Virtual and Mixed Reality Geodatabases: The Importance of Integrating Engineering Geological Field Techniques with New Methods for Site Characterization

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ABSTRACT
With continuous advances in computational technology, remote sensing (RS) techniques can acquire increasingly larger and more comprehensive datasets in engineering investigations. The need to efficiently store, model, interpret and most importantly, communicate information is a challenging task. Over the last decade, there has been a significant increase in the use of Virtual (VR) and Mixed Reality (MR) techniques in a wide range of disciplines, however, the applications within engineering and geoscience remain limited. Notwithstanding these advances, there is a continued need to develop new and effective VR/MR approaches through virtual geodatabases.
We demonstrate the application of VR/MR in geotechnical data collection, analysis, and communication by integrating field and RS data collected from different project sites within virtual geodatabases. An innovative workflow using VR/MR integrated with field, RS, GIS, and numerical modelling is presented for a wide range of engineering projects including natural hazards, tunnelling, mining, oil and gas, pipeline integrity, surface, and underground engineering investigations.
An innovative engineering geological VR/MR geodatabase approach to investigate the 2014 Jure landslide in Nepal is demonstrated. Furthermore, this paper not only demonstrates the VR/MR capability of effectively storing, interpreting, and communicating large quantities of 3D data, but also presents innovative VR/MR methods to conduct and compare discontinuity mapping on rock slopes, terrain mapping, tunneling, mining/geotechnical applications, and recently developed 3D holographic rockfall modelling. This paper demonstrates how a VR/MR approach has the potential to lead to a step-change in how future engineering investigations are conducted, communicated, and can be used for a wide range of engineering/geoscience projects.

RÉSUMÉ
Avec les progrès continus de la technologie informatique, les techniques de télédétection (RS) peuvent acquérir des ensembles de données de plus en plus vastes et complets dans les enquêtes d'ingénierie. La nécessité de stocker, de modéliser, d'interpréter et, surtout, de communiquer efficacement des informations est une tâche difficile. Au cours de la dernière décennie, il y a eu une augmentation significative de l'utilisation des techniques de réalité virtuelle (VR) et de réalité mixte (MR) dans un large éventail de disciplines, cependant, les applications en ingénierie et en géosciences restent limitées. Malgré ces avancées, il existe un besoin continu de développer de nouvelles approches VR/MR efficaces via des géodatabases virtuelles.
Nous démontrons l'application de VR/MR dans la collecte, l'analyse et la communication de données géotechniques en intégrant des données de terrain et de RS collectées à partir de différents sites de projet dans des géodatabases virtuelles. Un flux de travail innovant utilisant VR/MR intégré à la modélisation de terrain, RS, SIG et numérique est présenté pour un large éventail de projets d'ingénierie, y compris les risques naturels, le creusement de tunnels, l'exploitation minière, le pétrole et le gaz, l'intégrité des pipelines, les enquêtes d'ingénierie de surface et souterraines.
Une approche innovante de géodatabase géologique VR/MR pour étudier le glissement de terrain du Jure en 2014 au Népal est démontrée. En outre, cet article démontre non seulement la capacité VR/MR de stocker, d'interpréter et de communiquer efficacement de grandes quantités de données 3D, mais présente également des méthodes VR/MR innovantes pour effectuer et comparer la cartographie des discontinuités sur les pentes rocheuses, la cartographie du terrain, l'exploitation minière/géotechnique. applications et la modélisation 3D holographique des chutes de pierres récemment développée. Cet article démontre comment une approche VR/MR a le potentiel de conduire à un changement radical dans la manière dont les futures investigations d'ingénierie sont menées, communiquées et peuvent être utilisées pour un large éventail de projets d'ingénierie/géosciences.

1 INTRODUCTION

A comprehensive characterization of rock slopes is required to gain a better understanding of slope stability and deformation behavior relies on multiple factors including lithology, geomorphic processes, geological structures, stress distribution, hydrology, and groundwater regime fluctuations (Stead et al., 2019). However, characterization of unstable rock slopes can pose a high level of risk toward the engineer/geoscientist from inaccessibility, ongoing instability, and various other safety concerns that prevent the comprehensive collection of geomechanical data by traditional field methods. With considerable advances in remote sensing (RS) technology, data collection approaches, field equipment, monitoring, and numerical modelling techniques in addition to workstation computational power have all improved our understanding of the causes, triggers, and mechanics of slope failures (Clague and Roberts, 2012; Stead and Eberhardt, 2013). It should be emphasized that RS methods should not be considered an alternative to field-based traditional methods, but as a complementary site investigation tool. Detailed site investigation must still, wherever possible, be implemented in the field to gather reliable rock mass parameters including intact rock strength, joint aperture, roughness, infill, and discontinuity alteration; all rock slope characteristics that require the engineer/geoscientist to directly access the rock slope (Mysiorek, 2019).

Rapidly improving RS techniques, including Terrestrial Laser Scanning (TLS), Terrestrial Digital Photogrammetry (TDP), and Unmanned Aerial Vehicle Structure-from-Motion and LiDAR (UAV-SfM/LiDAR) are today routinely increasingly employed for engineering site investigations. These methods allow acquisition of 3D datasets from inaccessible terrain, at sub-centimeter accuracy. Datasets can be utilized for various engineering purposes including discontinuity mapping (Onsel et al., 2019, Mysiorek et al., 2019b), change detection analysis (Mysiorek, 2019; Lato, 2021), terrain stability mapping, and to provide accurate high-resolution surface data for 3D holographic rockfall modelling (Mysiorek et al., 2019a). These recent advances require new and efficient approaches to effectively communicate discontinuity mapping and rock slope characterization. The ability to store and view both field and high-resolution RS 3D datasets in a VR/MR environment provides the engineer/geoscientist with an immersive and enhanced experience that can be utilized to not only complement, but also improve all stages of a project site investigation.

2 SITE INVESTIGATION METHODOLOGIES

2.1 Traditional Fieldwork

Conventional rock engineering fieldwork investigation for slope characterization includes a complete description of the rock mass and discontinuity characteristics at safely accessible areas. It is standard practice that at each field station, discontinuity mapping is undertaken by measuring discontinuity planes as a dip and dip direction using an engineering compass and according to the ISRM (1978) guidelines. Lithology, structures, water conditions, surface roughness, and infill type are also recorded to estimate the shear strength of the discontinuities (ISRM, 1978). The rock mass blockiness and shape are determined based on the discontinuity orientation, persistence, and spacing (ISRM, 1978).

2.2 Remote Sensing

New tools and methods to acquire, model, and interpret data are being introduced; from complex numerical modelling, UAVs, to machine learning. Ground and satellite based remote data acquisition has been applied within engineering/geoscience ranging from LiDAR, high-resolution photogrammetric techniques, UAV-SfM, InSAR, hyperspectral, and thermal imagery.

2.2.1 Light Detection and Ranging (LiDAR)

TLS, also referred to as LiDAR, involves the emission of a laser pulse which travels towards a desired object and is reflected back to the laser scanner. By analyzing the direction and attitude of the scanner (pitch, roll and yaw), and the time of arrival of each signal, the position of multiple reflective surfaces in 3D space are automatically computed and stored as point clouds. The range, resolution, repeatability, and attainable accuracy from the 3D point cloud slope reconstruction has made TLS one of the most utilized techniques in rock slope characterization (Sturzenegger and Stead, 2009; Donati et al., 2017).

With technology rapidly improving, cost-effective LiDAR systems are readily available in the field allowing engineers/geoscientists to obtain quick and accurate georeferenced 3D models, including the use of cellular phones such as the iPhone 12 Pro. Examples of how the first author utilized a hand-held iPhone 12 Pro LiDAR at Clifton Engineering Group Inc. (Clifton) and developed a UAV mount attachment for projects including quarry mine bench stability analysis and site characterization. This enabled both accurate mapping and effective communication using holographic models with multiple users being able to view the models on a boardroom table, in the field, and in the office (Figure 1).

Figure 1. iPhone LiDAR 3D models and holograms acquired both hand-held and developed UAV bracket (Clifton). A) Holographic scanline outcrop and B) Pipeline.

2.2.2 Photogrammetric Techniques

Photogrammetric technique enables 3D reconstruction of slope geometries using multiple photographs obtained from strategic locations and angles. The main techniques used in practice include TDP and SfM collected by either ground or airborne platforms. SfM is a relatively low-cost photogrammetric technique that enables the generation of 3D point clouds. Compared to TDP, SfM relies on the successive automatic matching of features identified in multiple overlapping images captured from several different viewpoints either by ground-based or aerial assisted techniques.

2.2.3 Aerial Assisted Techniques

A recent major development in engineering site investigations is the use of UAVs (drones) to acquire SfM and LiDAR data. UAVs are popular as they provide a low-cost, quick, and safe alternative method to obtain data in inaccessible areas (Figure 2). These high-resolution georeferenced point clouds can be utilized for rock slope characterization, including discontinuity mapping (Mysiorek, 2019 a,b) (Figure 2).

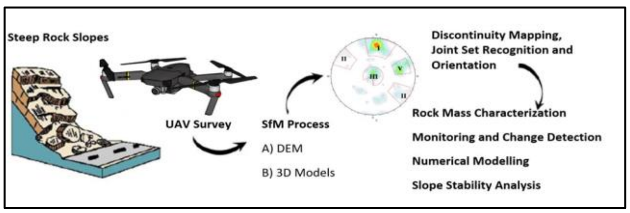

Figure 2. Flow chart with method for use of UAV-SfM/LiDAR in slope site investigation (Mysiorek, 2019).

The first author has utilized various UAV-SfM techniques for Clifton projects including mine bench stability analysis, geohazard management, structural mapping, and overall mine design (Figure 3).

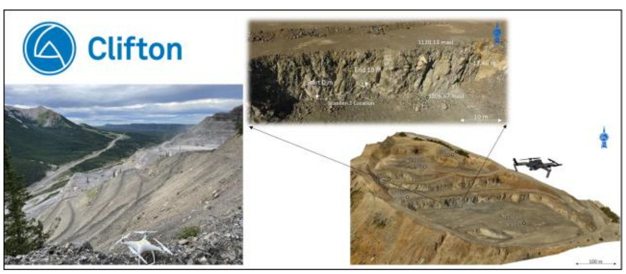

Figure 3. Clifton UAV assisted 3D topographic reconstruction for mine design and site characterization.

The cost and time to acquire project site RS datasets is high, and unfortunately, the data/results are mostly communicated to client, stakeholders, and academia using 2D projectors, computer screens and/or paper reports greatly diminishing their full potential. Advances in both hardware and software has resulted in the development of new platforms that improve user visualisation through VR and MR. Although both VR and MR are often observed solely as visual platforms, they can also significantly improve interpretation, site characterization and communication at all stages within a project lifecycle.

3 MIXED AND VIRTUAL REALITY

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 site investigations, remains limited. VR consists of completely immersing a user in a 3D rendered model by occluding their sight with a headset (e.g., Oculus Quest 2). This enables a user to be placed virtually inside inaccessible areas such as dangerous underground excavations or unstable rock slopes. VR has also been used in rock engineering for training of miners in underground rock support (Van Wyk and de Villiers, 2009).

MR differs from VR in that it does not completely obstruct a user's point of view and it continuously maps objects within a specific distance threshold (Figure 4). By continuously understanding the surrounding environment, both virtual and real objects can coexist in the same environment (Milgram et al., 1994) (Figure 4). In other words, virtual objects can interact with the surrounding real environment. This hardware enables applications such as distant mapping of geological structures (Onsel et al, 2019). The leading MR headset in the market, and used in this paper, is the Microsoft HoloLens.

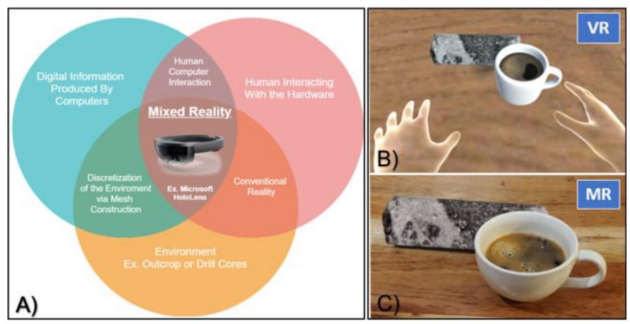

Figure 4. A) Simplified representation between the difference between B) VR and C) MR virtual core sample (Chang, 2021).

4 MR AND VR SITE CHARACTERIZATION

With VR and MR continuously improving it is important to develop and apply new methodologies in rock engineering to remain at the forefront. Simon Fraser University (SFU) Engineering Geology and Geotechnics Research Group (Link) developed several rock mechanics applications ranging from visual applications for educational purposes and field assessment. The following section will provide various examples of how VR/MR technology has been applied for site investigation and characterization projects such as communicating block caving induced slope instability propagation at the Palabora Mine Pit in South Africa (Onsel et al, 2018, 2019) (Figure 5).

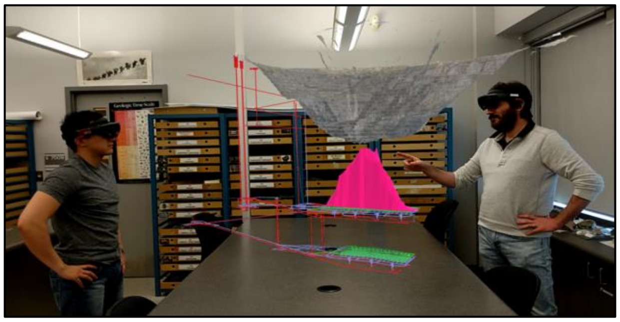

Figure 5. Palabora South Africa mine model being observed by multiple SFU students. Propagation of block caving, open pit model, and underground mine layout is observed holographically (Onsel et al., 2019).

4.1 Holographic Core Logging

Although core logging is a critical stage for mining, civil, petroleum and geotechnical disciplines, core tends to be assessed by junior staff with limited experience. Re-assessment and quality control of these datasets can also be challenging as core sheds are typically in remote regions or in the worst-case scenario the core is disposed of or deteriorates over time. Standardised logging procedures such as RQD (Deere, 1966), Q-System (NGI, 2015), and GSI (Hoek et al., 2013) also have potential for human error and bias that can lead to crucial features being improperly logged (Chang, 2021). These errors may result in increased project cost and improper design. To minimise errors, drilling datasets can be enhanced by implementing point data, such as TerraSpec Halo (Malvern Panalytical, 2021), 2D data, such as hyperspectral results (CoreScan, 2021; Enersoft, 2021), and 3D data, such as fullbore formation micro-imager (FMI) data (Schlumberger, 2021; Chang, 2021).

MR can assist both geological and geotechnical loggers by providing a holographic logging sheet (Chang, 2021). With recent advances in MR/VR, re-examination of holographic core runs can be performed remotely (Chang, 2021). Since the core is digital, other complimentary data sets such as thermal, hyperspectral, and assay results can be superimposed (Figure 6).

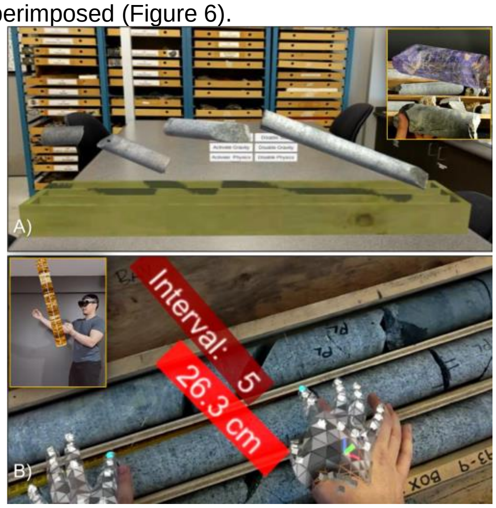

Figure 6. A) Holographic core and B) core sample mapped and measured within MR (Chang, 2021).

4.2 Discontinuity Mapping

3D point clouds of a rock slope outcrop can be utilized to virtually extract geological planes through computer-based manual/automatic software as well as recently developed holographic mapping (Onsel et al., 2019; Mysiorek 2019b). While immersed within MR/VR, a virtual outcrop appears, and multiple users can begin to collect real time orientation measurements with newly developed MR software EasyMineXR MR (Emre Onsel developed at SFU in collaboration with SRK Vancouver) (Onsel et al., 2019; Mysiorek et al., 2019a). The discontinuity measurement is accomplished by simply viewing the discontinuity with the HoloLens followed by an air-tap hand gesture. The poles of the measurements are displayed on a holographic stereonet, which can be exported as .csv file and imported for further analysis such as kinematic analysis software (Figure 7). By comparing field, RS computer-based software and holographic discontinuity mapping along the same rock slope, results indicate approximately 5° mean pole orientation different between discontinuity sets (Mysiorek, 2019a).

The HoloLens and manual computer software mapping techniques show the best agreement which is probably due to the ability of the users to manually fit planes, minimizing error through automated fitting methods (Mysiorek, 2019b). The HoloLens allows the user to be immersed within the geological rock slope environment, with ability to walk around and inspect the outcrop to map discontinuities allowing a much wider range of persistence scales to be recorded than in the field. The holographic mapping technique not only provides close agreement with traditional field and manual remote sensing discontinuity orientations, but also allows interactive mapping and communication while immersed in an interactive project site geodatabase. Such an approach improves communications at multiple levels from the engineer to the client and stakeholder.

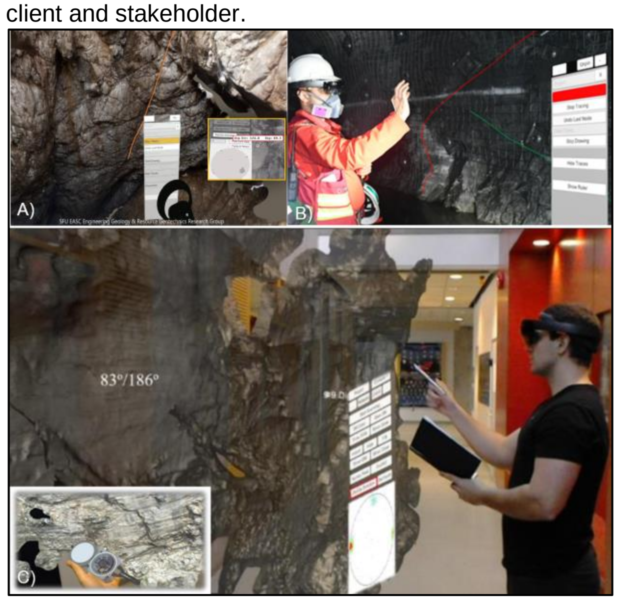

Figure 7. Example of RS outcrop model utilized for A) VR and B) MR. C) Extract and plot discontinuity information with EasyMineXR (Onsel et al., 2019, Mysiorek, 2019a).

4.3 Tunneling: Vancouver Skytrain

Large-scale underground engineering projects such as the Vancouver Skytrain, are not only complex in the planning/design, but also challenging to communicate acquired datasets and results. Imagine the ability to incorporate critical information leading to a successful project such as modelling results, project planning, and design in an effective and simplified MR/VR database. This has been completed and involved the TransLink Skytrain in Vancouver, British Columbia from Stadium-Chinatown to Waterfront Station. This sector takes the train underground, and thus, knowing the stress distribution around the tunnel is important for assessing the opening stability. The induced stresses were analyzed by the first author and Omar Chang (former SFU graduate student) using the finite element software RS2 and RS3 (Rocscience, 2018 a,b) with several scenarios including sequencing of mitigation (e.g., bolts, dowels, shotcrete). The major and minor principal stresses were observed through stress trajectories to investigate excavation stability (Figure 8 a,b). Once both models were satisfactory, they were brought into a HoloLens to display and communicate the results effectively. Moreover, the 2D and 3D results were imported into an interactive Vancouver field site geodatabase, with the multiple users (e.g., clients, professors, students) can virtually 'fly' over the city, select the station of interest, zoom in and see various results of interest with relevant technical reports (Figure 8).

Figure 8. Example of A) Vancouver SkyTrain Tunnel 2D and 3D modelling results within B) interactive MR database. C) The user can view entire Vancouver hologram while selecting results of interest.

5 MR/VR PROJECT: 2014 JURE NEPAL LANDSLIDE

A field, RS, and MR/VR approach was used to investigate the Jure landslide, a large (5 Mm^3) destructive landslide which occurred on August 2nd, 2014, near Jure village, 70 km northeast of Kathmandu, Nepal. The first author integrated their M.Sc., project thesis into an interactive 3D VR/MR field site, enabling an immersive and enhanced engineering 3D geovisualization experience (Mysiorek, 2019). The user can utilize hand and voice gestures by wearing Microsoft HoloLens glasses to observe the field site environment and easily move around the project site to observe different engineering geological features, RS stations, and to augment geotechnical data of interest (Figure 9). While immersed in the virtual geodatabase, a hand and voice movable holographic user-interface (UI) menu is always user oriented with buttons linked to various results of interest (Figure 10). Link of video (Link) (Mysiorek, 2019).

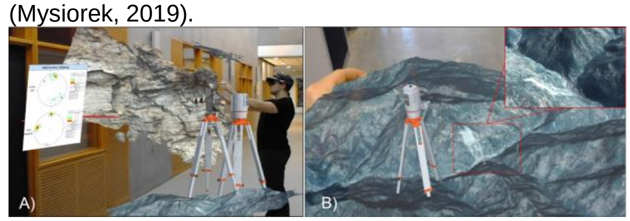

Figure 9. A) user interacting with virtual site database and B) embedded field stations (Mysiorek, 2019).

While in a virtual project site geodatabase, the users can effectively communicate and interpret data as a team in the office by accessing all the information stored by selecting the appropriate virtual menu. For example, GPS embedded LiDAR stations, and rock samples can be viewed as holographic icons, with the ability to interact individually with each station and be immersed as you are standing in the field (Figure 9, 10).

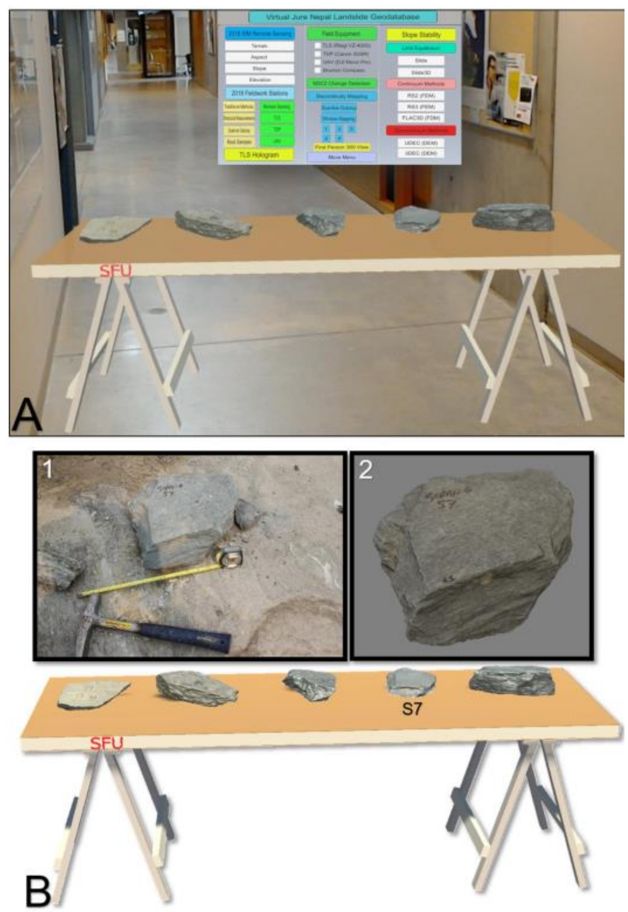

Figure 10. MR menu and rock samples (Mysiorek, 2019).

5.1 3D Holographic Rockfall Modelling

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

With four years of RS datasets available, we were able to conduct change detection analysis to identify post-failure areas of erosion and deposition for the 2014 Jure Nepal Landslide. Results identified multiple areas of natural rockfall release zones, however, at the time of the project, most of the readily available rockfall software required the user to simplify a high-resolution RS 3D reconstructed slope to a 2D cross-section for modelling. This section will describe an innovative approach developed that employs VR/MR environments to identify, model, mitigate, compare, and communicate rockfall computer simulation results. In 2019, the first author (Mysiorek, 2019) proposed a new, innovative method to enhance rockfall risk monitoring, modelling, mitigation, and effective communication, through an immersive MR geovisualization field site. The 2D rockfall modelling software RocFall 6.0 (RocScience, 2018c) and a 3D rockfall technique using a scripted Unity3D game-engine technology (Unity, 2019) were employed in analysis of the Jure slope rockfall activity. The user can fully interact with the rockfall simulation by simply clicking the menu to start/pause rockfalls, to add various mitigation structures, and to visualize the rocks as they travel down the hologram. The user can not only visualize, but also to interact with the holographic rockfall simulation, observing individual rockfall results (paths, bounce height, velocity, etc.) that are plotted in real-time by a simple air tap gesture (Figure 11) (Mysiorek, 2019).

This 3D rockfall simulation software integrated within MR/VR realms has the potential to provide a game-changing method to understand, communicate, model, and mitigate geohazards. We envision that this may lead to modelling software companies developing codes to enhance the geotechnical community slope stability capabilities in representative 3D high-resolution slope surfaces as well in MR/VR environments. Video Link.

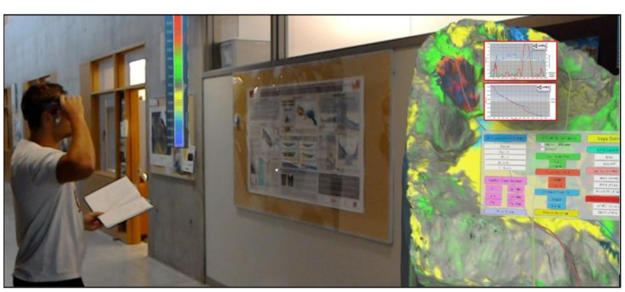

Figure 11. MR rockfall modelling with change detection analysis, and real-time results (Mysiorek, 2019).

5.2 VR/MR Terrain Mapping

The consideration of past geological events along with actively evolving geomorphological processes is important in understanding landslide initiation and failure propagation in an unstable slope. Engineering geomorphological maps are designed to show the form of the land (sub-divided polygons), the properties of the soil/rock material, and the processes currently active. Terrain stability mapping consists of identification of unstable or potentially unstable terrain prior to field ground truthing. These methods usually consist of utilizing stereoscopic air-photo interpretation or remote sensing data via 2D computer screens. The idea of MR/VR remained fictional for many years. It was only when the first stereoscope was constructed in 1838 that it finally started to move beyond science fiction to reality as 2D projections became representative of 3D models (Chang, 2021). The first author has developed a methodology to incorporate both traditional methods integrated with 3D holographic RS models of a project site, allowing multiple users to interact with various thematic maps as a team making informed terrain stability polygon mapping decisions (Figure 12 a, b) (Mysiorek, 2019). The ability to air gesture pinch polygons in MR or VR as a team creates a shared vision to develop meaningful and representative project-based decisions (Figure 12).

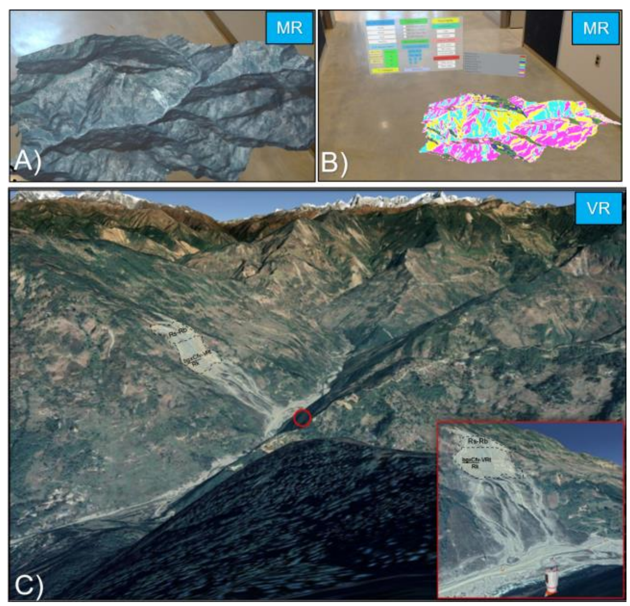

Figure 12. Virtual terrain mapping with A) terrain and B) slope aspect models in MR as well C) VR (Mysiorek, 2019).

5. CONCLUSION

This paper demonstrated various innovative VR/MR site characterization geodatabases that have been developed, integrating all the data collected into a virtual realm, enabling an immersive and enhanced engineering 3D geovisualization experience. Moreover, this paper demonstrated various newly developed techniques, including virtual discontinuity mapping, virtual terrain stability mapping, virtual tunnelling modelling, terrestrial/aerial cellular phone LiDAR data acquisition, holographic core logging and a 3D holographic rockfall modelling application. VR/MR has major potential in improving how future engineering investigations are conducted and communicated. The techniques employed throughout this paper can not only be applied to further investigation of geohazards but can also be implemented for various rock engineering site investigations throughout the world to effectively characterize, and most importantly, efficiently communicate complex sites. The author's vision is that complex 3D problems will be solved in fully 3D VR/MR programs and suggest that over the next decade. VR/MR techniques will significantly advance both in terms of hardware and software capabilities and have the potential to revolutionize the way engineers and geoscientists conduct geohazard site investigations.

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