Earthoria: Enhancing Situation Awareness of Landslide Risks with Situated Visualization and Tangible Terrain Models

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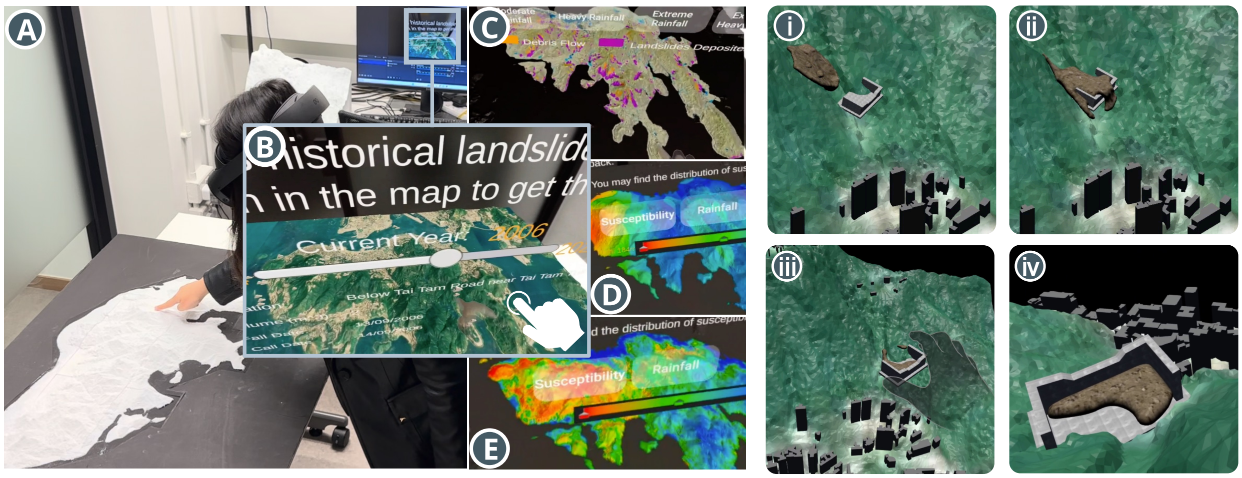

Fig. 1: Earthoria situates visualizations of landslides on tangible terrain models. It enhances situation awareness in landslide events through three main features: (A) augmented reality for situated visualizations highlighting landslide risks, (B) physical interactions on terrain models for intuitive use, and (C) first-person perspective for immersive hypothetical landslide experience.

Abstract—Landslides and other geohazards pose significant threats to public safety and infrastructure, yet public awareness and understanding of these situations remain limited. Situated visualizations have demonstrated remarkable potential in engaging the general audiences and seamlessly providing data information. Nevertheless, Augmented Reality (AR) interactions can be hindered by unnatural touch senses, inconsistent depth perception, and complicated overloads, resulting in a steep learning curve for general users. In collaboration with domain experts, we identified design requirements to enhance situation awareness about landslide risks. We explored the use of 3D printed terrain models for real-world geographic contexts, combined with embodied interactions through tangible interfaces. We present Earthoria, an immersive system prototype that integrates AR, terrain models, and tangible interfaces to offer an accessible, engaging, and informative experience for users to learn about landslide dynamics and their environmental impact. Users can physically interact with the terrain models to query and explore situated visualizations about landslide risks and perceive the geographical properties with touch senses. We designed an AR-based landslide simulation workflow to illustrate landslide prevention, precautions, and climate change implications. Earthoria was evaluated through expert interviews and design workshops, with results indicating that our prototype fosters enhanced situation awareness and increased engagement. Earthoria holds promise for broader applications in disaster management, environmental education, and public outreach initiatives.

Index Terms—Immersive analytics, Tangible interface, Geohazards, Landslide

1 Introduction

Landslides are geological phenomena referring to the downward rock and soil movements due to gravity. They occur under diverse environmental conditions [1], which result in their respective forms [2]. This study focuses on debris flows, a fast-moving flow-like landslide containing a mixture of *boulders* (large rocks) and *debris* (water, mud, aggregates, and other substances). other substances).

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Landslides cause significant economic losses and fatalities globally, with climate change increasing the frequency and intensity of rainfall-triggered landslides. Governments have implemented preventive measures, but the public underestimates their importance due to insufficient education and remote occurrences. Maintaining high situation awareness is crucial, and existing initiatives focus on understanding preventive measures and recognizing signs of danger. Inclusive approaches are needed to engage and inform the public about environmental risks.

In particular, challenges exist in reconciling engaging factors with potentially steep learning curves. AR provides opportunities for gesture-based interaction and realistic geological contexts, and has shown promise in educational environments. However, limited input methods and the absence of haptic feedback hinder natural interactions with virtual 3D objects. Spatial and embodied sensemaking in these scenarios are underexplored, and design guidelines for promoting environmental issues are scarce. Historical information may be insufficient to attract general users' attention.

This study explores using AR to promote landslide risk awareness and developed Earthoria, an immersive system that integrates AR and tangible terrain models to enhance situation awareness of landslide risks. The system leverages 3D printed terrain models, external tracking systems, and real-time simulation to facilitate what-if analysis and promote hands-on knowledge of relevant elements and associated landslide risks. The study conducted an iterative design process in close collaboration with domain experts and summarizes design implications. The main contributions are:

- Problem characterization and formulation of landslide risks in terms of situation awareness through iterative discussions with domain experts.
- Implementation of Earthoria, which harnesses the benefits of flexible AR-based situated visualizations and intuitive physical interactions with tangible interfaces, particularly 3D printed terrain models.
- Design implications and lessons learned from the co-design process of Earthoria, justifying the use of tangible models and providing insights into developing systems for general users.

2 Background and design requirements

We employed the Co-Design methodology [49, 50] to address the intricate domain of landslide risk communication. The co-design process was initiated through a collaborative research project focused on immersive education pertaining to landslide risks, incorporating the expertise of three domain experts on landslides. For the past six months, we conducted weekly meetings aimed at brainstorming strategies to involve the public and impart immersive education. As a result, the following design requirements were derived:

R1 Reduce learning curve and technical entry barrier.
Considering the target audience is the general public with diverse levels of expertise and keeping in view that our primary objective is to promote landslide risk awareness, it is necessary to design a system that can be accessed and utilized instantly with minimal technical requirements, akin to a 'walk up and use' model.

R2 Ensure simplicity and narrative quality.
Given our system's intended use in public education, it is essential that users can grasp the key message without dedicating excessive time. Hence, the information delivered to users must be kept simple, while simultaneously ensuring high narrative quality to enhance engagement.

R3 Foster situation awareness.
Landslides, like other disasters, are typically outside the realm of personal experience for most users and are therefore often perceived as abstract concepts. To help users perceive landslides as personal and immediate risks, it is crucial to facilitate situation awareness related to landslides.

3 Earthoria

EARTOPIA is an educational tool designed to illuminate the risks associated with landslides, particularly in the context of climate change. It incorporates two main features: a situated data visualization based on physical terrain and an immersive landslide simulation module.

Earthoria consists of five main components to link the physical and virtual world (**??**). These components work together to create an immersive and engaging experience for users (R3).

The tangible tracking system provides reliable physical interaction support by accurately tracking positions. It ensures that the user's interactions with the terrain models are correctly represented in the virtual world in real-time. It also provides a more natural and intuitive way to interact with digital content (R2), without learning a new set of mid-air hand gestures (R1).

The MR HMDs provide both capabilities for AR and VR. It recognizes hand gestures for more coarse and casual interactions and is responsible for providing physical contexts (*e.g.*, viewpoints) for other components while displaying the returned information (R1). Besides blending digital objects with physical contexts for casual interactions, the HMDs allow users to switch to VR view to experience the landslide immersively to increase situated awareness (R4).

The terrain models serve as the bridge between the physical and virtual worlds, as they are the main interfaces for geographical contexts and provide physical feedback to users. Rendered visualizations are overlaid on top of and situated nearby the terrain models to support depth perception and haptic responses for user interactions.

The server collects sensor data and domain information to support analytical tasks and query retrieval. It processes user interactions and provides the necessary information for rendering and visualization purposes.

The rendering system replicates the dynamic environment for users to assist in enhancing their situation awareness (R4). It renders visualizations according to physical interactions on the terrain models, ensuring that users can see the results of their actions in real-time.

The situated visualization provides users with three unique perspectives. The History View (A-B) offers detailed data on landslide events that transpired between 1984-2021, visualized directly on the physical terrain. The Climate Change View (C) depicts potential landslide impacts triggered by extreme rainfall scenarios. Finally, the Causality View (D-E) exhibits a heat map, which facilitates understanding the correlation between rainfall intensity and landslide susceptibility, using the historical torrential rain disaster from June 6-8, 2008, as a reference point.

Further enhancing the tool's educational scope, the landslide simulation module allows users to gain a practical understanding of the speed, size, potential damage, and the role of barriers in landslide events. This simulation utilizes a fluid- and particle-based simulation technique (-) to maintain real-time interactivity. Within this simulated environment, users can maneuver barriers using a tracker. This interactive process helps users comprehend how such barriers can mitigate landslides and reduce damage to residential areas (). Furthermore, the tool offers a real-time, first-person perspective that allows users to observe landslides from a vantage point on the actual terrain instead of a bird's-eye view (), thereby providing a more immersive understanding of the phenomenon.

4 Feedback from domain experts

Following the co-design study methodologies, we hosted monthly and bi-weekly feedback sessions with domain experts to evaluate the system designs and provide constructive feedback. We also recruited 12 post-graduate students and fellows (P1-12) from the local university who have backgrounds in civil engineering (4 females, 8 males; aged between 24-35). Their situation awareness in landslide scenarios is self-reported by a 5-point Likert-scale questionnaire in terms of perception (Mean = 4.17), comprehension (4.03), prediction (3.58), preparedness (3.53), and confidence (3.97).

Participants were encouraged to try the same components with and without the tangible terrain model to experience the difference. Until all participants finished their experience, they were invited to fill the questionnaire: the User Experience Questionnaire (Fig. 2) to evaluate the Earthoria system.

5 Discussion Future Work

In this study, we seek to promote situation awareness and understanding of landslide risks. Through close collaboration with domain experts and an iterative co-design process, we developed Earthoria, an immersive system prototype designed to enhance situational awareness of landslide risks in an engaging and accessible manner. Earthoria combines AR-based situated visualizations with tangible 3D printed terrain models, providing users with a seamless and intuitive tangible interface for interacting with landslide data and simulations physically.

Our work proves the concept of using terrain models to bridge the gap between the physical and virtual worlds. Earthoria can foster situation awareness and hands-on learning about landslide risks and prevention. Through the co-design process, we have derived design implications and lessons learned, highlighting the value of tangible terrain models and providing insights for developing similar systems targeting general users. As we face the increasing threat of landslides due to climate change and extreme rainfall events, tools like Earthoria can play a vital role in bridging the gap between expert knowledge

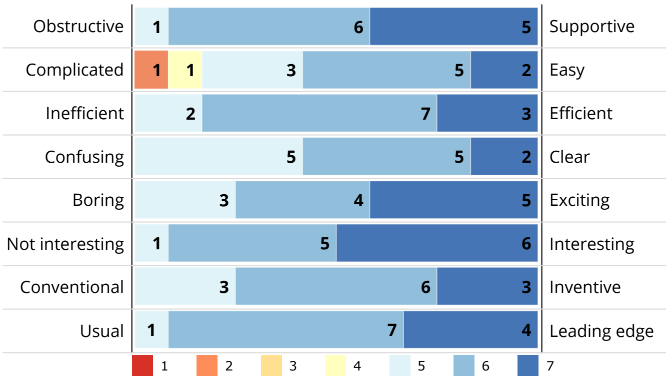

Fig. 2: The User Experience Questionnaire (UEQ) results in rating Earthoria by the overall system usability and user experience. The color indicates the marks. The numbers inside the figure indicate the number of users.

and public understanding, ultimately contributing to more informed decision-making via inclusive visualizations and a safer environment for all.

The current landslide simulation is based on the commercial solution of fluid simulation; however, the landslide mechanisms and other geohazards are intrinsically different. We will explore better rendering techniques to support real-time simulation of debris flow. Advanced landslide modeling could mitigate the computational load, and future HMD models might provide better performance in this regard. Touching on the terrain models is mainly tracked by Oculus which requires substantial attention to the hand positions. However, this is not ideal if users want to fully immerse or collaborate with others. Thus, external-tracking systems might be needed. The system that detects proxy objects during collaboration is underexplored.

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