BIM-based immersive virtual reality framework for understanding hydraulic transients in pressurized pipelines

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BIM-BASED IMMERSIVE VIRTUAL REALITY FRAMEWORK FOR UNDERSTANDING HYDRAULIC TRANSIENTS IN PRESSURIZED PIPELINES

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SUMMARY: *This paper presents a BIM-based virtual reality (VR) framework for the immersive visualization of hydraulic transients in pressurized hydropower systems. The approach integrates three-dimensional geometries derived from BIM models with hydraulic simulations based on the Method of Characteristics. The hydraulic model is implemented in an external computational environment and accounts for key boundary conditions, including upstream reservoir levels, surge tank oscillations, and turbine-related orifice flow at the downstream boundary. Simulation outputs are exported as time-dependent datasets and mapped onto discretized pipeline segments within a game engine platform. Dynamic visualization is achieved through real-time modification of textures and color encoding driven by custom scripts, enabling the representation of pressure wave propagation and flow variations. The framework is applied to a real hydropower plant case study, where users can simulate valve closure maneuvers within an immersive VR environment accessed through head-mounted displays. Results derived from a user study involving 29 participants with diverse backgrounds suggest a high level of perceived usefulness, highlighting how the integration of BIM models, numerical simulations, and immersive VR can support the understanding and visualization of complex hydraulic phenomena in engineering contexts.*

KEYWORDS: *BIM, VR, hydraulic transients, hydropower plants, immersive visualization.*

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1. INTRODUCTION

Hydropower is one of the oldest and most reliable energy sources in the world. Since the late nineteenth century, it has been a driving force behind industrial development in many countries (Edenhofer et al., 2011), and today, in numerous regions worldwide, it represents the primary source for renewable energy generation (IRENA, 2024; IEA, 2025; Berga, 2016).

Compared with highly intermittent sources such as wind and photovoltaic power, hydropower is the only programmable renewable energy source, owing to the storage of gravitational potential energy in water reservoirs. As a result, it plays a strategic role in the energy transition undertaken in recent years to mitigate climate change (Ramião, 2023; Kuriqi et al., 2021; Ugliotti, 2025).

In this context, the design of hydroelectric power plants poses complex engineering challenges that call for collaboration among multiple disciplines. Hydropower plants are complex systems, often characterized by long operational lifetimes, and therefore require advanced tools to support the understanding of physical phenomena as well as design, operation, and training activities.

In particular, understanding the hydraulic phenomena occurring within pressurized conduits represents a significant challenge, especially when unsteady flow conditions are involved. Transient phenomena such as rapid variations in flow rate and pressure, including water hammer effects generated during machine start-up, shutdown, or regulation maneuvers, are usually interpreted through two-dimensional representations (Fang et al., 2008). Although these phenomena have a substantial impact on plant safety and efficiency, they are often not very intuitive, especially for non-specialist users.

In response to these challenges, innovative technologies such as virtual reality (VR) offer new opportunities to enhance the visualization of these phenomena. By enabling the generation and exploration of immersive and interactive environments, VR makes it possible to associate the temporal evolution of hydraulic variables with visual representations directly embedded within the three-dimensional space of the power plant. The ability to observe, in real time, variations in pressure and flow rate along pipes, correlated with operational maneuvers, allows phenomena that are typically abstract or confined to graphs and numerical tables to be rendered visible. Within the digital twin (DT) paradigm, such approaches can also support the visualization of real-time measured data, spatially contextualized within the three-dimensional representation of the infrastructure.

Beyond facilitating the communication of physical phenomena, immersive VR plays a significant role in the training of personnel responsible for the operation and maintenance of hydropower plants. The ability to simulate realistic operational scenarios and to highlight time instants at which pressure values may become critical allows operators to be trained in a safe and controlled environment, thereby reducing risks associated with on-site learning. Through direct interaction with the virtual model of the power plant, personnel can develop greater awareness of plant behavior, improving their ability to recognize abnormal conditions and to understand the consequences of their actions on hydraulic variables.

This approach highlights the potential of immersive VR as an interface for the exploration of increasingly complex digital systems. From this perspective, the integration of VR within a DT framework represents a natural evolution of BIM–VR applications for hydropower infrastructures. The capability to incorporate real-time data within the VR environment opens new perspectives for the visualization of the plant's operational state. Variations in flow rate, pressure, and component status can be directly represented within the three-dimensional space of the facility, enhancing spatial contextualization and establishing a direct relationship between physical variables and the infrastructure configuration.

Immersive VR enables users to experience the infrastructure within a fully three-dimensional space, where components are perceived at real scale and in their actual spatial configuration (Millais et al., 2018). This interactive capability enhances the perception of cause–effect relationships between control actions and hydraulic responses. Such characteristics facilitate the understanding of plant components, control devices, and the overall extent of hydropower systems, while reducing the level of abstraction typically associated with conventional representations. By integrating spatial and temporal information within a single perceptual framework, immersive VR supports a more intuitive interpretation of complex and dynamic hydraulic processes.

Against this background, this study aims to investigate the effectiveness of immersive VR in the context of unsteady flow in pressurized systems, whose transient nature contributes to making its interpretation complex even for experienced operators. In this way, VR is positioned not only as an advanced visualization tool, but as a cognitive support for the analysis of hydraulic processes.

The adoption of immersive VR through head-mounted display (HMD) devices is motivated by the need to overcome the limitations of conventional screen-based visualization in representing complex and spatially distributed hydraulic phenomena, such as the reduced capacity to intuitively relate system geometry to the temporal evolution of hydraulic variables. HMD-based systems allow users to engage with the virtual environment from a first-person perspective, enhancing immersion and spatial perception.

The proposed application is primarily conceived as an introductory training tool for technical personnel, aimed at supporting the understanding of fundamental hydraulic principles and system behavior during transient conditions. At the same time, the accessibility of immersive VR technologies and the adopted development approach make the application suitable for a broader audience, including non-specialist users, thereby extending its potential use beyond domain-specific training contexts.

However, the effectiveness of VR applications in the context of hydropower plants strongly depends on the quality and structure of the information on which these applications are based. In this respect, building information modeling (BIM) represents a key enabling element for the development of VR environments that are reliable and consistent with the physical reality of the plant. Unlike traditional three-dimensional models, BIM allows the integration of the facility geometry and the technical information associated with individual components within a single digital environment, providing a structured data repository throughout the entire life cycle of infrastructure.

In hydropower plant projects, the BIM model enables an accurate representation of the elements that are relevant for the analysis and visualization of hydraulic phenomena, such as penstocks, control devices, turbines, and ancillary structures.

This detailed and hierarchically structured representation, which is increasingly established as standard practice in the design of large-scale public infrastructures worldwide, constitutes a valuable resource for the development of VR applications. It ensures spatial consistency, accurate geometric scaling, and facilitates user recognition and interpretation of the various system components.

Building on this foundation, the present contribution employs BIM as the basis for the development of a VR application that leverages such structured information to deliver an immersive experience, guiding users in the understanding of the hydraulic phenomena affecting hydropower plants. The main contribution of this work is methodological and technical, as it proposes and demonstrates a structured and replicable workflow for the development of immersive VR applications based on BIM data, through the integration of widely adopted software tools and technologies. In particular, the study focuses on the practical implementation of a BIM-to-VR pipeline, highlighting the role of specific platforms and development environments in enabling data-driven and interactive visualization of hydraulic phenomena.

The paper is organized as follows. Section 2 provides a structured state of the art on VR training for BIM models visualization and interaction data-driven. Section 3 details the proposed methodology, including the BIM-to-Unity workflow. Section 4 presents its application within a real hydropower plant project. Section 5 reports the validation results. Section 6 discusses advantages, limitations, and transferability conditions. Section 7 concludes the paper and outlines future research directions.

2. LITERATURE REVIEW

To support the proposed BIM-based VR workflow for representing method of characteristics (MoC) results in an intuitive and spatially grounded form, this section synthesizes prior work on BIM to VR interoperability, VR for training and operations, data driven DT interfaces, and immersive visualization of time varying hydraulic phenomena.

BIM to XR and game engine pipelines are increasingly used for infrastructure visualization and interaction, because BIM stores geometry together with object identity, hierarchy, and attributes that can be exploited at runtime. In many practical workflows, the BIM export becomes a set of polygonal assets; this improves real time rendering but it often removes semantic structure and stable identifiers, which makes it difficult to attach states and computed variables to the correct components in VR (Graham et al., 2019; Khalili, 2021; Kamari et al., 2021; Inzerillo et al., 2023). Graham et al. formalize a level of detail (LOD) strategy for BIM-derived VR narratives, with a clear link between the intended user experience and the amount of geometric and informational detail that should be preserved, so the model is optimized without losing the meaning of key areas and elements (Graham et al., 2019). Khalili proposes an extensible markup language (XML) based geo-semantic exchange where geometry and required BIM semantics are extracted, optimized for import, and reconstructed as structured VR objects. The method also supports a reverse conversion, enabling the transformation of XML data into IFC format, which directly targets semantic loss during engine import (Khalili, 2021). Similar needs appear in applied studies that use VR enabled by BIM for sustainability and cost assessment, where the VR scene is valuable only if it remains linked to the information model and its attributes (Kamari et al., 2021). For infrastructures, VR is also used to communicate complex assets and to support stakeholder understanding, but these works still highlight that model preparation and information consistency are central issues, not only graphics quality (Inzerillo et al., 2023). In the water and hydropower context, the integration of BIM with automation and asset information is discussed as an enabling layer for management and operations, confirming the relevance of BIM centric information structures for hydraulic infrastructures (Ye et al., 2021).

The integration of geographic information systems within this context further extends these capabilities by enabling geospatial visualization (Çöltekin et al., 2020; Pavelka and Landa, 2024), which supports the monitoring of environmental risks within immersive environments (Mudiyanselage et al., 2025) and facilitates the exploration and interaction with underground infrastructures that are otherwise difficult to access and inspect (Jurado et al., 2017).

VR has been extensively validated as an effective medium for training in industrial and safety-critical domains (Lucas et al., 2008; Urbanek et al., 2025). It supports procedural rehearsal and hazard recognition not only in the architecture, engineering, construction and operation (AECO) sector, promoting the simulation of emergency situations without any exposure to risk (Lorusso et al., 2022; Liu et al., 2025; Masiello et al., 2022; Zhao et al., 2025).

However, the integration of continuous, time-varying engineering states derived from physical simulations remains limited, although some studies show the advantages of viewing dynamic events in immersive digital environments (Fonnet and Prié, 2021; Kraus et al., 2021). This limitation is evident in the field of hydraulic engineering, where current studies focus on simulating laboratory activities (Mirauda et al., 2020) and connecting complex water system concepts with interactive training content and real-time guidance (Rahmani et al., 2025). In water infrastructure, the SmartVerse approach by De Paola et al. frames digitalization as a lifecycle toolchain, where 3D models, BIM, and advanced software services are combined to manage hydraulic infrastructures (De Paola et al., 2024). On the same line, VR frameworks have also been used for water management communication at the urban scale, showing the role of immersive visualization to explain system behavior and management choices in a city context (Pajorová and Hluchy, 2019).

In hydropower, conceptual frameworks for maintenance management emphasize the role of digitalization, records, and smart information systems to improve sustainability and performance, which again points to the need for reliable links between assets and operational knowledge (Singh et al., 2020). These studies reinforce the potential of VR for training and teaching purposes but are limited to steady or quasi-steady phenomena rather than fast transients in pressurized systems, where operational maneuvers and boundary condition changes generate fast waves that must be interpreted with respect to system topology and component locations. Classical references establish the governing equations and the MoC as a standard approach for one-dimensional transient flow analysis, with detailed treatment of boundary conditions and modeling decisions that strongly affect results and interpretation (Wylie and Streeter, 1978). Reviews also show that, despite the maturity of the theoretical and numerical basis, modeling and interpretation issues remain, including dissipation and turbulence response under transient conditions, which contributes to a persistent gap between computed outputs and actionable understanding (Bergant et al., 2006; Watters, 1984). In hydropower, this gap matters because flexible operation is increasingly requested, and this increases the number of unsteady regimes and the need to understand internal dynamics in relation to plant components and operating actions (Karekezi et al., 2025; Singh and Singal, 2017). Hydropower model and control reviews highlight the complexity of hydro turbine and plant behavior under varying conditions, and they motivate the need for tools that support interpretation beyond classical control and simulation outputs (Kishor et al., 2007). Zaman proposes using sonification theory to translate pressure values into sounds, providing an innovative means of presenting transient hydraulic phenomena (Zaman, 2025).

To evaluate the effectiveness of VR applications, several methodological approaches have been proposed in the literature, typically combining quantitative and qualitative measures. In the context of human–computer interaction, standardized instruments have been developed to assess complementary dimensions such as usability, user experience, and perceived workload. One of the most widely adopted tools is the system usability scale (SUS), which provides a rapid and robust measure of perceived usability through a ten-item Likert-scale questionnaire, producing a normalized score that enables comparisons across systems, even with relatively small sample sizes (Brooke, 1996).

To capture a broader perspective on user interaction, more articulated frameworks such as the user experience questionnaire (UEQ) extend the evaluation to both pragmatic and hedonic qualities, offering a multidimensional assessment through semantic differential scales and benchmark comparisons (Schrepp and Thomaschewski, 2019). In addition, the subjective sense of presence in virtual environments is commonly evaluated using instruments such as the Presence Questionnaire (PQ) by Witmer and Singer, which assesses factors including involvement, immersion, realism, and control (Witmer and Singer, 1998), as well as the Igroup presence questionnaire (IPQ) (Schubert et al., 2001).

User discomfort and cybersickness are typically assessed through the simulator sickness questionnaire (SSQ), which requires participants to rate the intensity of various symptoms (Kennedy et al., 1993), and its more recent adaptation for immersive environments, the virtual reality sickness questionnaire (VRSQ) (Kim et al., 2018).

The evaluation models referenced are summarized in the following Table 1.

Table 1: Description of evaluation models for VR applications.

Model	Reference	Aim	Description
SUS	Brooke, 1996	Assessment of perceived system usability	Ten-item attitude Likert scale (5-point scale)
UEQ	Schrepp and Thomaschewski, 2019	Assessment of the quality of the user experience	26 bipolar adjective pairs rated on a 7-point semantic differential scale
PQ	Witmer and Singer, 1998	Assessment of the perceived sense of presence	Multi-item 7-point Likert scale measuring perceived presence in virtual environments
IPQ	Schubert et al., 2001	Assessment of the perceived sense of presence	14-item Likert questionnaire (5-point scale) assessing spatial presence, involvement, and realism
SSQ	Kennedy et al., 1993	Assessment of the perceived cybersickness	16-item symptom checklist rated on a 4-point severity scale
VRSQ	Kim et al., 2018	Assessment of the perceived cybersickness	9-item symptom checklist rated on a 4-point severity scale

The key aspects of these evaluation approaches have been incorporated into the questionnaire adopted in this study to assess the effectiveness of the proposed VR platform, which builds upon the capabilities of immersive technologies highlighted in the literature.

The research context examined shows that existing immersive VR applications in hydropower have primarily addressed maintenance training and operational understanding at the unit level, demonstrating both feasibility and educational value. However, these approaches generally focus on component-oriented procedures, rather than on the visualization of spatially distributed transient variables derived from physical simulation models and explicitly linked to BIM-based assets (Ye et al., 2021; Inzerillo et al., 2023). This gap motivates this study, which investigates the role of immersive VR in improving the understanding of hydraulic unsteady-state phenomena through the integration of simulation data within an immersive and spatially coherent environment.

3. METHODOLOGY

The present study aims to develop a VR application for the representation and analysis of a complex and highly dynamic phenomena, namely hydraulic transients in pressurized conduits. The adopted approach is based on technical data and design parameters characteristic of hydropower systems and leads to the definition of a VR experience with advanced educational and outreach objectives.

The application is designed to allow non-specialist users to gain a qualitative understanding of the main operational criticalities associated with hydropower plant management, with particular emphasis on transient conditions, while also ensuring scalability and applicability across different plant configurations.

3.1 VR application structure

The application was developed using the Unity game engine, by integrating libraries specifically designed to support virtual reality devices. In particular, the OpenXR library was adopted for VR headset integration, while the XR Interaction Toolkit was employed for input management and the implementation of interactions within the virtual environment. These libraries provide open solutions for various headsets. For the present study, the Meta Quest 3 was selected, a HMD equipped with an integrated computational unit, capable of operating in standalone mode without the need for connection to an external computer.

As shown in the methodological scheme in Figure 1, the proposed application aims to innovate the way in which the results of hydraulic simulations are visualized and spatially contextualized relying on BIM models. In addition to the numerical simulation of transient phenomena, the application relies on a three-dimensional model used to highlight the effects of the analyzed processes.

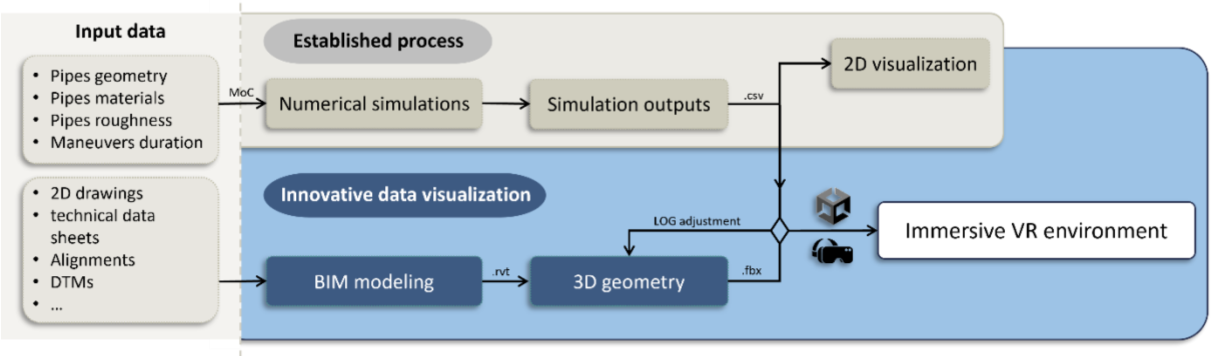

Figure 1: Workflow of the proposed framework combining hydraulic simulations and BIM-based 3D modeling for immersive VR visualization of transient phenomena.

The inputs required for hydraulic simulations are geometric and material data of pipelines and simulation parameters, such as the duration of the valve operation and the total time to be simulated. BIM modeling, on the other hand, requires preliminary project information, such as 2D drawings, alignment data, and digital terrain models (DTMs). Once 3D components have been exported from the BIM model, their level of geometry (LOG) can be adjusted using 3D modeling software to either enhance the realism of the experience or, conversely, to remove excessively detailed and negligible elements that would unnecessarily burden the application while providing limited benefit with respect to the intended objectives. In practice, the extent of this optimization depends on the original BIM purpose; ideally, a BIM model should be authored with only the information needed for the target use case, but when a shared, multidisciplinary BIM is adopted, post-processing is typically required.

The three-dimensional model constitutes the static component of the VR environment, which defines the spatial layout of the environment. On the other hand, the results of the hydraulic simulations form the basis of the dynamic component, which governs animations and user interactions within the virtual space. Figure 2 illustrates how these two domains contribute to the creation of the immersive VR environment.

The static component is built from the BIM model of the infrastructure, imported into Unity in .fbx format. Since this format does not preserve object material information, materials were reconstructed as native Unity assets and subsequently assigned to the various objects in the scene. For each structure, the materials specified during the design phase were digitally reproduced by creating corresponding material definitions within the Unity environment, including color, surface properties, and visual appearance, in order to approximate the intended design materials in a real-time rendering context.

To facilitate interpretation of hydraulic data, key UI elements were anchored to the user's viewpoint, remaining stationary as the user moved. Through text panels, the user interface provides a legend explaining the meaning of the color mappings used in the animations, as well as information on the values of the hydraulic variables being visualized. In addition, text panels are inserted at regular intervals along the penstock, allowing the user to read the hydraulic values at any given moment in time.

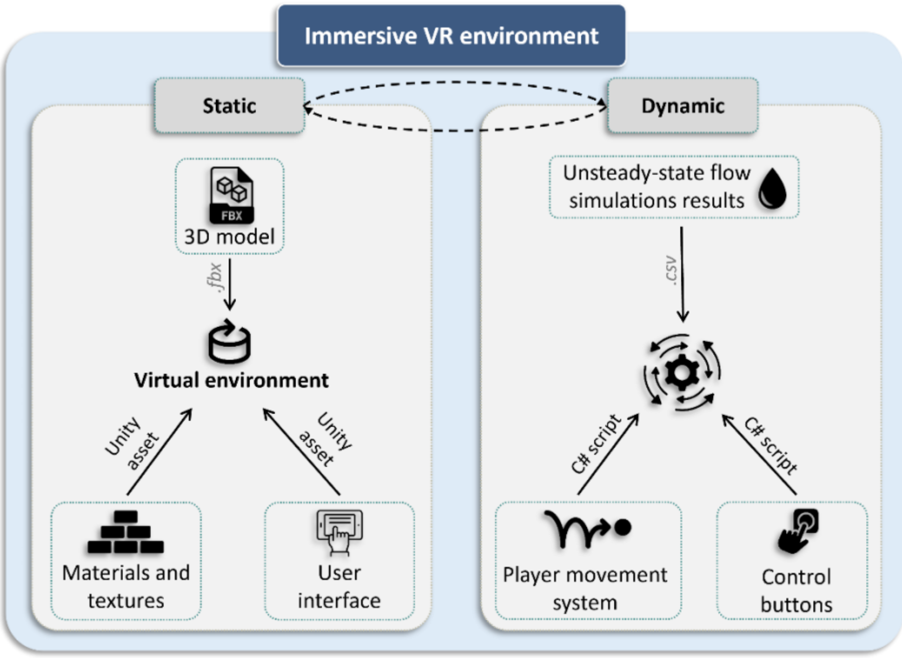

Figure 2: Digital components of the immersive VR environment proposed in this study.

The dynamic component is responsible for reading the results of the hydraulic simulations, which are stored in .csv files describing the spatial and temporal evolution of flow rate, hydraulic head, and pressure. Within the VR application, the transient evolution of pressure provides a direct representation of the corresponding variations in piezometric head along the pressurized conduit. This component also includes the development of C# scripts that control user navigation within the virtual environment and manage user interactions through control buttons, enabling the activation of scenarios and simulation events. User movement is implemented through a free-navigation system that allows the player to move unconstrained within the virtual space, independently of the ongoing simulations. Scenario activation and interaction with the environment are achieved through a ray-based interaction mechanism, in which virtual rays emitted from the VR controllers intersect with interactive panels placed within the scene, triggering the corresponding actions.

The following sections explore the BIM modeling and the development of hydraulic simulations in greater depth.

3.1.1 BIM modeling

The choice of extracting the 3D geometry from a BIM model is motivated by the steadily increasing adoption of the BIM methodology in the design of buildings and infrastructures, making the availability of BIM models increasingly likely in future hydropower plant projects (Wangchuk et al., 2024).

Hydropower plants typically encompass different structures in terms of size and functionality. Among the most critical components is the pressurized pipeline system, within which the hydraulic phenomena being visualized take place, together with the architectural and structural models of the buildings that constitute the facility.

In such systems, complexity arises from the coexistence of elements that require heterogeneous tools, expertise, and methodologies across the design and management phases. In particular, for effective BIM modeling, it is essential to account for the interaction between point-based structures, such as powerhouses and surge tanks, linear elements such as penstocks, and the surrounding environmental context, which represents a determining factor for infrastructures that are closely constrained by territorial characteristics.

Figure 3 outlines the methodology adopted for BIM modeling of the aforementioned components, which were subsequently imported and integrated into the VR scene.

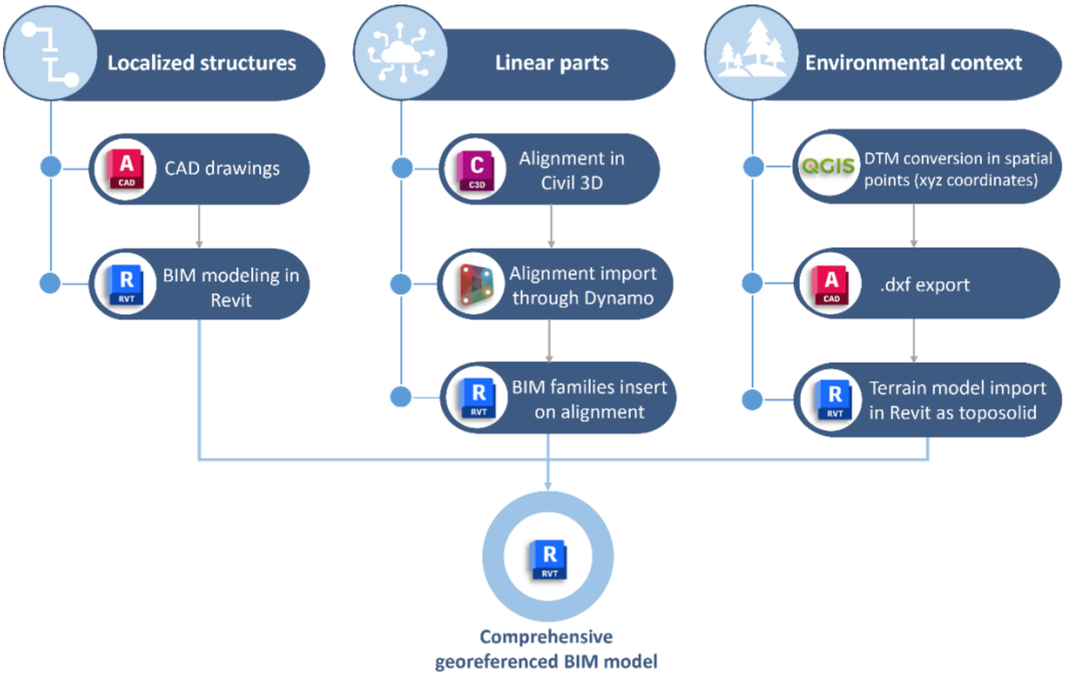

Figure 3: BIM modeling tools workflow for hydropower plants projects.

Autodesk Revit was adopted as BIM authoring platform for aggregating and managing models, owing to its versatility in integrating different design disciplines within a federated environment (Solihin et al., 2016).

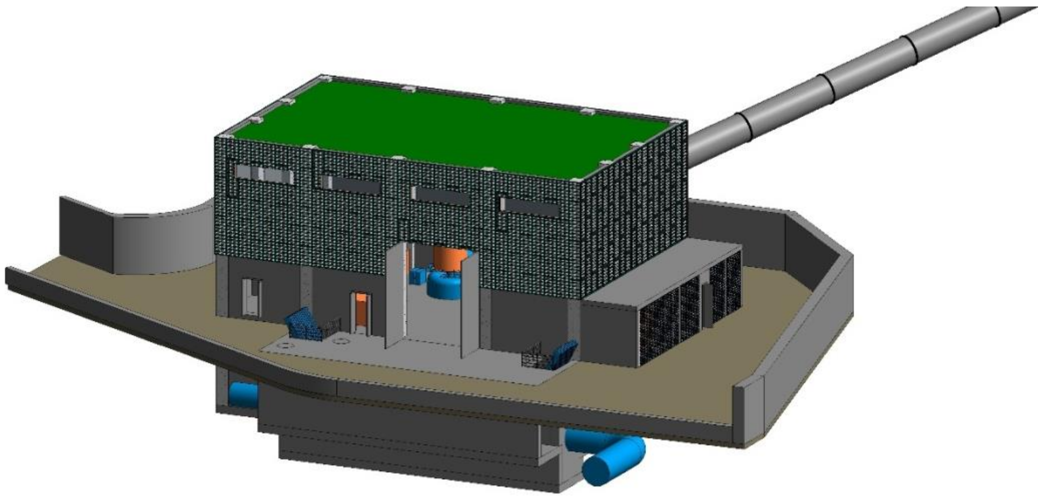

Figure 4: BIM model of a hydropower plant.

The overall dimensions and geometries of the main plant components were reproduced while preserving their shape and spatial orientation, in order to ensure an adequate LOD for a technical and economic feasibility study. However, ancillary equipment of the hydraulic systems was intentionally simplified. Electrical panels and electromechanical equipment inside the powerhouse were modeled only by their overall volume, as the focus of the application is not the detailed exploration of the powerhouse interiors but the visualization of hydraulic phenomena within the penstocks. To avoid unnecessarily increasing the model complexity, the stiffening rings were modeled as simple metallic disks, omitting the joint elements. This choice is motivated by the focus of the application, which is oriented toward the visualization of the temporal evolution of hydraulic phenomena along the entire length of the pressurized conduits, whose extent is on the order of several hundred meters.

The architectural, structural, and plant system models of the hydroelectric power station and the surge tank were developed in Autodesk Revit 2022 starting from two-dimensional CAD drawings, adopting a level of detail consistent with the requirements for visualization and interaction within a VR environment. Figure 4 shows the BIM model of a hydroelectric power plant developed in Revit.

The penstock was also modeled within the Revit environment. However, an automated approach was adopted for this component, which involved importing the alignment of its centerline from Civil 3D into Revit through Visual Programming Language (VPL) algorithms implemented using Dynamo. The BIM model of the penstock was then completed by inserting system families for circular-section pipes along straight segments and adaptive families for the representation of curved connections.

Finally, the terrain model was generated in Revit as a topographic solid, starting from a DTM converted into a set of point coordinates. All developed models were georeferenced and subsequently imported into a single federated project, which was used as the basis for integration and visualization within the VR application.

3.1.2 Hydraulic simulations

Alongside the geometry of BIM models, the results of hydraulic simulations play a central role in the development of the VR application, as they define its dynamic component by determining how hydraulic variables are visualized. The objective of the analysis is to investigate unsteady flow phenomena occurring in penstocks in response to opening or closing maneuvers of the downstream valve, which generate the propagation of pressure surge waves along the conduits and may potentially compromise the structural integrity of the system.

The mathematical model adopted to compute the temporal evolution of flow rate and hydraulic head during unsteady flow conditions is the MoC. This approach allows the system of partial differential equations (PDEs) describing hydraulic transients in pressurized pipelines to be transformed into an equivalent system of ordinary differential equations (ODEs), which is more tractable from a numerical standpoint (Chaudhry, 2014). The governing equations are the continuity equation (1) and the momentum equation (2):

$$\frac{\delta H}{\delta t} + \frac{a^2}{gA}\frac{\delta Q}{\delta x} = 0 \tag{1}$$

$$\frac{\delta Q}{\delta t} + gA\frac{\delta H}{\delta t} + RQ|Q| = 0 \tag{2}$$

Where:

- A is the cross-sectional area of the pipe;
- H is the pressure head;
- t is the time;
- a is the wave speed in circular pipes;
- g is the acceleration of gravity;
- Q is the flow rate;
- x is the distance along the pipeline;
- R is the resistance coefficient.

The transformation from PDEs to ODEs is carried out along the characteristic lines, schematized by the computational mesh shown in Figure 5, by imposing a single value for the ratio dx/dt, according to Equation (3):

$$\frac{dx}{dt} = \pm a \tag{3}$$

By integrating the equations along the positive and negative characteristic lines, Equation (4) and Equation (5) are obtained that allow the flow rate and the hydraulic head to be computed at the central nodes of the computational mesh:

$$Q_P = \frac{1}{2}[C_P + C_N] \tag{4}$$

$$H_P = \frac{Q_P - C_N}{C_a} \tag{5}$$

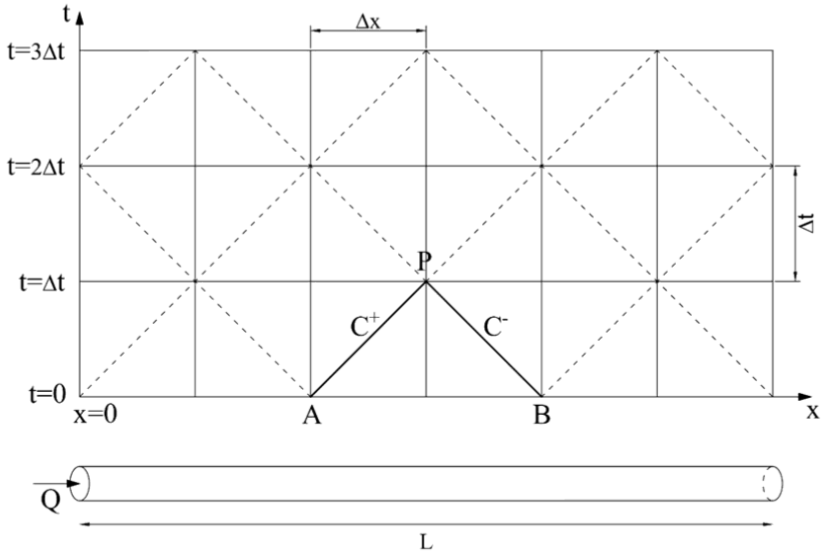

Figure 5: MoC model calculation mesh (adapted from Chaudhry, 2014).

These values describe the temporal evolution of flow rate and hydraulic head at discretized points within the system. From the hydraulic head values, the corresponding pressure values can be readily derived by inverting the equation governing total energy, as shown in Equation (6):

$$h = z + \frac{p}{\gamma} + 2\frac{v^2}{2g} \tag{6}$$

Where:

- h is the total head;
- z is the geometric elevation of the point with respect to a reference datum, such as mean sea level;
- p is the pressure;
- γ is the specific weight of the fluid;
- v is the fluid velocity within the conduit;
- g is the acceleration of gravity.

The velocity is computed from the flow rate and the cross-sectional area of the conduit, as shown in Equation (7):

$$v = \frac{Q}{A} \tag{7}$$

Where:

- Q is the flow rate;
- A is the cross-sectional area of the pipe.

Outputs of hydraulic simulations were organized in tabular form and exported as .csv files, in order to ensure their correct reading and integration within the Unity development environment. The .csv file is organized such that each row contains the simulated flow rate and pressure values at a specific time instant, while each column refers to a specific position along the conduit. The following section illustrates how these values drive the dynamic behavior of the VR application.

3.1.3 VR animations development

This study proposes a visualization of the temporal evolution of hydraulic transients through the dynamic updating of textures applied to penstocks, based on flow rate and pressure values read from the .csv files at each temporal and spatial discretization step. In this approach, the flow rate governs the motion of the texture along the conduit, while pressure controls its chromatic variation.

To support this visualization strategy, photorealistic steel textures were deliberately avoided for the penstock, within which overpressure phenomena occur, in order to assign purpose-designed, color-based textures. These textures were specifically conceived to encode pressure values and to enhance the interpretability of transient hydraulic behavior. To this end, each straight segment of the penstock were subdivided during the BIM modeling phase into short sections whose length, closely matches the spatial discretization used in the MoC–based hydraulic simulations. This correspondence enables a clear visualization of both the temporal evolution of pressure and the propagation of pressure waves along the pipeline, achieved by dynamically updating the color of the texture applied to each segment. In particular, three distinct textures were defined and associated with different pressure ranges: a base texture for values between 0 and 10 bar, and two additional textures for values respectively below 0 bar and above 10 bar.

In order to visualize both the magnitude and direction of flow rate values within the conduit, the three textures were equipped with a color gradient fading toward white. This gradient is animated along the longitudinal direction of the penstock segments, with a velocity proportional to the flow rate value, thereby enabling a qualitative representation of water flow during hydraulic transient events.

Once the three-dimensional scenario was defined, the development of the VR application required the design and implementation of the user movement system. Given the objective of enabling observation of the evolution of hydraulic variables along the entire extent of the penstock, a first-person navigation mode was adopted, allowing the user to move freely within the virtual space without the application of gravitational constraints.

The only constraint introduced concerns the management of collisions between the user and every object present in the scene. The user's physical footprint within the virtual environment is schematically modeled by a three-dimensional capsule, to which a C# script is assigned to manage movement by continuously reading user input from the VR controllers. To ensure a fully immersive first-person experience, the virtual camera is rigidly attached to the capsule and follows its movements, allowing the user to perceive the environment from within the simulated body while interacting with the scene. Collision handling was therefore implemented by assigning colliders to every three-dimensional element, preventing interpenetration between the user's capsule and the infrastructure geometries. The terrain model constitutes an exception, as it was not equipped with colliders in order to enable inspection of the underground portions of the infrastructure.

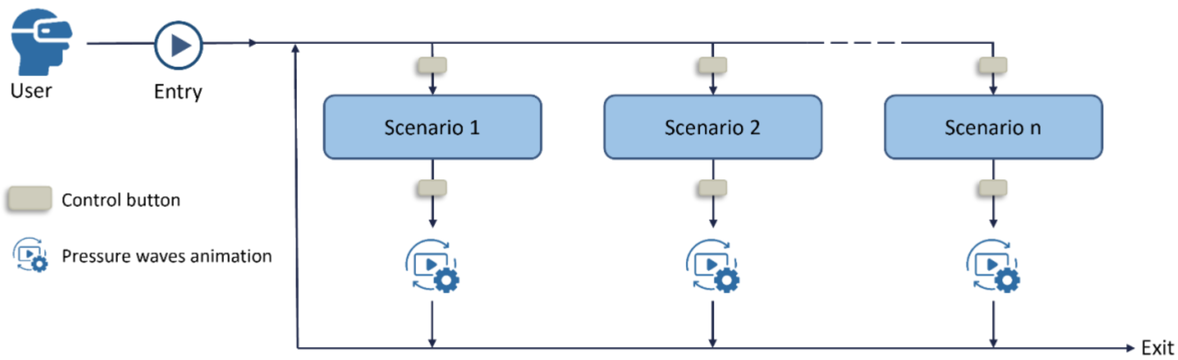

Figure 6: Schematization of the user experience.

3.2 User experience

The prototype developed in this study includes two different valve closure maneuvers, namely a fast closure maneuver lasting 12 seconds and a slow closure maneuver lasting 60 seconds. This configuration allows the user to compare and appreciate the markedly different magnitudes of pressure waves generated under two substantially different operating conditions. Nevertheless, the application architecture is designed to be scalable, enabling the integration of additional scenarios, as shown in Figure 6, through the inclusion of further .csv files derived from hydraulic simulations.

Activating a scenario triggers an update of the parameters assigned to the objects involved in the animations. In particular, these parameters define the .csv file to be read and are associated with the penstock segments, the informational panels positioned along the conduit, and the panels forming part of the user interface.

Through a second button located near the hydropower plant, the user initiates the valve closure operation. From this moment onward, the appearance of the penstock evolves dynamically as a function of the time-dependent pressure and flow rate values read from the .csv files. Informational panels positioned along the penstock at intervals of approximately 100 m are updated in real time, displaying the numerical values of the hydraulic variables, while the color and motion of the textures applied to the penstock change progressively throughout the simulation.

Figure 7 shows the user interaction with the panels used to activate the scenario and to initiate the valve maneuver.

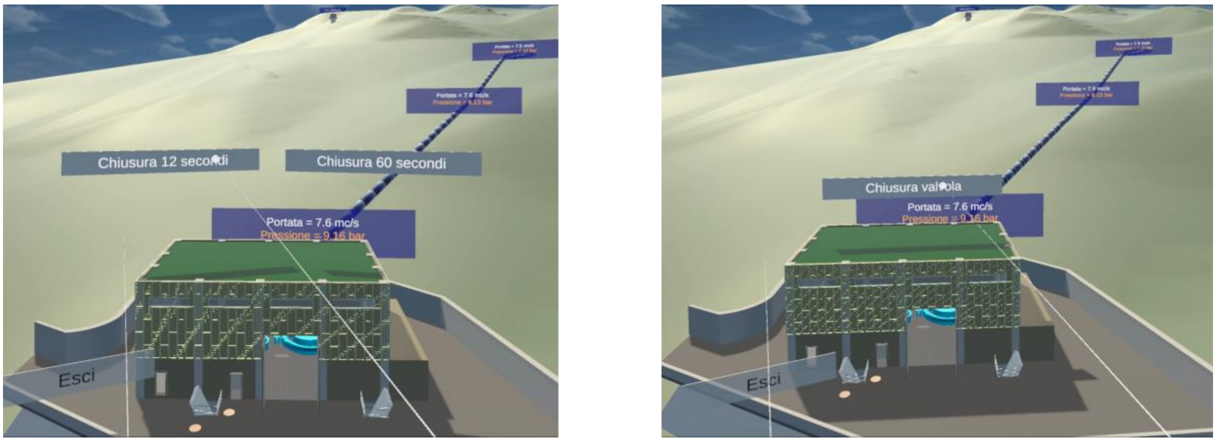

Figure 7: User interactions to activate the scenario and initiate the visualization of simulated data.

By exploiting the subdivision of the penstock into segments, a C# script performs the sequential reading of the rows and columns of the .csv file containing the flow rate time evolution. The script dynamically updates a parameter associated with the textures of each segment, adjusting the speed and direction of the color-gradient motion as a function of the flow rate value being read. As flow rate increases, the animation parameter is increased proportionally.

Pressure values are instead represented through a color-based encoding of the textures. Specifically, a second C# script, which accesses the .csv file in a manner analogous to the previous one, assigns to each segment the texture corresponding to the pressure range detected at each time step. In this way, the penstock assumes a time-varying coloring, providing the user with immediate visual feedback under critical conditions, such as excessively high pressures or negative pressure states. These conditions are particularly hazardous in pressurized pipeline systems, which may lead to pipe collapse or implosion phenomena associated with air entrance, are thus directly perceived by the user through distinct changes in texture and coloration, as shown in Figure 8.

The developed scripts are designed to ensure scalability and adaptability to tables of varying dimensions. They can be automatically adapted to a different number of rows, as each row represents a simulation time step. Once the last row of the .csv file is reached, the algorithm stops updating the texture animation parameters, effectively halting the dynamic evolution of the visualization.

A more articulated management strategy is required for adapting to tables characterized by a different number of columns. Each column contains the values of the hydraulic variables associated with a specific spatial discretization Δx, making it necessary to establish a consistent mapping between the numerical data and the segments that constitute the penstock in the BIM model. This issue was addressed by associating the value contained in the first column with the most upstream segment and the value contained in the last column with the most downstream segment. For the intermediate segments, the column index to be associated is determined through linear interpolation between the number of segments present in the BIM model and the number of columns in the .csv file. The same association method was also applied to updating the flow rate and pressure values displayed on the informational panels positioned along the conduit.

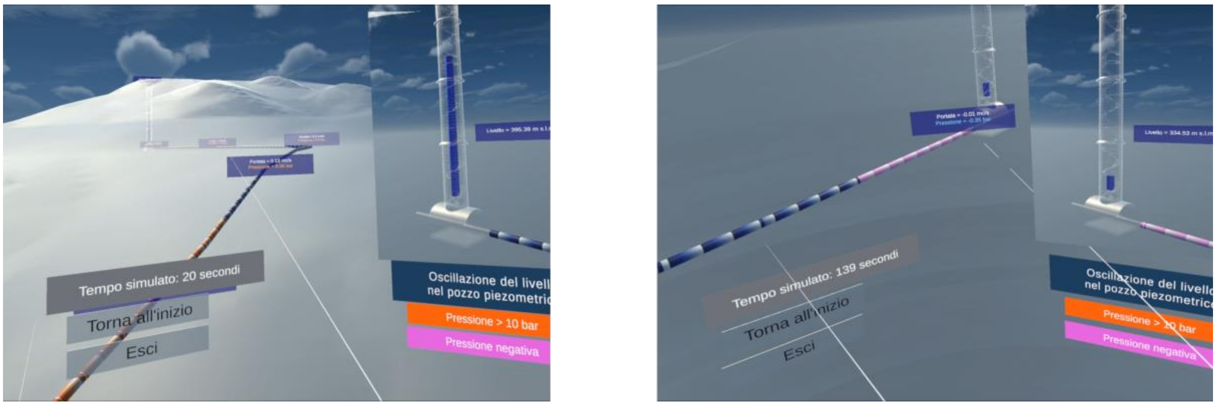

Figure 8: Texture changes for pressures above 10 bar (orange) and negative pressures (pink).

This approach enables the integration of simulations characterized by different temporal durations and spatial resolutions, provided that the structure of the input files arranges time steps along the rows and spatial positions along the columns.

An additional dynamic animation was implemented to visualize the oscillation of the water level within the surge tank (Figure 8, top right), a structure typically adopted in hydropower plants to dissipate overpressures generated by water hammer phenomena. The water level values are reported in the first column of the .csv file containing hydraulic head data.

By modeling the water column contained in the vertical conduit of the surge tank as a cylinder, a C# script dynamically updates its vertical extent at each time step as a function of the water level value read from the input file. To facilitate visual understanding of the phenomenon, the external casing of the surge tank is made transparent at the beginning of the VR simulation. In addition, an informational panel is placed near the top of the vertical pipe and updated in real time, displaying the numerical value of the water level and providing quantitative feedback consistent with graphical representation.

3.2.1 User interface

The user is guided through the visualization of the unsteady flow event by means of a minimal user interface, designed to provide only the most relevant information, as shown in Figure 9. A dedicated panel monitors the temporal evolution of the event starting from the initiation of the valve closure maneuver, while an explanatory legend clarifies the meaning of the colors assumed by the penstock as a function of pressure values.

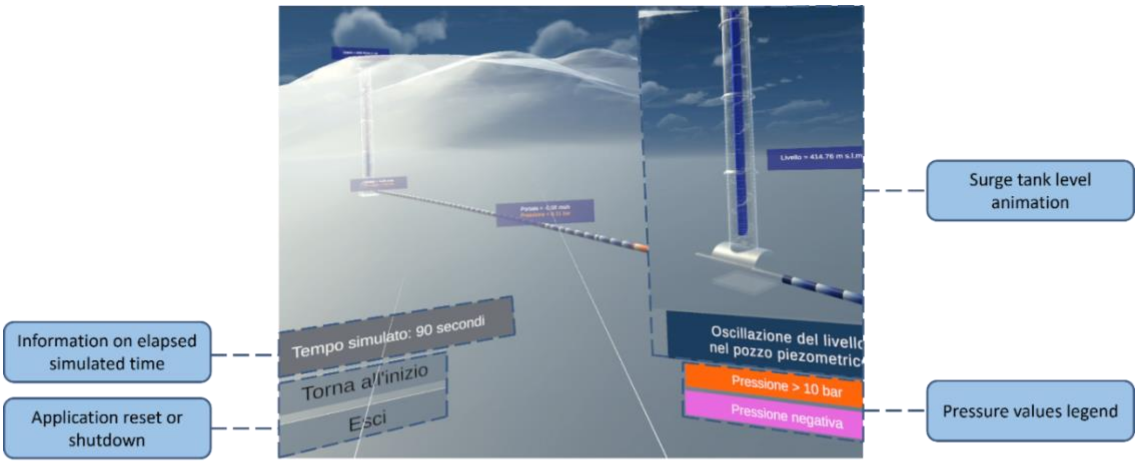

Figure 9: Panel of the user interface.

The behavior of the surge tank is visualized within an informational window that is automatically activated at the start of the maneuver. This feature was introduced to facilitate understanding of the role of the surge tank, which acts as a compensation volume during overpressure phases by storing water and then gradually empties once the overpressures are dissipated. This dedicated focus is particularly useful given the significant distance between the surge tank and the user's initial position, which is located near the hydropower plant to allow an overall view of the system extent.

The following sections describe the development of the prototype within a real project for a new hydropower plant, with particular focus on BIM modeling, the implementation of hydraulic simulations, and the operation of the VR application.

4. RESULTS

4.1 Case study

The proposed methodology was applied to the new Campolattaro hydropower plant, located in the province of Benevento in southern Italy. This project is not aimed solely at electricity generation, but also includes the subsequent treatment of the water volume for drinking and irrigation purposes, serving a population of approximately two million inhabitants.

For this study, only the first part of this large infrastructure was considered, which follows the typical layout of hydropower plants (Kishor et al., 2007), as shown in Figure 10.

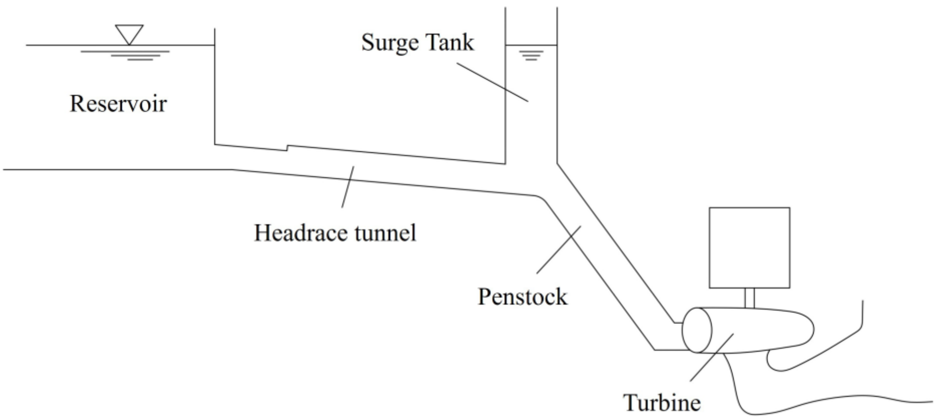

Figure 10: Hydropower plant layout.

It consists of a long, low-slope underground headrace pipeline connected with the water intake structure and transports a maximum flow of 7.6 m³/s to a steeply sloped penstock located upstream of the hydropower plant. To mitigate the effects of water hammer phenomena, a surge tank (ST) is positioned between these two pipelines. Finally, at the downstream end of the system, the water is treated for potable use before being distributed to utilities. All pipelines analyzed in this study have a circular cross-section and are made of steel, with the long adduction pipeline divided into two sections of different diameters.

The following Table 2 gives a summary of the geometric parameters of the main system components.

Table 2: Dimensions of the main elements of the system.

Element	**Length [m]**	**Diameter [mm]**	**Thickness [mm]**
Headrace tunnel (initial section)	14,0	1800	16
Headrace tunnel (final section)	7304,1	2200	16
ST	72,1	2200	16
Penstock	546,8	1800	16

The hydropower plant features two hydraulic turbines, a Pelton and a Francis, that operate with varying flow rates depending on the time of year. Flow rate adjustments are regulated by a valve located upstream of the hydraulic turbines. The dynamics of these maneuvers lead to the generation and propagation of pressure waves along the pressurized conduits. In the present study, the magnitude of the resulting overpressures was analyzed using a MoC-based approach.

4.2 Practical application

The numerical simulation starts from the initial conditions at time t = 0, which can be assumed to correspond to steady-state flow. In order to continue the computation over time, the model must include boundary conditions defined by the upstream reservoir, assumed to be sufficiently large to maintain a constant water surface level, and by laws governing the flow rate through the downstream valve and at the surge tank entrance.

The MoC-based approach allows the computation of hydraulic variables at discrete points of the system, both in the temporal and spatial domains. It is worth noting that the fixed ratio between the spatial discretization (Δx) and the temporal discretization Δt implies that achieving a high spatial resolution requires the adoption of very small simulation time steps. In the analyzed case study, the simulations were carried out with a time step Δt of 5 ms, corresponding to a spatial discretization (Δx) of approximately 4 m.

In the considered application context, this theoretical formulation was implemented through a code developed in the Python programming language, and the results were subsequently organized into tables in Excel format. In these tables, each row represents a discrete time instant (Δt), while each column is associated with a specific position along the penstock (Δx). Correct interpretation of this data structure is fundamental for converting the numerical values into a coherent dynamic representation, which is subsequently implemented in the proposed VR application.

In order to enable the visualization of discretized pressure values along the penstock within the VR environment, the conduit was subdivided using Dynamo into segments with a maximum length of 4 m, in accordance with the spatial discretization adopted in the hydraulic simulations.

5. VALIDATION

To validate the proposed BIM-based immersive VR application and assess its effectiveness in communicating complex hydraulic phenomena, a post-experience questionnaire was administered to users after interacting with the digital platform. The experimental study was structured around two main research questions:

- **RQ1**: How is virtual reality perceived in supporting the understanding of complex hydraulic phenomena?
- **RQ2**: How is virtual reality perceived in terms of its usefulness for professionals in the AECO industry?

In light of the domain-specific nature of these objectives, a tailored questionnaire was developed by integrating key constructs from established evaluation frameworks, including SUS, UEQ, and presence and cybersickness scales. While these instruments provide robust, multi-item and psychometrically validated measures, their direct application does not fully address perceived usefulness in specialized educational and professional contexts. The proposed questionnaire therefore adopts a concise set of single-item measures targeting key aspects of the experience, including prior VR exposure, perceived discomfort, interaction difficulty, and perceived usefulness and effectiveness, complemented by optional qualitative feedback. Although these measures can be conceptually related to established constructs such as usability, user experience, and cybersickness, they are assessed here in a simplified and non-standardized manner, prioritizing alignment with the research objectives and the exploratory nature of the study.

The user study was conducted during orientation days and construction industry exhibitions, resulting in a mixed sample including both technically skilled individuals and users without prior knowledge of hydraulics, in line with the intended general-purpose and educational scope of the application. In particular, the study involved 29 participants aged between 17 and 60, with heterogeneous levels of prior experience in immersive VR, ranging from low to high. Figure 11 shows profiling data of the participants.

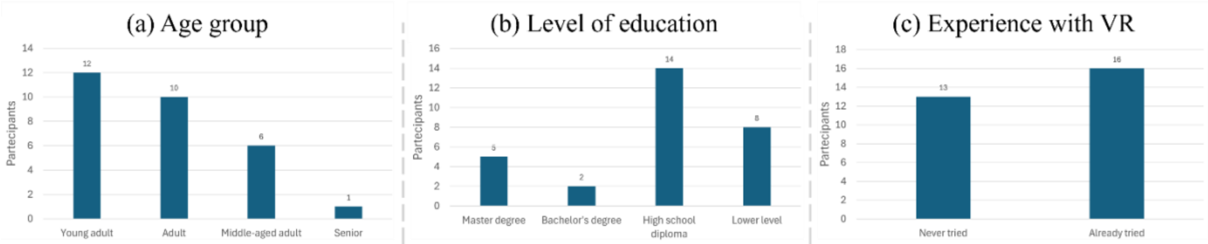

Figure 11: Profiling of questionnaire participants.

Each session lasted approximately 10 minutes, during which participants individually explored the virtual environment and observed the evolution of hydraulic transients. Before starting, the objectives of the experiment and the basic interaction techniques were briefly explained; participants were then allowed to freely select the scenario to be visualized, with continuous support provided by the research team throughout the experience.

5.1 Questionnaire design

The questionnaire was structured into five main sections:

- The first section focused on user profiling, collecting information on age range and educational background;
- The second section investigated prior familiarity with virtual reality, asking whether participants had previously experienced immersive VR applications;
- The third section addressed user comfort and usability, including questions related to physical discomfort (e.g., nausea or motion sickness) and perceived difficulty in mastering the VR controls;
- The fourth section focused on perceived effectiveness, directly addressing the two research questions through numerical ratings on a 1–10 Likert scale;
- The final section consisted of an open-ended question, allowing participants to provide free-form comments and qualitative feedback on the experience.

5.2 Questionnaire results

Following the user profiling phase, an assessment of user comfort was conducted, as it represents a key factor in VR-based applications since the onset of cybersickness or physical discomfort can limit prolonged use and ultimately reduce the effectiveness of immersive experiences (Lackner, 2014; Zhang et al., 2016). The results indicate that the vast majority of participants did not experience any discomfort during the session: 86% reported no symptoms of nausea or related effects, while 14% experienced only occasional mild discomfort.

In terms of interaction and control usability, 89% of participants rated the VR controls as very easy or fairly easy to use. A smaller portion (3.6%) reported a neutral experience, while 7.4% found the controls difficult to master. These results indicate a generally high level of usability, despite the heterogeneous background of participants.

Figure 12 shows the results regarding user comfort and control usability.

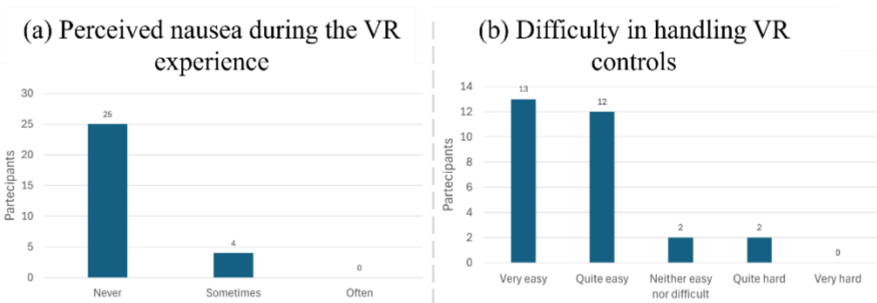

Figure 12: Percentage of participants who experienced discomfort during the experience (a) and ease of handling the VR controls (b).

To address RQ1, participants were asked to rate how effective the VR experience was in supporting the understanding of complex hydraulic phenomena. On a scale from 1 to 10, 51.7% rated the experience with the maximum score of 10, 17.2% assigned a score of 9, and 20.7% rated it 8. Lower ratings were less frequent, with 6.9% assigning a score of 7 and 3.4% a score of 6, as shown in Figure 13. These results suggest a strong perceived educational value of the VR application.

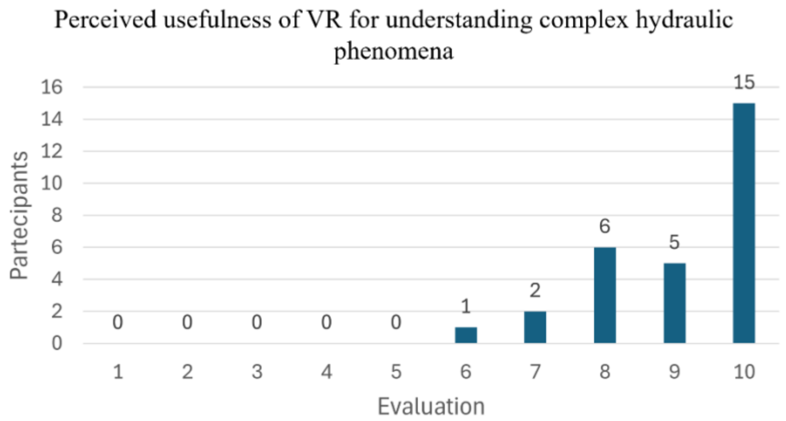

Figure 13: Distribution of participant ratings on a 1–10 Likert scale for the perceived usefulness of virtual reality in understanding complex hydraulic phenomena.

The second question (RQ2) investigated the perceived usefulness of VR applications for professionals working in the AECO sector. Although the proposed experience was designed for a general audience rather than for hydraulic specialists, participants were asked to evaluate the potential of VR in professional contexts based on their experience. The responses were again strongly positive: 51.7% rated usefulness as 10, 24.1% as 9, 13.8% as 8, 6.9% as 7, and 3.4% as 6, as shown in Figure 14.

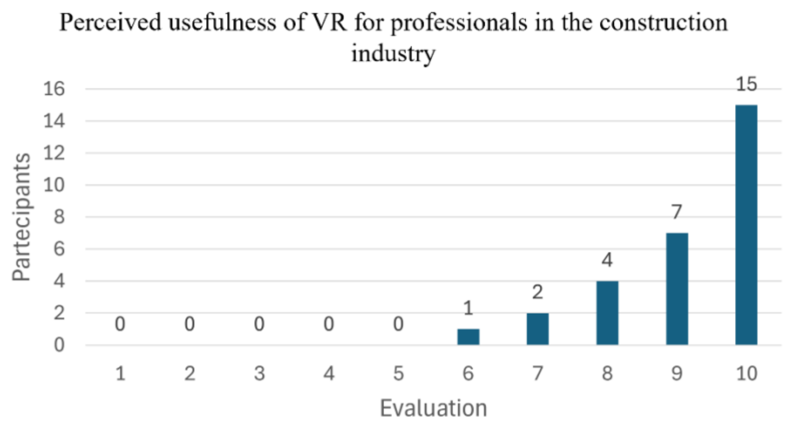

Figure 14: Distribution of participant ratings on a 1–10 Likert scale for the perceived usefulness of virtual reality for professionals in the construction industry.

6. DISCUSSION

The results of the initial validation suggest that the application can support a more intuitive understanding of hydraulic transients in pressurized conduits. The experience also indicates its potential to raise awareness of hydropower plant operation and management. These findings are consistent with the questionnaire results, in which most participants assigned high ratings to the ability of the VR experience to support the understanding of complex hydraulic phenomena. Overall, the results suggest that immersive visualization can effectively bridge the gap between abstract numerical representations and intuitive physical understanding.

These results should be interpreted in light of the methodological choices adopted in this study. The main objective of this work is to present the technical and methodological development of the proposed VR application, rather than to provide a fully standardized evaluation of user experience. For this reason, the assessment relied on a tailored questionnaire instead of established models. Compared to standardized tools, this approach enables a rapid and context-specific evaluation but lacks validated reliability, construct decomposition, and direct comparability with existing benchmarks. In addition, given the limited sample size, the use of multi-item validated scales would not have necessarily led to statistically robust conclusions. A simplified evaluation approach was therefore considered more appropriate for this preliminary investigation, while acknowledging its limitations in terms of reliability, validity, and generalizability. A more extensive and standardized evaluation, based on established assessment frameworks in the literature, is therefore left to future work.

These results can be better understood by considering how hydraulic transients are usually communicated. They are typically represented through graphs showing the variation of a hydraulic variable either along the conduit at a given instant or over time at a specific location. Capturing both spatial and temporal dynamics therefore requires animated content. The proposed application goes beyond conventional video-based visualizations by enabling a fully immersive and spatially contextualized experience. Immersive VR allows all components of the system to be visualized at the same time. This makes the infrastructure more realistic and easier to interpret. Users can freely move within the model and observe the phenomena from different viewpoints and scales. This is not possible with static representations such as graphs or videos, where the viewpoint is fixed. The animation of textures and three-dimensional objects also supports the visualization of flow direction and velocity within the conduits, reinforcing the perception of dynamic behavior. These elements are combined with a minimal user interface designed to guide users without overwhelming them with information.

Feedback from open-ended responses further supports these observations. Several participants highlighted the usefulness of the experience for students and early-career professionals. They noted its potential to accelerate the understanding of complex physical phenomena and engineering systems. Other users appreciated the possibility of linking design choices to their operational consequences. This increased awareness of critical conditions during plant operation. These comments suggest that VR-based BIM environments can support not only education, but also design understanding and operational awareness.

Participants also provided constructive feedback on the user experience. Some suggested improvements to the interaction design, such as allowing more flexibility in repositioning informational panels, which sometimes obstructed the field of view. Others expressed interest in a complementary VR experience focused on free navigation inside the hydropower plant, with greater emphasis on hydraulic and electromechanical equipment. These suggestions provide clear directions for future developments and confirm user engagement with the proposed approach.

From a development perspective, the availability of three-dimensional geometries from the BIM model facilitates the transition from design to immersive visualization. Import into Unity is enabled through the .fbx format, which can be directly exported from Revit. However, this process introduces some limitations. The main issue is the loss of BIM parameters. While geometry, spatial coordinates, and object hierarchy are preserved, alphanumeric information is not accessible in Unity. A practical approach to mitigate this limitation consists in coupling the .fbx geometry with an external data file (e.g., JSON or XML) containing BIM parameters exported via the Revit application programming interface or visual programming tools such as Dynamo, using unique element identifiers to enable data mapping within Unity. Nevertheless, in the application proposed in this study this limitation is not critical, as the relevant data are related to the temporal evolution of hydraulic variables and are generated externally through numerical simulations. A second limitation concerns the loss of material definitions. All materials and textures had to be recreated in Unity and manually assigned. Although this increased development effort, it also allowed greater control over the visual representation of hydraulic variables, contributing to a clearer and more effective visualization of the phenomena.

7. CONCLUSION

The use of BIM as the foundation for the development of the proposed VR application promotes digital continuity across the design, construction, and operation phases of hydropower infrastructure. The information model, initially developed to support design activities, can be reused and enriched for simulation, training, and operational support purposes, reducing data duplication and increasing the overall reliability of the system. In this way, VR does not emerge as an isolated visualization tool, but rather as an extension of the BIM process, capable of enhancing its informational content through an immersive interface.

From a training and operational support perspective, the BIM-VR combination enables the creation of virtual environments that faithfully reflect the actual configuration of the plant, including spatial relationships among components and operational conditions. This is particularly relevant for maintenance personnel, who can interact with a virtual model based on reliable and updatable data, improving system understanding and reducing the gap between digital representations and physical reality. In this context, BIM not only enables the development of the VR application, but also largely determines its effectiveness as a tool for communication, analysis, and training.

The results of the user study further confirm the effectiveness of immersive VR in supporting the comprehension of complex and dynamic hydraulic phenomena. In particular, the possibility for users to actively interact with the virtual environment, through intuitive controls that trigger operational maneuvers and associated animations, enhances engagement and facilitates the understanding of cause-effect relationships between operational actions and hydraulic responses.

Future developments may extend the proposed framework toward a DT paradigm, by integrating real-time measured data within the VR environment. In addition to the hydraulic variables currently visualized, future implementations could incorporate further operational parameters, such as valve opening, turbine rotational speed, torque, and other performance indicators, providing a more comprehensive representation of hydropower system behavior. The visualization of live operational data, such as pressure, flow rate, and component status, directly within the three-dimensional representation of the infrastructure would further enhance situational awareness and support monitoring, training, and decision-making activities throughout the asset lifecycle.

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