Electrical resistivity monitoring of an earthslide with electrodes located outside the unstable zone (Pont-Bourquin landslide, Swiss Alps)

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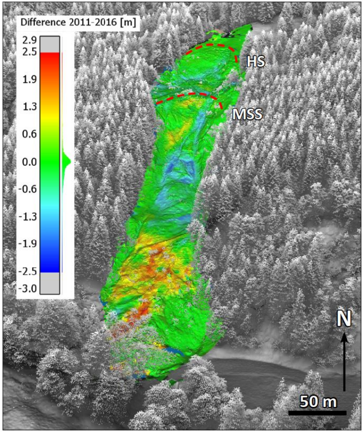
- Objectives
- State of the art
- Results
  - Geophysical imaging (2D & 3D)
  - Numerical modeling
  - Monitoring
- Conclusion(s)



Differential LiDAR DEM (Bièvre *et al.*, 2018)

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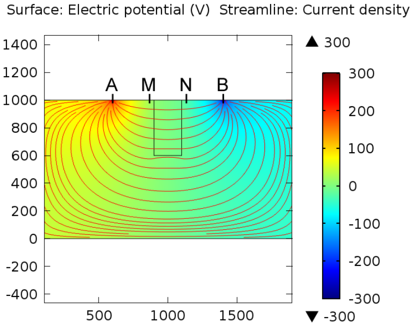
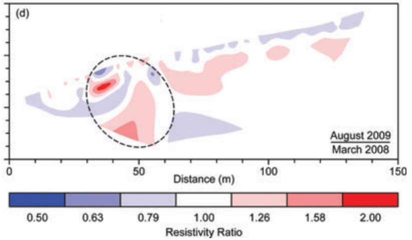
ERT Monitoring of landslides : how to deal with moving sensors ?

$$\rho = K \times \frac{V_{MN}}{I_{AB}} = \frac{2\pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}} \times \frac{V_{MN}}{I_{AB}}$$

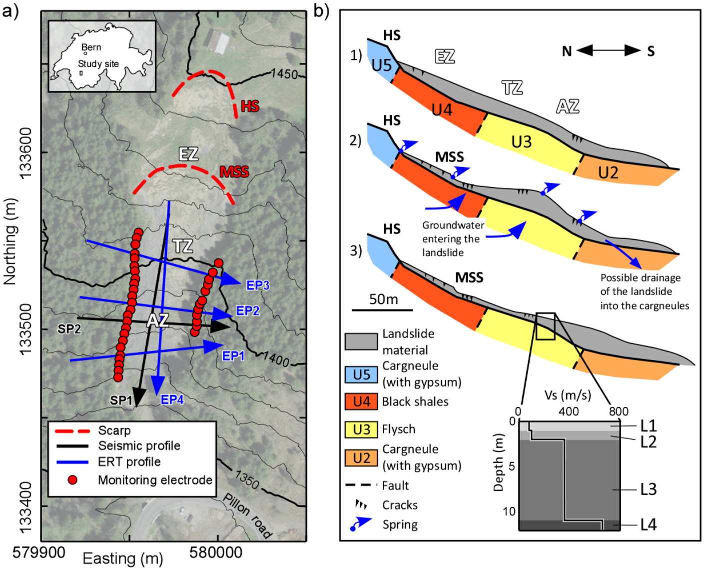
- Electrical resistivity is sensitive to multiple parameters : mineralogy/lithology, moisture, ionic charge, temperature, etc.
- Time-lapse ERT has long been used to study water-related process at (generally) shallow depth in landslides
- However, electrodes within a landslide move relatively to each other $\rightarrow \Delta\rho$ is not only related to $\Delta\frac{V}{I}$ but also to ΔK
- Wilkinson *et al.* (2010, 2015) retrieved electrode displacements thanks to $\Delta\rho$. This needs the assumption that only K varies when displacement occurs
- $\rightarrow$ test of monitoring with electrodes located outside the unstable zone to get rid of potential ΔK effects :
  - is it possible to achieve a global monitoring of the unstable zone ?
  - what would be the spatial resolution ?
  - what are the parameters of influence on resistivity ?





Wilkinson *et al.* (2010)

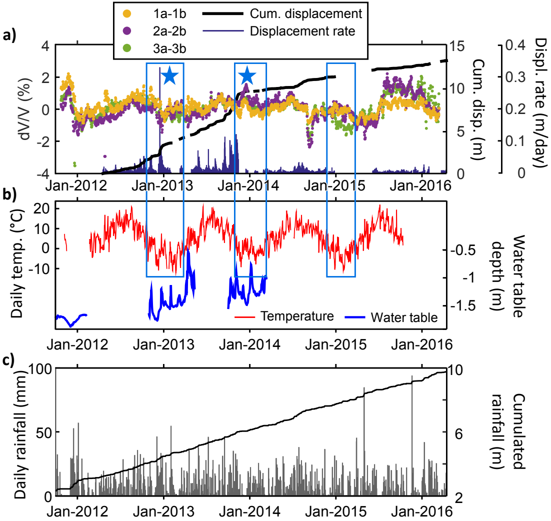
The Pont-Bourquin Landslide (PBL)



EZ : erosion zone ; TZ : transportation zone ; AZ : accumulation zone ;
HS : main headscarp ; MSS : main secundary scarp.

The Pont-Bourquin Landslide (PBL)

- Monitoring $\Delta V/V$:
  - Significant drop (6 %) several days before the failure of late August 2010 (Mainsant *et al.*, 2012)
  - No significant drop between October 2011 and March 2016 (along with no failure)
  - Observation of tiny periodical / reversible variations related to environmental parameters (temperature, rainfall, etc.)
  - Main drawback : no location of the information
- Resistivity monitoring :
  - possible to locate resistivity in 3D (after inversion)
  - possible to derive a $\Delta\rho/\rho$

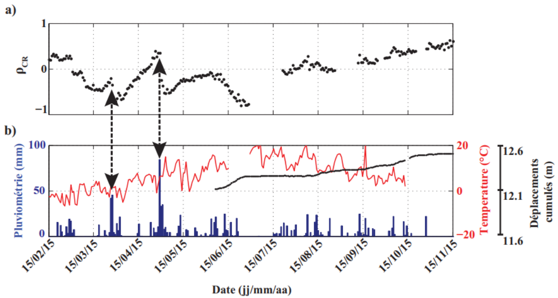


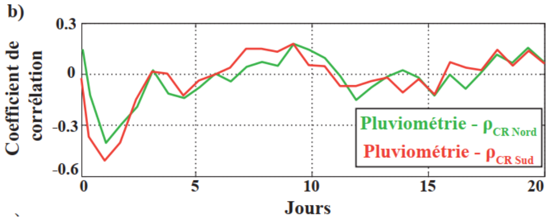
Bièvre *et al.* (2018)

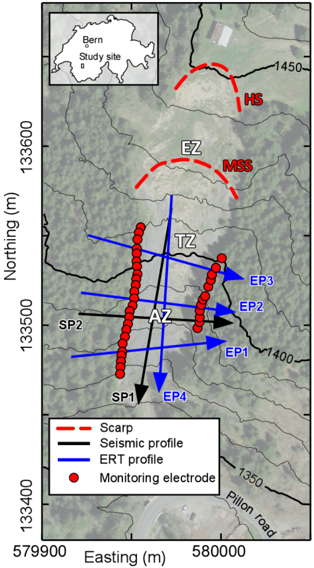
The Pont-Bourquin Landslide (PBL)

Resistivity monitoring :

- PhD S. Carrière (2016)
- no inversion of apparent resistivity (so what ?)

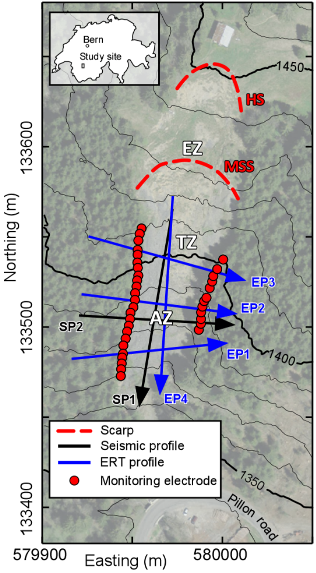






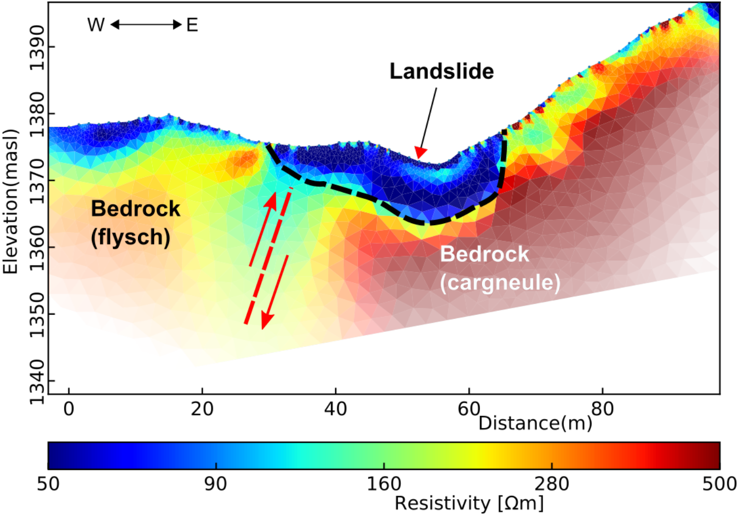
Materials & methods

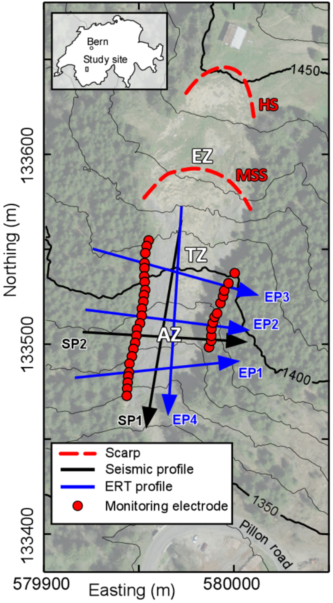
- Imaging :
  - 1, 3D large model (whole landslide) : 2D profiles from 2009 and 2014 (not shown here)
  - 1, 3D model (bottom part) : 2D MG and DDP profiles from 2014
  - 2 seismic profiles from 2014 (not shown here)
- Monitoring :
  - 24 electrodes on the right flank
  - 12 electrodes on the left flank
  - 1 daily sequence of 1654 measurements from 15 February 2015 to 23 November 2015
  - Equatorial Dipole-Dipole with reciprocal measurements
- Processing :
  - Seismics : pyGIMLI (Wagner *et al.*, 2015)
  - ERT : BERT package ; Boundless Electrical Resistivity Tomography (Günther *et al.*, 2006)



Results - 2D imaging

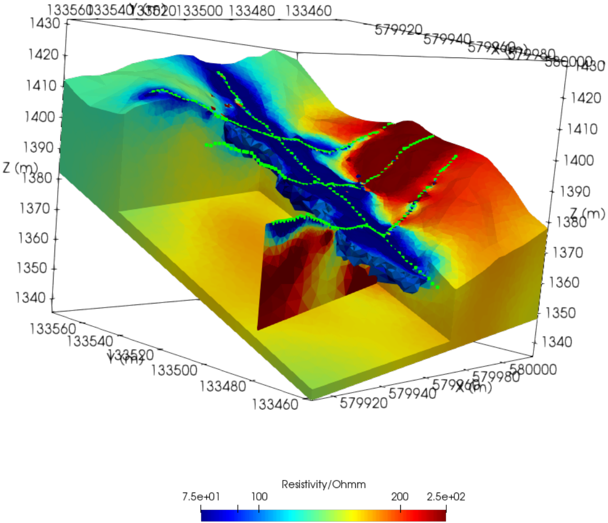
Profile EP1

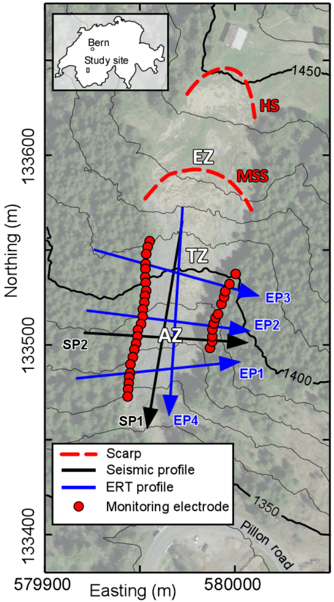




- $\chi^2 = 0.9$; RRMS = 4.7 %
- good contrast between the landslide and the bedrock
- Landslide characterized by resistivities $< 100\,\Omega$.m

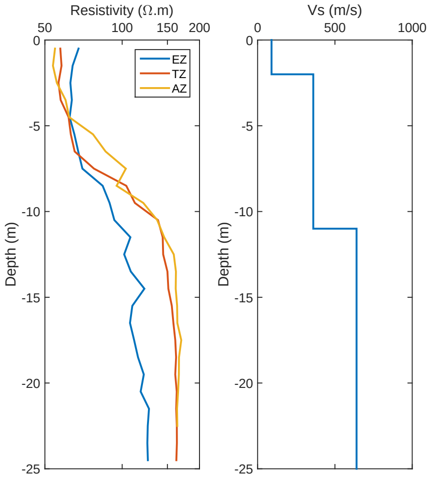
Results - 3D imaging

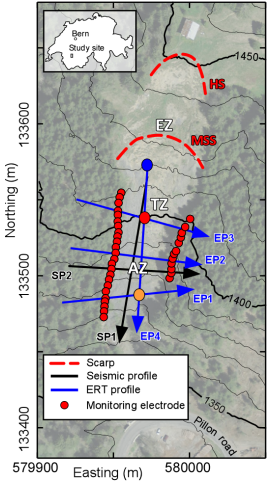




- $\chi^2 = 0.88$; RRMS = 13 %
- Landslide characterized by resistivities $< 100\,\Omega$.m
- Landslide volume below the MSS $\approx 22.5 \times 10^3$ m^3 (this is not the whole landslide)

Results - 3D imaging

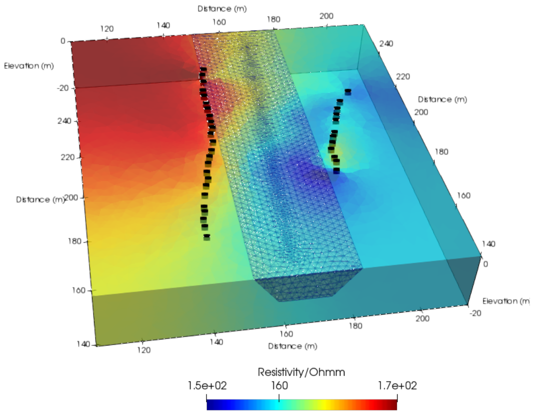




- Landslide characterized by resistivities $< 100\,\Omega$.m
- Thickness $\approx$ 10 m in TZ and AZ, 15 m in the bottom part of EZ (or partially weathered black shales ?)
- Good agreement with Vs results of Mainsant *et al.* (2012)

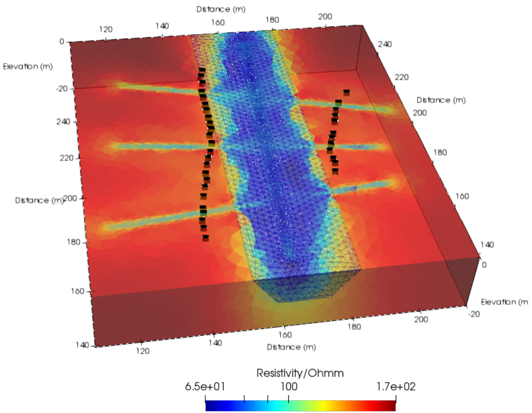
Results - Numerical modelling : 3D reconstruction

Using monitoring data only :



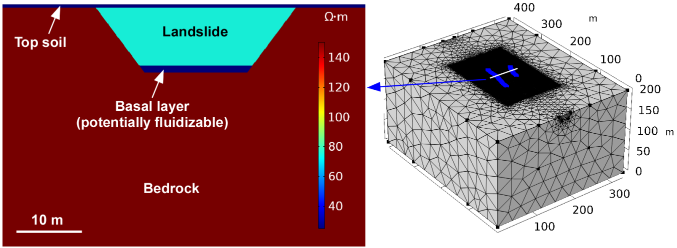
- No possible reconstruction of the structure with the monitoring setup only
- Need to use a more complete set of data

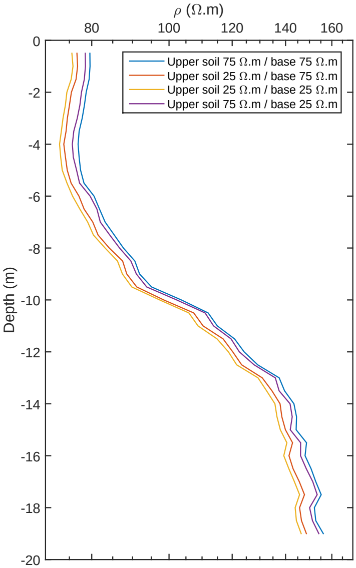
Using the 4, 2D profiles :



- Highest gradient at 10 m depth (100 Ω.m)
- "True" landslide volume : 30500 m ^{3}
- Retrieved landslide volume : 25000 m ^{3} (-15 %)

Results - Numerical modelling : ability to detect Ω variations





- Highest gradient (100 Ω.m) located at 10 m depth
- A resistivity change at surface induces a resistivity variation down to 20 m depth → no possible localization
- A resistivity change at the base of the slide induces a (small) resistivity variation of the whole model

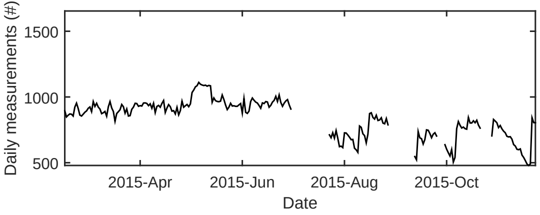
→ Experimental setup not likely to detect localized variations

Results - Monitoring

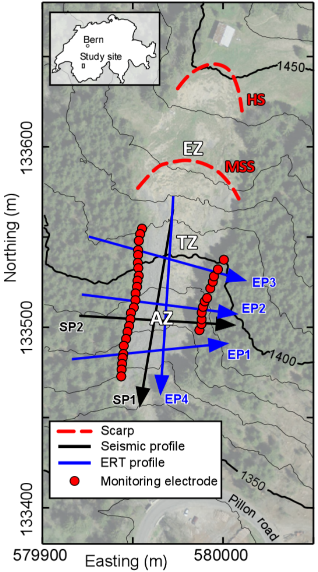
- 1654 daily measurements ; 235 time-series

- Raw data filtering :
  - reciprocity threshold : 3 %
  - repeatability threshold : 3 %
  - minimum measured voltage (V_{MN}) : 0.01 V
  - negative resistivities deleted

- After filtering :



- Inversion strategy :
  - Difference inversion (LaBrecque & Yang, 2001) → too heterogeneous temporal dataset
  - Ratio inversion (Schütze *et al.*, 2002) → too heterogeneous temporal dataset
  - Use of a common **Reference start model** for each daily sequence



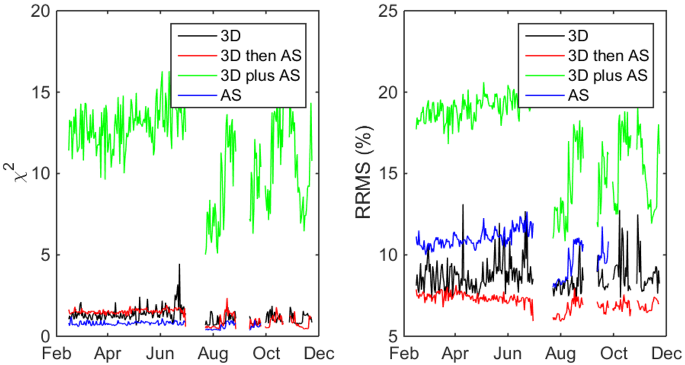
Results - Monitoring

Inversion strategy :

1. 3D model from the 4, 2D profiles → starting model (**3D**)
2. 3D inversion of the median monitoring sequence with 3D as a starting model → starting model (**3D then AS**)
3. 3D inversion of [2D profiles + median monitoring sequence] → starting model (**3D plus AS**)
4. 3D inversion of the median monitoring sequence alone → starting model (**AS**)

Convergence criterion : χ^2
Residuals are adjusted relatively to an experimental error (3 % here).

$$\chi^2 = \frac{1}{n}\sum_{i=1}^{n}\frac{d_i - m_i}{e_i} \approx 1$$



Choice of the starting model :

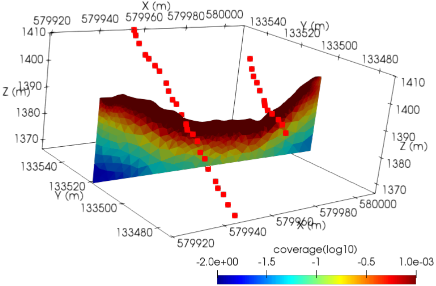
- χ^2
- **RRMS**
- sensitivity
- geometry

Best numerical results : 3D and 3DthenAS

Results - Monitoring

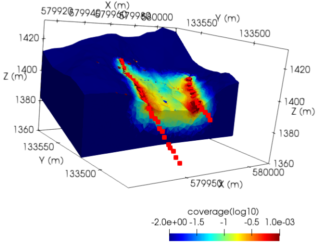
Choice of the starting model :

- χ^2
- RRMS
- **sensitivity**
- **geometry**

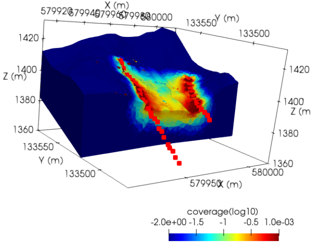


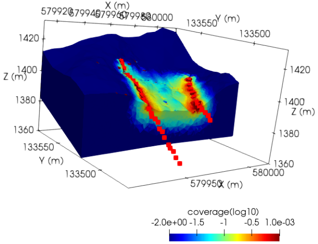
Profile pe02 - Sensitivity

3D

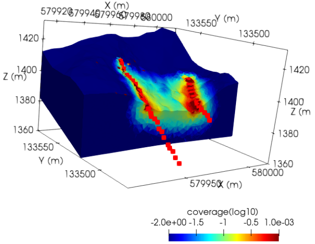


3D then AS





3D plus AS



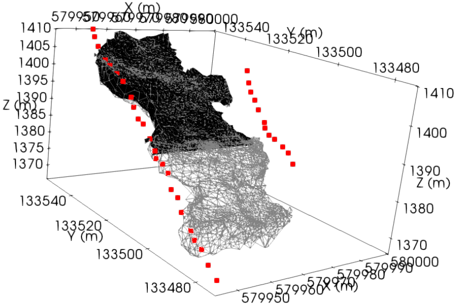
AS

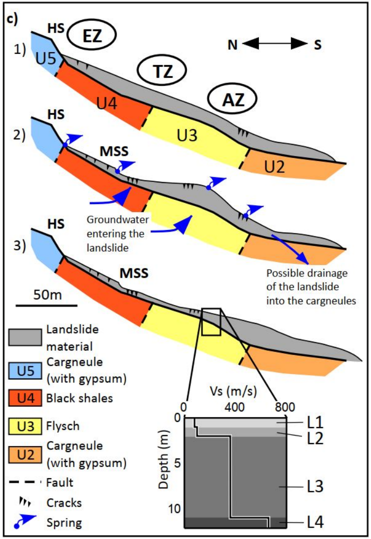
Best numerical results : 3D and 3DthenAS

Results - Monitoring

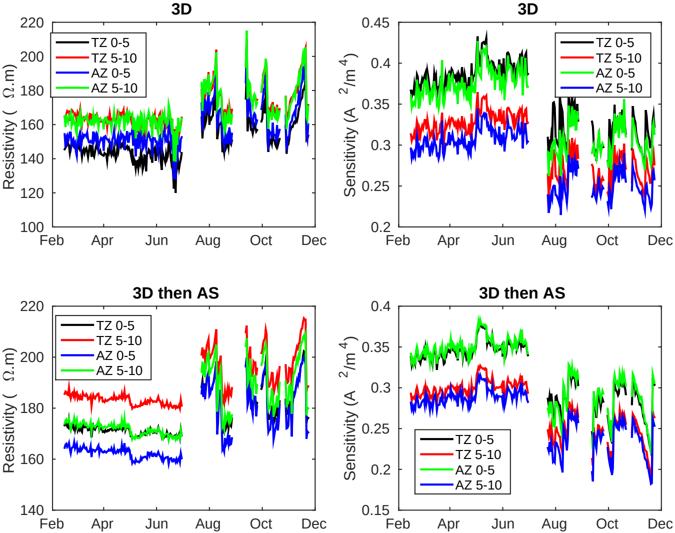
4 zones :

- Transport Zone, depth 0 to 5 m : **TZ 0-5**
- Transport Zone, depth 5 to 10 m : **TZ 5-10**
- Accumulation Zone, depth 0 to 5 m : **AZ 0-5**
- Accumulation Zone, depth 5 to 10 m : **AZ 5-10**



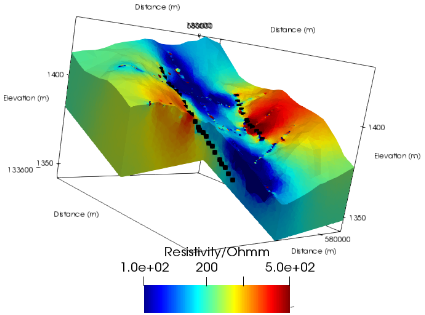


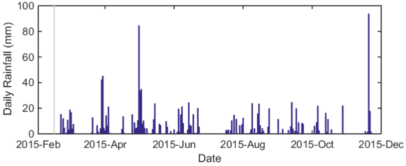
Results - Monitoring

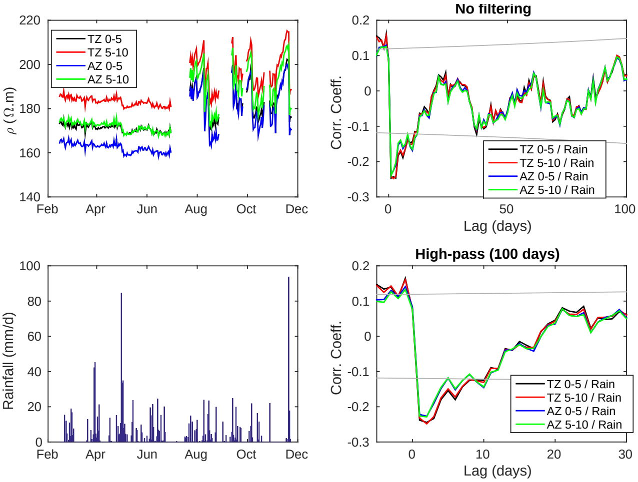


Results - Correlation with rainfall

Reference : 3D then AS





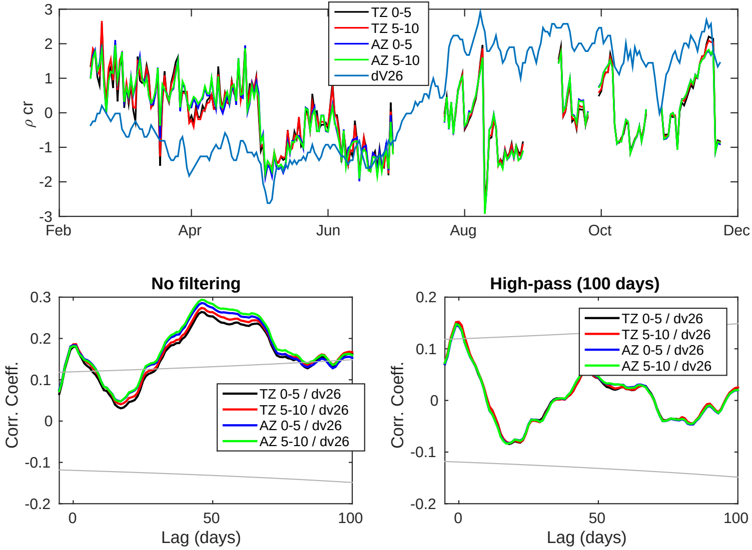


- the 4 zones behave identically
- Quick reaction to rainfall
- Effect of rainfall on ρ lasts 2 to 3 days

Results - Correlation with $\Delta V / V$ (mechanical parameter)

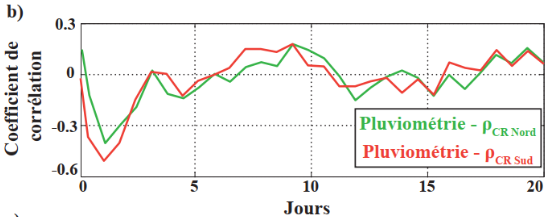
Reference : 3D then AS

- ρ and $\Delta V / V$ are positively correlated with no lag, and a very low correlation coefficient
- the 4 zones behave identically

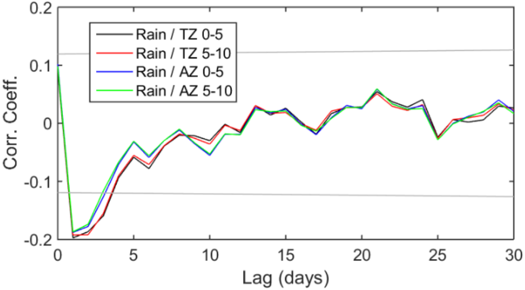


Conclusions

- Imaging :
  - Good detection of the unstable mass with ERT except in EZ because of a too low contrast with the bedrock (black shales) ;
  - No resistivity stratification observed within the landslide (contrarily to Vs from MASW)
- Monitoring :
  - relatively short resistivity time series (235 days)
  - 3D inversion of monitoring data with no temperature correction (no effect for depths > 5 m) $\rightarrow$ To do !
  - Use of a reference start model with 4 strategies : best numerical results obtained with 3DthenAS ;
  - No distinct behaviour observed between the 4 zones $\rightarrow$ not enough resolution and/or no distinct behaviour ?
  - Quick reaction of ERT to rainfall & behaviour similar to $\Delta V / V$ $\rightarrow$ both parameters covary and are highly influenced by superficial changes
  - The interest of inverting data with this monitoring setup is questionable (Cf figs on the right)
  - The interest of using electrodes outside the unstable zone **only** appears limited but provides informations complementary to (and in agreement with) passive seismics



Apparent resistivity (Carrière, 2016)



Inverted resistivity (this work)

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