# World Landslide Forum

# 3D landslide models in VR

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| **Corresponding Author:** | Hans-Balder Havenith, Dr.<br>Universite de Liege<br>Liège, BELGIUM |
| **Corresponding Author Secondary Information:** | |
| **Corresponding Author's Institution:** | Universite de Liege |
| **Corresponding Author's Secondary Institution:** | |
| **First Author:** | Hans-Balder Havenith, Dr. |
| **First Author Secondary Information:** | |
| **Order of Authors:** | Hans-Balder Havenith, Dr. |
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# 3D landslide models in VR

Hans-Balder Havenith

## Abstract

The present paper describes the elaboration of 3D surface and geological models generated for a series of landslide sites, zones marked by large incipient slope failures, or those presenting structural characteristics of an ancient giant mass movement. For both, surface and geological models, high-resolution satellite or drone imagery was draped on the digital elevation model constructed from the same imagery or using Radar or LiDAR data. The geological models further include geophysical data, supported by differential GPS measurements, complemented by georeferenced geological and tectonic maps and related geological sections. The soft layer thickness information and borehole data are typically represented in terms of logs inside the model. For several sites also slope stability analyses were performed, either in 2D or in 3D. Inputs for those analyses were directly extracted from the 3D geomodels, outputs were again represented in the models.

Some of those models, such as the one produced for the right-bank slopes of the Rogun Dam construction site can be quite complex and we clearly could notice that an immersive analysis using VR technology helps understand their internal structure and perform a better slope stability analysis. Still these analyses have their limits, as a study in Virtual Reality is purely individual (at present time, the visiting researcher is separated from the rest of the World). Therefore, we suggest that a real advancement can only be achieved if the technological developments go along with a stronger collaboration between scientists from the various geo-domains, who could also be immersed in the same virtual model (~collaborative VR).

## Keywords

Landslide dynamics, geomodel, 3D analysis, immersion, collaboration

## Introduction

Among all geosciences, geological-geophycal hazard research is probably the one that presents the highest challenge with respect to spatiotemporal perception requirements (Havenith et al., 2019). Geological hazards, including landslide hazards, can involve highly dynamic processes, such as rock failure, wave propagation, changing groundwater pressures, extremely slow creep, shearing, subsidence or uplift movements, or rapid collapse, which occur at micro-scale or affect wide areas, even entire mountain structures.

While exploring related hazards within a combined model is still well beyond state-of-the-art, recent technological and conceptual advances should help reach this goal in near future. At present, most single hazard components can be assessed – at least empirically - and many underlying processes can also be reliably simulated and some can be coupled, but representing them in an adequate multi-scale space-time frame is limited by existing modelling capabilities. In Havenith et al. (2019) we provide a (small) overview of what is possible today in geohazard analysis. It should be noticed that many of those tools were actually designed for other purposes related to geography-geomorphology, construction, geotechnical engineering, or mining. The geohazard scientist just adopted them for his/her applications. The most commonly applied representation basis for collected data is still the one of a 2D plane. Digital maps can be visualised and processed by using Geographic Information Systems (GIS). A series of elements can be added to these maps. A series of numerical modelling tools also handle 3D data distributions, generally with limited extent. Both the GIS and the modelling software can also propose 3D views of the respective 2D targets, or of 3D in- and outputs if implemented in the modelling software.

From the preceding it could be understood that the main difference between GIS and numerical modelling software is the orientation of the plane on which geographic-geological elements are represented. Another difference relies in the type of analysis performed with those tools as well as in the temporal component. Usual GIS software only allows for statistical analyses applied to data which include limited discrete, if any, time information (e.g. seismic hazard maps for different return periods, multi-temporal landslide inventories or volcanic eruption maps, etc.). Numerical simulation tools can produce quasi continuous time-dependent outputs (using a time-step adapted to the type of process analysed) for sections or 3D models. However, those outputs are generally strongly limited in time and space (due to limited available computation or storage capacities and/or due to limited data availability).

A compromise is proposed by a third type of modelling techniques that can be grouped together under the general term of 3D visualisation tools or, more specifically, of 3D geomodellers. Related software can represent at the same time large maps and much smaller cross-sections or 3D numerical models representing simulation outputs. The geological modelling (or simply geomodelling) software is generally not used to create the data, but it helps represent in- and outputs in the 3D space. In addition, this software allows for some pre-processing of information needed for the numerical models and for the development of 3D volumes on the basis of points, lines or surface data distributed within a 3D space. As volumes are the core part of 3D geomodels, geomodelling tools must be able to visualise efficiently the 3D space. Therefore, their 3D visualisation capabilities generally exceed by far those of GIS or original numerical modelling tools. Geomodels also allow for 3D spatial and temporal analyses (if the required data are included in the model). Some workflows related to local geohazard studies involving also geomodels are presented in paragraph 4 (case studies) below.

Geomodels are only used by a limited number of geoscientists (typically geo-engineers), first, because geomodelling is time-consuming and, second, because the software is relative expensive for most applications, while probably all (or almost all) geoscientists, including geohazard experts, use the freely available Google Earth® (GE) software. This software provides some pseudo-3D view that is much more efficient than the one proposed by common GIS tools but it does not really exceed the basic capabilities of the latter as all elements are distributed over or above the Earth surface - just as in the GIS maps.

The preceding finally might suggest that we already possess the 'ideal' software system combining GIS, numerical and geological modelling tools supplemented by GE, which covers all aspects of what is required to complete spatiotemporal geohazard analyses. But, there is still something missing, as explained in the next section.

## Immersive models

### Modelling vs Visualisation

Landslide hazard assessment involves the collection of information about the possible slope destabilisation factors (e.g., presence of active faults, unstable volcanic structures, or changing groundwater pressures) for a site or a region as well as their integration within a model that can be used for simulations of dynamic geological processes. But, how to represent and visualise those elements and processes in a single digital 'space'? Typically, input data processing and simulations are run outside the visualisation environment – as real-time processing and simulations require long computation times. Additionally, incompatibilities of data in- and outputs are often observed by changing the software; some outputs can only partly be read by the post-processing or visualisation tools.

### An integrated 'digital geohazard space'?

One of the longest lasting systematically improved systems targeting multi-dimensional dynamic geographic analysis, enhanced collaboration between geoscientists and interaction with elements to be analysed is the 'Virtual Geographic Environment' (VGE, see Lin et al., 2013). The VGE concept has been developed over many years in order to enhance collaboration between geoscientists using the same or similar datasets. Yet, we note that integrated collaboration is still extremely underdeveloped – especially in geohazard sciences. This way of inefficient collaboration in most geo-institutes is surprising if one considers that a few 'collaborative virtual environments (CVEs)' or 'collaboratories' have already been set up many years ago as indicated by MacEachren et al. (2006). Their approach to collaborative visualisation and analysis of geo-data combines mapping elements, cognitive aspects, interaction, cooperative work, and semiotics. They had started 'to address the full range of space-time collaborative situations that can involve group work in the same or different places and at the same or different times.' MacEachren et al. (2006) explain that 'the collaboratory allows users to organize their data streams into hundreds of individualized displays - 3D visual renderings and virtual reality rooms - that are then shared (both synchronously and asynchronously) with other collaborators.' More recently Jurik et al. (2016) developed the idea of the virtual worlds (VW) providing the 'possibility to dynamically modify content and multi-user cooperation when solving tasks regardless to physical presence. They can be used for sharing and elaborating information via virtual images or avatars.'

Former versions of those VGEs did not specifically involve immersive visualisation. And, notwithstanding many technological advances and strongly enhanced availability of VR tools, applications in geosciences and specifically in geohazard research are still rare. Though, Kellog et al. (2008) clearly state that 'an immersive visualisation system is ideal for Earth scientists' as it allows them to better approach the complex multi-scale geo-processes that often change rapidly in time and space. Their main argument in favour of an immersive geo-visualisation is that it 'allows scientists to use their full visual capacity, helping them to identify previously unrecognized processes and interactions in complex systems. … Reaping the full intellectual benefits of immersive VR as a tool for scientific analysis requires building on the method's strengths, that is, using both 3D perception and interaction with observed or simulated data'.

Now, the relatively low price of VR technology (compared to the situation before the massive release of affordable mobile systems; see paragraph below) allows most geoscientists to really use the advantages of 3D perception and interaction - also in geohazard engineering. In particular, it will 'allow users to explore inaccessible past or future environments or distant present environments, not only through their static objects but through processes that mirror their real dynamics' (Lin et al., 2013). Garcia-Hernandez et al. (2016) further state that 3D visualisation can provide more insight in multi-variable data analysis.

### Technological aspects

The aforementioned widespread availability and affordability of VR hardware enables new applications in many fields. We developed applications to visualise fault scarps, landslide geometries, and our geohazard database for Central Asian mountain ranges. Such environments require multi-scale visualisation platforms bridging several orders of magnitude in space (and would also in time, but until now we have no full spatiotemporal model types visualised in VR).

In parallel with its improved availability, the installation and use of the VR hardware and software has also been simplified over the past decade. Although their use remains complex, their present degree of integration and documentation make this technology much more accessible than it has been in the past. This has been developed in such a way that programming skills are not required any more for certain smaller projects.

To represent the landscape in geo-models we use the (possibly textured) DEM surface. The entire geo-model also includes subsurface geological and seismotectonic information (e.g. geological cross-sections, fault structures, earthquake hypocentres), geophysical profiles (e.g. seismic or electrical tomography, various logs) that have generally been processed by adapted software. Most of those data also require georeferencing with a 3D geomodelling software before being imported in the virtual scene. The basic data for georeferencing are generally provided by geodetic measurements completed in connection with the field surveys.

Below we first present some simple surface models of landslides created from drone imagery and, second, some more complex full 3D geomodels of studied landslide sites. For representation

## Landslides and potentially unstable slopes in VR

### A 'Belgian' landslide model

As indicated by Havenith et al. (2019), most of our local geohazard-related studies now also include the preparation of data for visualisation in VR. This preparation follows the scheme described above, based on the creation/adaptation of a surface model (DEM), possibly textured with remote imagery, introduction of geophysical-geological profiles, logs, interpolated underground surfaces (e.g. geological layers, faults), volumes. Typically, point data, logs, surfaces and volumes are first processed in a geomodelling software. The example shown in Fig. 1 presents a landslide site along the seismically active Hockai Fault Zone (HFZ) in East Belgium. An integrated 3D geomodel made with Leapfrog® visualises the study site in terms of its surface and subsurface structures on the basis of the collected data. The inputs of this model include the DEM based on high resolution (LiDAR) surface data (possibly textured by georeferenced orthorectified remote imagery), subsurface geophysical data: microseismic ambient noise measurements (H/V – see logs in figure 1c), seismic refraction (P-waves) tomography and surface wave analysis results (not shown here) as well as electrical resistivity tomography (ERT, shown in Fig. 1b).

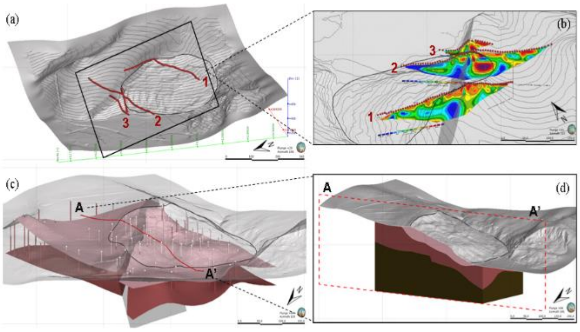

Fig. 1. 3D geomodel of a landslide (grey polygon in all figures) and fault scarp site in East Belgium (created with the Leapfrog® software) showing: a) view to the SE of the shaded LiDAR DEM with location of ERT profile lines, shown in (b); c) view to SE of modelled DEM and subsurface layers, inferred from H/V thickness estimates (colons); d) view to SE of combined shaded DEM and subsurface layer volumes cut along section AA' also shown in (c).

The landslide developed in a softer conglomerate unit (upper part in reddish-brownish layer shown in Figs. 1c and 1d) that could be outlined through its seismic resonance characteristics (H/V results). Related geophysical logs include two information: first an intermediate contact could be identified thanks to a higher frequency resonance peak (found only within the landslide zone, as highlighted by Mreyen et al., 2018) and the bottom of the log corresponds to the thickness of the entire softer conglomerate. Thus, the intermediate contact was considered to be related to the compaction change between the weakened conglomerate within the landslide and the intact conglomerate below (seismic refraction surveys showed that this contact is related to a change of shear wave velocity from 300 m/s inside the landslide material to 600 m/s inside the intact conglomerate; the bedrock below is marked by a shear wave velocity of more than 1000 m/s. Both contacts were interpolated in the Leapfrog software to create triangulated surfaces. Between those surfaces and for the bedrock, volumes have then been formed as shown in Fig. 1d. For the interpretation of related complex inputs (high-resolution terrain and subsurface data, geophysical profiles) and outputs (modelled surfaces and volumes) we use 3D stereo visualisation using a headset system allowing for full immersion in a virtual environment.

### The Koytash landslide case history

In spring 2017, Kyrgyzstan suffered high losses from a massive landslide activation event, during which also the largest deep-seated mass movement of the former mining area of Mailuu-Suu, landslide Koytash, was reactivated. We had started studying this and the neighbouring landslides already many years ago (in 2000), by geophysics and by using optical and radar satellite data. Thereby, we could highlight deformation zones and identify displacements prior to the collapse of Koytash landslide.

Multiple types of DEMs, including a very high-resolution DEM (0.2 m) created on the basis of drone imagery acquired in summer 2017 (after the massive failure). Fig. 2 presents an oblique view of the surface model of the landslide that can also be viewed in our VR lab. Fig. 3 (from Piroton et al., subm.) shows map views of the same area with the UAV DEM included (within red polygon) in the regional TanDEM-X (11 m resolution) surface model.

The comparison of multi-temporal digital elevation models (satellite and UAV imagery-based) highlights areas of depletion and accumulation, in the scarp and near the toe, respectively. The differential synthetic aperture radar interferometry analysis identified slow displacements during the months preceding the reactivation in April 2017, indicating the long-term sliding activity of Koytash. This was confirmed by the computation of deformation time series, showing a positive velocity anomaly on the upper part of Koytash. Furthermore, the analysis of the Normalized Difference Vegetation Index, revealed land-cover changes associated to the sliding process.

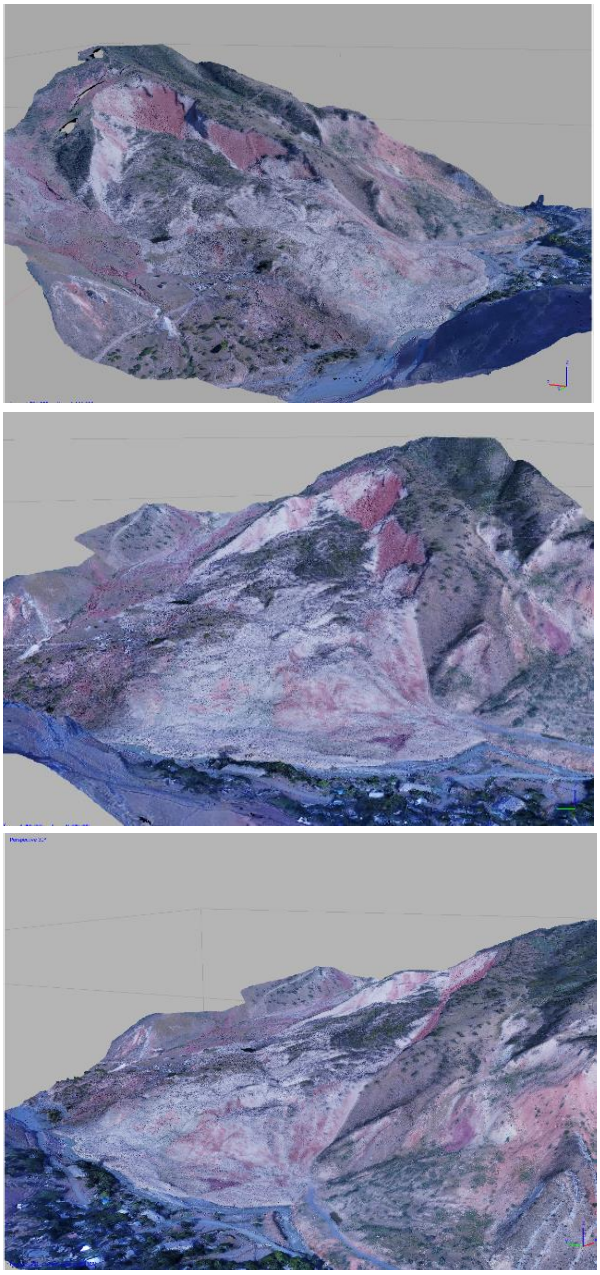

Fig. 2. Oblique views of the Koytash post-collapse (summer 2017) landslide view (UAV imagery covering the 0.2 m resolution DEM constructed from the same images) as it can be seen in VR.

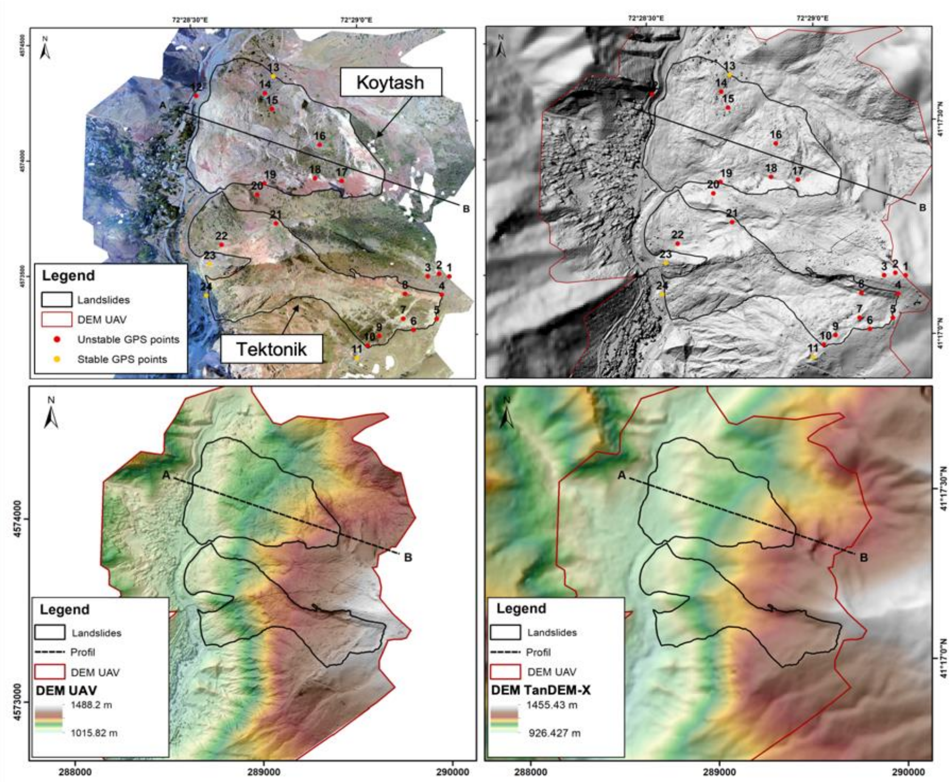

Fig. 3. Maps of Koytash landslide (upper black polygon). a) UAV orthophoto map; b) combined TanDEM-X (outer part) and UAV (central part) DEM hillshades; c) 0.2 m UAV DEM of the Maily-Say area; d) 12 m TanDEM-X DEM of the target area.

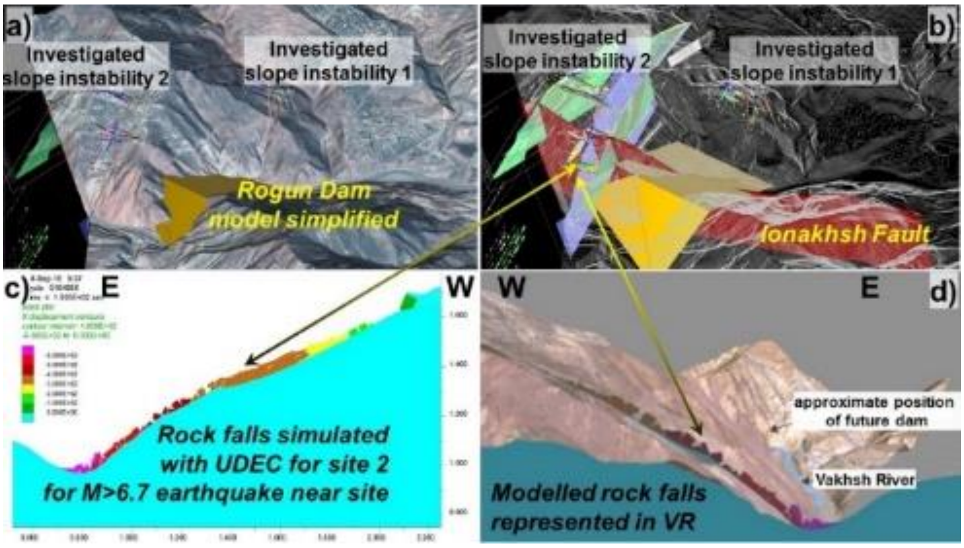

Fig. 4. 3D geomodels and numerical simulation results for slopes investigated near the Rogun Dam construction site in Tajikistan (modified from Gerlach, 2016) with general view (a), surface representation by contour lines and subsurface elements of 3D geomodel (b), modelling section showing rock falls simulated with UDEC for M~6.7-6.9 scenario earthquake near site (c) and simulation results shown in virtual environment (d).

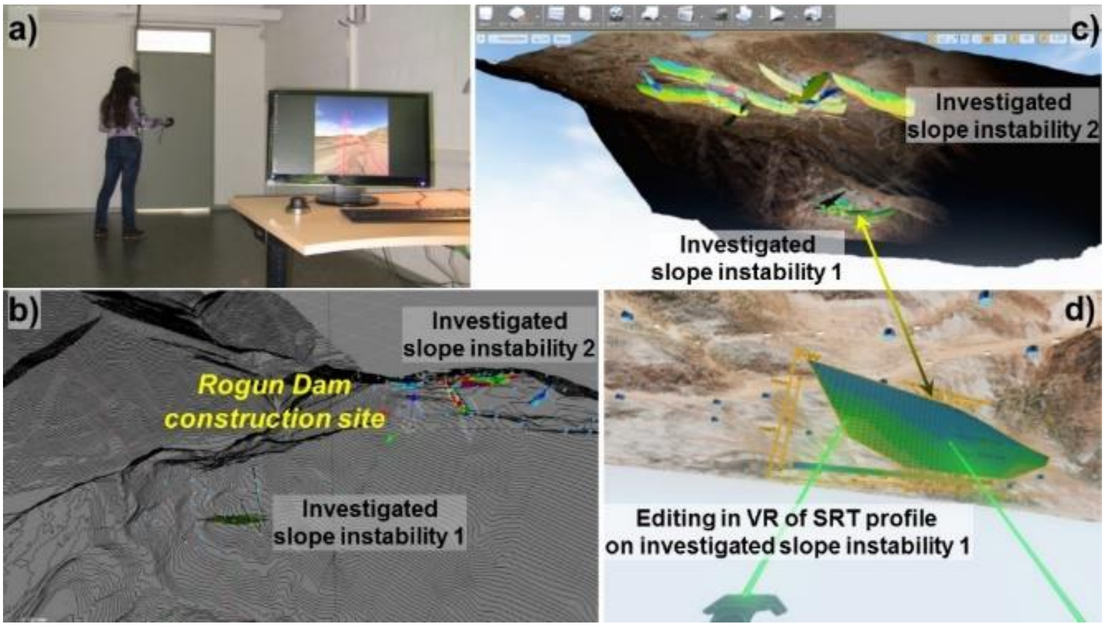

Fig. 5. Rogun site in virtual reality. a) Researcher visiting the site in VR. b) General semi-transparent surface view showing subsurface profiles. c) Illuminating collected subsurface data near the Rogun site inside the virtual environment. d) Visualisation of geophysical (SRT) profile edited (placed at correct location) in VR. For this site also simulations of rock falls were completed in 2D with the UDEC (ITASCA) software. Final results are included as section in the virtual model (see Fig. 4d).

### The Rogun right-bank slope model

For the seismically active Tien Shan Mountains in Central Asia we had created a full GIS geohazard database (Havenith et al., 2015) that we have now transformed into a 3D geodatabase. For smaller sub-areas inside the Tien Shan region, and sites of particular interest, we also developed detailed 3D models, generally as basis for dynamic slope stability calculations or local seismic hazard analyses. Related 3D geodata visualisation examples include the results of a survey completed near the Rogun Dam construction site in Tajikistan (Figs. 4 and 5, from Havenith et al., 2018). The initial pure 3D geomodel has been used to create a 2D numerical model of the slope that was analysed with UDEC (Itasca). The entire rock structure had been represented in this model on the basis of the geological sections, borehole data (shown in Fig. 4b) and geophysical tomographies (see Fig. 5) included the 3D geomodel. Rockfall simulation results were reintroduced into the model as shown in Fig. 4d. Thus, geomodelling and numerical modelling have been completed outside the virtual environment – which until now has been used in our laboratory only for visualisation purposes. In the next paragraph we will, however, show that simulations are now also possible directly in the virtual domain.

In his PhD thesis, M. Ondercin (2016) outlines the possibilities of physics engines belonging to the game engine model series to simulate rock fall events almost in real-time while visiting the virtual environment. Examples are shown in Figs. 6 and 7. These simulations take into account the effect of gravity, bouncing effects (according to a restitution coefficient, see impact represented in Fig. 7) and friction, considering also energy loss during interaction with other objects.

### What about uncertainties in VR?

A scientific analysis, be it in 2D or in VR, is not possible without representing the reliability of the data, and, thus, related uncertainties. Intuitively, all people know that predicting geohazards is subjected to uncertainties. Sword-Daniels et al. (2016) highlight the necessity of considering this uncertainty in connection with natural hazard assessment, considering that ‘the non-linear and dynamic nature of many complex social and environmental systems leaves uncertainty irreducible in many cases.’ Thus, any user and, in particular, any responsible scientist, engineer, or risk manager, entering a virtual world where those uncertainties do not exist would at the end mistrust what has been represented – because it has been shown as a fact (while it is not in reality!).

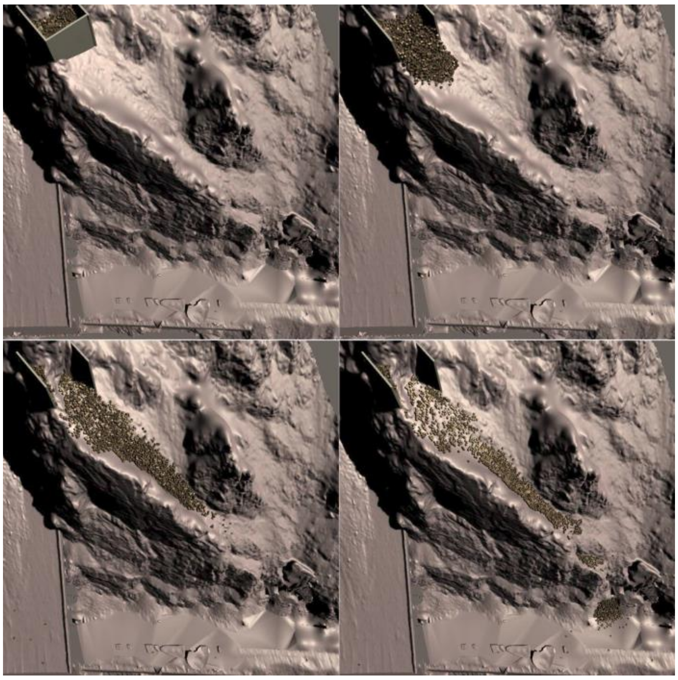

Fig. 6. Model showing the progression of a debris flow down the slope. First the blocks are allowed to settle and then are released. A total of 2047 blocks were used, each with a volume of 0.008 m3 (from Onderci, 2016).

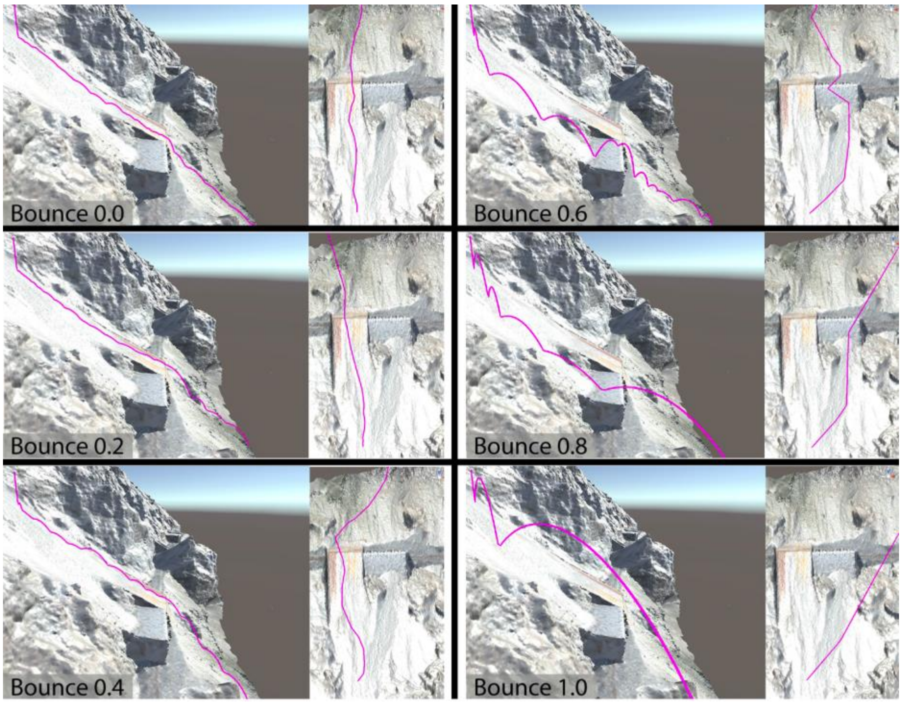

Fig. 7. A cubic rockfall occurring in the same location, changing only the bounce parameter for every test. The friction factor is set at 0.6 and a cubic shape of 1 m3 is modelled (from Ondercin, 2016).

Total uncertainty is typically subdivided into epistemic and aleatory uncertainty, each of which can be represented in a different way. Epistemic ('we do not really know') uncertainties are best presented by 'shading' elements affected by those, or by making them partly transparent according to the degree of missing knowledge. Aleatory uncertainty ('related to the occurrence probability') is best visualised through the variability of possible data outputs. For graphs, such variability is shown through the standard deviation curves, maximum and minimum possible models, etc.

Comparably, in a 3D geohazard space, the variability of geohazard models (scenarios) has to be shown to represent related aleatory uncertainties. It is likely that VR technology could help visualise this variability of multiple possible 'realities' (through multiple parallel visualised models, changing scenarios with depth – distance models are less, front models are more likely), but according to our knowledge, presently, there are no holistic solutions to do this. Brodlie et al. (2012) stated with respect to uncertainty visualisation that 'there remain significant research challenges ahead. While incorporation of uncertainty into 1D and 2D visualisation, both as a scalar and a vector, is relatively straightforward, there are difficult perceptual issues in adding an indication of uncertainty in 3D.'

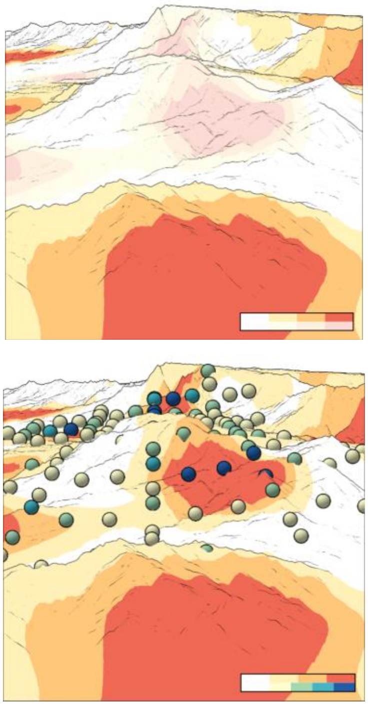

Fig. 3. Intrinsic (above) and extrinsic (below) encoding of uncertainty (here for wind prediction), respectively, by using transparency or additional coloured uncertainty symbols (white=low, blue=high values)

Dübel et al. (2017) provide a wide overview of possible uncertainty visualisation (see one simple example in Fig. 8), clearly stating that the author must decide if data visualisation, or related uncertainties or background conditions (e.g. hillshade of terrain) should be prioritized. If uncertainty is a major issue, then some extrinsic representation as additional symbols may be used to indicate the local data uncertainty value (as in the lower part of Fig. 8).

Finally, we can say that a digital geospace should be able to manage uncertainties affecting inputs and outputs, but at present there are no ad hoc solutions available and further research is necessary to do so. Related studies have to accompany the development of the basic characteristics of the 4D geospace described below.

## Conclusions

Havenith et al. (2019) describe six essential qualities of the digital geospace - which are not specific for landslide or any geological hazard assessment, but will certainly enhance it. They can be summarized as this : the geospace should be (1) multi-dimensional, considering that X,Y,Z must not necessarily refer to the 'geometrical space', multiple dimensions can also refer to multiple disciplines or multiple parameters to be represented; (2) spatiotemporal as many geoscientific disciplines, including those related to geohazard assessment are also 'temporal'; (3) fully interactive, allowing for marking elements and modifying them; (4) (tele-)immersive, as it can be expected that an immersive analysis may engage the investigator, viewer, more intensively in finding solutions, than an non-immersive approach; (5) collaborative : all the preceding points essentially require technical solutions. The goal of improving those solutions is the improved collaboration between multi-disciplinary teams. So, this last quality would be an all-embracing consequence rather than an additional characteristic. For geohazard research, achieving this goal could represent a revolution as multi-disciplinarity is essential for establishing reliable spatiotemporal models able to predict dynamic processes that may occur anytime and anywhere with a certain probability. Such models typically require inputs and re-evaluation by more than one single person!

Are there now technical solutions to create a digital geospace that could help assess geohazards better? Obstacles outlined above first include insufficient possibilities for interaction and collaboration in VR. Thus, present software developed in connection with the HMD hardware does not automatically allow for editing or collaboration in the virtual space.

To model 3D changes over time to simulate geological processes, changes in both geometry (expansion) and topology (discretisation) must be considered. Despite the progress observed in many fields, we still lack the ultimate 3D model that will allow us to integrate different representations and models from different domains.'

And even if we manage to develop fully integrated 3D geohazard models combining outputs from multiple disciplines and adapted for immersive analysis, we need to check if they really allow for an improved understanding. As Romano et al. (1998) wrote 'an immersive virtual environment (VE) usually requires a considerable investment. Therefore it would be interesting to determine if a simple desktop VE could be used to achieve a sense of presence sufficient to provide trainees with an experience of the same cognitive value as one in the real world without the need to construct a full immersive VE with all its associated costs.' This can be complemented by the conclusions of Westerteiger (2014) that not every problem can be efficiently solved in VR. He considers for example vector maps as type of data that are better represented in a 2D (desktop) digital environment. For this author the 'key to the acceptance of VR methods, then, is the seamless interoperability between (existing) desktop systems and VR environments.'

Thus, the final usability of VR in any scientific research has to be analysed in a critical way, respectively, for each discipline and for multi-disciplinary approaches.

## Acknowledgments

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Hans-Balder Havenith (✉)
Liège University, Department of Geology, Georisks and Environment, Liège, Belgium
e-mail: HB.Havenith@uliege.be