**Title**: Immersive Virtual Reality fieldwork investigation of a landslide in Hokkaido, Japan

Azim ZULHILMI[1], Yuichi S. HAYAKAWA[2]

**Abstract**

Virtual reality (VR) is an emerging platform that has the potential to advance techniques in geological fieldwork. However, geologists currently lack the variation of necessary VR toolsets for this purpose. The reason is that VR as a technology, is still relatively new and developing. This is the reason most VR research relating to geoscience have been relatively limited and niche, with a predominant focus on more social-related studies. Therefore, this paper aims to showcase an alternate application approach of VR by conducting a geological investigation and interpretation of a small landslide in Hokkaido, developed during the 2018 Hokkaido Eastern Iburi Earthquake. To accomplish this task, a virtual replica of the landslide was reconstructed in VR using drone remote sensing techniques along with accompanying VR measuring tools. The outcome identified and discussed relationships of pre-topographical influence on the landslide's current morphology and deposits pattern based on VR based topographical measurement results. Furthermore, this study also provides some insight into smaller landslide types which are typically overlooked in current research works. It is recommended that future research further explore VR fieldwork applications across different geomorphological subjects. This research offers valuable insights for practitioners interested in adopting VR technology, while also enhances the current understanding of the landslide phenomenon through a VR-based perspective.

**Keywords** Virtual Reality, Geology, Landslides, Fieldwork, Immersive

**Author information**

1. Azim Zulhilmi (**Corresponding Author**)
   - Azimzulhilmi@ees.hokudai.ac.jp
   - Graduate School of Environmental Science
   - Hokkaido University, Sapporo, Japan
   - https://orcid.org/0000-0003-3303-9369
2. Yuichi S. Hayakawa
   - Faculty of Environmental Earth Science
   - Hokkaido University, Sapporo, Japan
   - https://orcid.org/0000-0003-2053-8986

**Conflict of Interest** The authors declare no competing interests.

**Acknowledgements**

The authors would like to acknowledge the support of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of the Japanese government for providing the scholarship that sponsored this study.

This work is partially supported by Japan Society for the Promotion of Science (JSPS) KAKENHI Grant Numbers JP21H00625 and JP21H00627, and 2023 Hokkaido University COI-NEXT fund.

The authors would like to express their sincere gratitude to the anonymous reviewers for their valuable feedback and insightful comments, which have greatly contributed to the improvement of this manuscript. Their thoughtful suggestions were instrumental in refining this work and enhancing its clarity and depth.

## Introduction

Landslides are complex three-dimensional (3D) geological phenomena that necessitate a multidisciplinary perspective taking insights from various fields such as geology, hydrology, geography, and engineering. To have a well-rounded understanding of the intricate interplay of the mechanisms that contribute, control, and shape the creation and evolution of landslides requires a comprehensive holistic approach (Lissak et al., 2020). Virtual Reality (VR) emerges as a transformative tool that may have substantial potential for making significant contributions to Geoscience. It stands to become an invaluable new asset in the arsenal of a geologist, offering a unique and immersive perspective that has the capacity to enhance various aspects of geological studies. VR is defined as a computer-generated immersive and interactive environment that simulates a realistic 3D experience that can be accessed by using a VR head-mounted display (HMD) and the respective input peripherals. In the industry, it is part of the broader concept, known as Extended Reality (XR) or spatial computing, alongside Augmented Reality (AR) and Mixed Reality (MR).

Modern VR predominantly serves the entertainment industry, where it originated with the 2011 Oculus Rift prototype by Palmer Luckey. Most VR innovations still arise from the entertainment industry and later extend to fields like healthcare, education, and military. Despite being in its infancy, VR adoption is growing rapidly; Alsop (2023) reported a rise in VR headset shipments from 4.46 million in 2019 to 14.19 million in 2022. Emerging technologies, such as biometric sensors to interact with virtual objects includes brain-computer interfaces (mind-based control), olfactory devices (smell), and biosensing gloves (feel), aim to enhance user immersion (Demolder et al., 2021; Kim et al., 2021; Liu et al., 2023). These advances hint at promising applications in geoscientific disaster research and education.

*Literature review*

In terms of adoption within academia, there have been academic activities that have already begun using VR as a platform for knowledge dissemination (1st International Symposium 2022: The Metaverse and XR Technology – Educational Applications and International Collaboration; VRC Science assembly; 2nd International Mountain Development and Tourism Conference 2023; GeoVT Multiplier Event). These are all stylized in the form of VR oral presentations and poster sessions attended by a diverse group of audiences from all over the world.

Few studies have applied VR in geological disaster contexts. Spero et al. (2022) used VR to simulate the 1976 Teton Dam failure, combining hydrogeologic modeling and VR for flood visualization. Skinner (2020) developed "Flash Flood!" to engage the public using real geomorphology data. De Lorenzis et al. (2022) created a VR Training System for first responders, offering realistic scenarios for hydrogeological risk management.

For earthquake disasters, Feng et al. (2020) used VR with serious games to enhance earthquake response and evacuation preparedness. Takeichi et al. (2020) applied VR for multi-disaster evacuation simulations, aiding non-expert preparation for events like floods, earthquakes, and fires. Maragkou et al. (2023) developed "VR Quake," an immersive VR tool for seismology education and disaster preparedness.

Alene et al. (2023) used VR to visualize debris flow landslides, showing road users' perception of impending landslides varies with viewing angle. This insight supports strategic placement of early warning systems.

As noted above, VR-related research spans a vast variety of topics across different geological disaster fields. However, VR research work in these fields extending beyond social studies remains limited, niche, and experimental, requiring attention from the scientific community to frame its place. For geoscientists, this problem is largely due to the lack of a comprehensive suite of dedicated tools and software for conducting such VR analyses.

*Objectives*

Therefore, to further diversify this limited VR research sphere, this paper explores the use of consumer-grade immersive VR technology for a geoscientific investigation of a small landslide specimen, focusing on VR-based measurements, comparisons, observations, and retrodictive interpretations of its development and stabilization. To the authors' knowledge, such VR applications in geoscience have not been previously conducted. It also details the reconstruction of the landslide into VR for those interested in creating their own virtual environments. This study aims to demonstrate VR’s potential in advancing remote landslide research, offering a geoscientific approach distinct from the prevalent social study methodologies, and contributing to the existing knowledge consensus of landslides in the study area.

**Overview of study area**

The location of the landslide is in Hokkaido, Japan in the subprefecture of Atsuma (Fig. 1). The coordinates are as follows: 42°46'43.5"N 142°00'48.3"E. It is a small (approximately 32 x 57 m) landslide subject situated not far from the Apporo Dam towards the northeast. It can be interpreted as a shallow landslide characterized as a type of earthflow (Varnes, 1978; Cruden and Varnes, 1996; Osanai et al., 2019). This location is about 120-140 m above sea level. According to Ritonga et al., (2021), the dominant forest cover species are Betula platyphylla, Quercus mongolica, Larix kaempferi, and Abes sachalinensis. The major grass species here is the Sasa kurilensis (a.k.a. Sasa dwarf bamboo grass). Given the volcanic nature of the region's surface geology, the landslide debris mainly comprises a mixture of the region’s vegetation and tephra.

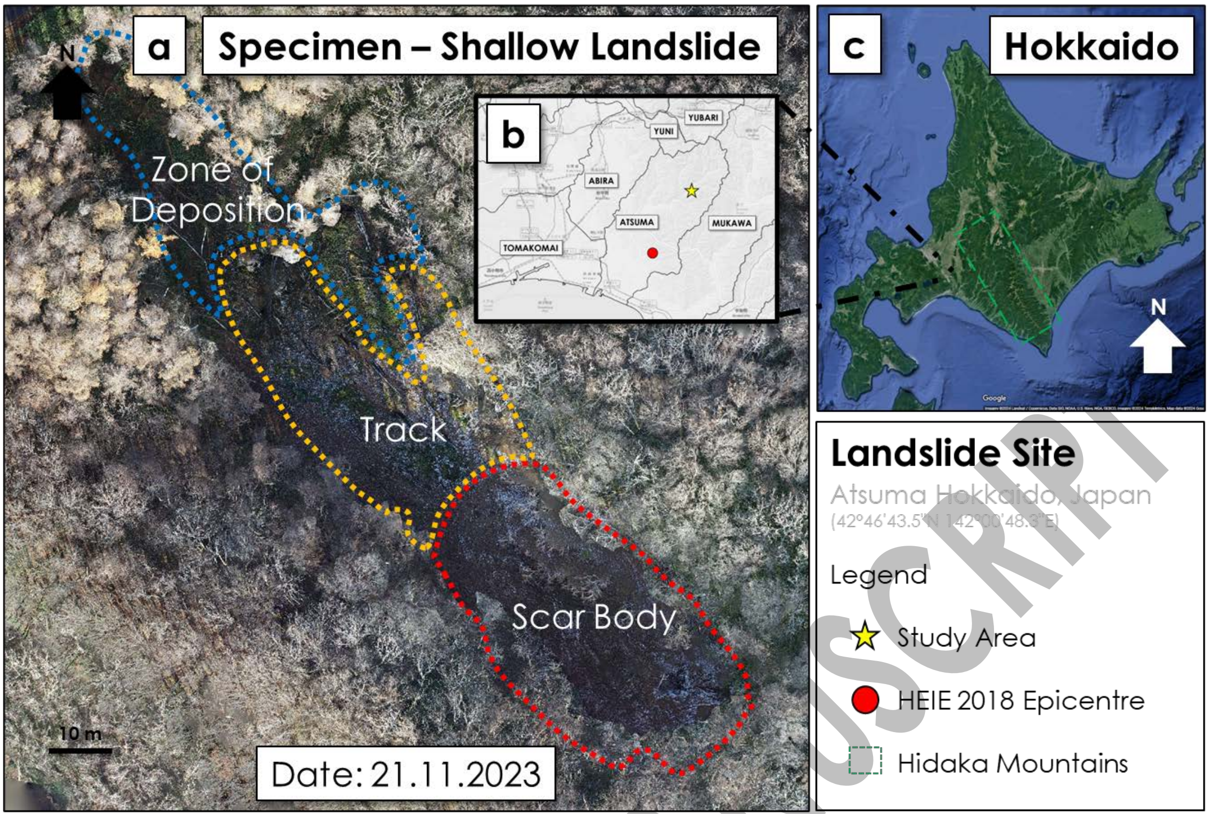


**Fig. 1** Study site location. (a) Interpretive sketch of the anatomy of the landslide specimen examined in this study. (b) Location of the landslide in Atsuma respective to the earthquake. (c) Map of Hokkaido highlighting Atsuma location near the Hidaka Mountains.

The 2018 Hokkaido Eastern Iburi Earthquake (HEIE) ($M_w = 6.6$) struck on September 6, 2018, triggering 5,625 co-seismic landslides in the Atsuma region and neighboring areas (Yamagishi & Yamazaki, 2018; Zhang et al., 2019). These landslides likely occurred due to the Halloysite-rich Tarumae-d layer, which retained water from rainfall and was destabilized by seismic waves (Osanai et al., 2019; Wang et al., 2021; Zhang et al., 2019; Zhou et al., 2021). As of 2022, landslide progression continues slowly, influenced by seasonal freeze-thaw cycles in the volcanic substratum (Nakata et al., 2021; Lo, 2021).

**Methodology**

The research workflow comprises two parts: VR and True Reality (TR). In VR, landslide specimens are reconstructed into VR environments, with custom VR tools developed for essential topographical measurements, creating a complete VR fieldwork experience. TR involves conventional fieldwork using standard geological equipment to validate VR-derived measurements. Fig. 2 summarizes this framework.

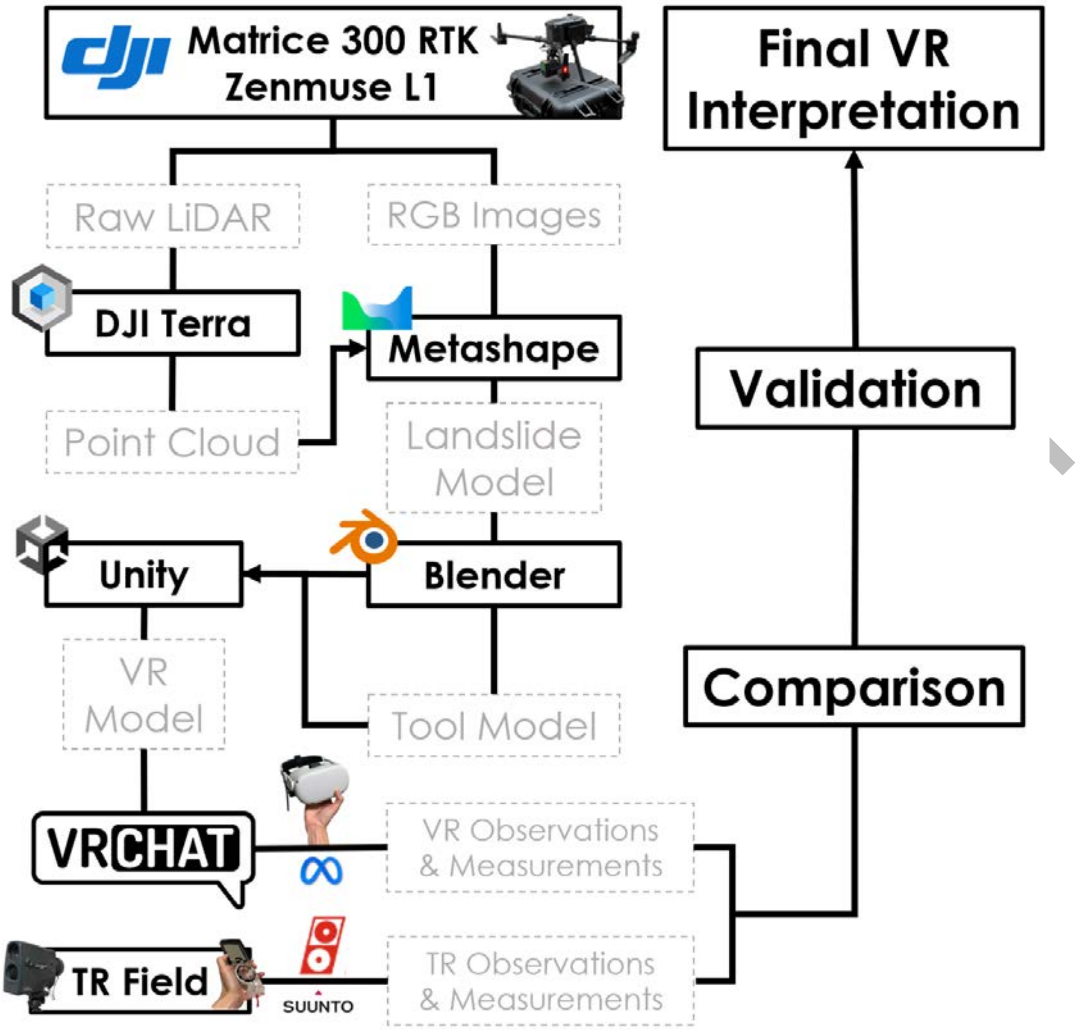


**Fig. 2** The workflow of this study

*Preliminary Data Compilation and Preparation*

Data for the study was collected and prepared from data repository of prior drone missions done in the study area. The data used was taken during the Autumn season on the 21st November 2023 under partially cloudy conditions with wind speeds of < 2.3 m/s at a temperature ranging between 0.7– 11.8°C (Japan Meteorological Agency).

These were Light Detection and Ranging (LiDAR) and Structure-from-motion Multi-View-Stereo (SfM-MVS) datasets that were taken from the same optical laser sensor Zenmuse L1 (ZL1) payload that was mounted on a DJI Matrice 300 RTK (M300RTK) Unmanned Aerial Vehicle (UAV). The UAV was flown at approximately 80 m (± 20 m) altitude capturing the landslide subject in a single grid route and georeferenced with DJI D-RTK 2 antenna to attain less than 10 cm of positional accuracy. The workstation used in this research for processing the data was self-built with the specifications listed in Table 1.

**Table 1**

*Workstation specifications*

| Component | Model |
|---|---|
| CPU | AMD Ryzen 5 7600x 5.3 GHz |
| GPU | NVIDIA RTX 3080 Ti 12GB 1785Mhz |
| RAM | 8GB x 2 5200MT/s DDR5 CL40 XMP 3.0 |
| SSD | WD SN770 M.2 2280 1TB |
| PSU | Corsair RM850e CP-9020249-JP |

*Note. Windows 11 Pro (Operating System)*

The SfM-MVS data of this research consists of 50 georeferenced RGB images taken from an aerial perspective of the subject with 70-80% overlap. They are then imported into Agisoft Metashape (Version 1.8.5), bundle adjusted, aligned to create the required tie points, and subsequently generate the dense point clouds. To optimize performance, dense point clouds were manually filtered to remove unnecessary trees and noise, focusing on topography. This, along with View Frustum Culling, reduces computational load by only rendering visible elements, improving VR rendering efficiency and user experience. The terrain was left intact during filtering. The dense, filtered point clouds were converted into meshes and textured with 16K resolution using RGB photos from the M300RTK ZL1 UAV. Blender 3.6 was also used to perform minor cleanup of stray meshes following the conversion process.

LiDAR datasets are subjected to initial processing using DJI Terra (Version 3.9.3) to extract the point clouds to be used in Agisoft Metashape. Likewise, with SfM-MVS data, they are processed, noise filtered, developed into meshes and texturized with 16 K resolution textures using the images taken from the same M300RTK ZL1 UAV.

Both meshes are then exported from the software with their texture atlas material library file and are then imported into Unity (2019.4.31f1) where VR properties are assigned (e.g. walkability, physics, and interactability) to simulate the VR experience. The virtual models was hosted in a VR social platform known as VRChat (VRC) which runs on the Unity engine, integrated using its legacy Software Development Kit (3.1.13). VRC is a free software with the capability to store virtual worlds for either public or private accessibility. It has not yet been observed to be used in geoscience-related research but is well used in research works of the past relating to social sciences experiments (Barreda-Ángeles & Hartmann, 2022; Maloney et al., 2020; Saffo et al., 2021). This platform is also used to host a VR display museum revolving on this paper for outreaching purposes (refer to the supplementary section).

*VR tool design*

The virtual tool design in this study is inspired by traditional geological fieldwork tools, including a 2-m ranging rod, clinometer, compass, navigational tablet (NavTab), and water bottle (Fig. 3). These tools are adapted for VR, considering aspects like size, interactivity, and intuitiveness. Using Blender, 3D models are created and exported with textures to Unity, where VR properties (e.g., wieldability, kinematics, interactability) are assigned for deployment in the virtual space.

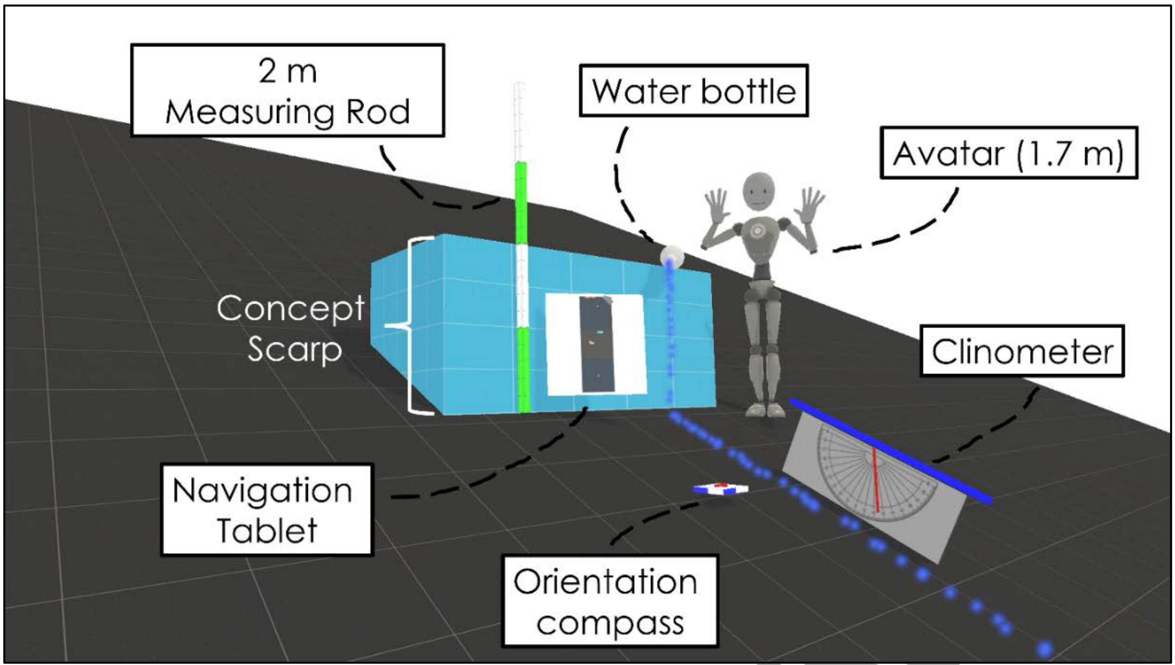


**Fig. 3** Concept measurement using VR measuring tool created for this study

*VR Fieldwork*

This paper defines VR geological fieldwork as such only when it possesses these key attributes:

- Inclusion of a virtual environment twin of the geological subject
- Capability to employ VR tools for interactive measurement and data collection
- Capacity to facilitate immersive VR observations and locomotion

The VR fieldwork in this study consists of doing two separate tasks which are to make immersive virtual measurements and virtual observations.

The Oculus Quest 2 HMD was selected for visualizing the VR landslide due to its affordability, versatility, and popularity, as shown in the 2023 Steam Hardware Survey. Using VR tools, slope angles, directions, and scarp height were measured, with the landslide divided into left and right flanks (Fig. 4). Slope characteristics were deduced using a virtual water bottle to measure angle and direction, repeated 10 times (5 per flank). Scarp measurements were taken along a 25-point line at ~4 m intervals with a VR measuring rod. These measurements were averaged to enable a straightforward comparison using the available VR data.

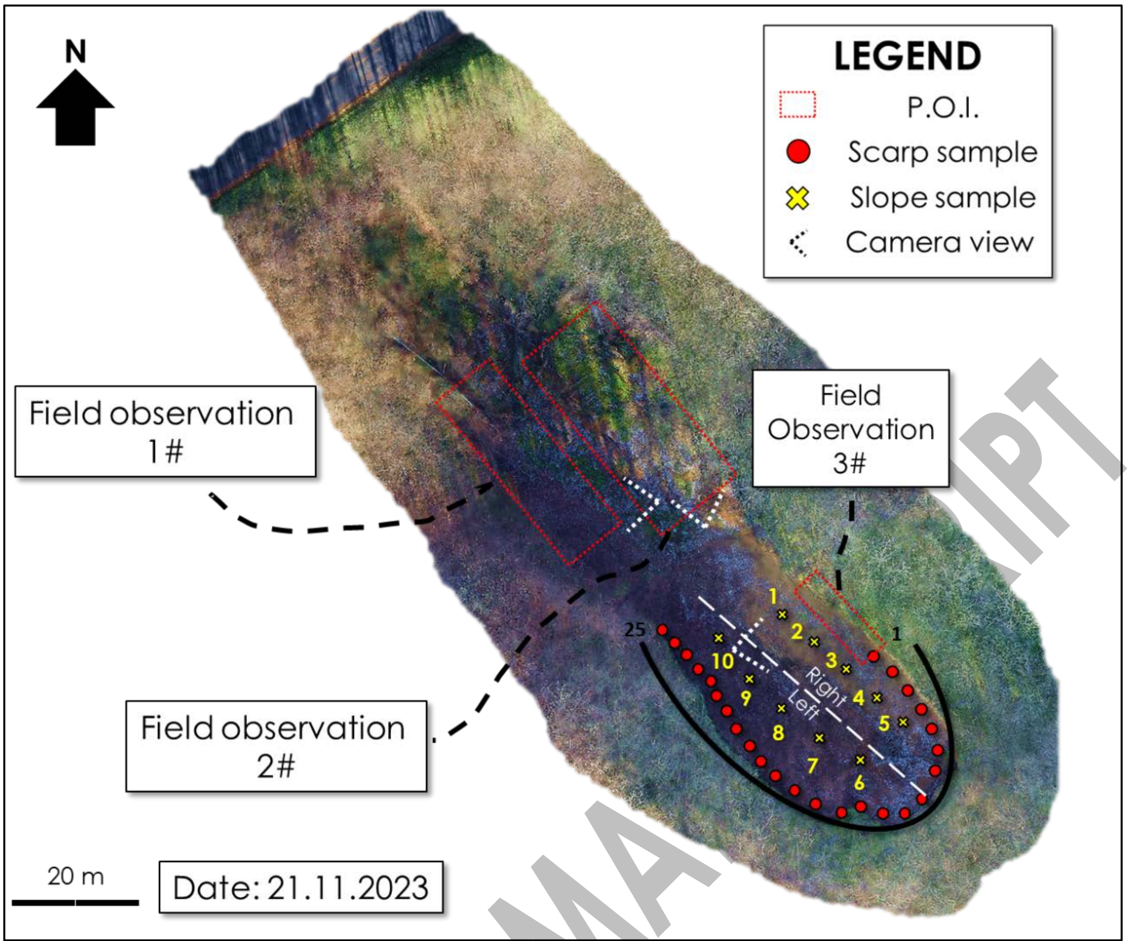


**Fig. 4** This image shows the measured sample location on the landslide, camera view of POI, and the partitions of the left/right flank (alternate image from Autumn 2022 is available in the supplementary section)

In virtual observations, the authors leverage the mobility afforded by VR to explore the landslide subjects from diverse angles and perspectives. This includes walking, sprinting, jumping, levitation, and phasing. The authors logged observations, took virtual field pictures using a VR camera system, and made notes of several points of interest (POI) at the study site. For positioning-related concerns, the authors relied on the NavTab which feeds live information of the user's location on the map.

*TR Fieldwork*

For the case of TR fieldwork, the aim was to validate the observations and measurement results that were collected in VR. Similarly to the VR workflow, there are two parts in TR fieldwork which consist of 'boots on the ground' measurements and observations. The fieldwork was conducted on 31st October 2023 from 10:30-3:00 pm (~5-hour duration) under cloudy conditions at ambient temperatures of 15-17°C.

In TR, measurement was done on the landslide slope angle, directions, and scarp height replicating as it was conducted in VR. For slope-related measurements, a geological field compass, SUUNTO MC-2 G Mirror Compass (plastic needle version) was used and calibrated with a magnetic declination of 9° west derived based on the World Magnetic Model 2020 (Chulliat et al., 2020). For scarp measurements, the TRUPULSE ® 360° B Rangefinder was used to gather approximate measurements at a safe distance, with similar sample counts taken in VR of the scarp from the ground until the base of the grass cover.

The logged POIs identified during VR observations were confirmed to exist based on prior observations conducted in TR. Field photographs were captured using an iPhone 12 Pro and a RICOH Theta X.

*Validation and Interpretation*

The measurement results taken from VR are then compiled and compared to the accumulated TR field measurement results. The purpose is to simply establish reliability, thereby enabling this research to proceed with the VR field investigation style of its methods (not to be mistaken for a comprehensive accuracy study). The authors took the mean average results of the slope and scarp measurements of each flank and use these values to compare, and the results are considered as the validated results. Lastly, field notes and photographs from both TR and VR observations are utilized to form an initial interpretation of the field site. These observations are then integrated with the validated measurement results to construct a comprehensive VR-style interpretation of the landslide subject.

**Results**

*Virtual field observations*

Here, several key observations related to the landslide specimen identified. Fig. 5 illustrates the observations from both VR and TR perspectives, outlined as follows:

- Incomplete scarp development (right flank)
- Oriented tree deposits
- Deviation in the flow path of the landslide

The first observation reveals an incomplete scarp, that resides on the right flank of the landslide which appears to have initiated midway, as depicted in Fig. 5a and 5b, alongside the presence of a scarp mound that lies next to it (Fig. 5j). The second observation are the tree deposits that are oriented in the area indicating the landslide direction oriented towards the northwest, as shown in Fig. 5d, and 5e. Furthermore, the third observation is that there is a noticeable deviation in the landslide's flow path, gradually shifting from the northwest to a direction closer to the north, as evidenced in Fig. 5g, and 5h. Observations in TR is as shown in Fig. 5c, 5f, and 5i.

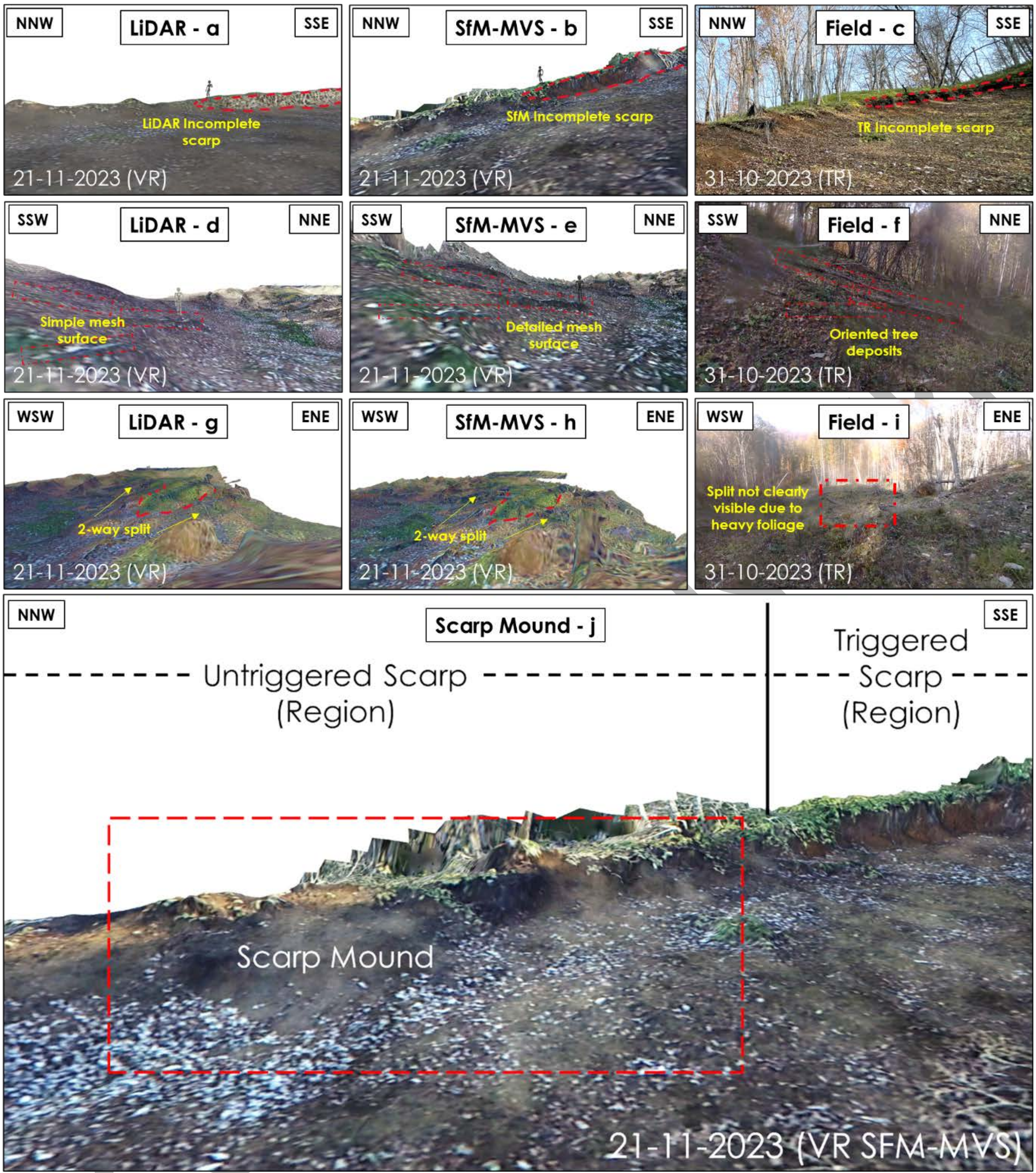


**Fig. 5** Observed POIs as seen in VR LiDAR, VR SfM-MVS and field (higher-resolution images available in supplementary materials)

*Interpretation of the landslide*

Based on the VR-based measurement results, observation and current knowledge of the landslide event, a preliminary interpretation of the landslides was performed. In interpreting the data, it is proposed that the process of the landslide occurred through six simultaneous and rapid steps. (Fig. 6a-f):

1. Initiation of scarp failure– The landslide was initiated as a simultaneous cohesive event, with the first half of the right scarp remaining inactive (Fig. 6a).
2. Shallow landslide – The landslide exhibited high fluidity due to seismic waves and halloysite-induced liquefaction (Wang et al., 2021; Zhang et al., 2019). The main flow

originated from the steep, unobstructed left flank, while the right scarp lagged due to obstruction by the inactive landslide section (Fig. 6b).

3. Overflow and abrasion – As debris moves northwest, the unactivated region is abraded at two angles by the main flow and right flank subflow, generating material at the contact point. Combined with north- and west-facing slopes, this excess material surpasses the flow path's capacity, creating a chokepoint that ejects debris northward into the non-landslide area (Fig. 6c).
4. 1st deposition and momentum loss – This brief and instantaneous phase suggests overflow material encountering obstructing trees in this non-landslide area, resulting in their collapse and immediate deposition (Fig. 6d).
5. 2nd deposition and momentum loss – Haphazardly deposited trees in the overflow region impede the main flow, reducing momentum. This effect, common in tree-rich areas (Ritonga et al., 2021), combined with gentler terrain and lower elevation, initiates the second deposition phase at the landslide lobe (Fig. 6e).
6. Final deposition – The final deposition sees the trailing trees at the tail of the landslide being deposited preserving the orientation of the original flow. Furthermore, the obstruction from the inactivated scarp is fully reduced into a scarp mound as seen in the virtual field (Fig. 6f).

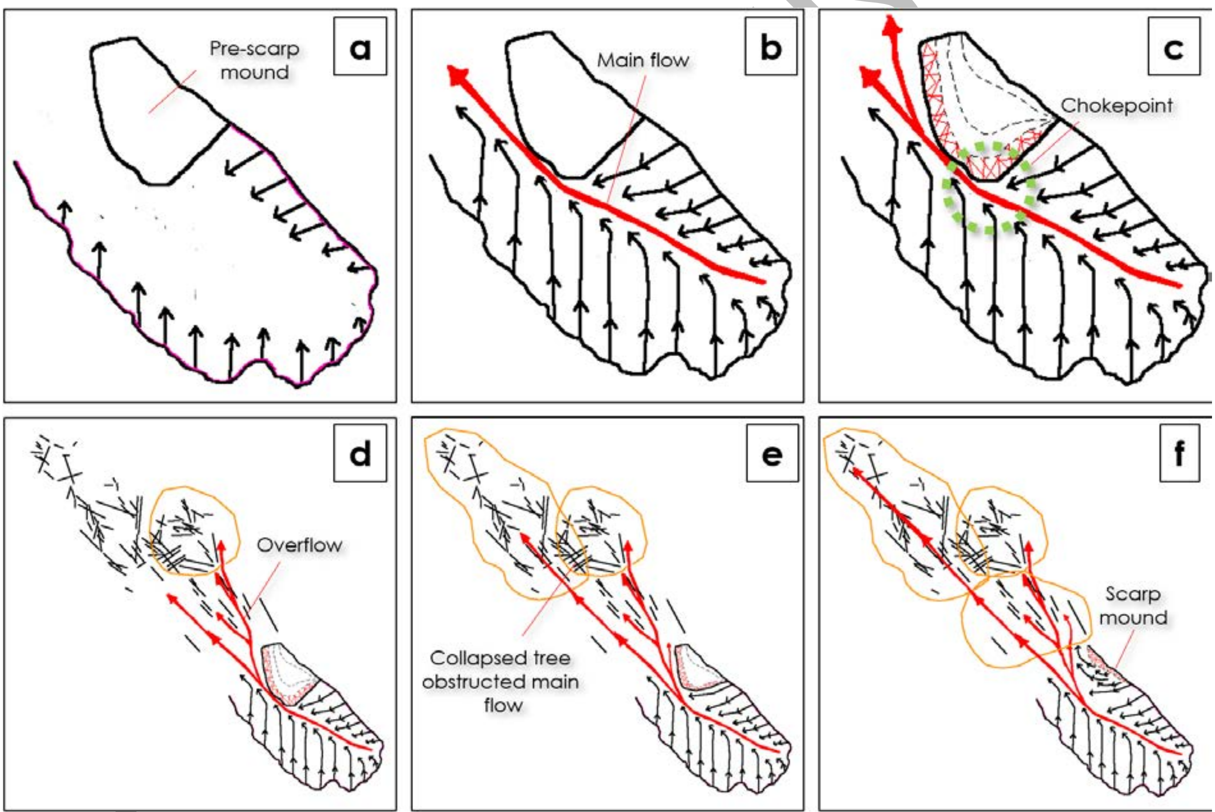


**Fig. 6** Pre-liminary field interpretation sketch of the landslide's progression stages based on VR observations and data. a) Initiation of scarp b) Main flow development c) Overflow and contact abrasion d) 1st deposition and momentum loss e) 2nd deposition and momentum loss f) Final deposition

*VR and TR measurements*

VR measurements for both sides of the landslide are averaged (Tables 2, 3, and 4). Raw measurements are displayed as scatter plots and bar charts (Fig. 7).

Right flank slope angle measurements showed a mean of 32° for VR LiDAR and 33° for VR SfM, deviating by 2° and 3° from the TR mean of 30°. For the left flank, both TR and VR LiDAR measured 36°, while VR SfM-MVS measured 35°, with deviations of 0° and 1°, respectively. Overall, VR measurements deviated by an average of 1° from TR values. These results indicate the right flank is generally gentler than the left.

The mean slope direction of the right flank is 268° for TR, 280° for VR LiDAR (12° deviation), and 269° for VR SfM-MVS (1° deviation). For the left flank, TR is oriented at 0°, with VR LiDAR and VR SfM-MVS at 354° and 357° (3-6° deviation). Overall, VR measurements deviate by 1-3° from TR. These findings suggest the right slope generally faces west, while the left slope faces north.

Significant deviations exist between TR and VR scarp measurements. TR shows an average scarp height of 0.95 m (1.0 m right, 0.9 m left), while VR LiDAR averages 1.4 m (1.4 m both sides), and VR SfM-MVS averages 1.55 m (1.6 m right, 1.5 m left), with deviations attributed to vegetation and canopy interference in SfM-MVS samples 6 to 9. The deviation between TR and VR measurements ranges from 0.4 to 0.5 m. Although VR LiDAR aligns more closely with TR than SfM-MVS, both show significant gaps from actual values.

**Table 2**

*Average Landslide Measurement in True Reality*

| Left Slope (°) | Right Slope (°) | Left Scarp (m) | Right Scarp (m) | Left Slope Direction | Right Slope Direction |
|---|---|---|---|---|---|
| 36 | 30 | 0.9 | 1.0 | 000 N | 268 W |

*Note.* 31st October 2023

**Table 3**

*Average Landslide Measurement in Virtual Reality LiDAR*

| Left Slope (°) | Right Slope (°) | Left Scarp (m) | Right Scarp (m) | Left Slope Direction | Right Slope Direction |
|---|---|---|---|---|---|
| 36 | 32 | 1.4 | 1.4 | 354 N | 280 W |

*Note.* 21st November 2023

**Table 4**

*Average Landslide Measurement in Virtual Reality SfM-MVS*

| Left Slope (°) | Right Slope (°) | Left Scarp (m) | Right Scarp (m) | Left Slope Direction | Right Slope Direction |
|---|---|---|---|---|---|
| 35 | 33 | 1.5 | 1.6 | 357 N | 269 W |

*Note.* 21st November 2023


**Fig. 7** Bar chart representing the raw data (a) scarp height, (b) slope angle, and (c) slope direction (raw data is available in supplementary section)



## Discussion

*VR measurement comparison*

Slope angle data shows the gentlest slope is the right flank (32–33°), followed by the left (35–36°), with only ~1° deviation between VR and TR (Tables 3 and 4). These findings align with typical HEIE 2018 landslide angles (20–40°) (Osanai et al., 2019; Zhang et al., 2019). VR measurements closely match TR values, with negligible errors. Minor discrepancies likely stem from the lower-quality point cloud of the low-cost UAV LiDAR compared to SfM-MVS. The right flank slope generally faces west and the left faces north, with orientation deviations of 1-5° from TR, which are considered minor. The most significant offset is in scarp measurements. VR LiDAR shows a height deviation of 0.4-0.5 m, and VR SfM-MVS deviates by 0.6 m from TR, with VR LiDAR being closest to actual values. However, both VR methods exhibit a noticeable gap in scarp measurements, making them unreliable for interpretation.

Several field conditions can impact the quality of VR environments generated by UAV remote sensing workflows. Aerial SfM-MVS is sensitive to vehicle and subject movement (Liao et al., 2021). For example, influenced by factors like wind, uneven lighting, dead vegetation, moving objects (e.g., swaying trees), and occlusion. Wind drafts may alter UAV flight paths, while uneven lighting complicates feature matching, hindering tie-point generation (Cawood et al., 2017). Dead biomass on landslide surfaces occludes sensors, adding noise instead of capturing true surfaces. Vegetation can distort point cloud accuracy, affecting mesh height (Obanawa et al., 2020). Additionally, equipment calibration may introduce further uncertainty.

LiDAR methods typically generate fewer point clouds than SfM-MVS (Cawood et al., 2017; Kalacska et al., 2021; Obanawa et al., 2020). In this study, LiDAR produced 998,302 points, while SfM-MVS yielded 3,182,394. Lower point cloud density in LiDAR can increase errors, resulting in a smoother mesh surface compared to the more detailed, rougher surface from denser SfM-MVS (Sánchez-Aparicio et al., 2020).

LiDAR VR scarp measurements align more closely with TR than SfM-MVS (Fig. 7), due to dense Sasa bamboo along the scarp edge, which blocks the laser from reaching the true surface, merging grass height with scarp height. SfM-MVS further exaggerates height due to wind-swayed grass, making conditions less ideal (Obanawa et al., 2020; Rotnicka et al., 2020). Future studies might consider mobile LiDAR for closer, more accurate capture of occluded areas.

In summary, LiDAR and SfM slope measurements are both accurate, deviating from TR by only 1°. However, both methods showed significant errors in scarp measurements, making them unreliable for this purpose. If vegetation obstructions are minimal, UAV LiDAR is recommended for geomorphologically accurate VR environments, while SfM offers a cost-effective alternative with negligible deviation. Flying the UAV closer to the subject is advised to capture finer details, although this was not feasible here due to elevated trees posing collision risks. Adopting this approach would improve VR environment accuracy for both methods.

*VR observations*

Three main observations were made during the VR fieldwork.

The first VR observation focuses on the incomplete scarp formation on the landslide's right flank (Fig. 5a & b). From an aerial view, this feature isn't immediately clear, but VR's 3D perspective enhances identification, highlighting one principal advantages of VR. It is hypothesized that this scarp was not activated but experienced "contact abrasion" from debris of activated scarps. Supporting evidence includes its location on the gentler slope (Tables 2, 3, and 4), the presence of a scarp mound instead of a clear scarp (Fig. 5j), and its lower, more stable elevation (all suggesting this area may not have met landslide initiation criteria).

Buried trees with consistent orientations, observable in VR (Fig. 5d & e), indicate the landslide's flow path, extending from the tail to the lobe (Fig. 8). The flow direction is northwest, at ~320° based on VR measurements. The landslide has two main slopes (one west and one north) which theoretically, based on vector addition, if there is flow along these slopes of equal material and momentum, would combine to a flow direction of 315°. The slight 5° deviation toward ~320° is likely due to the steeper and wider left flank, which held more debris than the gentler right flank, influencing the flow's momentum and direction.

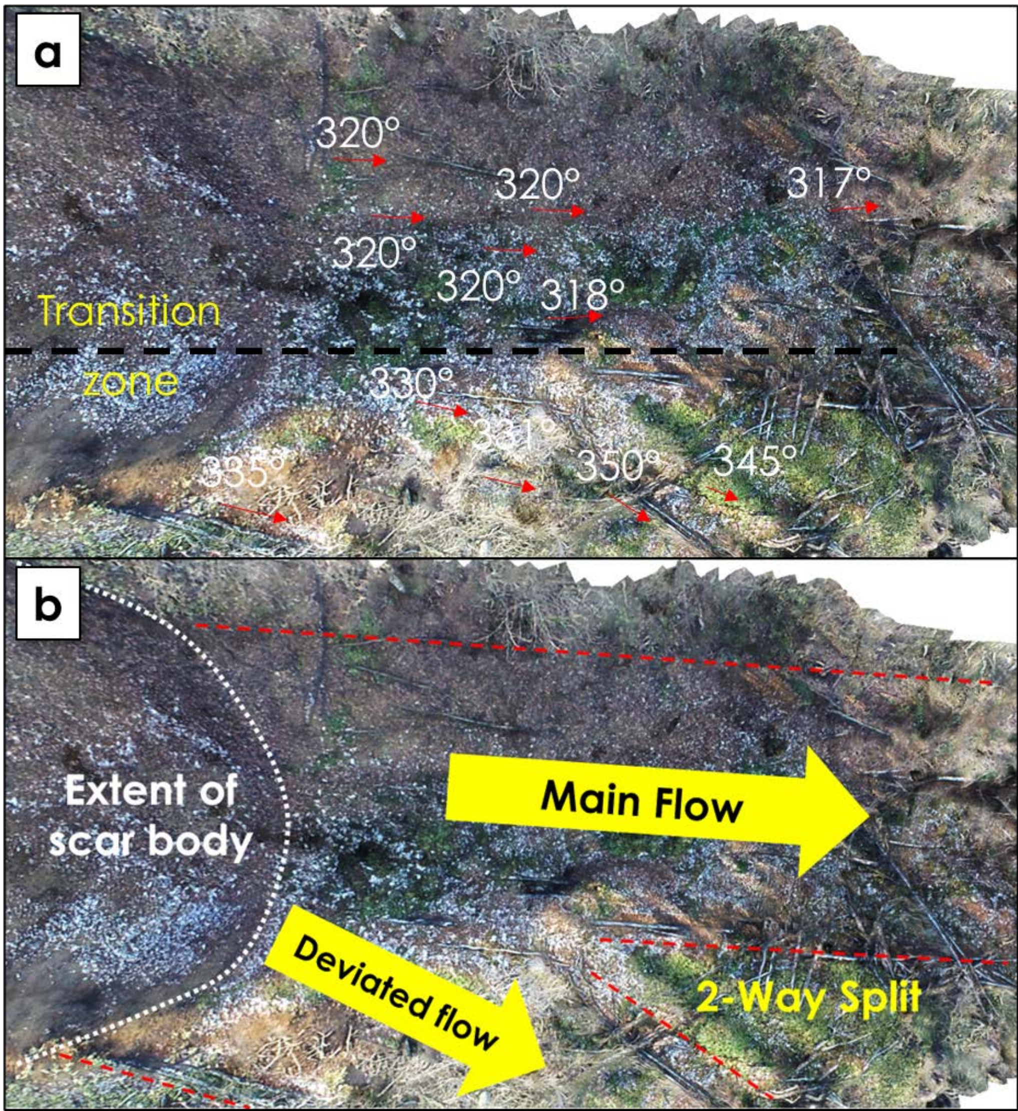


**Fig. 8** a) Aerial VR perspective of the track area of the landslide showing the sampled tree deposit's orientations: main flow (317-320°) and overflow (330-350°). b) The two flow directions relative to the scar body

The final observation is the deviation in the landslide's flow path (Fig. 5g & h). The deposit appears to shift from the original flow (~320°) to a new orientation of ~350°, as seen in the buried trees' gradual change in alignment (Fig. 8a). This deviation (Fig. 8b) likely results from several factors: a greater pre-event material load on the steeper and wider left flank, initial scarp material being obstructed by stationary material (pre-scarp mound) from the unactivated scarp, and multiple material feeds (left, right scarps, and abrasion of the obstructing unactivated landslide scarp material. These factors likely created a "chokepoint," causing overflow and the large (>10–30°) directional shift.

The VR SfM-MVS environment provided a more detailed mesh of buried trees, while the VR LiDAR environment struggled to detect them. This difference is due to the entry-level LiDAR sensor used, which produced a lower point cloud density compared to the more detailed photogrammetry. An industrial-grade LiDAR might resolve this issue. As a result, VR SfM-MVS preserved more surface details due to its higher point cloud count, whereas VR LiDAR offered a more summarized view. In TR, such features are typically hard to identify due to poor visibility unless specifically sought.

In summary, observations made in VR, such as those that were encountered, can be frequently overlooked when done in a conventional fieldwork setting or through static photograph assessments due to the inherent complexities of the real-world environment. The field presents an abundance of sensory distractions that can obscure features of interest, including visual elements like dense foliage, soil, shrubbery, color variations, shapes, and textures (Orion and Ault, 2007). Additionally, physical challenges such as navigating steep terrain, climbing, and restricted lines of sight may further contribute to the potential for oversight. In the VR environment, the simplified nature of the VR landslide subject coupled with the freedom of movement such as flight, intangibility, ease of traversal, and limitless stamina allows for different angles of perspective not usually explored in conventional fieldwork. This makes 3D features that are difficult to identify in the field and aerial photographs much more prominent and obvious in VR.

*Limitations of the VR interpretation*

VR-based interpretation may require some TR fieldwork to validate observations, as VR environment quality depends on the characteristics of the data used for its creation. While SfM-MVS offers photorealistic textures, mesh simplicity can misrepresent real features, leading to potential misinterpretations, especially for finer details like cracks or surface roughness. Additionally, VR environments lack dynamic elements of real life, limiting their authenticity as just 3D static snapshots of the field. Although the lack of realism is a significant challenge for this study VR environment, it also serves as a key area of focus for continuous improvement.

Regardless, VR significantly enhances this study interpretation process by making obscured features more visible through VR visualization (with 3D detailed depth) compared to typical 3D-pseudo representation, enabling the extraction of critical observational data often overlooked in traditional methods. These insights provide essential context for understanding landslide phenomena. Additionally, VR's scalability, complete immersion, and vast locomotion freedom improve observational capabilities, allowing for detailed and accurate interpretations. At present, VR stands as the best effective immersive tool for closely simulating geoscience fieldwork.

## Conclusions

In this article, a landslide subject was explored and assessed using VR technology with the theme of using VR tools inspired by traditional geological measuring methods. By doing so the research produced results, conducted analysis, made suggestions, and disseminated knowledge from the perspective of VR. This study concludes that VR can be applied as a tool for field investigation, identification, and interpretation for geological fieldwork. Based on the results, this research recommends the SfM-MVS workflow as a starting pathway to generate reliable, versatile and cost-effective VR fieldwork environments that can be replicated for most geomorphological subjects. The concluding advantage of VR technology for fieldwork is that it is a capable tool for preliminary investigations, planning, and interpretations which provides an additional angle for supplementing a more comprehensive study of a geological subject. VR is currently the only technology that is capable enough to fill the immersive niche for geoscientists that no other conventional technology or methods can replicate. Afterall, geology is an observational science.

Future studies may consider fusing different types of geological data creating a more immersive hybridized dynamic field investigation experience compared to this research's more static one.

The findings of this research contributes a supporting perspective to the current knowledge consensus of the HEIE 2018 landslides and also highlight some of the possibilities offered by VR technology in its application in geoscience. This has the vast capacity to benefit not only scientists, but also stakeholders, and educators alike, serving VR as a platform for communicating science, creating collaborations, and research opportunities.

**Data availability**

Data available under certain conditions.

**Supplementary information**

Supplementary VR Museum link: https://vrch.at/ynjy376s

**Authors contribution**

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Azim Zulhilmi and Yuichi Hayakawa. The first draft of the manuscript was written by Azim Zulhilmi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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