LANDSLIDES FROM THE *INSIDE*

Anne-Sophie Mreyen, Philippe Cerfontaine, Léna Cauchie, Hans-Balder Havenith
Department of Geology, University of Liege, Belgium
Corresponding author: as.mreyen@uliege.be

Introduction

The mapping of internal structures of landslides is a challenging task. A series of investigation methods are needed to comprehend the interior of a slope. Those include direct exploration, such as drilling and trenching, enabling a direct contact with the material of the subsoil and indirect exploration comprising geophysical techniques, either in boreholes or for surface applications. A very efficient tool to integrate the ensemble of collected subsurface information into a visual format is 3D geomodelling. It allows for a comprehensive compilation of multiple subsurface and surface data, including borehole logs, 1D, 2D, 3D geophysical information, remote imagery and a digital elevation model, in a 3D space.

Here, we present some applications using indirect explorations, i.e. 1D and 2D geophysics (active and passive seismic as well as electrical tomography), on landslide slopes in Belgium and Romania (Mreyen et al., 2017). For the representation of the actual surface of the study area, a high resolution digital elevation model is used, based on LiDAR data. For the subsurface modelling, interpolation techniques are used to link contrasts in geophysical properties identified within the landslide mass that possibly indicate the vertical and lateral boundaries of the fractured material on top of the bedrock. The interpolated surfaces allow us to define the geometry as well as the volume of the failure and furthermore to reconstruct the pre-failure morphology of the studied slope.

Such an analysis of a landslide from the inside, can also be supported by virtual reality techniques that help the researcher get immersed in the model (Havenith et al., 2017).

Study areas in NW and SE Europe:
- *Hockai Fault Zone, Belgium ("Bévercé landslide")*
- *Carpathian Mountains, Romania ("Balta landslide" & "Eagles Lake")*

Methods

I. Geomorphological analysis – A geomorphological field analysis of the studied slope is essential to trace key surface structures: main detachment scarp, counter slopes, depletion and accumulation zones of failed mass, hummocky structures, lateral boundaries of deposits, wet zones and water sources. Digital surface data and imagery, such as high-resolution DEM's (e.g. based on LiDAR scans) and orthophotos, facilitate this task and are used as basis to create 3D geomodels.

II. Geophysical survey – The combination of several geophysical techniques is used to explore the internal structures of a landslide body. For this work, we used the following methods:

- **H/V** 1D single station ambient noise measurements
  - ⇨ f_0 peaks (impedance contrast of materials)
  - ⇨ landslide basal / lateral boundaries
- **Array** Multiple-station ambient noise measurements
  - ⇨ Vs profiles
- **SRT** Seismic refraction tomography (active source)
  - ⇨ 2D profile of Vp contrasts
- **MASW** 1D multi analysis of surface waves (active source)
  - ⇨ Vs profiles
- **ERT** Electrical resistivity tomography
  - ⇨ 2D profile of resistivity contrasts
  - ⇨ Water content of landslide deposits

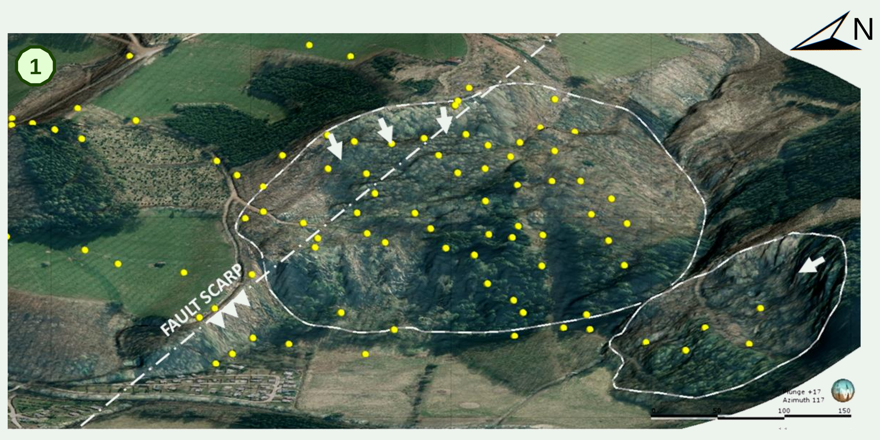
III. Geomodelling

The acquired field data represents the basis of the modelling part. The integration of the results is followed by a thorough analysis considering the lithological, geological, hydrogeological and seismo-tectonic background of the sites. Surface and subsurface data are linked efficiently to define the landslide limits visible at the surface and detected in the subsurface. The data is interpolated to lithological contacts and volumes.

The software used for this work is Leapfrog ® Geo (Version 4.5) from Seequent Limited ©.

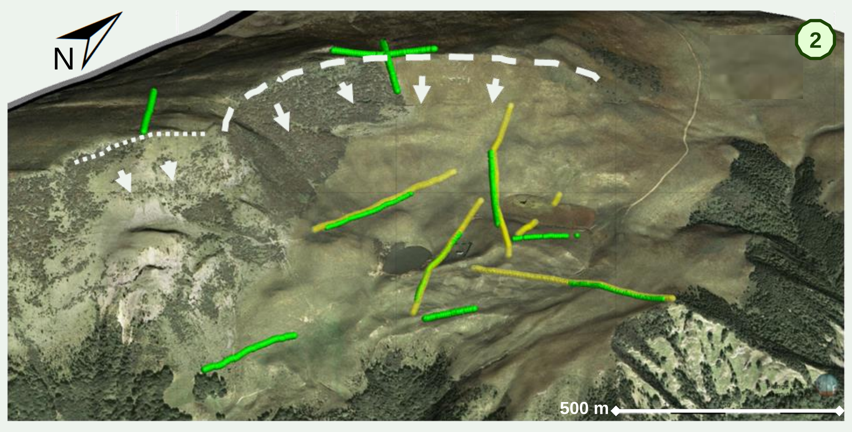
Results

I. Geomorphological analysis & Surface models



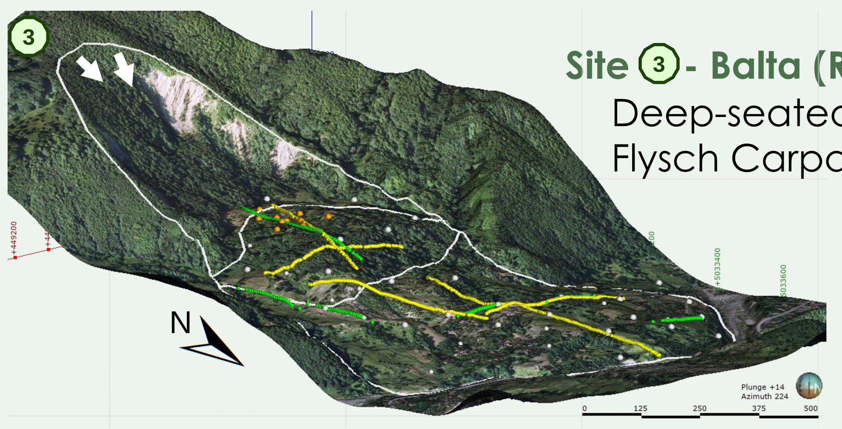
Site ① - Bévercé (B)

Two landslides developed in a Permian conglomerate, sitting on a fault zone (Hockai Fault Zone, East Belgium).
- Fault scarp
- Counter slopes
- Hummocky surface



Site ② - Eagles Lake (RO)

Ancient landslide in the Romanian Carpathians, possibly shaped by several (seismic?) events.
- Detachment scarp (altered) and block slides
- Soil pressure waves
- Lakes (ephemeral and water filled)



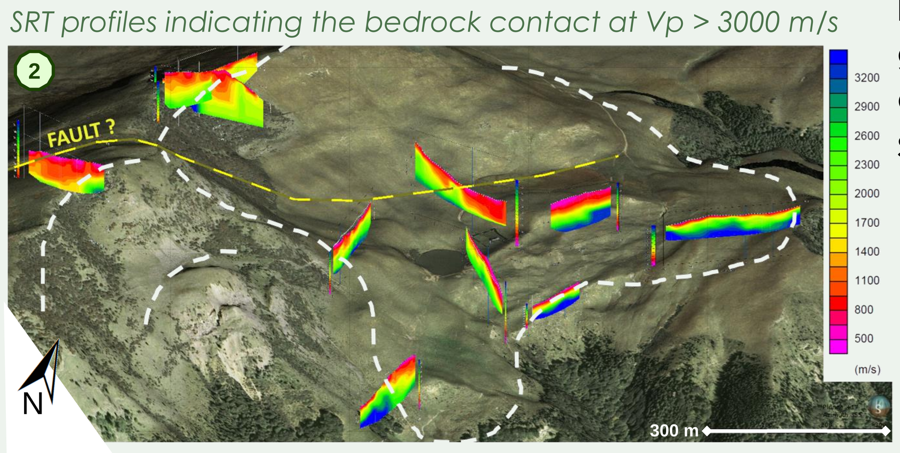
Site ③- Balta (RO)

Deep-seated landslide in the Romanian Flysch Carpathians, possibly co-seismic.
- Profound scarp
- Anti-dip slope (Flysch layering)
- Plateau (deposits)
- River deviation

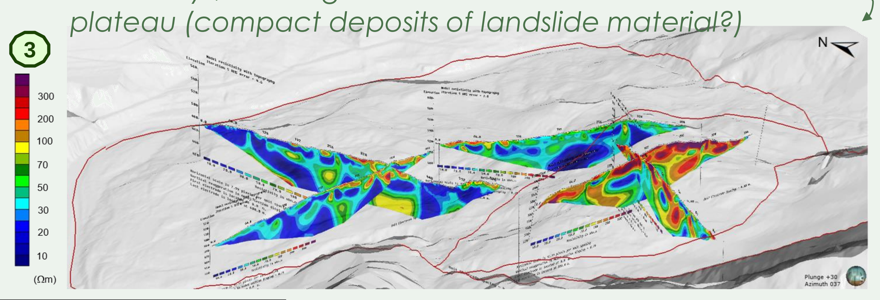
II. Integration of geophysical data

The H/V technique has proven most effective to understand the internal structure as well as horizontal borders of landslide bodies, since it allows to trace impedance contrasts (frequency peaks) up to great depth. By performing multiple measurements, we are able to define possible intermediate lithological contacts and the basal shearing horizon at multiple points. Information on surface waves velocities needed to interpret H/V data are inferred from seismic arrays and MASW. The SRT and ERT surveys are furthermore used to delineate horizontal and lateral limits of failed versus insitu material. ERT, the most popular geophysical technique used for landslide investigation, as it helps detect groundwater and determine the compactness of soils, revealed to be less effective in defining subsurface contrasts.

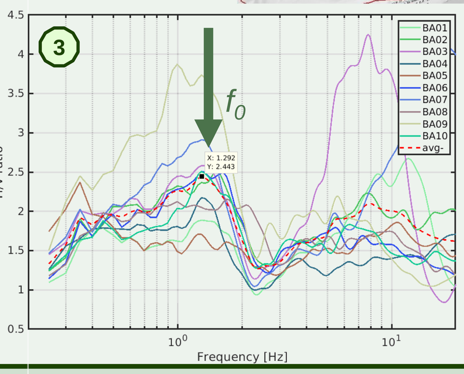
SRT profiles indicating the bedrock contact at Vp > 3000 m/s



ERT surveys, showing less conductive material at the plateau (compact deposits of landslide material?)



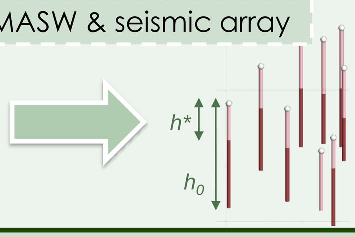
H/V signals of 7 seismometers at the array installation at Balta, they all show a peak frequency at ~ 1.3 Hz

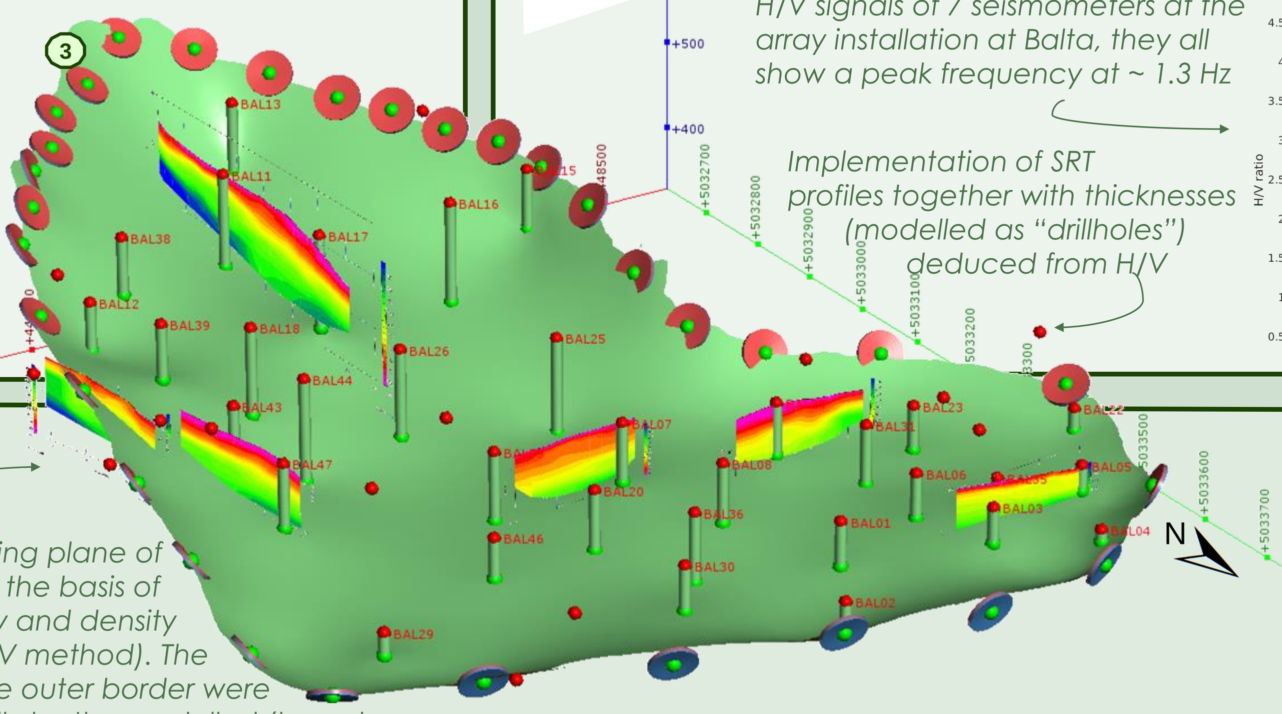


Implementation of SRT profiles together with thicknesses (modelled as "drillholes") deduced from H/V

f_0 from H/V (fundamental frequency peak)
+
Vs from MASW & seismic array

$$f_0 = \frac{V_s}{4h}$$

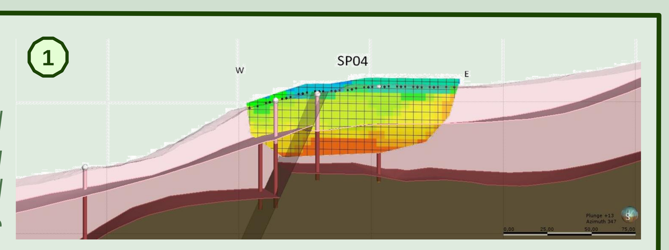




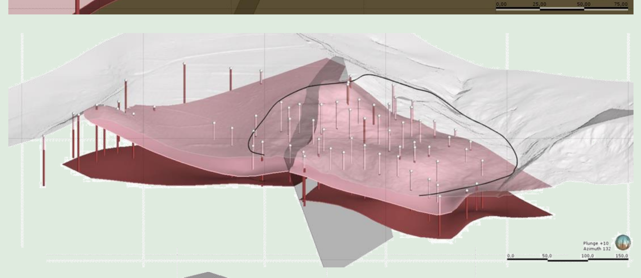
Modelled basal shearing plane of the Balta landslide on the basis of the measured velocity and density contrasts in depth (H/V method). The delimiting points at the outer border were implemented artificially by the modelled (based on the geomorphological markers at the surface)

III. Geomodelling

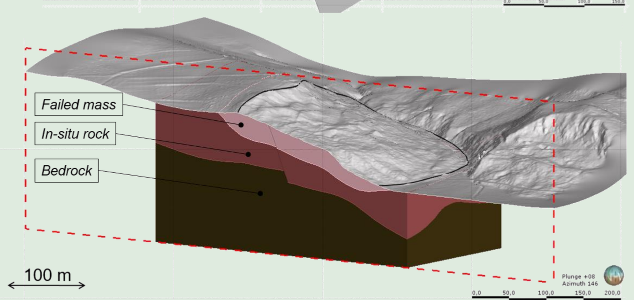
After the implementation of the collected surface and subsurface data, surface layers and volumes can be created. For this, point data is interpolated to surfaces and interpolation results are verified by the 2D imagery (geophysical tomographies). These surfaces can represent fault planes, lithological layers (e.g. bedrock contact) and, as in our case, physical contrast (fractured material vs. in-situ rock). The landslide deposits are delimited by the modeler on the basis of the prior geomorphological analysis, since the lateral boundaries are difficult to define (since the H/V measurements demonstrate only vertical contrasts). At last, volumes can be created to represent the total displaced mass of the slope failure.



Interpolation of 1D and 2D geophysical data (SRT and H/V) and modelling of fault plane

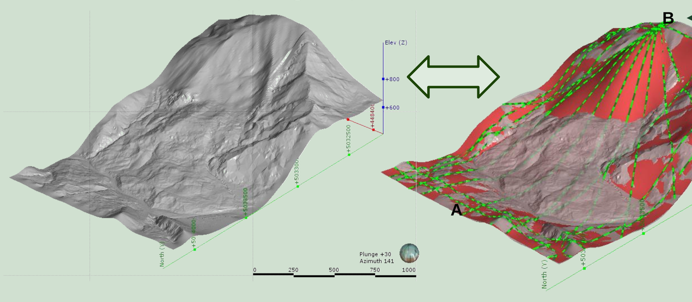


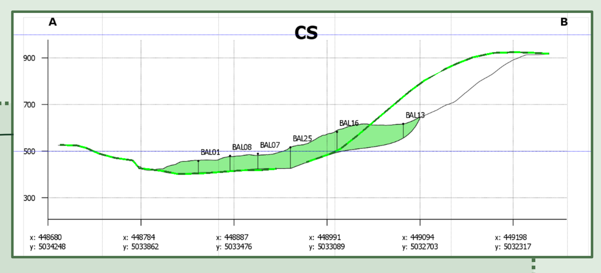
Creation of lithological surfaces based on H/V impedance contrasts (1st fractured conglomerate, 2nd conglomerate-bedrock contact)



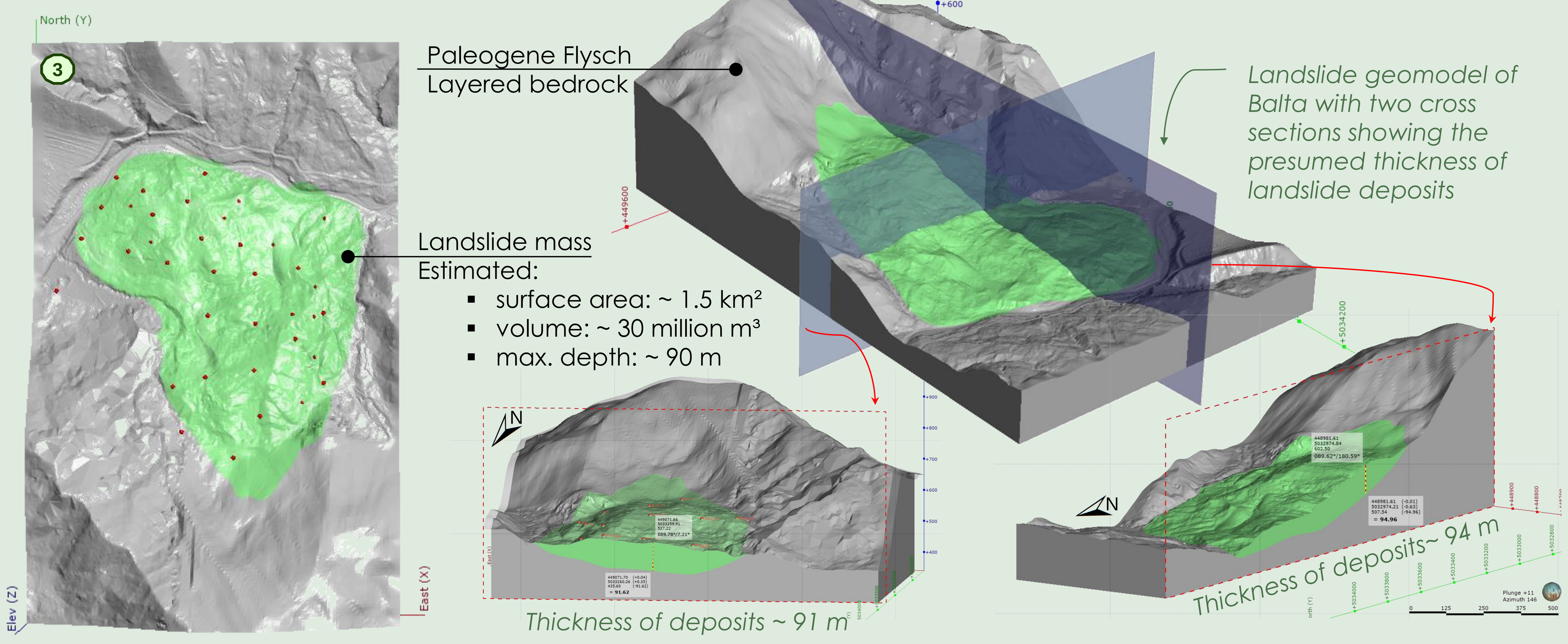
Final geological model with modelled landslide base (lateral borders defined with 2D geophysical profiles and geomorphological markers). The bedrock contact is marked by the normal fault – depth difference from H/V surveys)

Excursion: topographic reconstruction





Based on the calculated volume of the failed mass, multiple 2D cross sections can estimate a mass-balance of depletion and accumulation in order to establish a possible pre-failure topography.



Landslide geomodel of Balta with two cross sections showing the presumed thickness of landslide deposits

Conclusion & Outlook

- Geomodels of landslides should be based on high resolution surface data and a thorough geomorphological and structural analysis.
- In this work, geophysical methods were used to characterise the internal structure of slope failures, while the combination of the selected techniques is particularly wall adapted to survey deep-seated landslides.
- The models depend on data resolution and quality, as well as the scientific analysis and interpretation of the collected data.
- The estimation of the geometry and volume of a landslide body allows for a topographic reconstruction of the pre-failure state of the site (that can later be used for further computational modelling (e.g. back-analysis of slope development, also in the dynamic domain).

REFERENCES - **Havenith H.-B.**, Cerfontaine P., & Mreyen A.-S., 2017. How Virtual Reality can help visualise and assess geohazards. International Journal of Digital Earth, 1-17. **Mreyen A.-S.**, Micu M., Onaca A., Cerfontaine P. & Havenith H.-B., 2017. Integrated geological-geophysical models of unstable slopes in seismic areas. In workshop on World Landslide Forum, pp. 269-279, Springer.