3D Virtual Reality Model of a Landslide in Urban Area

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Abstract

This work presents a methodological approach for developing a 3D Virtual Reality model of a landslide in the urban area of the municipality of Petrópolis, State of Rio de Janeiro, Brazil. The 3D virtual reality model was generated from data obtained by Unmanned Aerial Vehicle, 3D modeling, and data integration in an immersive and interactive geovisualization environment. Some images from before the event were used to reconstruct the buildings on the hillside, and 3D modeling was carried out using parametric rules. The generated model can be used in a virtual reality room (for a team experience) or with virtual reality glasses (for an individual experience). Although the Virtual Reality models do not replace fieldwork, they aid in understanding the landslide triggering process and analysing the impact caused and have the potential to be used in educational projects for disaster prevention and risk reduction.

1. Introduction

In environmental and natural disaster studies, 2D representations are more common than 3D ones due to their simplicity, accessibility, and efficiency for more common tasks. However, 2D data are not sufficient to represent depth variations in the real world, for example, cross-sections, urban structures, and relief surfaces.

Driven by the emergence of concepts such as Industry 4.0 and Digital Twins, which utilize virtual reality (VR) and augmented reality (AR), 3D scenarios have gained prominence in recent years. VR uses technologies to simulate reality through 3D modeling of objects in a scenario that approximates reality, immersing the user in a virtual space (Asgary et al., 2024). However, most of the 3D VR models are not georeferenced.

In view of this, Geographic Information Systems (GIS) integrated with 3D modeling can provide georeferenced 3D visualizations (Havenith et al., 2019), giving rise to a new generation of 3D-GIS-based tools that enable virtual 3D analysis of the generated environment.

A 3D VR representation of buildings and elements in the environment enables the analysis of urban space occupation and the relationships between these elements. In disaster events, georeferenced 3D VR models can help estimate the impacts caused (Pham et al., 2014; Axel and Van Aardt, 2017) and provide a documented historical record of the event for future study (Nava et al., 2023). This offers valuable historical records that can support planning and prevention strategies. Thus, 3D VR can play an important role in disaster management. A 3D visualization of a disaster scene can be used to represent both past and current conditions, as well as simulate future conditions of the disaster site (Hu et al., 2018).

Currently, unmanned aerial vehicles (UAVs) have become one of the most widely used remote sensing platforms for data acquisition due to their flexibility and low cost, and the high spatial resolution of the images (Jiang et al., 2022). In landslide events, UAVs serve as the main tools for obtaining up-to-date images of the impacts caused and for assisting in decision-making

In this sense, this work presents a methodological approach for developing a 3D VR model of a landslide in an urban area. The 3D VR model could be useful for understanding the impacts and damage caused, as well as the processes that trigger landslides. The proposed method used UAV data and 3D modeling to generate a 3D VR model of a landslide that occurred in 2022 in Petrópolis, a city in the mountain region of the state of Rio de Janeiro, Brazil.

2. Geohydrological disaster in Petrópolis, 2022

The municipality of Petrópolis (Figure 1), located in a mountainous region of the state of Rio de Janeiro, Brazil, has a history of landslides due to its main physical and anthropogenic characteristics. Petrópolis occupies an area characterized by extensively faulted and fractured rocks, steep slopes, deep soil profiles and heavy rainfall concentrated in the summer months between December and March (Guerra, 1995).

On February 15, 2022, Petrópolis was hit by torrential rains that caused flooding and landslides, mainly in the urban area. The precipitation event occurred in the early afternoon, and the city experienced one of its worst geohydrological disasters, with the loss of 235 lives and more than four thousand people displaced or homeless (G1, 2025). The following month (March 20), rain returned to the municipality, causing new landslides, resulting in seven more fatalities. Among the various landslides (more than 600), the landslide at Morro da Oficina, also known as

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Morro do Centenário (Figure 1), stands out, hitting several buildings and causing the death of 93 people.

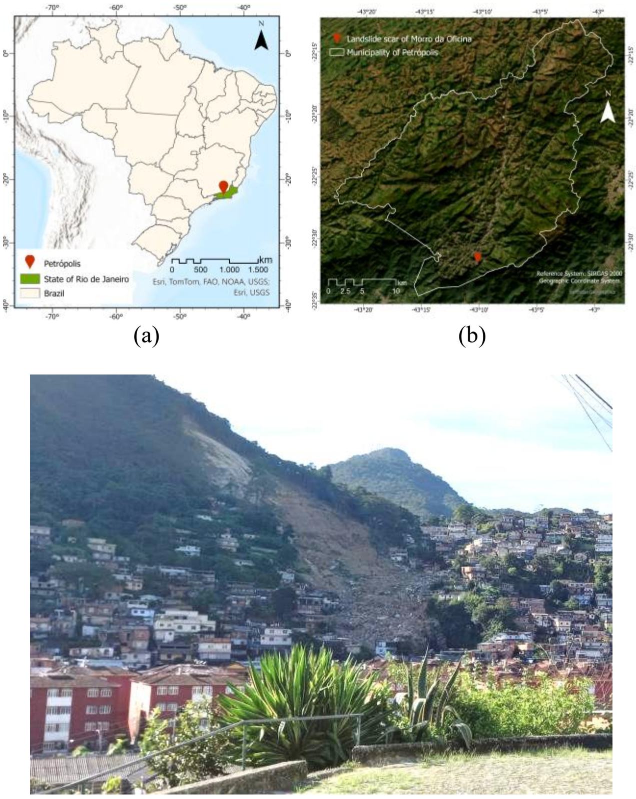

Figure 1. Study area. (a) Brazil, State of Rio de Janeiro, and Petrópolis; (b) Municipality of Petrópolis. (c) Landslide on Morro da Oficina.

3. Material and method

A DJI Mavic 2 UAV with an RGB sensor was used for an overflight and image acquisition of the landslide scar and its surrounding area. The flight to acquire the images was conducted on April 25, 2022, with longitudinal and lateral overlay through flight planning. Table 1 presents mainly flight data.

Flight data	
Number of images	115
Flying altitude	247 m
Ground resolution	5.28 cm/pix
Coverage area	0.654 km^2

Table 1. Resume of flight data

Ground Control Points (GCP) were used in the model to improve accuracy, and Checkpoints were used to assess the quality of the products generated (Figure 2). The coordinates of the support points were obtained with dual-frequency Global Navigation Satellite System (GNSS) receivers, using the post-processed relative geodetic positioning method.

Images acquired were processed in Agisoft Metashape software using the GCP to generate a 3D point cloud, orthomosaic, TIN model, and texture image. The orthomosaic (Figure 2) was generated with a spatial resolution of 0.10 m.

The discrepancy between the model coordinates and Checkpoints coordinates (obtained by geodetic positioning) can be quantified using the Root Mean Square Error (RMSE), which is used as a benchmark for evaluating the errors (Subramaniyam et al., 2024). Thus, based on the Checkpoints coordinates, the products showed a RMSE of 0.18 m.

The 3D point cloud representing the Digital Surface Model (DSM) was filtered to remove points that do not belong to the terrain surface, i.e., those above the terrain, leaving only ground points. Based on the difference between DTM and DSM, the normalized DSM (nDSM) was generated at the same spatial resolution. The nDSM can be used to estimate the building and tree height relative to a plane.

Point cloud point filtering and transformation into raster format were performed using the Point Cloud tools from the 3D Analyst Tools available in ArcGIS Pro software. These models were generated with a spatial resolution of 0.10 m.

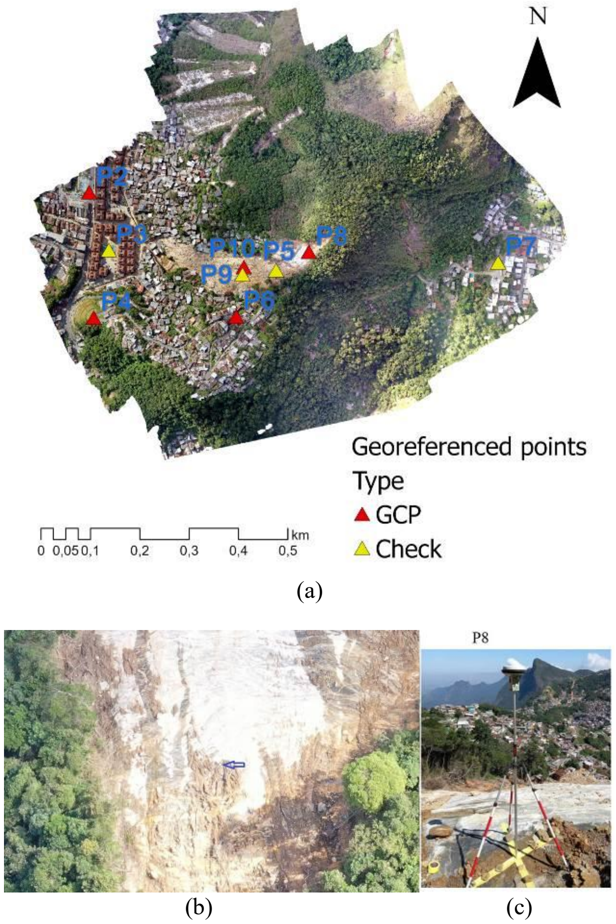

Figure 2. (a) Orthomosaic with GCP and Checkpoints; (b) Point on the rock (point 8); and (c) Positioning using a GNSS receiver.

Images from Google Street View and Google Earth Pro were used to extract building characteristics in the study area before the landslide event. OpenStreetMap (OSM) data and high-resolution images from Google Earth Pro were used to delineate the building footprint, since no prior records or high-resolution images were available for this area.

The footprint and its attributes were used to model the buildings in the ArcGIS Pro via procedural rules (Figure 3). Considering

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the Level of Detail (LOD), the buildings were modeled according to LOD2, using the parametric modeling by procedure rule package LOD2BuildingShells_Meters.rpk, available at the task 3D Building from ArcGIS Pro.

The parametric modeling process is understood as an encoding of a set of information through procedural codes and algorithms. The importance of this technique is evidenced by the studies of Ghorbanian and Shariatpour (2019) and can also be applied in urban planning and disaster management (Elfouly and Labetski, 2020).

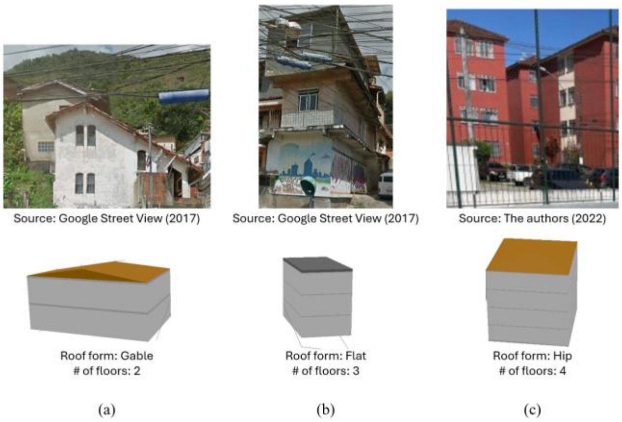


Figure 3. Examples of buildings that surround the landslide scar: (a) Two-floor building with a gable-type roof; (b) Three-floor building with a flat-type roof; and (c) Four-floor building with a hip-type roof.

The procedural rule involved input parameters which are obtained based on nDSM, DTM, and their geometric characteristics, as BLDGHEIGHT (building height), EAVEHEIGHT (distance of the ground to the lowest points of the roof), BASEELEV (elevation on the ground), FLOORHEIGHT (height of each floor), and ROOFFORM (roof type – Gable, Flat, Hip are more common).

The TIN model, which represents DSM using a triangular mesh, has a high triangle density, consuming significant storage space and increasing computational costs. Retopology of the triangular mesh was performed to simplify the topology and minimize these issues with care not to deform the objects in the scene.

The 3D model was exported to a geovisualization environment for immersive and interactive VR, such as Virtalis' Geovisionary software, developed by the British Geological Survey. This software allows the integration of georeferenced data from different sources and formats. Immersion and interaction can be achieved through projection in a VR room or using 3D VR headsets. Other software, such as Unity, can also be used for this purpose.

For interaction with the 3D VR model, some points of the scene were programmed as visitation areas. Images and text about the event were added to the scene as additional information.

4. Results and discussions

Figure 4 presents two ways to visualize and interact with the 3D VR model generated. Figure 4(a) shows Morro da Oficina in 3D VR within the Geovisionary software environment. This enabled immersive experience in a room, as shown in Figure 4(b), using passive 3D glasses and interactivity via a 3D mouse.

Figure 4. Interaction with 3D VR model: (a) Geovisionary software environment; (b) A group of people in a room using passive 3D glasses and 3D projection on a wall; and (c) Individual interaction using 3D VR headset glasses.

Another form of immersion and interaction with the 3D VR model can be through a 3D VR glasses headset (Figure 4(c)). In this case, the immersive and interactive experience is individual, but it tends to be more realistic.

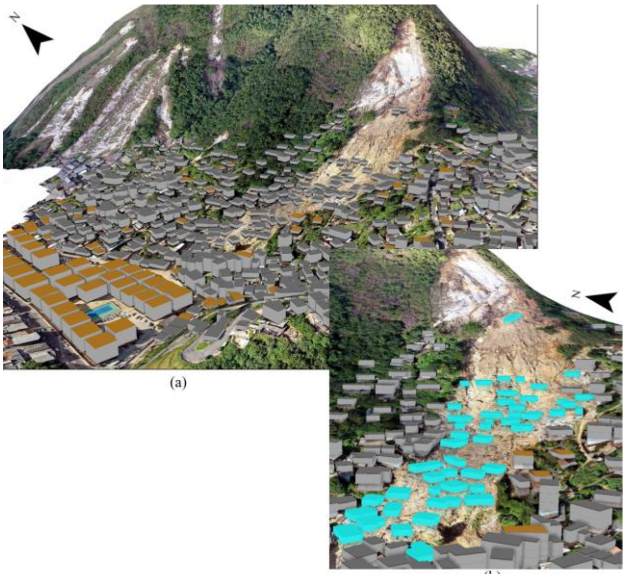
Based on the data for building modeling and products generated, it was estimated that 80 buildings were destroyed (53) or partially damaged (27). Of these, 45 were located in areas with slopes greater than 30%. In the landslide scar, the minimum and maximum altitudes measured were 857 m and 1007 m, respectively, with a relief amplitude of 150 m.

Figure 5 presents the building in the 3D model, highlighting 53 buildings destroyed by the landslide.

The pattern of buildings in the study area tends to become increasingly precarious as one advances up the slope, with access usually only via staircases (Lima et al., 2022). The land parcels are small, increasing the population density of the area. Exceptions for some properties higher up the hill, which had a larger parcel and presented a better construction pattern.

Fieldwork at the site and the Google Street View images revealed that the buildings in the vicinity of the landslide scar typically have two or three floors. In addition, most buildings have flat roofs, made of concrete slabs or metal roofing sheets. Water tanks in these buildings are typically located on flat roofs or small structures and are therefore more exposed to the elements. These settlement characteristics are common in hillside areas with a more vulnerable population.

It is important to note that the 3D VR models have their limitations, many of them based on the quality and availability of the data. In the case of the study area, high-resolution data were not found to assist in modeling the area before the event, causing data to be estimated, such as the height of buildings and the number of buildings buried.

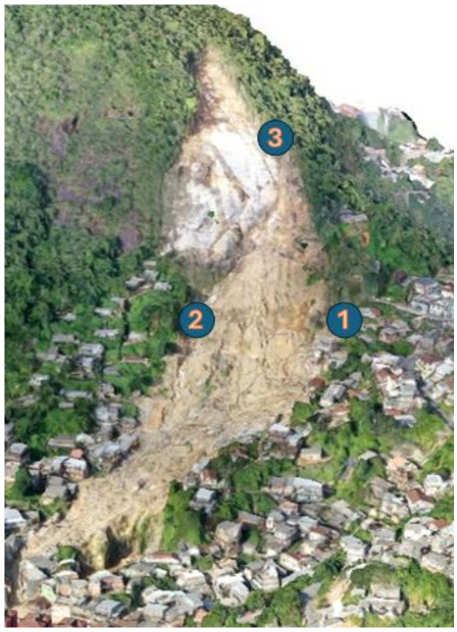


(a) (b)

Figure 5. (a) Buildings modeled by procedural rules superimposed in the DTM and orthomosaic; and (b) buildings destroyed by the landslide (highlighted in cyan).

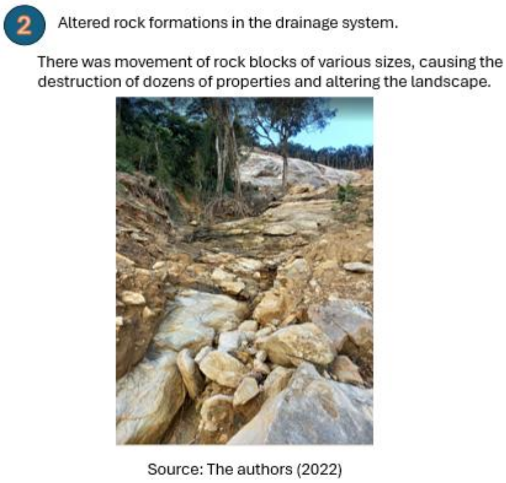
Data acquisition using UAVs has contributed to access to images and data of very high spatial resolution at low cost. Furthermore, the models can be complemented with georeferenced or non-georeferenced data from other sources, enriching the information. Software that allows the integration of this data into GIS environments, ensuring the spatial representation of the data, is promising for diverse applications, considering the concepts of Digital Twin.

For interaction with the 3D VR model, users can explore the scene through a view of the point cloud or the created geometric model. As complementary data to the 3D virtual model of the landslide area, areas of interest were inserted as points of visit (Figure 6). These areas were considered the region's most critical areas, but other areas can be added. Data such as images, photos, videos, and text about the event are considered important additional information and aid in understanding the landslide triggering process and risk prevention.
In this work, some visit points (Figure 6a) are presented. Figure 6b shows a property entrance before and after the landslide. Figure 6c shows altered rocks in the drainage system. At the top of the scar, the 3D VR visualization allowed you to observe the soil thickness in the landslide-triggered area (Figure 3d) as well as the exposed rock fractures.

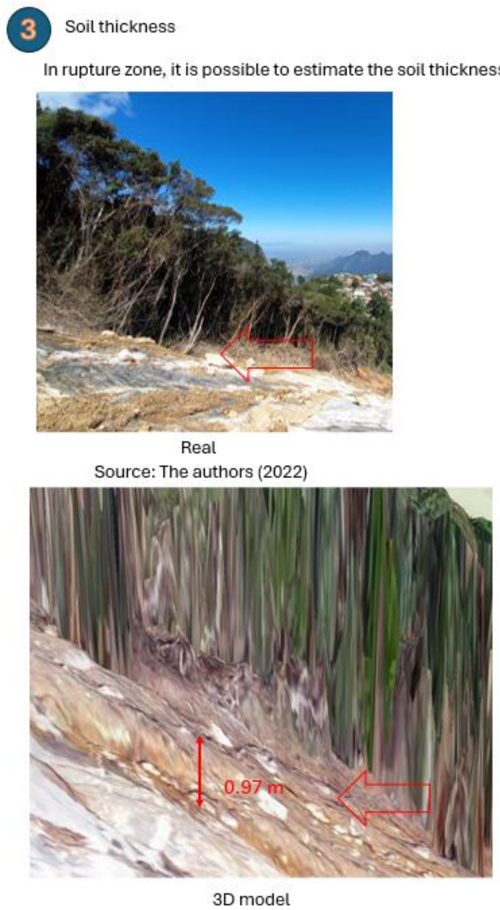


(a)

(b)



(c)



(d)

Figure 6. (a) Points of visit and interactions in the 3D VR model. (b) Before and after accessing a property in one of the highest areas of the hill; (c) Detachment of altered rocks accumulating in the drainage system; and (d) Estimated soil thickness in the landslide rupture area.

The simulation of the pre-landslide scenario with modeled buildings helped to understand the hill's occupation and the construction pattern. In this case, since there are few photographic records of the area before the landslide, the 3D VR allowed us to obtain a panoramic view of the area before the landslide.

According to Blaudt et al. (2023), the municipality of Petrópolis has buildings in hillside areas with very steep slopes, even without soil, or downstream from rocky slopes, where landslides and rockfalls frequently occur.

Although the virtual approach to analysis does not replace fieldwork, it enables a significant reduction in costs and optimization of external operations. It also allows a group of researchers and technicians to analyse and discuss a specific problem, the landslide triggering and conditional factors, or risk prevention situation in a situation room using a virtual environment very close to reality and geovisualization resources, at a lower cost and with less risk for the technicians involved.

VR models can also be used in risk and disaster reduction activities involving resident and school communities located in areas of geological risk. By interacting with risk areas or areas that have already suffered mass movement, community members can help indicate areas with specific hazards, as well as possible escape routes and meeting points.

5. Conclusions

The method proposed in this work allowed the generation of 3D VR models of a landslide to aid in the understanding of the triggering processes and the affected areas, aiming to provide subsidies for discussions involving researchers and technical experts about the triggering and conditional factors and risk prevention.

Furthermore, these models have the potential to be used in educational projects for disaster prevention and risk reduction for use in school and local community activities, integrating new technologies to address the theme.

Although VR models do not replace fieldwork and have their limitations related to data quality and availability, they allow multidisciplinary teams to analyse the landslide area, which is often inaccessible, and assist in decision-making.

As future activities, it is intended to use the model proposed in this work in school communities in risk areas as part of extension university activities.

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