigns carried out by LNEC at the Cabril Dam. In those campaigns, the data acquisition was made using laser scanning. The acquired point cloud data was processed to remove noise, outliers, and artifacts, to ensure the quality and accuracy of the data.

The next step was surface reconstruction. A mesh representation of the structure was generated using reconstruction through surface-based methods [23]. Once the surface was reconstructed, further processing was required to refine and optimize the mesh. This processing included smoothing, decimation, and hole filling to enhance the quality of the mesh representation.

The following stage consisted of applying a texture to the 3D structure object. The texture was created by mosaicing a set of photographs of the dam, captured with a multisensor laser scanner. A photo mosaic was thus obtained. Lastly, texture mapping was carried out based on assigning the texture coordinates to the 3D object.

The completed model was exported to a file type (.fbx) compatible with the graphics engine. The model was then imported to the Unity engine environment and edited according to its dimensional and positional characteristics in real life. In particular, it was positioned in the correct vertical (YY) coordinate (using as reference the central point of the crest at an elevation of 295 meters). It was also scaled to make a meter correspond to a unit in the graphics engine. In the subsequent steps, these adjustments allowed a more direct transposition of the elements existing in reality to the model.

The landscape surrounding the dam structure was also modeled following similar steps. A terrain mesh was initially created using elevation data. This mesh was then processed so that the model of the dam structure would fit seamlessly into the terrain. This task was carried out using Unity's terrain tools.

A mosaic of aerial photographs was then used to create the terrain texture. This texture was applied as a base layer to the terrain mesh to ensure the terrain hues were as close to reality as possible. On top of this base layer, a second layer of 3D elements of trees, bushes, undergrowth, and rocky outcrops was added. Due to the vegetation density, this second layer is graphically heavy. The level of detail of this layer can be adjusted during runtime to ensure acceptable performance, even on computers with lower specs.

The last element of the immersive environment model consists of the bodies of water. The reservoir (upstream water body) and the river (downstream water body) are represented.

Fig. 3. The Cabril dam representation [17, p. 5] in DamVR.

While the model depicts the river by a simple static plane, the reservoir level has a more complex geometry. Because the upstream water level varies over time, a flat mesh had to be built programmatically so that the intersection with the dam structure is adapted dynamically.

2) Sensors: The sensor networks are a central element of the interaction in DamVRs' immersive environment. A wide range of sensors and other measuring devices was addressed in the prototype. While other existent XR applications [1] represented sensors symbolically, in DamVR, this equipment is depicted in a geometrically accurate way (Figure 4).

Three types of sensoring equipment are represented in the prototype: sensors for measuring structural displacements, for determining accelerations, and for registering water levels. The first type includes geodetic marks, plumblines, GNSS equipment, and leveling marks. The second type is comprised of uniaxial and triaxial accelerometers, as well as data acquisition units. The third type includes water elevation sensors.

Some of these sensors, located outside the dams' structure, are always visible when the users are in front of the downstream face. Others are initially occluded inside the structure. Occluded sensors can be revealed by pointing the selection beam at a portion of the structure and activating a kind of 'X-ray' functionality. That portion will become semi-transparent, revealing the sensors inside. When hovered with the selection beam, the individual sensors are highlighted with a bright color. The sensors can then be selected by pressing the trigger button in the controller.

3) Panels: When the user selects a specific sensor, an interactive panel is displayed detailing the characteristics of that sensor. The set of information shown on the panel includes the name of the sensor (*e.g.,* 'FPI4'), its type (*e.g.,* 'plumb line'), orientation (*e.g.,* 'inverted') and relative order (*e.g.,* 'position 4'). The panel also includes toggle buttons for accessing sensor readings, additional information about the sensor, and help on how to interact with DamVR.

When toggling the sensor readings button, a new panel is shown in the immersive environment. This panel contains a set of interactive 2D idioms containing the evolution of measured physical quantities over time (or for a localized dynamic event, like an earthquake, in the case of accelerometers). These idioms are detailed in the following section.

If the users select the additional information option, a new panel will display the type of physical quantities the selected sensor measures. The new panel also contains the last recorded value for each one of those quantities and the date when the values were registered. If the selected sensor is an accelerometer, the dates and epicenters of earthquakes are shown instead.

Fig. 4. Some of the sensors that are represented in the immersive environment. From left to right: leveling marks, water elevation sensors, and GNSS equipment [17, p. 34].

The help panel contains simple instructions on how to interact with DamVR. Among other aspects, it depicts diagrams illustrating the purpose of each controller button. These diagrams cover the interaction when navigating the immersive environment or selecting and positioning the different panels.

The panels share general interaction characteristics. As such, when the users point the selection beam to a panel, its border is highlighted to hint that the panel is open for interaction. A number of interactions are then possible. By pressing the trigger button on the controller while pointing to the panel, the users can drag it and position it in the space around them.

Dragging a panel will keep it at the same distance from the user. The panel will also automatically rotate so its front keeps facing the user. However, while a panel is being dragged, pushing the controller's thumbstick up or down will change its distance to the user (increase and decrease the distance, respectively). Likewise, pushing the thumbstick left or right will change the scale of the panel (the left will decrease the size, and the right will increase).

4) Idioms: As previously mentioned, when the sensor readings panel is toggled, a set of interactive 2D idioms containing the evolution of measured physical quantities over time is shown. For all sensor types except accelerometers, this set includes three different idioms organized vertically: a line chart with the evolution of average daily air temperature, a single area chart with the upstream water level, and a line chart with the radial and tangential displacements.

In the case of accelerometers, a single idiom is shown. This idiom is a line chart depicting the readings on the sensor for a collection of time-localized seismic events. For uniaxial accelerometers, a single line is shown for radial acceleration. For triaxial accelerometers, lines pertaining to radial, tangential, and vertical accelerations are represented.

The idioms have multiple levels of interaction. For example, users can direct the selection beam at a point in the chart if they want information regarding a specific measurement (*e.g.,* the horizontal displacement at a specific point in time). A tooltip will appear containing the timestamp and the respective physical quantity value. The charts can be equally panned (by 'dragging' the chart canvas) and zoomed. A specific time frame can also be zoomed in using a more precise brush-like interaction.

The three idioms share the same timeline on the horizontal axis. The timeline sharing between idioms is key for dam engineers to better frame a specific measurement in the scope of a certain water level and air temperature combination. As an isolated value, *e.g.,* a displacement reading has reduced significance for detecting structural behavior deviations. Because the timeline of the three idioms is bounded, the same interaction is automatically reproduced in the other two when panning or zooming.

IV. Evaluation

The prototype was evaluated through a user study with 22 participants, from which informed consent was obtained. This study aimed to assess the system's usability and compare the results with the ones obtained in an existing study pertaining to an AR tool with similar functionalities. With that objective, domain experts interacted with the prototype and performed predefined tasks. They were requested to complete a feedback questionnaire assessing the prototype's usability characteristics. During the test sessions, quantitative and qualitative data were recorded.

A. Methodology

The study was conducted with an experimental group of dam and structural engineers from LNEC. It took place in a CDD room reserved exclusively for that purpose. Initially, the participants filled out a consent form and a characterization questionnaire with demographic information and their professional experience regarding the safety control of dams. They were then asked to perform predefined tasks using the VR prototype (Figure 5).

The hardware setup consisted of an Oculus Rift VR headset with two controllers and two sensors, which detect the movements of the participant. The VR headset was connected to a desktop computer with an Intel Core i7-8700 CPU @ 3.20GHz processor, 16GB of RAM, and an NVIDIA GeForce GTX 1060 3GB graphics card. A monitor, keyboard, and mouse were also used (for filling out questionnaires).

Each participant was asked to perform a set of two tasks. These tasks matched the ones proposed by Verdelho Trindade *et al*. [1]. The first task (T1) had a broad scope, allowing the user to interact with the different interface levels. For that task, the participants were asked to determine the displacement value measured in a specific type of sensor at a specific position. It required the participant to find the sensor by navigating through the environment, find the correct position for that sensor, browse the panels, and explore the idioms to determine the asked value.

Fig. 5. Participant using the prototype during the evaluation sessions [17, p. 52].

The second task (T2) had a narrower scope. It focused on evaluating the visibility of the sensors in the virtual environment and determining the easiness of recognizing and differentiating each type of sensor. In this task, the user was asked to determine the designation of a sensor located at a recognizable position of the dam.

During the tests, a set of objective metrics were registered. They included the time required to complete each task (measured in seconds) and the number of wrong steps done in each task. A time limit for completing each task was set, representing the time that a dam engineer would predictably take to complete the same task using conventional methods. As they interacted with the prototype, the participants were encouraged to adopt the think-aloud verbal protocol [24] by expressing their thoughts while performing the tasks. These metrics were registered using screen and audio recordings.

After finishing the tasks, the participants removed the VR equipment and were asked to complete a final questionnaire composed of system usability and dam safety control suitability questions. The questionnaire had 22 questions and used a five-level Likert scale for agreement (1:Strongly disagree and 5:Strongly agree).

B. Results and discussion

The group of 22 domain experts was composed mainly of dam engineers (86%) belonging to the different units from the CDD at LNEC, and 14% were other structural engineers. From the dam engineers, 42% belonged to the Modelling and Rock Mechanics Unit, 26% to the Applied Geodesy Unit, 21% to the Monitoring Unit, and 11% to other dam-related research units outside the CDD. All the participants currently worked in or had previous contact with the safety control activity. Only 32% of the participants had former contact with VR, and a mere 14% had used VR in a professional scope.

The results obtained from the individual user-experience questionnaire were framed in seven categories: comfort of use, usefulness in the field of dam safety control, intuitiveness of the interface, discernibility of the different sensors, visual quality of the models, realism of the environment, and immersive sensation. These reflect the different system usability and dam safety control suitability aspects that were addressed. The obtained scores for each category (mean (standard error); median (interquartile range)) were close: comfort (4.45 (.029); 4.80 (1.00)), usefulness (4.48 (.031); 5.00 (1.00)), intuitiveness (4.67 (.025); 5.00 (0.69)), discernibility (4.66 (.025); 5.00 (0.88)), visual quality (4.74 (.021); 5.00 (0.20)), realism (4.45 (.032); 5.00 (1.00)), and immersiveness (4.55 (.027); 5.00 (1.00)). The results are depicted in Figure 6.

These results support the positive usability of the prototype. The participants scoring of the intuitiveness may indicate, on the one hand, the small learning curve of the interface, even for inexperienced VR users (68%). On the other hand, it highlights the potential advantages of situated visualization in improving safety control analysis. Such improvement is achieved through

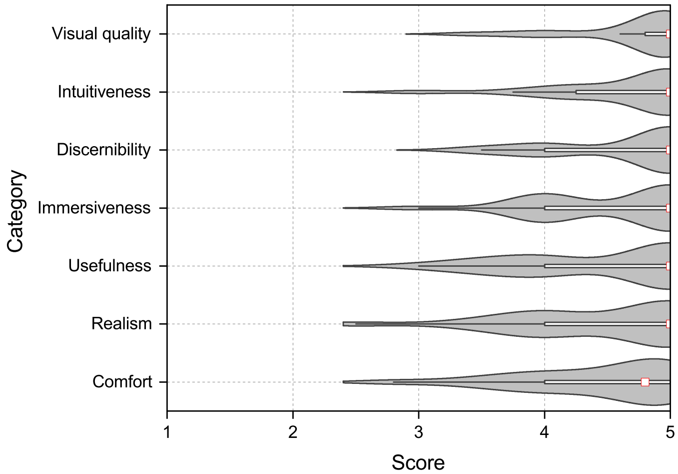

Fig. 6. Distribution of participant's score for each user-experience category.

the ability to frame the data within the visual context of the dam. This conjecture is further supported by the positive scoring that the participants gave to realism and visual quality features.

Regarding objective metrics, the time necessary to complete T1 was significantly higher than the time to complete T2 (medians of 97 and 16 seconds). This difference can be explained by the fact that T1 had a broader scope and a significantly higher expected interaction time. However, more users (95%) completed T1 successfully (within the time limit) than T2 (91%). For T1, the comparison of the registered times with the ones obtained in the previous AR study (Figure 7) shows significantly higher completion times for DamVR (median of 97 seconds against the 20 seconds of AR). For T2, the completion times are similar (medians of 16 seconds for both VR and AR).

The significant deviation between the performance of DamAR and the AR prototype for T1 may be explained by differences between the two prototypes' interface levels, namely in the number of steps necessary to achieve the goal of this task. Indeed T1 required the participant to navigate through the interface in all its depth. This supposition is supported by the fact that the comparative results for T2 (a task that also involved spacial navigation but required fewer steps in the menu system) were similar between the two. One could also argue that because the AR version uses the real dam for situated analysis, it offers advantages in the contextualization of data (even if the visual realism and immersiveness of DamVR were highlighted by the participants).

Concerning the number of errors made by the participants, T1 had a higher number of errors than T2. Less than half (48%) of the participants completed T1 without making any mistakes. In contrast, 95% of the participants completed T2 without any errors. Furthermore, 42% of the participants completed both tasks without making mistakes. The comparison of the registered number of errors with the previous AR study (Figure 8) shows a higher number of errors for DamVR for both tasks.

C. Limitations and Future Work

It is essential to be aware of some of the limitations of this study and the rationale behind the methodological decisions when interpreting the results. The first is that the sample size is relatively small and that the study could have been carried out on a larger scale (*e.g.,* by making the application available online or using engineers from other areas). We opted for a more controlled experimental environment, with a smaller but more uniform sample selection consisting exclusively of domain experts.

A relevant methodological limitation is using a non-standard protocol for the user-experience survey. Using a standard questionnaire, *e.g.,* System Usability Scale (SUS) (although very similar), would allow a more straightforward generalization and comparability of the results. Other methodological limitations include the fact that the results of the VR prototype are compared with the results of another study carried out at a significant temporal distance. Nevertheless, despite this difference, the two prototypes closely share the tested user sample. The interfaces of the two prototypes also have relevant differences in structure and depth.

As previously mentioned, this prototype is just a first step towards developing a fully-fledged immersive situated analysis system for dam safety control. Potential future research directions may include overcoming some of the limitations mentioned above. Future work in the situated analysis of safety control data will also necessarily have to go through

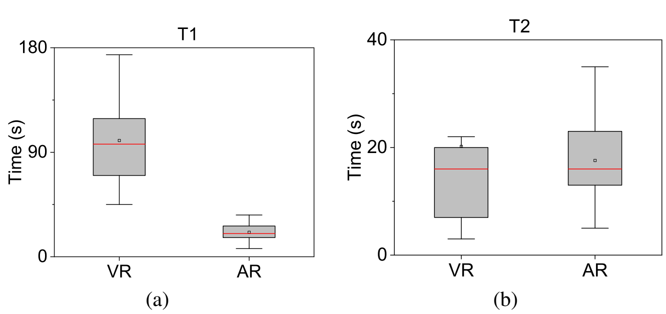

Fig. 7. Comparison between the time required to complete T1 (a) and T2 (b) both in VR and AR.

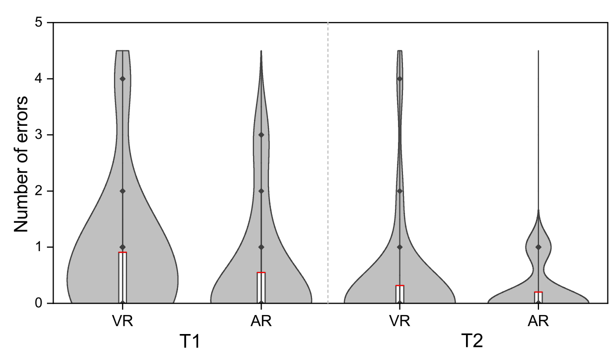

Fig. 8. Number of errors that users made in T1 and T2, both in VR and AR.

the development of photorealistic dam environments and more extensive integration with BIM. Other possible research directions include collaborative and sensor-rich environments.

V. Conclusion

This work presents a novel prototype tool for immersive situated analysis in dam safety control. It discusses its different characteristics, application scenarios, advantages, and limitations. It also addresses the evaluation of the prototype with domain specialists. This evaluation process involves an individual survey to assess user experience. Results show that the prototype is intuitive and comfortable, even for users with no previous VR experience. They also show that it offers a realistic, immersive environment and is helpful in the scope of safety control. Furthermore, its performance results are compared with the ones obtained in a previous study regarding an AR tool. This comparison shows that DamVR offers similar completion times in more straightforward tasks but suffers in performance in more complex tasks. Likewise, its usage shows no improvements in the number of user mistakes compared to the AR version.

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