

Engineering Geological Characterization of the 2014 Jure Nepal Landslide: The Future of Interactive Mixed Reality Field Sites, Hazard Identification and Mitigation Through Game Engines



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ABSTRACT

This paper presents an innovative, alternative 3D Virtual/Mixed Reality (VR/MR) workflow that can be employed to better understand, visualize, and mitigate complex geohazard phenomena. On August 2nd, 2014, ~80 km northeast of Kathmandu, Nepal, a large (~5.5 Mm³), destructive landslide occurred near Jure in Sindhupalchok. The slope is still potentially in an unstable state, undergoing progressive rockfalls/slides with the most recent major event (~20,000 m³) in August 2017. Results presented in this paper describe both the field and remote sensing methods utilized in addition to change detection analysis. A comparative rockfall simulation analysis with 2D (RocFall 6.0) and a 3D game engine (Unity) will be described to demonstrate and identify the limitations, advantages and disadvantages. Furthermore, 2D and 3D results on the Jure landslide have been incorporated into an interactive 3D VR/MR holographic field site database, enabling an immersive and enhanced engineering 3D geovisualization experience. We demonstrate how VR/MR techniques can provide a game-changing way engineers/geoscientists understand, communicate, model and mitigate geohazards.

RÉSUMÉ

Ce document présente un flux de travail alternatif 3D en réalité virtuelle / réalité mixte (VR / MR) qui peut être utilisé pour mieux comprendre, visualiser et atténuer les phénomènes géohazards complexes. Le 2 août 2014, à environ 80 km au nord-est de Katmandou, au Népal, un important glissement de terrain destructeur (environ 5,5 Mm³) s'est produit près de Jure, dans le Sindhupalchok. La pente est toujours potentiellement instable et subit des éboulements / glissements progressifs avec l'événement majeur le plus récent (environ 20 000 m³) en août 2017. Les résultats présentés dans le présent document décrivent les méthodes de télédétection sur le terrain et à distance utilisées, ainsi que l'analyse de détection de changement. Une analyse comparative de simulation de chute de pierre avec 2D (RocFall 6.0) et un moteur de jeu 3D (Unity) sera décrite pour illustrer et identifier les limitations, avantages et inconvénients. En outre, les résultats 2D et 3D du glissement de terrain Jure ont été intégrés à une base de données de sites de terrain holographique 3D VR / MR interactive, permettant une expérience de géovisualisation 3D immersive et améliorée. Nous montrons comment les techniques de RV / MR peuvent offrir une manière révolutionnaire pour les ingénieurs / géoscientifiques de comprendre, communiquer, modéliser et atténuer les risques géologiques.

1 INTRODUCTION

Large landslides are among the most destructive natural events (Clague and Roberts, 2012). Characterizing the post-failure stability conditions of large landslides is essential to properly identify, monitor, mitigate, and communicate potential future hazards such as rockfalls. The consequences and impact related to post-failure rockfalls can sometimes be equal to or even more devastating than the initial landslide event itself.

The identification and mapping of potential rockfall source zones using traditional on-site engineering field methods is time-consuming and often can pose a high levels of risk due to access and safety issues. More recently, rapidly developing remote sensing (RS) techniques including Unmanned Aerial Vehicle Structure-from-Motion (UAV-SfM), Terrestrial Digital Photogrammetry (TDP), and Terrestrial Laser Scanning (TLS) are being increasingly employed for geohazard investigation, as they allow acquisition of high-resolution 3D point clouds across otherwise inaccessible or

hazardous terrain (Sturzenegger, 2010; Jaboyedoff et al. 2012; Abellan et al. 2014; Kromer et al. 2015; Lato et al. 2015; Williams, 2017). The development of new, efficient approaches to process, simulate, interpret, and effectively communicate rockfall modelling results has therefore become an important area for further research.

Since the 1980s rockfall hazard mitigation, including ditches, gabions, high-strength steel cable fences, and meshing has been widely used to substantially improve the safety of unstable slopes (Wyllie, 2014a). However, in order to identify the correct placement and design of mitigation, it is critical to obtain reliable information, including detachment location, path, deposition area, impact energy, and trajectory of the rockfalls from both field visits and computer simulation modelling programs (Wyllie, 2014a).

In this paper we describe an innovative approach that employs Virtual (VR) and Mixed Reality (MR) environments to identify, model, mitigate, compare, and communicate rockfall computer simulation results. We illustrate how field and remote sensing methods have been applied in the

investigation of the Jure landslide, Nepal. At this site, four years of data has been collected and used for change detection. GIS analysis has been undertaken to identify potential rockfall source zones, paths, and depositional areas along the slope. We describe a comparative 2D and 3D rockfall computer modelling simulation analysis using the 2D code RocFall 6.0 (RocScience, 2018) and the 3D [Unity](#) game engine. Furthermore, we demonstrate how the use of a [Microsoft HoloLens](#) headset can enhance visualization, communication, and comparison of 2D and 3D datasets and results. We describe how, using interactive menus and holograms, users can: a) visualize 2D rockfall cross-sections referenced on 3D holographic slopes; b) visualize real-time bounce heights, velocities, and colour coded rockfalls as the virtual rocks travel down the hologram and interact with the 3D surface; and, c) implement various mitigation designs using simple voice commands and hand gestures. We illustrate how this new MR technique, as one part of a larger Jure Nepal virtual landslide geodatabase, can advance the way rockfall identification, modelling, and mitigation is conducted and communicated to various stakeholders including academia, government, consulting clients, and communities living in potentially hazardous areas (Mysiorek et al. 2019).

2 CASE STUDY: BACKGROUND

The mountainous country of Nepal (location of Mt. Everest) is found within the Himalayan mountain range of South Asia (Figure 1A). This region is susceptible to continuous slope failure and hazardous rockfalls due to unfavorable geology, physical weathering, active tectonics and yearly monsoonal precipitation (Acharya et al., 2016).

This paper focuses on post-stability rockfalls related to a large (~5.5 Mm³), destructive landslide that occurred in the early morning of August 2nd, 2014 along the Sunkoshi River near the village of Jure, ~70 km northeast of Kathmandu in the Sindhupalchok district (Figure 1B). The landslide dimensions are approximately 1500 m in length, 500 m in width down valley, and 780 m in height with the headscarp located at 1575 masl. The overall slope is structurally controlled, with the average slope dipping at approximately 35° towards the southeast (136°).

The slide destroyed over two dozen houses, caused ~150 fatalities, and the displacement of more than 400 families (Champati et al. 2014). The debris completely destroyed the Arniko Highway, a major trade and strategic route between Nepal and China, before depositing in the Sunkoshi River. Debris and mud splash were identified more than 50 m above the river on the opposite valley wall. The debris dammed the Sunkoshi River for almost 12 hours, forming a 3 km long, 8 Mm³ landslide-dammed lake (LDL), causing damage to the Sunkoshi and Sunima hydropower plants, downstream and upstream of the landslide site, respectively (Figure 1C) (Acharya et al., 2016). Due to combination of a quick response by the Nepal Army applying repeated explosive blasting on the landslide dam and major rainfall, the water breached the dam 37 days after the failure (September 7th, 2014) without causing a major outburst flood (Shrestha and Nakagawa, 2016).

Historical satellite imagery confirms that the slope had intermittently experienced mass wasting events in 2000, 2004, and 2012 (Figure 2). The slope remains in a potentially unstable state, as rockfalls and minor slope failure events continue to occur in and proximal to the slide area. The largest post-2014 event took place in August 2017, and involved the detachment of ca. 20,000 m³ of rock (Figure 2D).

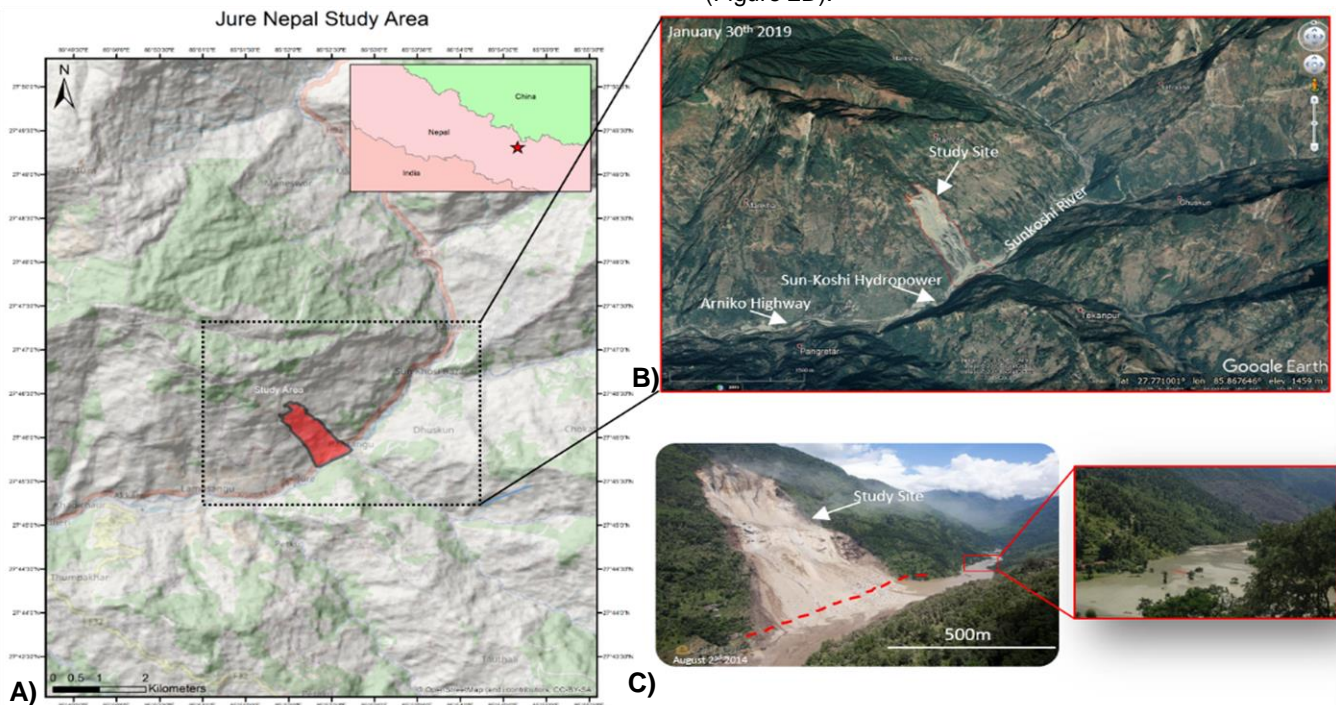


Figure 1. A) Overview map with case study site outlined in red (27°46'9.50"N, 85°52'10.40"E) (Insert map: Jure landslide study site indicated with red star). B) Satellite imagery of Jure landslide (Modified after Google Earth Pro, 2019). C) Photograph taken on the day of the landslide (red dashed line is approximate Arniko highway) with insert of flooding upstream (Modified after www.ekantipur.com) (Mysiorek et al. 2019).

Geologically, the Jure landslide bedrock is constituted from within the Lesser Himalayan rocks of the Kuncha formation, which comprises Proterozoic, low-grade metamorphosed rocks (phyllite, phyllitic quartzite, metasandstones) characterized by a silky metallic, greenish-blue-gray luster (Upreti, 1999; Dhital, 2015). For additional details on the geology and tectonics near the study site the reader is referred to Upreti (1999), Dhital (2015), and Mysiorek et al. (2019).

3 METHODOLOGY

The workflow utilized for this paper is displayed in Figure 3. Additional information regarding the Jure landslide field, remote sensing data acquisition, processing and analysis can be found in Mysiorek et al. (2019).

3.1 Field geological data

Conventional fieldwork, including complete description of the rock mass (lithology, Geological Strength Index, block size/shape, location, weathering) and discontinuity characteristics (orientation, persistence, joint roughness coefficient, seepage, infill, spacing, etc.) was conducted over four years (2016 – 2019) at the Jure landslide study site. Furthermore, engineering geomorphological mapping of the slope was employed, noting breaks in slope, type of surficial materials (exposed bedrock, talus, etc.), gullies, tension cracks, and loose/overhanging blocks. Field information has been utilized as input for rockfall modelling.

3.2 Remote sensing data

TLS, TDP, and UAV-Structure from Motion (SfM) surveys were employed at the Jure landslide annually (~2 weeks in the field each year) from 2016-2019. This data provided high-resolution point clouds for slope

geometries and change detection analysis. GPS-derived Ground Control Points (GCP) targets were surveyed along the site where accessible.

TLS was performed using a Riegl VZ-4000, with a maximum range of up to 4km (Riegl, 2018). TLS data was collected at the toe of the landslide along the Arniko Highway (830 masl elevation, 500 m from mid-slope, with an average ~1.5 cm final point cloud spacing). To reduce occlusion and error during change detection, three additional scans were taken from higher elevations east of the Sunkoshi River on the adjacent slope (960 masl, 1500 m from mid-slope, achieving a ~2 cm final point cloud spacing) (Figure 2D).

TDP stations were conducted at the same locations as the TLS using a 50 MP Canon 5DS-R camera ($f=200$ and $f=400$ mm telephoto lenses) mounted on [Gigapan Epic Pro V](#) robotic head. This automated photogrammetry method enables the stitching together of high-resolution panoramic images that were used to complement field, TLS, and UAV data in determining surficial geology and potential rockfall source zones/paths (2019 Gigapan links: [Toe](#) and [adjacent slope](#)).

A [DJI Mavic Pro](#) UAV with 4K (12 MP) imaging was deployed with permission of the Nepal Army/Sindhupalchok district authorities to capture overlapping images and create a SfM model (~2 cm slope geometry point spacing).

Remote sensing (RS) point clouds were filtered to remove extraneous points and vegetation using an automatic terrain filter algorithm within RiSCAN Pro (Abellan et al. 2014; Riegl, 2018). Furthermore, point clouds were then registered approximately by manually matching points followed by Multi Station Adjustment (MSA), which is based on an iterative closest point (ICP) algorithm that minimizes the distance between points by determining a least-square plane until they align to within ~2 cm (Riegl, 2018).

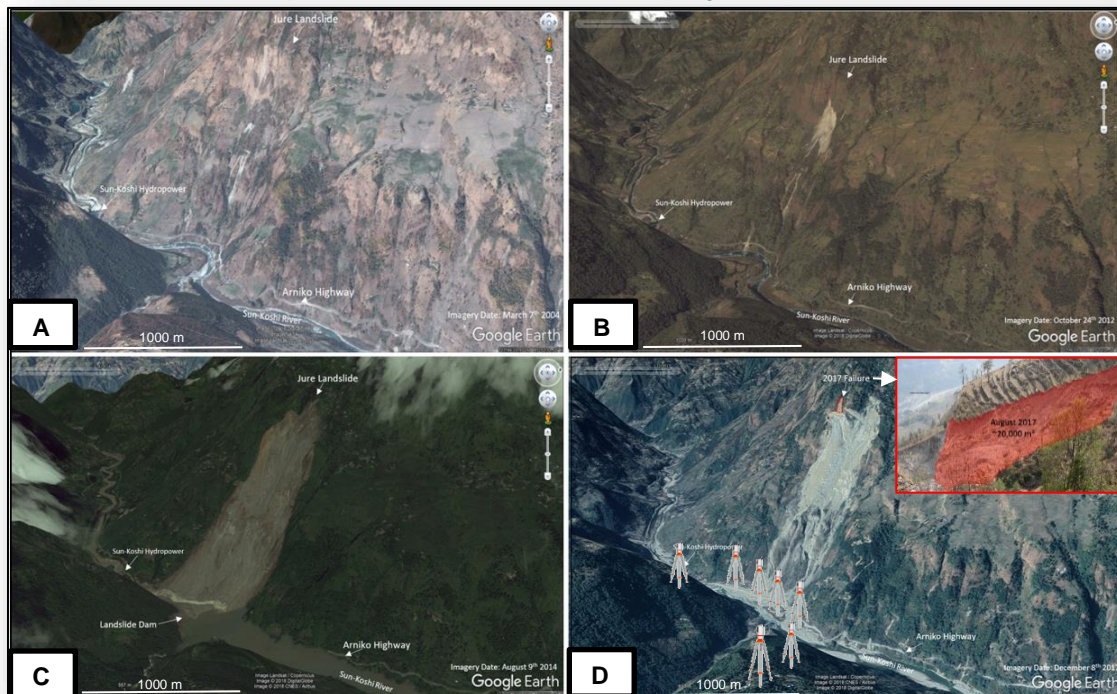


Figure 2. Satellite imagery of the Jure landslide case study. A) Rockfalls/slides identified throughout the slope and highway (March 7th 2004). B) Various rockfalls and large mid-slope scar (October 24th 2012). C) Jure landslide dammed lake (LDL) (August 9th, 2014). D) Post-failure (December 8th, 2017) progressive rockfalls/slides with a large (20,000 m³) failure above the southwest headscarp. Insert photograph taken during March 2018 fieldwork. Note the remote sensing locations for the Terrestrial Laser Scanner shown as silver/orange tripod icons. (Modified after Mysiorek et al. 2019).



Figure 3. Flowchart of research methodology illustrating the various steps followed in this paper to conduct a comparative 2D/3D mixed reality rockfall analysis.

3.3 Change detection analysis

By obtaining four years of slope geometry data, we are able to compare the models to identify areas of slope elevation change, due to loss (erosion) or gain (deposition) of material. The change detection analysis was performed using the Multiscale Model to Model Cloud Comparison tool (M3C2) available in CloudCompare (James et al., 2017). Interpreting these change maps enables the user to clearly identify rockfall source zones (erosion), rockfall paths, and areas with varied coefficient of restitution (CQR), which form key input parameters for 2D RocFall 6.0 (Figure 4A) (Ondercin, 2016; RocScience, 2018).

The change detection results have been incorporated within a VR/MR holographic environment, enabling enhanced interpretation and communication of potentially hazardous rockfall source locations and possible location and type of mitigation structures that could be implemented. M3C2 results have been exported from CloudCompare, and subsequently imported into Unity3D as a texture applied to the terrain. This enhanced the interpretation of real-time 3D simulation of rockfall, described later in this paper, using the HoloLens headset (Figure 4B).

For a detailed slope monitoring workflow and description of the CloudCompare change detection plugin algorithms utilized in this study, the reader is referred to

Lague et al. (2013), James et al. (2017), and Williams (2017).

3.4 GIS analysis

ArcGIS 10.5 software from ESRI (2018) was utilized to manage, analyze, and visualize the RS data in 2 and 2.5D. After constructing and comparing the RS point clouds in CloudCompare, a Raster Digital Elevation Model (DEM) (0.5 m pixel size) was exported and imported into ArcGIS to create hillshade, slope and aspect maps. The purpose of these thematic maps was to further enhance engineering judgment of potential rockfall path locations from the previously identified source zones by using interpreted breaks, gullies, talus, and to then implement these into Unity/HoloLens holograms. After determining the potential source zone, path and depositional areas, the interactive profile graph generated using the 3D Analyst tool (within ArcGIS) was used to derive a 2D graphical representation of three slope profiles (Figure 5). Furthermore, the results from the 2D rockfall analysis were incorporated and compared within 2.5D ArcScene where the elevation data was embedded within the DEM. Representative rockfall path slope profiles were exported from ArcGIS as .txt files, allowing direct import as geometries for slope stability rockfall analysis.

4 ROCKFALL MODELLING

Rockfalls can be simulated using various conventional modelling programs including RocFall 6.0 (RocScience, 2018) and PIERRE2D (Mitchell, 2015), and 3D codes such as RAMMS Rockfall (Bartelt et al., 2016), PIERRE3D (Gischig et al. 2015), and Unity3D (Unity Technologies, 2019). For this paper the goal is not to rigorously test rockfall modelling programs, but rather to propose a new, innovative method to enhance rockfall risk monitoring, modelling, mitigation, and effective communication, through an immersive Mixed-Reality geovisualization field site. We have employed the 2D rockfall modelling software RocFall 6.0 and simulated a 3D rockfall technique using Unity3D game-engine technology.

4.1 Analysis in RocFall 6.0

RocFall 6.0 (RocScience, 2018) is a 2D rockfall computational program that simulates rockfall behavior on slopes with the ability to include rockfall barriers. The three profiles have been directly imported into the software from ArcGIS (Figure 4A/5B). A cubic (phyllitic) rock shape (based on rock samples collected in the field and measured dimensions of blocks in the point clouds) were considered for simulating ten individual rockfalls at each location. The model results strongly depend on the coefficient of restitutions (CQR) assigned in the software to model the nature of block impact and energy distribution. Three different material types with corresponding CQR (bedrock, talus, and talus with vegetation) have been identified and input along the 2D rockfall model based on visual examination of the UAV-SfM models (Figure 6). A low cost, stone-filled gabion retaining wall was implemented during the second simulation to examine how it would alter the probability of a rock travelling down slope and impacting infrastructure beneath the landslide scar (Figure 6B). After running the simulations, results (bounce height, velocity, paths) were exported and referenced into Unity3D for direct comparison in a MR holographic environment. For a detailed description of input parameters and CQR for RocFall 6.0, the reader is referred to Wyllie (2014a, b) and Ondercin (2016).

4.2 Analysis in Unity3D

To accomplish a reliable, thorough, and visually stimulating 3D comparative rockfall analysis, the software selected for developing the rockfall simulations was the freely available personal edition version (2018.2.13) of Unity3D (Unity Technologies, 2019). This game engine provides various functionality, has an active online support community, and includes a routinely tested, state-of-the art physics engine that is ideal for rockfall simulation (NVIDIA Corporation, 2017; Unity Technologies, 2019). This game engine is capable of importing high-resolution, fully georeferenced 3D slope mesh geometries developed from RS point cloud data and simulates rockfalls that can be then analyzed in VR/MR environments. To enhance the visualization during simulation and MR applications, the texture of the holographic slope was obtained from the M3C2 results, with a legend that is always user oriented in the virtual

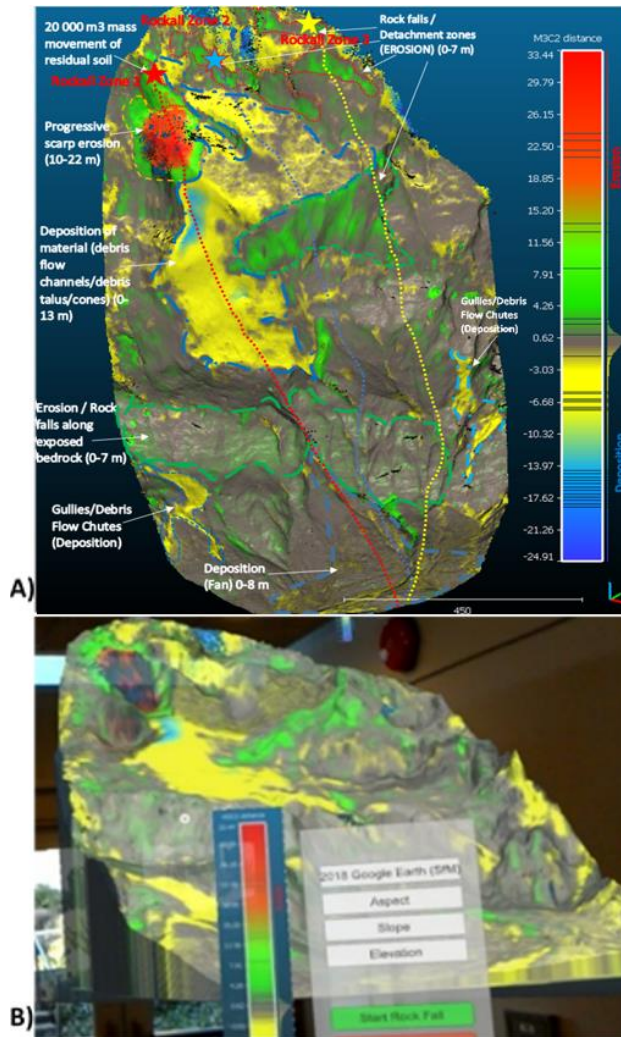


Figure 4. M3C2 change detection results using the Jure Landslide remote sensing data. A) M3C2 results with red/green (erosion) and yellow/blue (deposition). Identification of three potential rockfall source zones and corresponding rockfall paths. B) M3C2 results draped on Microsoft HoloLens mixed-reality holographic Jure landslide geodatabase with the ability to simulate 3D rockfalls.

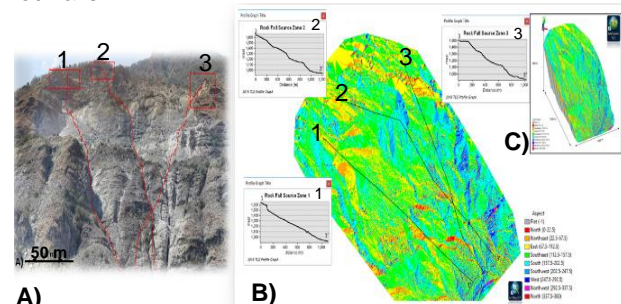


Figure 5. A) Potential rockfall source zone, path, and deposition identified through M3C2 B) ArcGIS (slope aspect) extracted slope profile graphics exported for rockfall analysis. C) ArcScene 2.5D comparison for visualization and confirmation of rockfall profiles.

realm (Figure 4B). After creating the representative 3D slope geometry, falling rocks were modelled from each source zone. To remain consistent with the 2D comparative analysis, a cubic rock shape was created, and ten rockfall were simulated for each source zone. Calibration of model input parameters (friction/bounce/viscoplastic dampening, etc.) were adjusted based on the mechanical properties of rock in the field, and the results obtained from RocFall 6.0 were imported to compare rockfall paths and bounce throughout the simulation. To enhance the ability to visually track each rockfall, rock blocks at specific source zones have been colour-coded (i.e. Red = Zone 1; Blue = Zone 2; Yellow = Zone 3) by adding a new material in the mesh render. Each rock remains static at the start of the simulation (no gravity applied), allowing the user to embed an interactive User Interface (UI) and to toggle various commands (explained in further detail in section 5).

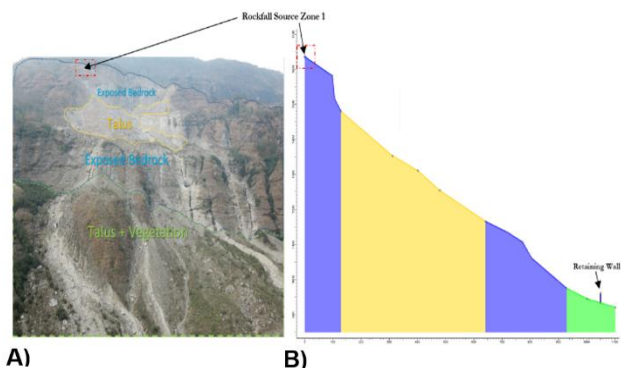


Figure 6. Example of identified rockfall source zone 1. A) CQR estimate based on field and 2018 UAV-SfM model. B) Representative 2D RocFall 6.0 slope model set-up.

3D mitigation design models, including a stone-filled gabion wall were constructed using the SketchUp 3D modeling software (Trimble Inc, 2019). The dimensions and textures of the gabion wall were obtained from the GeoBrugg website (<https://www.geobrugg.com/>). Mitigation structures are set as inactive and require to be toggled on by simply pressing the appropriate button in the UI. The user is also able to visualize the effects of each structure when impacted.

To enhance the user comparative visualization analysis experience within Unity, results obtained from the 2D RocFall 6.0 software have been implemented into appropriate 3D space as cross-sections. Furthermore, the cross-sections have a box collider in order to allow two hand manipulation scripts (the user is able to grab, rotate, scale the sections within the Unity simulation). RocScience RocFall 6.0 results are set as inactive and require to be toggled on by simply pressing the UI button in the designed menu interface.

For a detailed description of the input parameters required by Unity, investigation of the parametric and sensitivity analyses including friction and restitution coefficients, mesh size, block size/shape, physics engines, slope/rockfall geometry, viscoplastic dampening, the reader is referred to Ondercin (2016) and Sala (2018).

5 MIXED REALITY MICROSOFT HOLOLENS RESULTS

In recent years, there has been a significant increase in the use of VR/MR techniques in engineering. However, to date the application within geotechnical engineering, including landslides and geohazards, remains limited. Virtual Reality (VR) includes virtual objects such as computer-graphic simulations of rock slopes or underground excavations where the user is fully-immersed within a VR realm (Milgram et al. 1994). Whereas in a Mixed Reality (MR) environment, the technology in for this paper, the real world and virtual world objects are integrated together (Milgram et al. 1994). This allows users to see both the world around them and the holograms at the same time. The user can add digital elements to their real world environment, creating an immersive realm in which results, geotechnical mapping/investigation, [interactive field sites](#) and geohazard modelling can be viewed and interrogated by multiple concurrent users (Mysiorek et al. 2019).

As VR/MR technology continues to advance, it is important to develop and apply these new techniques in engineering and geotechnical disciplines. In this paper, the results of conventional field mapping, 3D RS, change detection in addition to the developed rockfall comparative analysis simulation has been integrated into the [Microsoft HoloLens](#). The Microsoft HoloLens is a Windows 10 computer attached to fully untethered transparent glasses and uses physical input, object recognition, location and spatial sound to immerse and enhance the user's environment. To become part of this virtual environment, the HoloLens continuously scans the immediate surroundings, discretizing it into an interactive mesh.

While wearing Microsoft HoloLens glasses, the user is able to utilize hand/voice gestures to observe the virtual fieldsite, moving and interacting around the landslide to observe various features of interest with the holographic user-interface menu always user oriented and incorporating buttons hyper-linked to all the data collected/processed in the database (Mysiorek et al. 2019). While immersed in MR, the engineer/geoscientist can select displacement results that are draped over the holographic RS point cloud at either a 1:1 scale and/or scaled down to desired size for effective communication and including the ability to interact in a group setting with various audiences (Figure 4B). The user is fully immersed within the virtual environment and feels as if they are standing at the toe of the 1 km high Jure rock slope. They user has the ability to fully interact with the rockfall simulation by simply clicking the menu to start/pause (single and/or multiple) rockfalls, to add various mitigation structures, and to visualize the rocks as they travel down the holograph. The user is able to not only to visualize, but also to interact with the holographic rockfall simulation, observing individual rock results (paths, bounce height, velocity, etc.) that are plotted in real-time.

Furthermore, the comparative rockfall modelling analysis can be visualized by multiple engineers/geoscientists in the MR Jure landslide geodatabase environment, analyzing and comparing the 2D and real-time 3D Unity rockfalls as an interactive team (Figures 7 and 8).

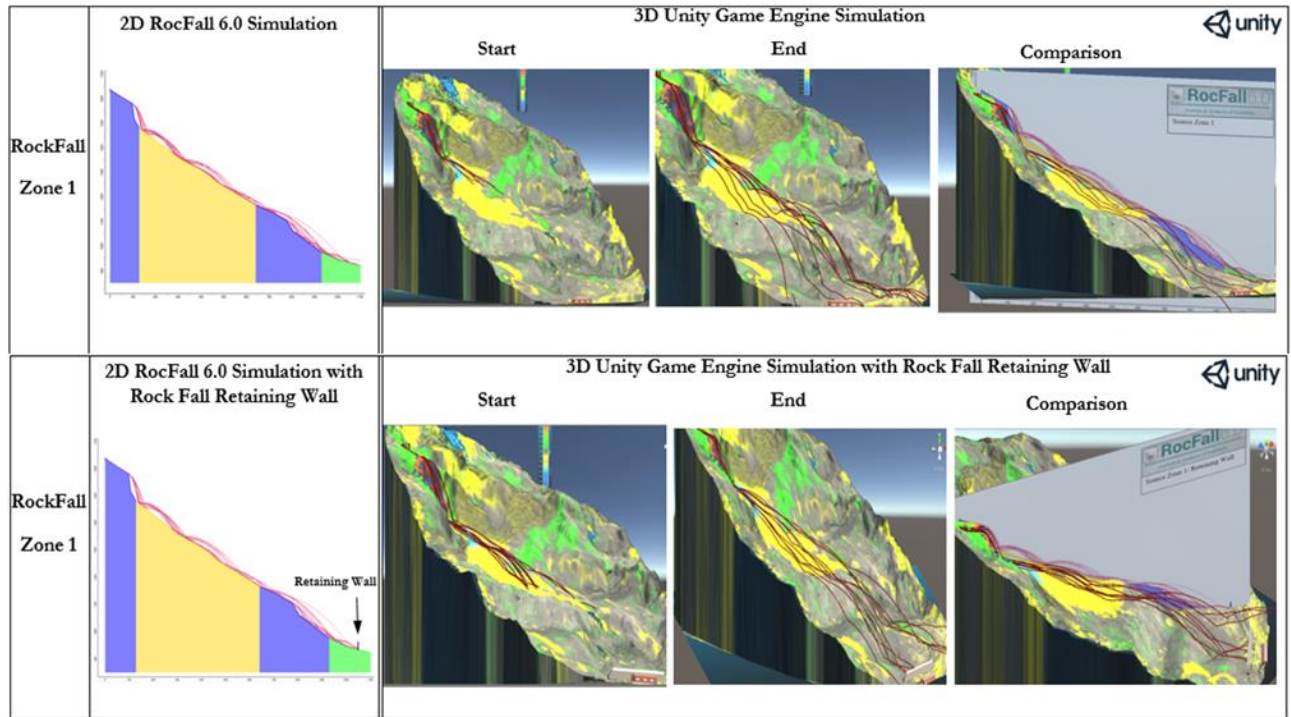


Figure 7. Example of source zone 1 comparative 2D and 3D rockfall modelling analysis with (top) and without (bottom) mitigation structures. Start, end, and comparison displayed. Note that in 2D rockfall the blocks will only have the ability to travel down the user selected profile and heavily reliant on the CQR input, unlike the Unity fully 3D holographic simulation that allows the rocks to interact with the topography. Comparing bounce height, generally 3D Unity modelling calculates higher magnitude results, especially at locations of loose talus (yellow) where the 2D results shows the rock sliding.

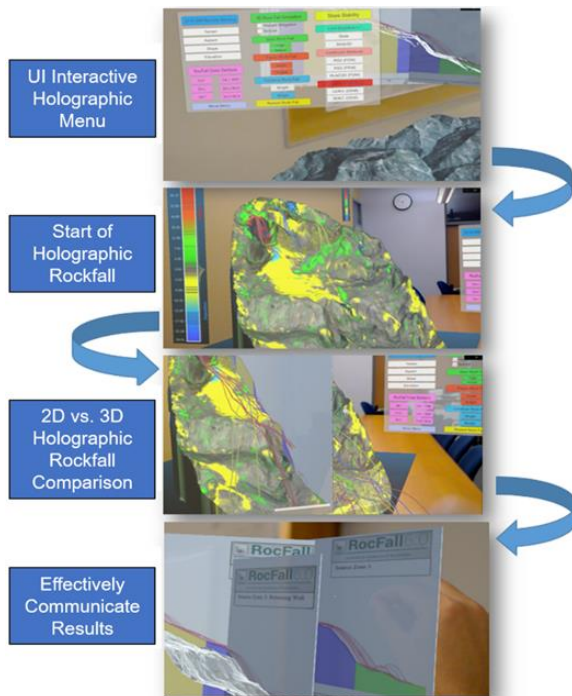


Figure 8. Unity3D developed rockfall comparative analysis simulation integrated into MR Microsoft HoloLens workflow for an immersive, effective and efficient way to model/communicate rockfall hazards and results. Video of holographic simulation available at: [Demonstration](#).

6 SIGNIFICANCE AND FUTURE APPLICATIONS

The primary objective of this paper is to advance the field of geohazard identification, modelling, mitigation, and communication using an innovative VR/MR workflow through the development of a detailed case history. An innovative interactive holographic Jure landslide geodatabase using VR/MR methods integrated with traditional field, remote sensing, change detection, 2D and 3D rockfall modelling is presented, which can be adapted to various engineering/geoscience problems in the fields of mining, surface/underground rock excavations, site investigation, or natural hazard projects.

The paper demonstrates the advantages of undertaking 2D and 3D rockfall simulations and integrating results into an interactive VR/MR geovisualization experience. RocFall 6.0 and Unity3D have been employed for the 2D and 3D simulation of rockfalls. However, future modelling can be completed/compared with other 2D/3D rockfall computer simulation programs. We expect that over the next decade, VR and MR techniques will significantly advance both in terms of hardware and software capabilities. This will potentially enable manipulation of larger, high-resolution datasets that may revolutionize not only the way future geohazard investigation is conducted, but also can be applied in a wide range of rock engineering projects, from site investigation, to the construction and post-construction phases.

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