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QuickAware: a virtual reality tool for quick clay landslide hazard awareness

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Abstract

Disaster emergency management is crucial for safeguarding lives and the environment in the face of natural and human-caused calamities, such as quick clay landslides. Disaster emergency management encompasses hazard identification, prevention, response, and recovery, most of which require knowledge and information acquired through training initiatives. Quick clay landslides pose a substantial hazard in regions like Scandinavia, Canada, Alaska, and Russia. With numerous historical incidents, knowledge-based awareness of quick clay landslide hazards is of paramount importance. In recent years, the area of application of virtual reality (VR) has grown tremendously from the entertainment industry to the military, to mental health, to hazard identification training and our daily lives. VR has been widely employed in hazard identification and prevention, safety training, evacuation, search and rescue, and damage identification of hazards. This study outlines the design, development, and implementation of QuickAware, a VR tool designed to create awareness of quick clay hazards. The development process of the tool started with a co-design approach where stakeholder experts were brought to collaborate in setting up VR scenarios and defining the VR environment contents. The contents were then conceptualized and translated into a VR experience. The novelty of the tool is that it immerses users in a realistic experience, allowing them to engage directly with the causes and consequences of quick clay landslide disasters which would be dangerous in real-life. The usability of the VR tool was examined by surveying 16 participants. The preliminary results of the survey indicated that the tool has a promising value in improving awareness creation for quick clay landslide hazards.

Keywords Quick clay · Virtual reality · Hazard identification · Hazard awareness · Emergency

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1 Introduction

Communities consistently face vulnerabilities stemming from a range of natural and human-caused disasters, including fires, earthquakes, floods, landslides, volcanic eruptions, storms, industrial incidents, and acts of terrorism. These calamities not only jeopardize human lives but also pose risks to the environment. For example, over the past five decades, the globe has witnessed more than 11,000 instances of natural disasters, contributing to a staggering toll of over 2 billion human fatalities and an economic loss surpassing US$ 3.6 trillion (WMO 2019). These stark realities underscore the necessity for communities to embrace the principles of disaster emergency management to navigate these challenges most effectively and proactively (Wilson and Oyola-Yemaiel 2001).

In a broader sense, disaster emergency planning encompasses pre-emergency preparedness involving hazard identification and prevention, response during emergencies encompassing evacuation and rescue efforts, and post-disaster recovery involving rebuilding and restoration (Zhu and Li 2021). It is important to highlight that both pre-emergency preparedness and the responses during emergencies require a certain level of knowledge and appropriate information that can be acquired through training initiatives or schemes designed to develop skills and enhance awareness. These knowledge-building and information-conveying endeavors play an integral role in equipping individuals, communities, and relevant stakeholders with the skills, information, and understanding required to effectively navigate the complexities of disaster scenarios.

In recent years, advancements in virtual reality (VR) technology coupled with the accessibility and affordability of VR hardware and software tools have resulted in its widespread adoption and diverse applications across various domains. One of the major and compelling uses of VR is in training across different domains, such as the military (Li and Harris 2008; Pallavicini et al. 2016), sports (Akbaş et al. 2019), healthcare (Pawassar and Tiberius 2021), construction safety (Perlman et al. 2014; Le et al. 2015; Zhang et al. 2019, 2022; Getuli et al. 2020; Xu and Zheng 2021), disaster preparedness (Liang et al. 2019; Sermet and Demir 2019; Isleyen et al. 2021) and emergency training (Smith and Ericson 2009; Rüppel and Schatz 2011; Gong et al. 2015; Li et al. 2017; Çakiroğlu and Gökoğlu 2019; Cao et al. 2019; Feng et al. 2020; Lovreglio et al. 2021; Sermet and Demir 2022).

The essence of VR application in training lies in its ability to create a virtual environment that accurately simulates real-life scenarios, including dangerous and high-risk environments that are often difficult or even impossible to explore in the physical world. VR enables trainees to improve their skills and perception in a safe and controlled setting, reducing risks and costs associated with real-world training (Xie et al. 2021).

1.1 Overview of quick clay landslide hazards

Quick clay soils are sensitive fine-grained soils characterized by a tremendous reduction of undrained shear strength upon disturbance due to loading. They can be firm in the undisturbed form but flow as a fluid when overloaded. Quick clay behavior is primarily described by a material property known as sensitivity. Sensitivity defines the ratio between the intact (undisturbed) and remolded (disturbed) shear strengths. Quick clay soils are mostly found in the northern parts of the world which include Scandinavia, Canada, Alaska, and Russia (NGI n.d). In Norway, quick clay is defined traditionally by a remolded shear strength of less than 0.5 Kpa and sensitivity of greater than 30 (NGF 1974).

Quick clay landslides can develop rapidly when the initially firm clay is exposed to sustained loading that can lead to remolding. After remolding, the clay mass is transformed into a floating liquid in its pore water. The causes for the remolding can be natural activities such as erosion and pore pressure increase or man-made actions including excavation on a toe and loading on the top of a slope made up of quick clay soils. Quick clay landslides can propagate retrogressively backward, and the debris can travel at a notable velocity, covering considerable distances.

Norway has experienced several significant events that emphasize the serious dangers of quick clay landslides. One of the earliest and deadliest quick clay landslides, the Verdal landslide of 1893, left an enduring mark on the nation's history (Walberg 1993). This catastrophic event unleashed a staggering 55 million cubic meters of clay, inundating Verdal city, claiming the lives of 116 individuals, killing 600 livestock, and destroying 105 farms. The Rissa landslide of 1978 happened to be the most well-documented quick clay landslide which displaced 5 to 6 million cubic meters of clay leading to the loss of one life and the ruin of 15 farms and four houses (L'Heureux et al. 2012).

In 2009, the Kattmarka landslide event resulted in the displacement of approximately 0.3 to 0.5 million cubic meters of clay (NTNU 2009). This event led to the displacement of ten houses and left a significant and enduring impact on the affected area. The Byneset landslide is another example of a quick clay landslide that happened on the January 1, 2012, at Esp, about 10 km outside the city of Trondheim (NVE 2012). There were no casualties, but 50 people were evacuated for several days.

In 2015, the Skjeggestad landslide led to the consequential demolition of the Mofjellbekken Bridge, causing a profound impact on the traffic of E-18 road (NVE 2015). In 2016, the Sørum landslide, spanning dimensions of 400 m by 300 m, claimed the lives of three individuals (NGI 2016). The most recent incident, the Gjerdrum landslide of 2020, reminds us of the ongoing risks. This event mobilized approximately 1.35 million cubic meters of clay and resulted in the loss of ten lives (Penna and Solberg 2021).

According to the Norwegian Directorate for Civil Protection (DSB), quick clay landslide is one of the 16 hazards or threats that can trigger serious events for Norwegian society (DSB 2019). Consequently, Norway places a robust emphasis on the active pursuit of quick clay hazard assessment and risk management. Within the framework of this assessment, the process of mapping potential quick clay prone areas was initiated in the 1980s, in the aftermath of the Rissa landslide incident, and this work is still ongoing. The Norwegian National Database for Ground Investigations (NADAG) has collected almost 370,000 borehole ground investigation results that can assist in landslide hazard zonation and other quick clay issues (NGU 2020). In some situations, a combination of geophysical and geotechnical investigation methods has been used to detect quick clay soils (Solberg et al. 2012). The outcomes of these mapping endeavors have revealed that over 100,000 people live in areas that have been mapped as containing quick clay soil and much more live in areas where quick clay can potentially occur (Ryan et al. 2022). As of today, more than 2300 known quick clay zones, from which around 1000 are high-risk zones, have been identified.

Currently, there are no early warning systems designed for quick clay landslides, as they can be triggered suddenly and are difficult to forecast. However, there are several structural and non-structural measures to reduce quick clay landslide risks. The structural mitigation measures include erosion control, terrain modifications to improve safety factors and soil reinforcements. Some non-structural measures such as construction monitoring and banning certain human activities can also be considered mitigation measures. The fact that quick clay soils are dominant in relatively densely populated areas makes banning

developments unrealistic and unwanted. In addition, such measures may sound unreasonable to the general public unless it has adequate awareness of the consequences.

The process of quick clay landslide mapping and mitigation heavily relies on the expertise of professionals. Describing the necessities of mappings and mitigation measures to the general public is challenging, as there is no elaborate way of communicating these mappings and other risk assessment results to the public. A survey carried out by Pedoth et al. (2021) indicated that there is a lack of knowledge about existing hazard maps and the public wants to be better informed and more involved.

On the other hand, even though erosion is the most common natural triggering reason, many large quick clay landslides are still triggered by human activities such as excavation, landfilling, and construction works. In the last 70 years, the number of large quick clay landslides in Norway that have been triggered by human activity, of which various construction activities have been the main cause, is more than 50%. A survey by L'Heureux et al. (2018) showed that between the years 2010 and 2018, about 90% of the incidents have been triggered this way. Consequently, it becomes imperative for stakeholders such as planners, decision makers and community leaders to be well-informed about origins and consequences quick clay landslide hazards in order to effectively communicate with the general public and to assume responsibility for further reducing the associated risks. VR emerges as a fitting solution to address these challenges. By enabling individuals to directly experience a simulated quick clay hazard scenario in a safe and cost-effective way, VR has a potential to play a pivotal role in empowering the stakeholders and the general public with understanding of the causes and consequences of such hazards. Through VR, stakeholders can enhance their capacity to convincingly convey the importance of adhering to regulations related to these hazards, ultimately fostering greater awareness and safety among the public.

1.2 Overview of virtual reality (VR)

VR is a computer-based system that employs software, screens, and interactive devices to generate a simulated 3D environment. At its core, VR comprises three essential elements: the virtual environment (VE), immersion, and interactivity. The VE is a digital space within which users can engage, interact, and experience immersion (Fox et al. 2009). Immersion refers to a sensation of complete presence within the VE, leading users to disregard their immediate physical surroundings while being engaged in the virtual realm (Steuer 1992; Zheng et al. 1998). Interactivity means the ability of humans to interact with the objects and events in the VE. The immersions and interactivities often require specialized hardware such as head-mounted displays (HMDs), handheld controllers, and tracking systems, which enhance the sense of presence and enable user interaction (Sermet and Demir 2020).

In the context of disaster emergency management, VR has been widely employed in hazard recognition and prevention, safety training, evacuation, search and rescue, and damage identification of hazards (Zhu and Li 2021). Lovreglio et al. (2021) compare fire extinguisher training using a VR simulation with a non-interactive training video and the results show that the VR-assisted training provided better knowledge acquisition, retention of information, and change of self-efficacy. A VR-based training framework by Çakiroğlu and Gökoğlu (2019) indicated that VR enhances fire safety behavioral skills in participants and facilitates their application in real-world settings.

VR is highly applied in construction safety and hazard recognition training. A study by Perlman et al. (2014) showed that participants subjected to VR identified more hazards

correctly in the virtual environment than those who studied photographs and documents. Xu and Zheng (2021) developed interactive VR training to improve the safety awareness of construction workers and a comparison with traditional training methods showed that the VR trainee could memorize critical points more effectively. Liang et al. (2019) and Isleyen et al. (2021) presented VR simulations of underground rock-related works to improve the assessment of tunnel roof hazards and the result showed a potential to change the safety situation of underground mines and evaluate the level of safety awareness and risk aversion of the miners in the future.

Gong et al. (2015) and Li et al. (2017) proposed VR earthquake drill simulation systems of indoor environments for training purposes and showed promising results in perceiving dangerous objects in earthquake-affected areas. Liang et al. (2018) implemented a VR-based training prototype to enhance evacuation safety by including an earthquake simulation, damage representation, interactions, and feedback and the result showed that the prototype has proven to be promising for enhancing earthquake evacuee safety and shows positive pedagogical functions. Feng et al. (2020a) proposed an immersive VR training system to improve earthquake behavioral responses and post-earthquake evacuation preparedness. The system was tested in a hospital and results showed that there was a significant knowledge and self-efficacy increase after the training.

Sermet and Demir (2019) developed a VR framework that utilizes realistic 3D gaming environments, including real-time and historical weather and disaster conditions. The goal was to enhance public disaster awareness using gamification techniques and to train and assess emergency responders through lifelike simulations. Fujimi and Fujimura (2020) examined public interventions for flash flood evacuation using VR flood simulations, revealing that VR experiments are effective in designing and empirically assessing interventions that encourage evacuation during natural disasters through environmental and social cues. Simpson et al. (2022) experimented to compare the effects of desktop and immersive VR displays on risk perception and spatial learning. They employed a custom immersive simulation of storm-surge flooding and found that the immersive VR display enhances map damage ratings and improves accuracy in estimating real-world flood heights. Alene et al. (2022b) proposed a framework to integrate numerical simulation results of debris flows into VR so that the temporal and spatial understanding of the debris could be perceived better.

VR can play an important role in the teaching process by enabling to presentation of a state of knowledge, teaching practical skills according to previously acquired knowledge, and teaching how to use acquired knowledge when faced with challenges (Kamińska et al. 2019). Dinis et al. (2017) developed a VR tool to investigate building components such as beams, columns, and walls in the civil engineering discipline so that students could able to assemble or disassemble those components to understand more about the building system. Janiszewski et al. (2020) demonstrated that a VR system created for teaching rock engineering, geology, and mining increases students' active learning time by 50%. Román-Ibáñez et al. (2018) integrated immersive VR with a robotic simulator to facilitate the teaching of robotics.

VR offers a great opportunity to prepare a virtual field trip in the domains of geography, geology, geomorphology, and astronomy without visiting the site, in a risk-free, cost-friendly, and time-saving manner. In geology, VR enables trainees and students to experience real-life geological outcrops and get a comprehensive understanding of depositional environments or structural features, as shown in (Minocha 2014; Dinis et al. 2017; Pugsley et al. 2022). VR can also be used as a valuable resource for improving the teaching and learning process in geography (Bos et al. 2022; Wright et al. 2022).

Table 1 Description of experts involved in the co-design activities. E3 and E5 served as conductors

ID	Background	Professional expertise	Educational level	Previous VR experience
E1	Geotechnics	Geotechnical modeling for geohazards	Ph.D.	No
E2	Geotechnics	Geotechnical design of offshore foundations	Ph.D.	No
E3	Geotechnics	Spatial variability of soils	Ph.D.	No
E4	Geotechnics	Landslide hazard mapping	M.Sc.	No
E5	Geotechnics	Flow-type landslide modeling	Ph.D. candidate	Yes
E6	Hydrology	Hydrological modeling	Ph.D. candidate	Limited
E7	Psychology	Human psychology	Ph.D. candidate	Yes
E8	Psychology	Psychology background in communication	Ph.D. candidate	Limited
E9	Electronics and VR	Digital storytelling	Ph.D. candidate	Yes

In general, the application of VR is limited in geohazards such as landslides. Moreover, as highlighted by Gamberini et al. (2021), even in the most studied disasters, there is little research that shows how and what elements should be included in the VR tools. To fill these gaps, first, two collaborative design sessions involving experts from various fields were carried out. These sessions aimed to gather insights into the essential elements of VR and how they should be integrated into the virtual environment to create an effective VR tool for enhancing awareness of quick clay landslide hazards. Subsequently, QuickAware, a VR tool for quick clay landslide hazard awareness, was developed based on the insights gathered from these sessions. Lastly, the tool underwent testing with a small group of participants to assess the realism of its elements for an immersive experience and to evaluate whether the key objects within the virtual environment are compelling enough to capture users' attention, ensuring they focus on the intended issues addressed by the tool.

The rest of this paper is organized as follows: Sect. 2 presents the methodology which entails the requirement gathering, VR planning, materials, and resources we used, system design and development, and the evaluation method. Section 3 outlines the results, including insights from co-design sessions, implementation details, and evaluation outcomes. Finally, the discussion and conclusion sections discuss the results and summarize the work, respectively.

2 Methodology

2.1 Requirement gathering: affinity diagram

A co-design approach, similar to the one implemented by Gamberini et al. (2021), was adopted to create an immersive and interactive virtual experience to improve risk awareness of quick clay landslides. Nine experts (Table 1) from diverse fields, including geotechnical engineering, hydrology, psychology, electronic systems, and VR, contributed to this co-design effort. This effort embraced affinity diagram sessions and brainstorming as mechanisms to capture useful insights related to quick clay landslide hazards.

Disaster management cycle basically encompasses preparedness before an emergency, actions during an emergency, and responses after the emergency. To align with

this framework, the entire scenario of a quick clay landslide disaster has been divided into two parts: One that concentrates on events occurring before a quick clay landslide, and the other that deals with events during and after the landslide. The affinity diagram, which is a tool used to organize complex information, was employed, similarly in two separate sessions: one for events before a quick clay landslide and another for events during and after the event. All the seven experts, led by conductors E3 and E5, shared their perspectives. Beforehand, the experts received a brief on quick clay landslides, VR, and its application in natural hazard risk emergencies.

In each session, conductors posed a general question about what events or situations should be simulated in VR to enhance public, political, and decision-maker awareness of quick clay landslide risks. The experts answered on post-it notes, followed by discussions to foster mutual understanding and comprehensive ideas.

2.2 VR experience planning: brainstorming

A brainstorming session involving a VR expert (E7) and a geotechnical engineer (E5) was conducted to conceptualize the virtual experience based on the outcomes extracted from the two affinity sessions. During this session, the data obtained from the affinity session were analyzed and transformed into operational VR scenarios, considering category priorities and the technological feasibility of VR capabilities.

2.3 Testing and evaluation

In addition to the usual tests during the development, the usability test of *QuickAware* was also carried out. During this phase, the aim was to assess the overall effectiveness of QuickAware as a VR tool and evaluate how its VR elements and narratives contributed to achieving their intended objectives. To gauge the tool's general effectiveness a survey questionnaire was created, adapting the VR Locomotion Experience Questionnaire (VRLEQ) outlined in Boletsis (2020). The survey was modified to align with the tool's context and purpose. This questionnaire also featured specific questions related to quick clay landslides, aiming to evaluate whether the VR elements effectively served their intended purposes.

The QuickAware tool was introduced to civil engineering students at the Norwegian University of Science and Technology. Ultimately, 16 volunteers (aged 18–34, comprising 12 males and 4 females) took part in the testing of the QuickAware tool and signed. After the testing session, a questionnaire was distributed to each participant. The research study received ethical approval from the Norwegian Center for Research Data (Reference ID 235133).

The survey consisted of questions grouped into three main categories: (a) general information and computer (IT) background; (b) general questions about prior VR experience; (c) questions about quick clay; (d) specific questions about this VR tool. The details of the questionnaire are provided in "Appendix". For the VR-related questions, two Likert scales were used; one for evaluating the general experience of the participants by scaling the statements provided in Table 4 of the Questionnaire and the second for evaluating the specific observations the participants made during their VR experience. In addition, the participants were asked open-ended questions about factors triggering quick clay landslides and to provide suggestions for improvements.

3 Results of the co-design sessions

The two affinity sessions led to the creation of two different VR scenarios. The first scenario was hazard identification which focused on the period before a quick clay landslide; while, the second was an emergency scenario which focused on during and post-landslide period.

3.1 The first affinity diagram: hazard identification scenario

In the initial affinity diagram session, ideas associated with the time before a quick clay landslide were generated and categorized into four groups: triggering mechanisms, realistic environment, knowledge, and actions (Table 2, columns 2 and 3). Triggering mechanisms encompass processes that can cause a quick clay landslide. The realistic environment category included relatable terrain features, actual infrastructure, and daily activities. The knowledge segment pertained to information dissemination, involving resources like quaternary maps, hazard maps, risk maps, and ground investigation results. Lastly, the actions category encompassed mitigation efforts like river inspections, erosion protection, and construction monitoring, all aimed at reducing quick clay landslide risks.

While implementing the hazard identification scenario, the focus was on showing the triggering mechanisms that can lead to quick clay landslides. Out of the four categories listed in Table 2, the actions category got the least priority and was omitted from the VR implementation. A partially collapsed riverbank with fallen trees and exposed rock was suggested to represent erosion directly. River channel morphology changes such as migrating of river course toward the riverbank adjacent to the toe of a given slope could be one indicator of dangerous erosion. In addition, river water level rise could represent erosion indirectly as a river flow increase exacerbates erosion. A pond created behind an overflowed culvert was proposed to show a gradual increase in river flow. Construction activities were represented by a simple construction site located on the top of a slope with trucks and excavators.

High realistic VR environment provides a greater sense of presence and immersion in VR experiences (Newman et al. 2022). Considering the realistic environment category, an actual village covered with quick clay was considered to represent the scenarios. The village was represented with a realistic digital terrain model (DTM), actual existing infrastructures, and terrain features. In addition, houses and other man-made features were included in a way that they reflect the way of life and culture of the people living in the selected village. To further enhance the realism of the environment, environmental sounds, and weather effects were added.

Under the knowledge categories, the lateral extent of quick clay in the selected clay was represented by hazard and risk maps. Hazard maps convey information related to the horizontal spatial extent of quick clay soil and its relationship with the triggering factors whereas risk maps relate the horizontal spatial extent and its relationship with both the hazards and the possible consequences of a landslide event. Therefore, both maps were included ton in the VR tool. The vertical extent is often represented by borehole profiles showcasing different soil parameters at varying depths. Boreholes and a corresponding total sounding chart were included in the virtual environment. In addition, a 3D geological model constructed from several ground investigation boreholes that showcase relative soil layering below the ground surface was added to the VR environment. Regarding the

Table 2 Ideas were collected from the first affinity session

No.	Main Category	Sub-category	VR implementation
1	Triggering mechanism	• Erosion • Human activities such as excavation on the toe of a slope, filling, and construction on the top of a slope	• Collapsed riverbank and exposed rocks • Flooded manholes • The rising water level of a river • Construction site
2	Realistic environment	• Realistic terrain • Realistic infrastructures • Day-to-day activities	• Actual terrain, rivers, roads, and houses • Vehicles and moving people
3	Knowledge and Information	• Hazard and Risk maps • Quick clay remolding • Awareness	• 2D hazard and risk maps • Demonstration video • Facts about quick clay formation and the history of quick clay landslides in the form of texts and videos
4	Actions	• Activities and situations related to mitigation works	Not implemented

behavior of quick clay, field, and laboratory videos, which demonstrate the behavior of quick clay when overloaded, were added.

3.2 The second affinity diagram: emergency

In the second affinity diagram session, the presented ideas were grouped into five distinct categories: landslide dynamics, physical consequences of the event, emergency activities, post-emergency activities, and hazard information (Table 3). The dynamics of the slide category referred to the temporal and spatial changes in the terrain and it comprised the initiation area, run-out distance, speed, and volume of the slide. The physical consequences category included all visible and audible consequences that a user could experience.

The emergency activities category included the contents of an experience that focused on behaviors and actions that could be performed during the emergency, for example, an escaping user, sirens, and emergency respondents, actions showing where to escape, and evacuation procedures. Post-emergency activities refer to all activities related to the period after the danger was gone. The hazard information category referred to the dissemination of information and media communication about the event. The hazard information and post-emergency activities categories got the least priority and were not used in the VR implementation.

In the VR implementation of the emergency scenario, the focus was on the dynamics and consequences of a quick clay landslide. Numerical simulation was suggested to represent the dynamics of the landslide. Houses, some of them destroyed and others moving intact with the landslide, represented the physical consequences of the landslide. In addition, a 3D audio that could imitate the sound of a landslide was suggested to make the scene more realistic. As shown in Table 3, the post-emergency activities and hazard information categories were omitted from the VR implementation.

At the end of this session, it was stated that VR offers 360 degrees of freedom to navigate within the virtual environment. In addition, the virtual environment is made large enough to include slopes, rivers, and villages. These conditions may bring a considerable risk that the user might miss the relevant elements of the virtual environment because the user's focus may be elsewhere. Integrating spatial audio and visual cues into the VR environment is a powerful way to guide the user and it can also smooth translation between stories within the virtual environment. Hence, audio, and visual cues such as arrows and billboards were suggested to guide the user (Table 4).

4 Design and development of QuickAware

4.1 Virtual environment representation

In developing the basis for building the 3D virtual environment is the site's terrain. A custom script based on Unity C#(C-sharp) was used to import the terrain into Unity using the method mentioned in the work by Alene et al. (2022b). This allowed us to show the actual location and orientation of natural features of topography such as rivers and slopes. The roads and rivers were added carefully so that they were as close as possible to their actual location. Building and trees were also added. Additional salient objects such as construction sites, boreholes, objects representing erosion, etc., as shown in Fig. 1 were added to the terrain. The terrain was also customized with weather

Table 3 Ideas were collected from the second affinity session

No.	Main Category	Sub-category	VR implementation
1	Dynamics of the slide	• Release area, • Speed and run-out distance • Deposition and unstable scrap	Realistic, physics-based quick clay landslide simulation
2	Consequences	• Sinking and floating objects, • Destructions • Sounds	• Sinking houses, demolished and floating houses • Landslide and destruction sounds
3	Emergency activities	• Sirens, • An escaping user, • Showing safe and dangerous areas	• Siren sound after the start of the slide, • Hepatic effect when the user goes through low-elevation areas
4	Post-emergency activities	• Rehabilitation of the area, • Identifying the cause for future learning, • Taking responsibility	Not implemented
5	Hazard information	• Media communication	Not implemented

Table 4 General statements about the general experience of QuickAware

ID	Statements
S1	Interacting with the 3D objects and environment helped me learn about quick clay
S2	Seeing the landscape in three dimensions gives me a better appreciation of it than maps and charts ever could
S3	The voice narratives in the VR experience helped guide me within the virtual environment
S4	I feel like I am in a natural environment at all
S5	The experience was intuitive; it took me a few minutes to master the tool by myself
S6	I liked that we could visit sites much more directly, without having to walk for kilometers
S7	I will use this and similar tools in the future
S8	I felt motion sickness such as feeling dizzy or nauseous, etc., during the use of this VR tool

Fig. 1 Diagram representing the contents of the virtual environment

effects to enhance the realism of the virtual environment. The maps and video demonstrations were represented by a two-dimensional (2D) graphical interface. They were put on the walls of a "showroom" (see Fig. 1) to represent the fact that maps are 2D objects and videos are mostly shown on 2D screens.

In VR, the space and the objects within it become the story (Fraga 2017). These objects and the virtual space must be organized in a manner that allows them to narrate a specific story without overwhelming the user (Silva and Brandão 2021). To attain this, the structure was designed to provide users the freedom to interact, while also requiring them to complete specific tasks to advance the story. For this purpose, some objects serving as visual cues to guide the user to follow the correct story path were added. Additionally, audio narratives were incorporated to complement these visual cues (see Fig. 1).

On some occasions, the objects inside the space may not be adequate to tell the intended story. In such instances, they were complemented with audio narratives and texts. For instance, the nature and properties of quick clay soil were provided as an audio narrative when the user was introduced to the VR tool and additional information was also added as a description of the erosion objects mentioned in the brainstorming session.

The emergency scenario does not necessarily occur just after the hazard identification scenario. Therefore, the virtual environments for both scenarios were customized with two different weather effects to present that both did not happen on the same day. Rainy and dry cloudy weather effects were used for the emergency and hazard identification scenarios, respectively.

4.2 Physics

To realistically simulate the dynamics of the landslide and its physical consequences, certain physics principles have been introduced in the virtual environment. We employed a realistic 3D Computational Fluid Dynamics (CFD) to replicate the dynamics of the landslide and a Unity built-in physics engine to simulate the destruction of infrastructures.

A. Quick clay landslide simulation

After completing it has undergone remolding, the quick clay is considered as a homogenous, viscous, and incompressible fluid. To simulate the flow of this fluid, we utilized interFoam, a multiphase solver based on the CFD toolkit OpenFOAM® (OpenCFD Ltd 2020). InterFoam solves the 3D continuity and the Navier–Stokes (N–S) governing equations (Versteeg and Malalasekera 2007) for an incompressible fluid. The governing equations are given as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu_e \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) + \rho g_i \tag{2}$$

where ρ is the density, t is the time, u_i is the velocity in $i = x$, y, z directions, p is the pressure, g_i is the gravitational acceleration in $i = x$, y, z directions, and μ_e is the effective viscosity.

The solver assumes that the landslide material and air are two incompressible phases, and the surface of the landslide material phase movement is captured with the volume of fluid (VOF) method (Hirt and Nichols 1981) that uses a step function α is governed by Eq. (3):

$$\frac{\partial \alpha}{\partial t} + \frac{\partial}{\partial x_i}(u_i \alpha) = 0 \tag{3}$$

Several studies (e.g., Coussot et al. 1998; Kaitna et al. 2007; Grue et al. 2017) have demonstrated that, the viscoplastic Herschel–Bulkley rheology is appropriate for describing the behavior of fluid mixtures comprising of fine-grained soils and water. The

Herschel–Bulkley rheology is defined by the relationship between shear stress and shear rate, as provided in Eq. (4).

$$\tau_{ij} = \left[\frac{\tau_y}{\dot{\gamma}} + K\dot{\gamma}^{n-1} \right] \dot{\gamma}_{ij} \tag{4}$$

where τ_{ij} is the shear stress tensor, $\dot{\gamma}$ is the shear rate, $\dot{\gamma}_{ij}$ is the rate-of-deformation tensor, τ_y is the yield stress, $\boldsymbol{K}$ is the consistency parameter, and n is the Herschel–Bulkley exponent. The strain rate is computed from $\dot{\gamma}_{ij}$ as follows:

$$\dot{\gamma} = \sqrt{\frac{1}{2} \dot{\gamma}_{ij} \dot{\gamma}_{ij}} \tag{5}$$

The effective viscosity, μ_e, in Eq. (2) is determined locally for each finite volume cell every time step since it varies spatially and temporally and can be computed from Eq. (4) as follows:

$$\mu_e = min \left[\mu_0, \left(\frac{\tau_y}{\dot{\gamma}} + K\dot{\gamma}^{n-1} \right) \right] \tag{6}$$

where μ_0 is a maximum viscosity value used for small shear rates when the effective viscosity approaches infinity.

The governing Eqs. (1), (2), (3), and (6) were solved based on the finite volume method (Eymard et al. 2000). The topography, available in DTM, was used as a basis of the solver's computational domain. First, the DTM was triangulated and translated into 3D volume by adding side and top walls. Next, the volume was spatially discretized by the OpenFOAM meshing utilities to obtain hexagonal finite volume cells. The temporal domain was split into time steps and the equations were solved in a time-marching manner.

In this study, mathematical and rheological models were numerically built and implemented using the release of version 2012 of OpenFOAM. The immediate outputs of the simulation are the pressure, velocity, α, and effective viscosity for each finite volume cell at each time step. These results were visualized and further processed in ParaView (Ahrens et al. 2005). In ParaView, a contour surface of $\alpha = 0.5$ resulted in a collection of coordinates on the interface of the remolded quick clay and air. These coordinates and their interpolated velocities were exported into Unity using customized C# script. The details of the procedure is outlined in Alene et al. (2022a; b). The details of the numerical simulation and preprocessing of the simulation results were given in supplementary information, SI1(online resource).

B.   Dynamic objects simulation

 To enhance the realism of the physical consequences of the landslide, the destruction of houses was simulated. The houses were considered dynamic objects or made up of dynamic objects. To have convincing physical behavior, the objects in the VR environment accelerate correctly and are affected by collisions, gravity, and other external forces. All of this was handled by Unity's built-in physics engine.

We categorized the houses into two groups: One group was demolished by gravity because the ground supporting them slid out and the other group was swept away by the quick clay. In the first category, the houses were made up of materials of varying mass and shape so that they fell at different times, simulating complete demolition.

For the first category, we designed the houses with various mass and shapes so that they fell at different times, simulating complete demolition. In the second category, we assumed the houses as monolithic structures and that they moved in the direction of the landslide. The Unity's built-in physics used two external forces derived from the numerical simulation of the quick clay landslide to simulate the sweeping away of houses. The two forces were buoyancy force and drag force. The buoyancy force used the flow height of the landslide simulation to determine the submerged height of the houses whereas the drag force used velocity from the landslide simulation.

The buoyancy and drag forces are given in Eqs. (7) and (8), respectively. Although the actual shape of the houses is mostly a combination of rectangular and triangular prisms, we assumed a spherical shape for the Unity engine physics simulation.

$$F_b = \rho g h V_l \tag{7}$$

$$F_d = \frac{1}{2} C_d \rho V^2 A \tag{8}$$

where ρ is the density of remolded quick clay, g is the gravitational acceleration, V_l is the volume of the submerged part of the house, C_d is the drag coefficient, V is the average flow velocity of the remolded quick clay mud in the vicinity of the house, and A is the surface area of the house.

5 Implementation and evaluation results

5.1 Implementation

In the implementation of the QuickAware VR tool, we chose to recreate the Gjerdrum landslide, an actual quick clay landslide event that happened on December 30, 2020 (Fig. 2). This landslide occurred in Ask, the administrative center of Gjerdrum municipality, situated in Viken County, Norway (Penna and Solberg 2021). This landslide led to the death of 11 people, the evacuation of more than 1600 people, and massive material destruction (Ryan et al. 2020).

The VR environment was created using Unity version 2021.3.11 (Unity Technologies 2022). Within this virtual space, we incorporated both natural and man-made elements found in the proximity of Ask and the designated run-out area that was followed by the landslide debris, as illustrated in Fig. 2. The 3D space of the virtual environment was based on a digital terrain model (DTM) obtained from the Høydedata[1] website. The DTM was provided as an ESRI ASCII raster format (.asc), offering elevation data representing the topography on a regular two-dimensional grid.

Hazard and risk maps were collected from the Norwegian water and energy directorate (NVE) web map service.[2] Several ground investigation results are available in the report by NVE (2021a), and seven boreholes were used in developing the tool. A geological model, reconstructed using Leapfrog software (SEEQUENT 2022) based on the ground investigation results, was used as a 3D geological model to represent the soil layering. Information
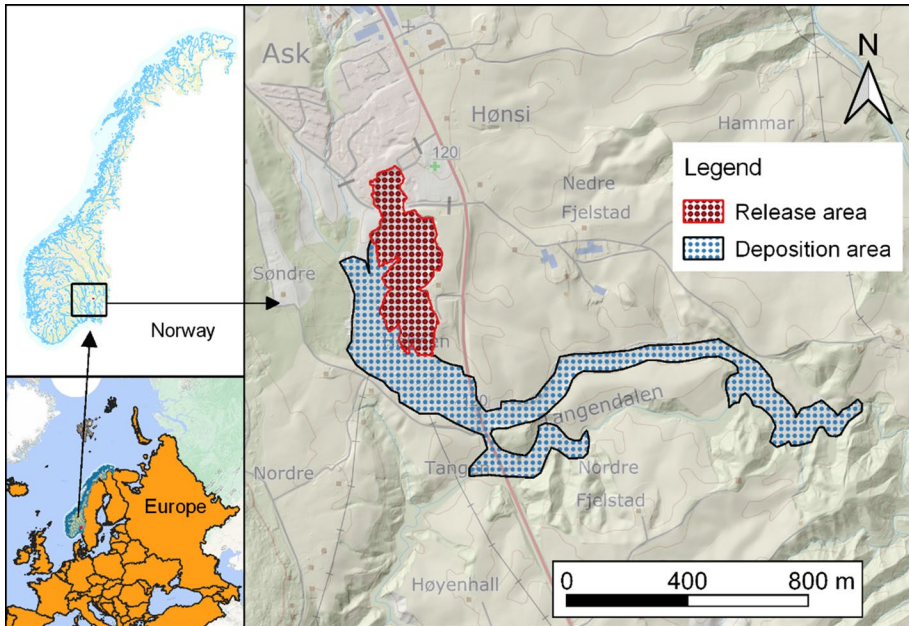
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[1] https://hoydedata.no
[2] https://temakart.nve.no/tema/kvikkleire

Fig. 2 Location of the area on which the virtual environment is based (source: base map from Norgeskart. no and DTM from hoydedata.no)

regarding river morphology and erosion was obtained from the Gjerdrum landslide report (Ryan et al. 2020). Additionally, four videos; two showing historic quick clay landslides (NGI 2011; ViralHog 2020), one quick clay soil sample demonstration (NVE 2020), and another illustrating the causes of quick clay landslides and associated mitigation measures (NVE 2021b).

We employed a laptop with an NVIDIA GeForce GTX 1070 graphics card and an Intel Core i7-8750H CPU @2.20GHZ, 16 GB RAM six-core processor to create the VR environment. The resulting VR environment has been set up to be used through Oculus Quest 2HMD (resolution: $1,832 \times 1,920$ px per eye; refresh rate: 90 Hz; Field of view: 100-degree est.; integrated speakers and microphone).

The tool started with an initial interface, as shown in Fig. 3a. Following the initial interface users encountered an instruction scene, as shown in Fig. 3b. This instruction scene was designed to introduce users to the tool and provide them with essential information. Its primary goal was to familiarize users with the tool's functionality and features.

The knowledge category encompassing maps, videos, and selected geotechnical investigation results is provided, as shown in Fig. 4. In Fig. 4a, the risk map for the area is presented, allowing users to access additional information about the risk maps by clicking on the description option. Figure 4b provides a visual representation of a video demonstration of quick clay behavior in both the field and the laboratory. Figure 4c presents the ground investigation results. On the left side, a cylindrical soil sample is depicted, showcasing various soil layers. The dimensions of each layer were determined from the field and laboratory investigation results found in NVE's report (NVE 2021a). Users can interact with each layer individually by griping and the type of soil could be displayed in front of the user. In this case, the tool enables users to visualize the distribution of soil layers which

(**a**)　　　　　　　　　　　　　　　　　　　(**b**)
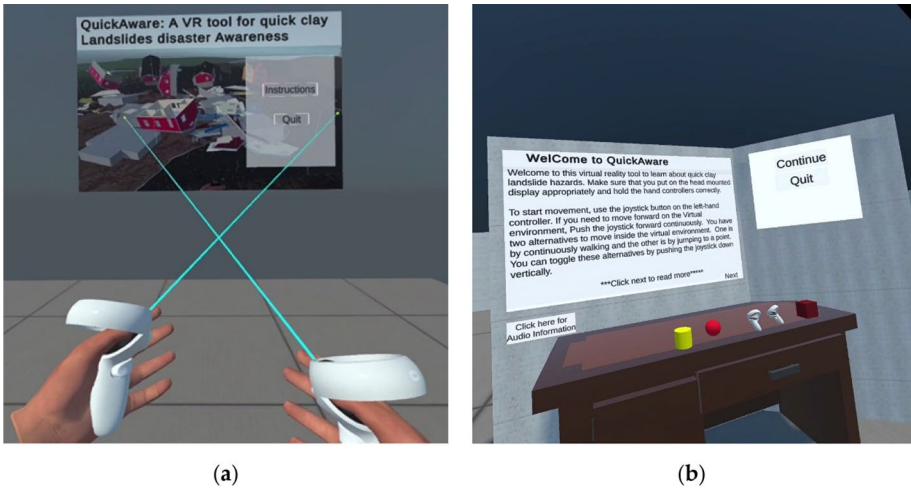
Fig. 3 Starting interface of QuickAware. **a** Initial interface; **b** the instruction scene
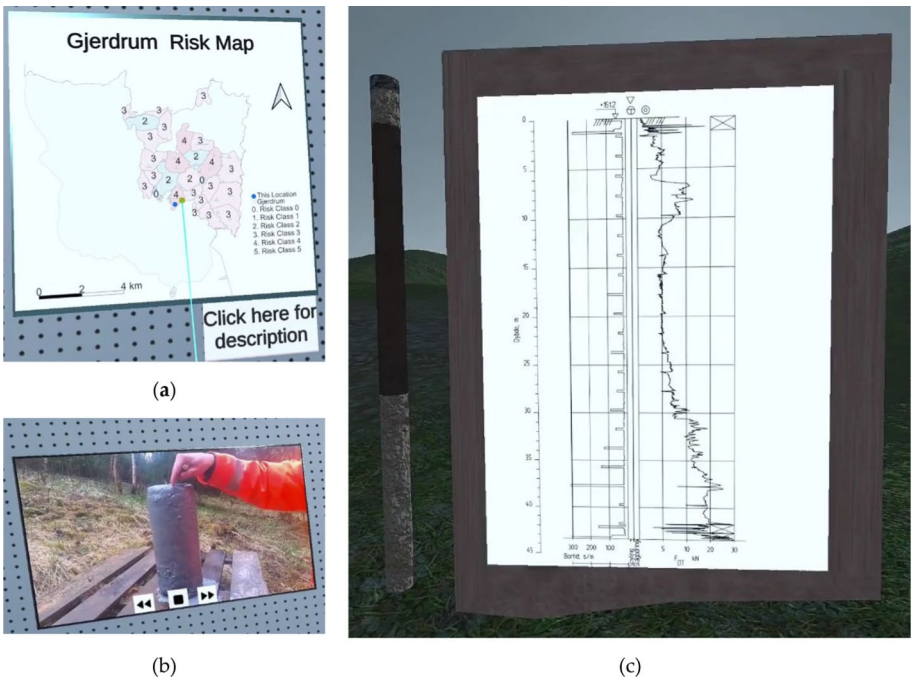

(**a**)

(b)　　　　　　　　　　　　　　　　　　　(c)

Fig. 4 A user going through the knowledge and information category of QuickAware. **a** The user looking at the risk map; **b** the user watching quick clay field and laboratory demonstrations; **c** the user visiting boreholes and looking at a layered soil sample (constructed no to scale) and a total sounding result
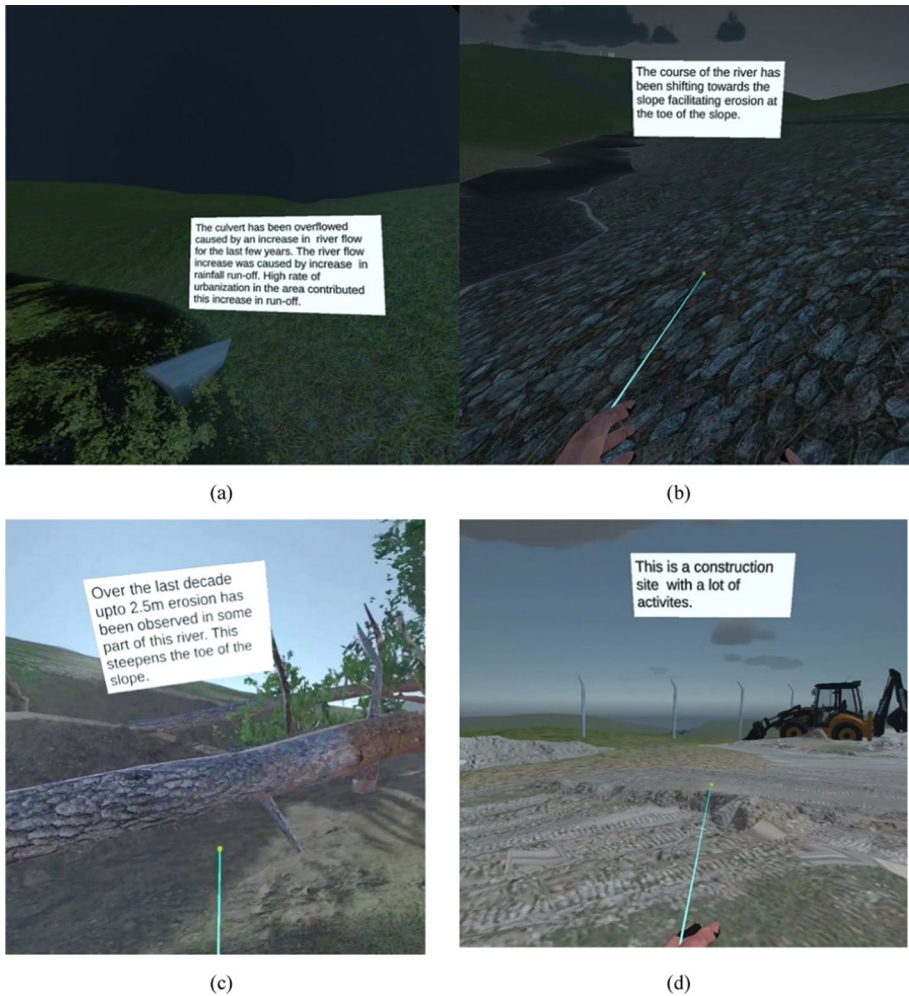
Fig. 5 A user inspecting the site for quick clay triggering factors **a** fully submerged culvert; (b) river morphology change; **c** riverbed and riverbank erosion; **d** construction site

is not possible in real-world setting. To the right, there is a total sounding result that is the most common ground investigation method in Norway. This result graphically illustrates the relative strength of the soil layers at various depths.

Figure 5 provides information concerning the triggering mechanisms of quick clay. In Fig. 5a, an overflowed culvert signifies a rise in the water level in the river, indicating an increase in river flow. Figure 5b illustrates a gradual change in the river morphology, i.e., a shift in the course of the river toward the slope. Figure 5c depicts erosion and its subsequent consequences, such as fallen trees. Lastly, Fig. 5d depicts a construction site located on flat terrain at the top of the slope.

Figure 6 illustrates the salient events after the occurrence of the quick clay landslide. One can observe the remolded clay, also referred to as mud, and the unstable landslide scraps. To prevent any potential confusion, we adopted the term "mud" in the survey to describe the

Fig. 6 Post-failure events showing the quick clay "mud," slide scraps and destroyed houses

(a)   (b)
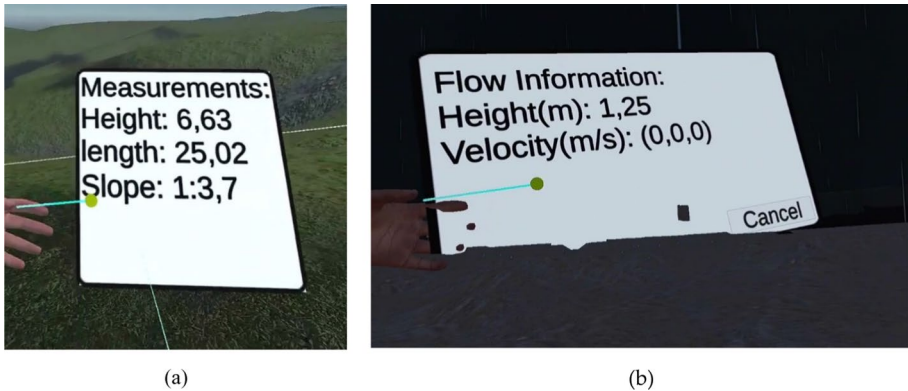
Fig. 7 Measurements; **a** slope measurement; **b** flow measurements

remolded quick clay. Additionally, it displays the aftermath of buildings destroyed as the soil mass supporting them slid away.

QuickAware offers users the capability to actively engage and inspect some characteristics of the quick clay landslide. Figure 7a indicates a user measuring the slope and slope height at a site where quick clay soil is abundant to confirm susceptibility against quick clay landslides. In Fig. 7b, a user is seen reading the flow characteristics of the quick clay flow landslide, including flow depth and flow velocity. A sample video about a user exploring the entire experience is provided in supplementary information, SI2 (online resource).
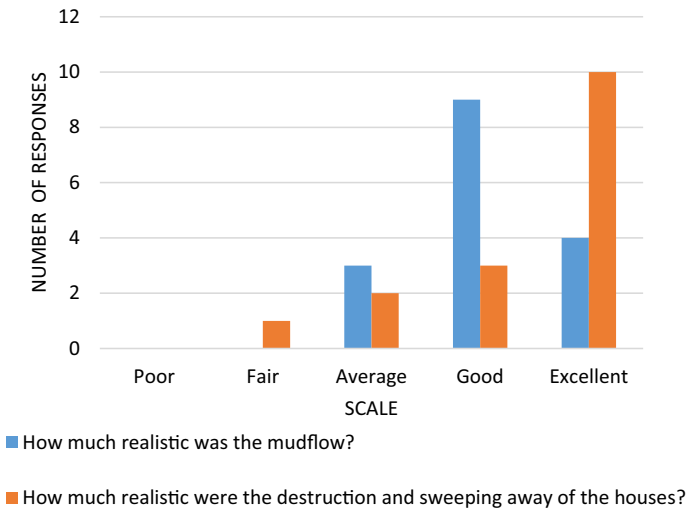
Fig. 8 Histogram for realistic visualization of the mudflow and consequences of the landslide

5.2 Results of the usability evaluation

From the background information of the participants, the majority of respondents indicated that they possess computer and IT skills above the average level (*mean:3.93 and SD: 0.92*). It is noteworthy that ten participants had no prior experience with VR headsets, signifying a segment of the participants new to VR technology. Moreover, thirteen participants reported having a gaming experience, ranging from little to some familiarity.

A reliability test on the 7 Likert-scale rating, excluding S8, presented an acceptable Cronbach's Alpha value ($\alpha = 0.63$), as it lies within the range of 0.6–0.8 (Shi et al. 2012). For the first seven statements (S1-S7), most of the participants held positive attitudes toward the general VR experience. The participants gave significantly higher ratings for the first seven statements (S1-S7), with an average rating of 4.13 out of 5 (SD=0.38). Examining individually, statement S1, addressing interaction capability, received an average score of 3.94 (SD: 0.854). The second statement, S2, which gauges the 3D perception of the tool, received predominantly positive ratings, with an average score of 4.38 (SD: 0.72). The effectiveness of voice narratives within the tool was assessed through responses to statement S3, which garnered a mean score of 4.31 (SD: 0.60). Similarly, the realism of the virtual environment was evaluated using responses to statement S4; while, the ease of use of the tool was measured by statement S5, both of which received mean scores of 4.19 (SD: 0.91). Statement S6, which gauges users' perception of the tool's intuitiveness and ease of navigation, received an average score of 4.5 (SD: 0.73). Additionally, statement S7, indicating participants' willingness to use such tools in the future, received a mean score of 4.31 (SD: 0.79).

The last statement, S8, was designed to assess the short-term discomfort or sickness that may result from the VR experience. To maintain consistency with the other statements, it was reversely coded. This statement received a relatively low score, with an average of 2.85 (SD: 1.48). Importantly, none of the participants interrupted the VR experience due to discomfort or sickness. The raw data generated from the usability evaluation can be found in Supplementary Information, SI3 (available as an online resource).

Fig. 9 Summary of the responses to the open questions about quick clay triggering factors

Figure 8 illustrates the realism levels of the mudflow and building destruction visualizations in the VR experience. In total 13 out of 16 participants expressed satisfaction with the realism of the house destruction and mudflow.

The participants' understanding of quick clay was assessed before their VR experience, and the results indicated a below-average understanding (mean: 2.44 and SD:1.26). Additionally, participants were asked if they were familiar with the triggering factors for quick clay landslides before the experiment, with more than half responding "yes." However, upon further examination, it was found that responses to a follow-up open-ended question regarding these triggering factors were biased. This bias was attributed to the questionnaire survey being conducted after the VR experience, leading many participants to draw from their VR experience when responding, even though they were asked about their knowledge before the experience. As a result, the responses to questions related to quick clay knowledge before the experience were disregarded.

Participants were also asked to respond to an open-ended question, "What quick clay landslide triggering factors did you learn from this Virtual Reality tool?" The responses are presented in Fig. 9, with "erosion," "construction," and "rainfall" being the most frequently mentioned factors.

6 Discussion

Drawing from the collective expertise of various experts, this study aimed to identify essential elements that should be incorporated into a VR tool for effective hazard awareness. Creating an effective tool for promoting awareness required an in-depth understanding of quick clay landslides, encompassing their causes, consequences, and mitigation measures. The insights gathered from the collaboration of the experts served as a foundation upon which *QuickAware*, a dedicated VR tool, was crafted.

In the context of disaster emergency planning, it encompasses preparedness before an emergency, actions during an emergency, and responses after the emergency (Zhu and Li 2021). To address this comprehensively, the entire scenario surrounding the quick clay landslide disaster has been divided into two distinct phases: the hazard identification scenario, which encompasses the time and situations before the landslide occurred, and the emergency scenario, which pertains to the situations during and after the landslide disaster.

During the analysis of insights in the brainstorming step, it was crucial to recognize that not all insights could be seamlessly integrated into VR due to some technical constraints. Consequently, certain elements, like erosion, were indirectly represented rather than being presented in their actual form as mentioned in Sect. 3.1.

QuickAware brings the realistic environment, situations, and realistic data that are already available to the experts into a VR experience so that lay people from diverse

backgrounds can have equitable access to information and knowledge. This tool serves a dual purpose, making it valuable for both education and communication. As an educational tool, QuickAware can provide students with a virtual field platform where they can measure slopes and slope heights (Fig. 7) and observe geotechnical field investigation results (Fig. 4). These topographic and geotechnical characteristics play a crucial role in quick clay landslides, and QuickAware facilitates hands-on learning in this regard.

Additionally, QuickAware can serve as a communication platform bridging the gap between experts and the public. By experiencing a landslide site in VR, individuals with limited knowledge of hazard and risk maps can better perceive the associated risks, facilitating effective communication and risk awareness. It has been reported by Ryan et al. (2022) that many of the quick clay landslides happening recently have been triggered by man-made activities. Therefore, creating awareness about the nature, cause, and possible consequences of quick clay landslides among the public can reduce the risks associated with the landslide. In addition, in Norway, numerous post-landslide reports, including the one by Ryan et al.(2022), emphasize the need for an improved knowledge base regarding quick clay.

As mentioned in Sect. 1.2, there is a general agreement in the literature, whether by practice or qualitative evaluations, that VR technologies are useful in education, safety training, and hazard identification. Furthermore, various companies are now incorporating VR training for hazard identification and accident awareness (e.g., Morgan 2021; Vagner 2022). While the initial findings from the questionnaire survey provide additional support for this viewpoint, it is important to acknowledge that the results, based on a sample size of only 16 participants, carry some inherent risk. In addition, the responses to the triggering factors, as shown in Fig. 9, showed that the participants could memorize and relate some of the contents of the VR tool that were intentionally included in the tool.

Our analysis of the questionnaire survey revealed that seven of the eight Likert ratings demonstrated acceptable internal consistency, as indicated by their Cronbach's Alpha values falling within the range of 0.6–0.8 (Shi et al. 2012). However, the inclusion of the last statement, S8, resulted in a reduction of Cronbach's Alpha value to below 0.6 after reverse coding. This suggests that either S8 should have been formatted differently, or a larger participant sample should have been considered for assessing the tool's susceptibility to cybersickness. Apart from this, the participants gave significantly higher ratings for the statements S1-S7 indicating the tool's potential for broader applications in the future.

Although the last statement in the Likert rating exhibited internal inconsistency with the other statements, it revealed that some participants suffered from cybersickness effects. An in-depth analysis of the usability of VR technologies regarding the cybersickness effects is beyond the scope of this work. However, from a technical standpoint, the frame rate and navigation mode of a given VR application significantly impact the feeling of sickness. We are aware that there are more detailed, systematic, and validated ways of evaluating the feeling of sickness resulting from the usage of VR technologies (e.g., Chang et al. 2020). Our goal was to highlight that there were some adverse effects perceived by the users and to evaluate the possibility of improving the tool from our end.

VR applications with a frame rate higher than 60 can help reduce sickness effects (Zhang 2020). In QuickAware, it was noted that there were a few moments where the frame rate dipped to around 30. In VR, there are two common ways of navigation within the virtual environment: continuous movement and teleporting. The continuous movement mode is more realistic than the teleporting one. However, a study by Veličković and Milovanović (2021) indicated that a teleporting way of navigation has less possibility of having sickness effects than a continuous movement mode. In this VR experience test, we mostly used

continuous movement as the navigation mode as navigation mode. However, following the test, we incorporated the option for users to choose between continuous movement and teleportation within the system. Additionally, it was suggested by Vagner (2022) that repeated exposure to HMD-based VR reduces cybersickness effects. In our personal experience, increased use of VR systems leads to greater user comfort with the VR experience. It is worth noting that the majority of the participants had never used a VR headset before, which may have contributed to cybersickness effects.

Referring to the responses are presented in Fig. 9, erosion and construction which were intentionally included in the VR environment to educate users that both are actual quick clay landslide triggering factors which reinforces one of the goals of the tool. An important observation from this response underscores the importance of careful VR content creation. Rainy weather was employed as a transition between hazard identification and emergency scenarios to indicate that both scenarios happened at different time frames. However, a significant number of participants indicated rainfall as a quick clay landslide triggering factor. In fact, rainfall is not an immediate triggering factor for quick clay landslides, although it can exacerbate erosion and overload a slope.

7 Limitations

Despite having a promising value in creating awareness of quick clay landslide hazards, this work has some limitations. Firstly, there are technical constraints associated with the development of realistic terrain. The terrain was manually textured, which may have led to a loss of realism. The use of terrain textures generated through photogrammetry could have significantly improved the realism of the VR environment. Secondly, this work has hardware limitations in that it requires the use of a Head-Mounted Display (HMD) and a VR-compatible computer, which may not be accessible to everyone.

Thirdly, the VR tool is currently built upon a single case study of the Gjerdrum quick clay landslide. To provide users with a comprehensive understanding of quick clay landslide hazards, consequences, and triggering factors, future iterations should incorporate multiple case studies that account for variations in topographic and geotechnical characteristics.

Lastly, it is important to recognize that the usability test conducted was limited in scope, as a result, it is insufficient to confidently conclude the tool's importance to the wider public. The participant sample size was not only very small, but it also consisted primarily of students. Therefore, future efforts should aim to gather feedback from people from all levels of society.

8 Conclusion

In Norway, much of the information related to quick clay landslides and other natural hazards is provided in the form of hazard and risk maps, geotechnical investigations, and risk assessment reports. Although such information is public and open-accessed, it is expert-oriented. To address the need for broader hazard awareness, this study employed VR technologies. VR allows users to immerse themselves in interactive virtual environments that depict natural hazard scenarios, offering a more accessible and engaging approach to education and risk mitigation.

This work has been focused on the development of QuickAware, a VR tool designed to enhance quick clay landslide hazard awareness. The development of the tool began with data collection where useful information was gathered to define the tool's contents. Raw data concerning the contents of the VR tool was collected from experts in geotechnics, hydrology, psychology, and VR technology. These data were processed and translated into a VR educational experience.

The planning phase of the VR experience led to the creation of two distinct scenarios: the hazard identification scenario and the emergency scenario. The hazard identification scenario focused on the moments that occurred before a quick clay landslide; whereas, the second scenario focused on the events during and after the quick clay started flowing or sliding.

For both scenarios, the basis for the 3D virtual environment was the terrain. To demonstrate the tool, we chose an actual quick clay zone in Ask, the administrative center of Gjerdrum municipality in Viken County, Norway. All the VR contents derived from the raw data collected from the experts were included to make the tool a full-fledged learning platform. Using HMD and hand controllers, a user can get immersed and interact with the virtual environment and its contents.

The usability evaluation was carried out with a relatively small number of participants. The analysis of the questionnaire responses has provided insights into the effectiveness of the tool in increasing awareness of quick clay landslide hazards. Most participants expressed their willingness to use such a tool or similar ones in the future. It is important to note that drawing broad conclusions from a survey of only 16 participants carries inherent limitations. Nevertheless, when considered within the broader context of the growing trend in the usefulness of VR tools, these findings, at the very least, hint at the potential of the tool to enhance awareness of quick clay landslides.

9 Supplementary data

The Unity project generated during the study will be available upon request to the authors.

Supplementary information 2, SI2: A sample video showing a user exploring the entire VR experience and it is available at https://www.youtube.com/watch?v=eA4f5pw-p8k.

Appendix: Questionnaire

a. The general information aimed at collecting anonymous demographic data such as age and gender.

  1. Choose your age group.

   - Under 18
   - 18-24
   - 25-34
   - Above 35

  2. Gender: How do you identify yourself?

   - Man
   - Woman

- Non-binary
- Prefer not to say

3. How do you rate your computer or IT skills?

- Excellent
- Good
- Average
- Fair
- Poor

4. How experienced are you in gaming technology?

- I do not play games at all.
- I have a little experience with gaming.
- I have some gaming experience; I play occasionally.
- I am very experienced and play games very regularly.

b. General questions about prior VR experience aimed at evaluating the prior experience of participants.

1. Have you ever used a VR headset or played a VR game?

- Not at all
- Just once
- Few times
- Used it regularly

c. (Questions about quick clay aimed at assessing the understanding of quick clay.

6. How do you rate your knowledge or understanding of quick clay before this experiment?

- Excellent
- Good
- Average
- Fair
- Poor

7. Did you know what can trigger quick clay landslides before this experiment?

- Yes
- No

8. If your answer to question 7 is yes, what are the triggering factors?

d. Specific questions about this VR tool aimed at assessing what the participants perceive about quick clay landslide.

9. How much realistic was the mudflow?

- Excellent
- Good
- Average

- Fair
- Poor

10.   How much realistic were the destruction and sweeping away of the houses?

- Excellent
- Good
- Average
- Fair
- Poor

e.   General statements about this VR tool aimed at assessing the general perception of the VR experience. The statements have five-level Linkert item responses: 1. Not at all, 2 slightly, 3 moderately, 4 fairly, 5 extremely

Declarations

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