EPFL

Slope Monitoring

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Slope Stability, 2025

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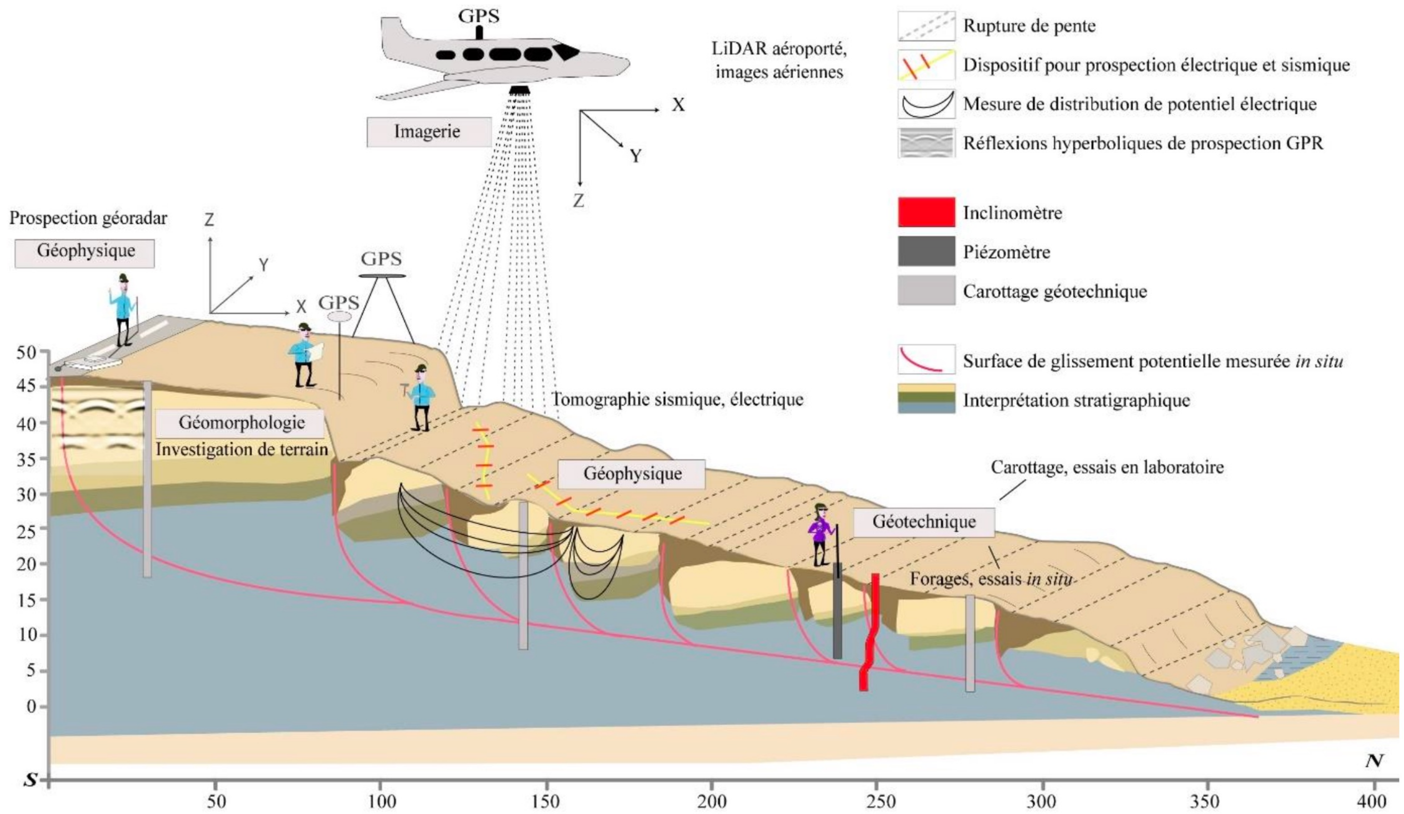
Why slope monitoring?

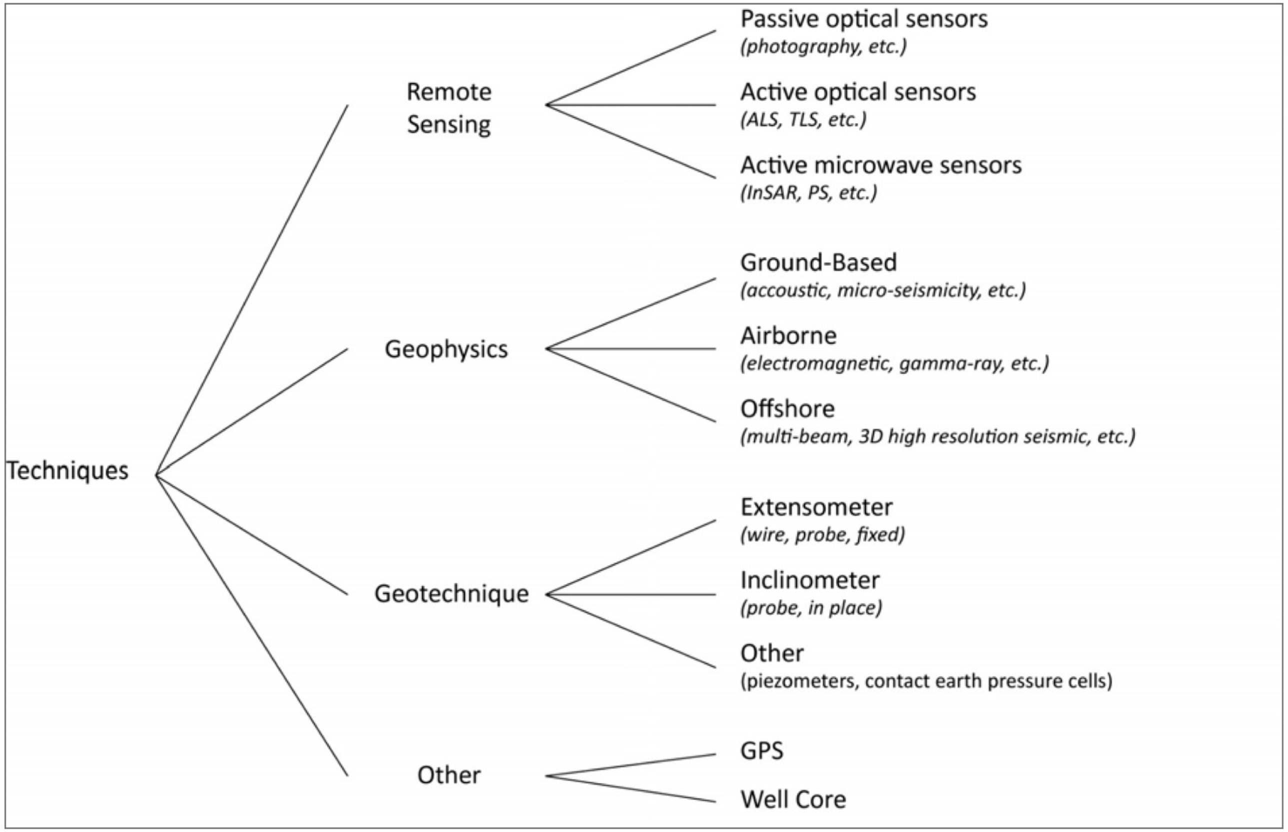
- Landslides pose major risks to infrastructure and safety
- Monitoring helps in early detection and prevention
- Enables data-driven design and mitigation

Different methods for slope monitoring



- Various field methods used to characterize an unstable slope (Lissak, 2012)

Different methods for slope monitoring



- Safeland (2010)

Different methods for slope monitoring

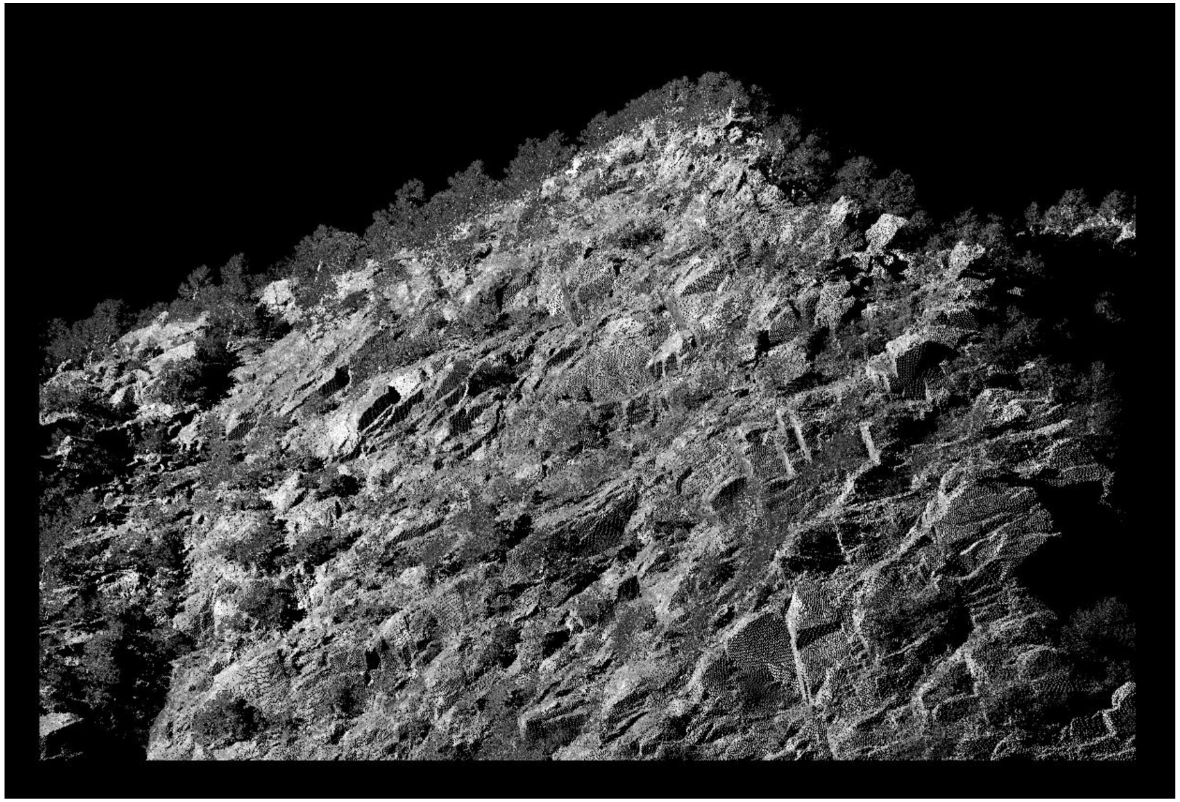


Figure 31: 3D point cloud of a rock slope. Discontinuity planes and vegetation are visible in this figure. The gray shades represent the intensity of the returning signal with low intensity (dark gray) on vegetated areas and high intensity (white) on rock surfaces perpendicular to the line-of-sight.

Bin

Example of a terrestrial laser scanning survey

- Safeland (2010)

Different methods for slope monitoring

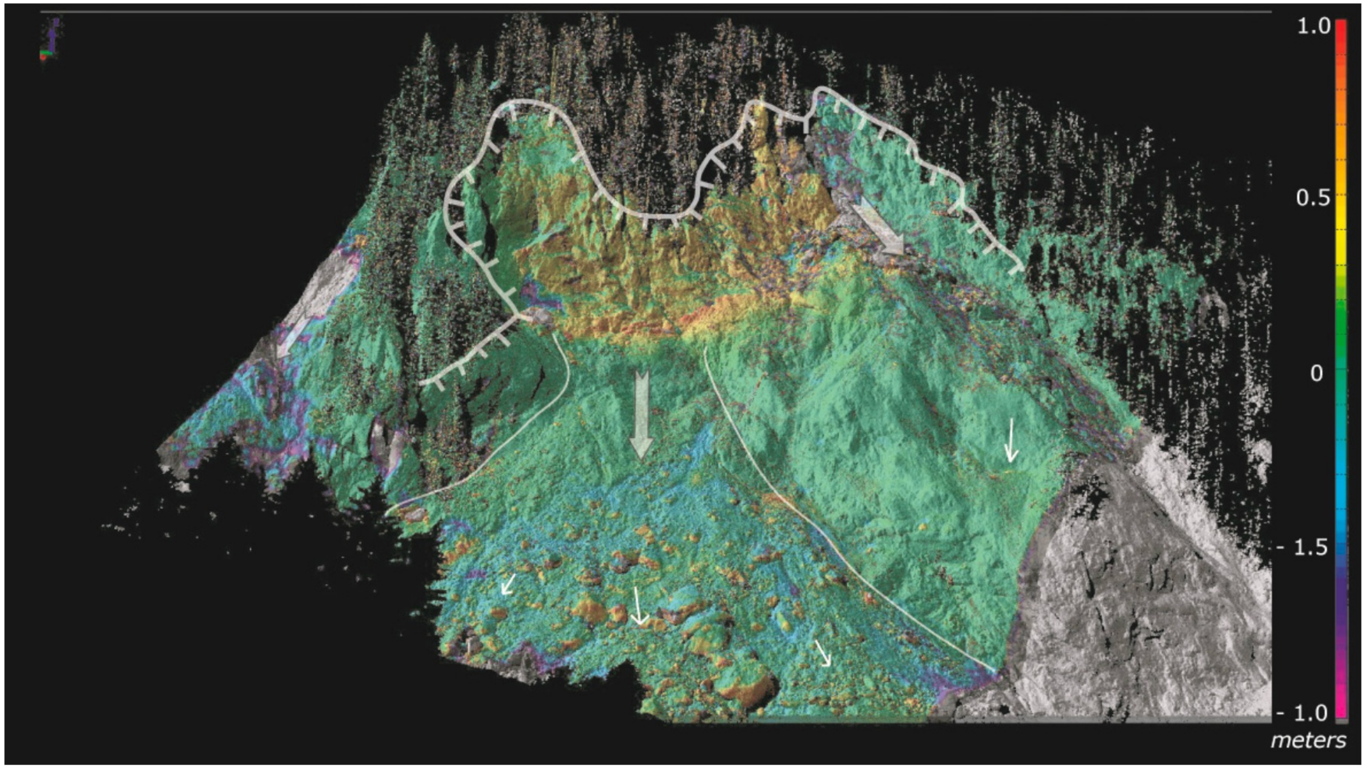
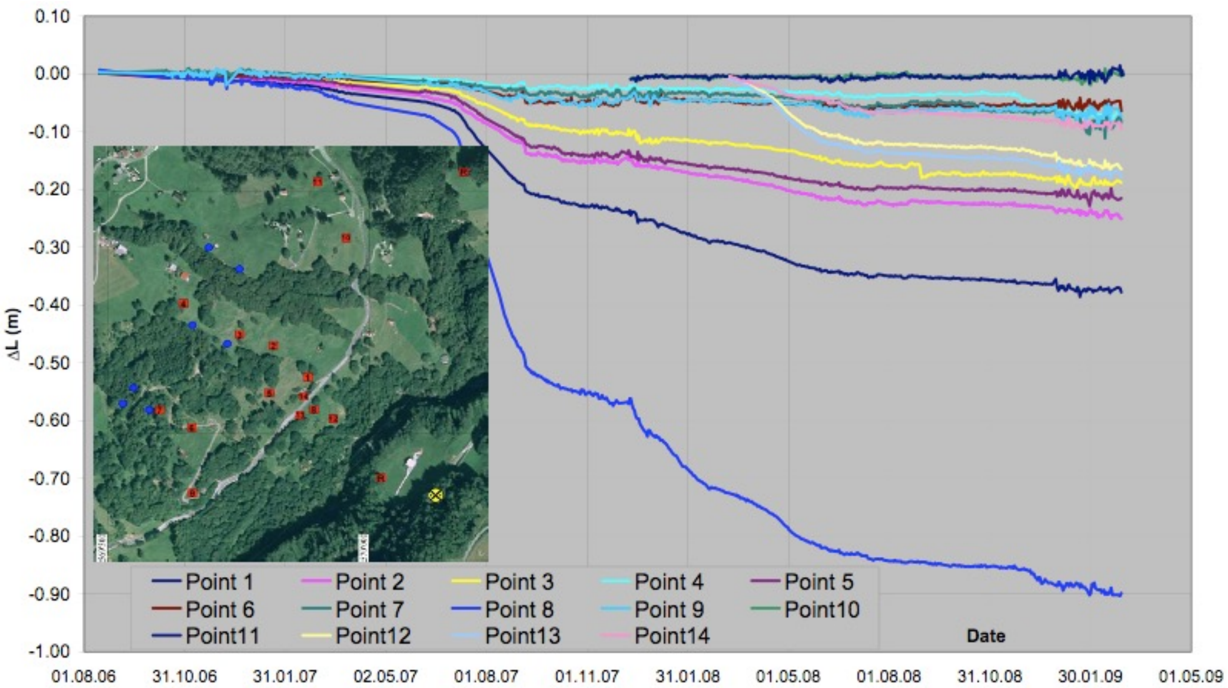


Figure 34: landslide precursory displacements at Val Canaria, Ticino, Swiss Alps. Figure extracted from Pedrazzini et al., 2010.

Multi temporal comparison of laser scanning can be used to assess displacement evolution over time

- Safeland (2010

Different methods for slope monitoring



High-precision laser measurements of in-field aims from a fix-point station

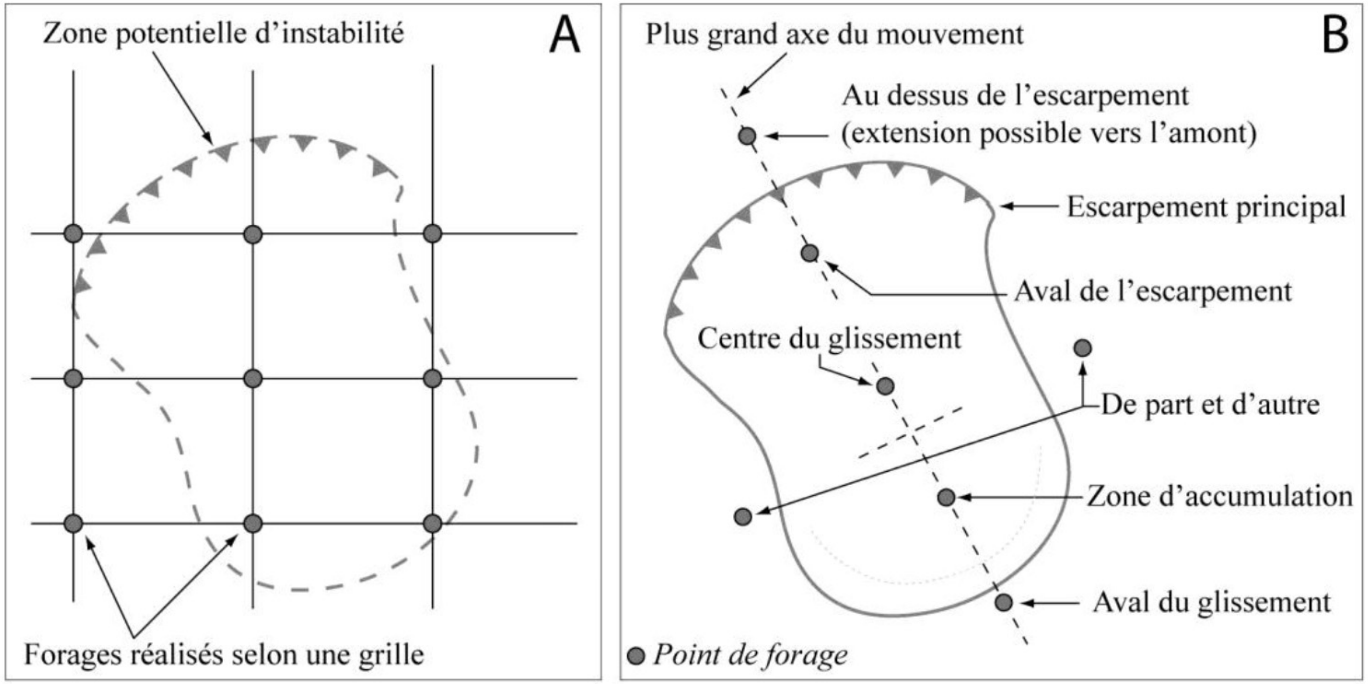
Designing an Appropriate Geotechnical Investigation Program

- Begin with a **morpho-structural and geological analysis** using field surveys, remote sensing, and archival research.
- Investigation must match the **type of instability.**
- A preliminary understanding of the **subsurface materials** is needed (e.g. difficoult sampling in coarse materials)
- Strategy must adapt to **site constraints**: slope steepness, vegetation, road access, (helicopter transport may be needed …)
- Plan borehole positioning and depth
- Plan for in-situ geotechnical testing
- Plan retrieval of samples for laboratory testing

Borehole positioning

- A **preliminary plan** should include:
  - Minimum of 3 boreholes (top, middle, bottom of slope)
  - Multiple profiles (longitudinal and transverse)
  - Sufficient density to avoid unreliable interpolation in heterogeneous areas

Borehole positioning



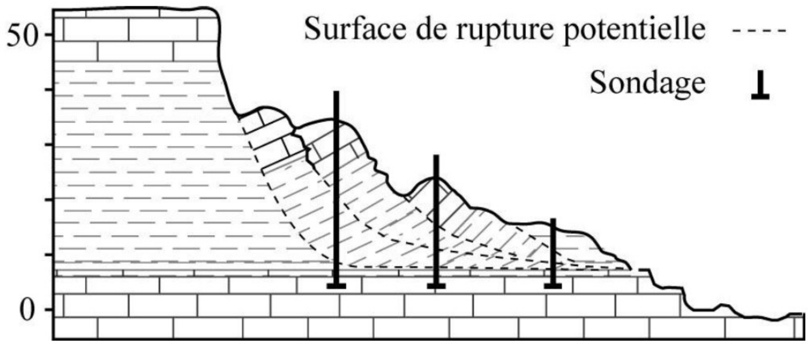
Location and layout of investigation points (after Mc Guffey et al., 1996): A. drilling grid in the case of a potential instability zone without confirmed movement; B. borehole placement in the case of a confirmed landslide."

Depth of investigation

- Defining the investigation depth in advance is particularly challenging. However, a few empirical rules can help estimate it:
  - The **depth of movement at the center of the landslide** is rarely greater than the **width of the unstable zone**.
  - The **maximum depth of the slip surface** is often approximately equal to the **distance between the initial rupture point on the slope and the uppermost scarp or fracture**.

Depth of investigation

- The investigation depth can be estimated using a **longitudinal profile aligned with the central axis of the gravitational movement**. It is possible to draw several potential **circular or elliptical slip surfaces**, which suggest the **maximum possible depths of movement**. LEM analyses can help to constrain the expected depth of the failure mechanism

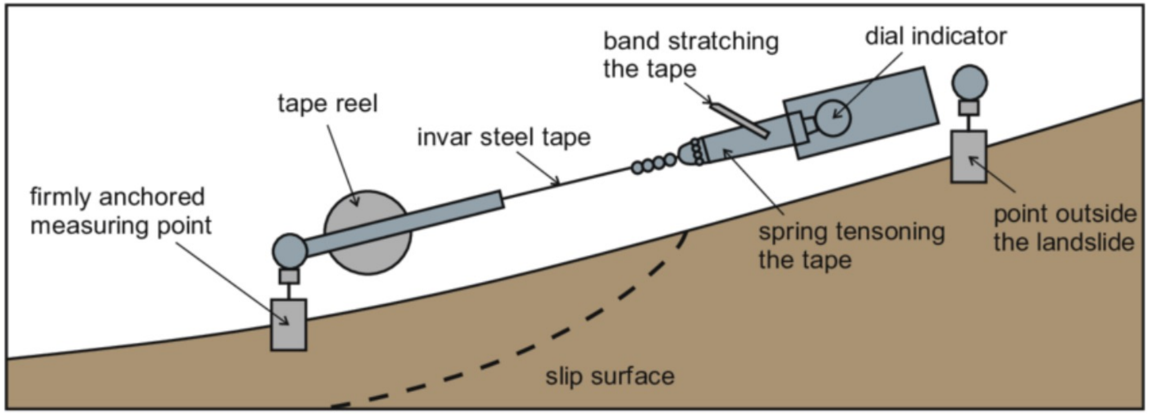


- Importantly, **at least one borehole** should extend **below the presumed slip surface** (by 3–4 meters at a minimum). This is also essential to securely anchor an **inclinometer casing** into the stable ground.

Extensiometers

- Measure the change in distance between two or more points
- Tape extensiometer for surface displacement:

Geosence.com



Matuszková et al. 2021

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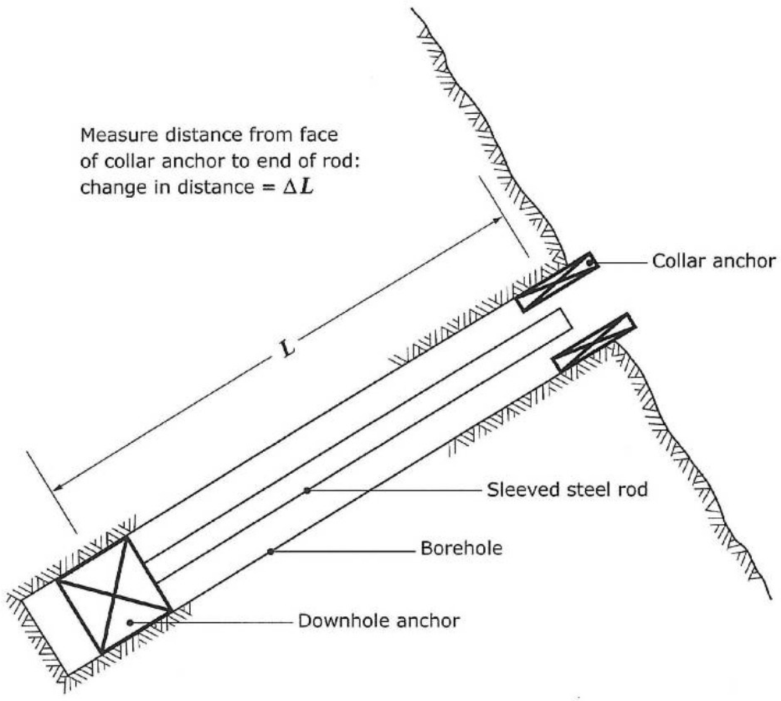
Extensiometers

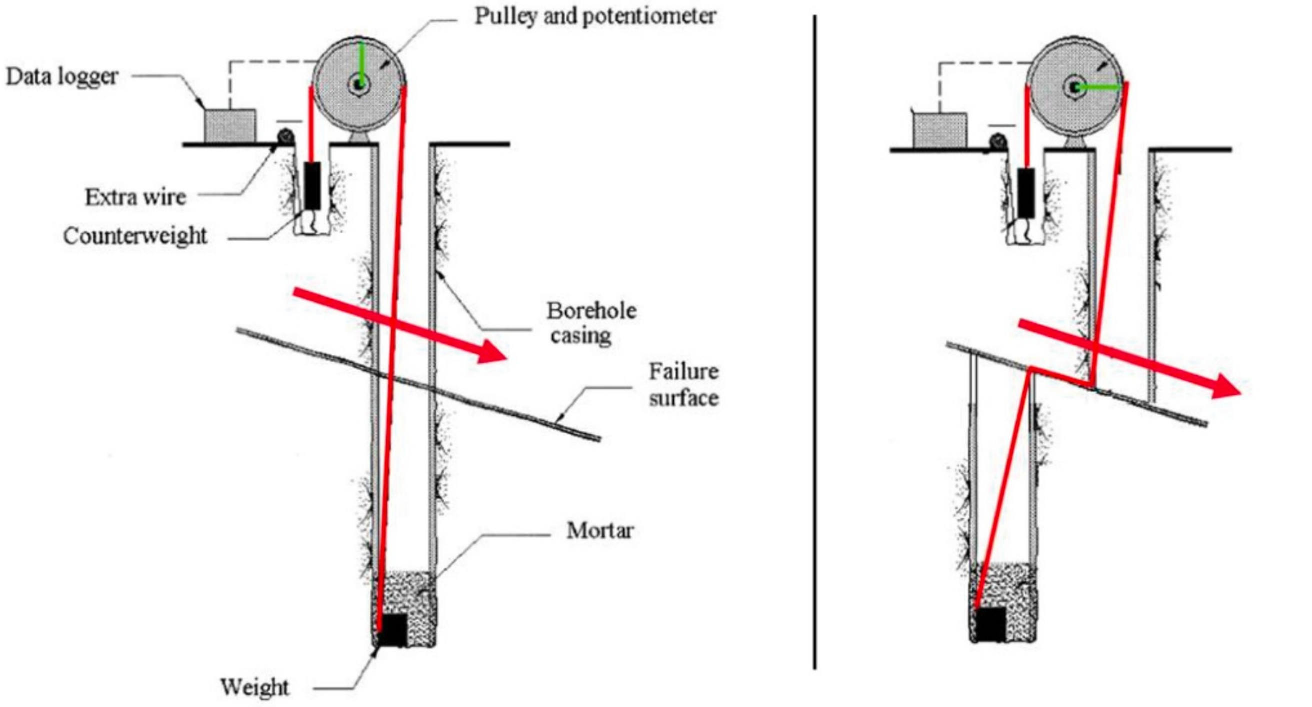
- Fixed borehole extensiometer



Dunnicliff et al. 2005.com

Extensiometers

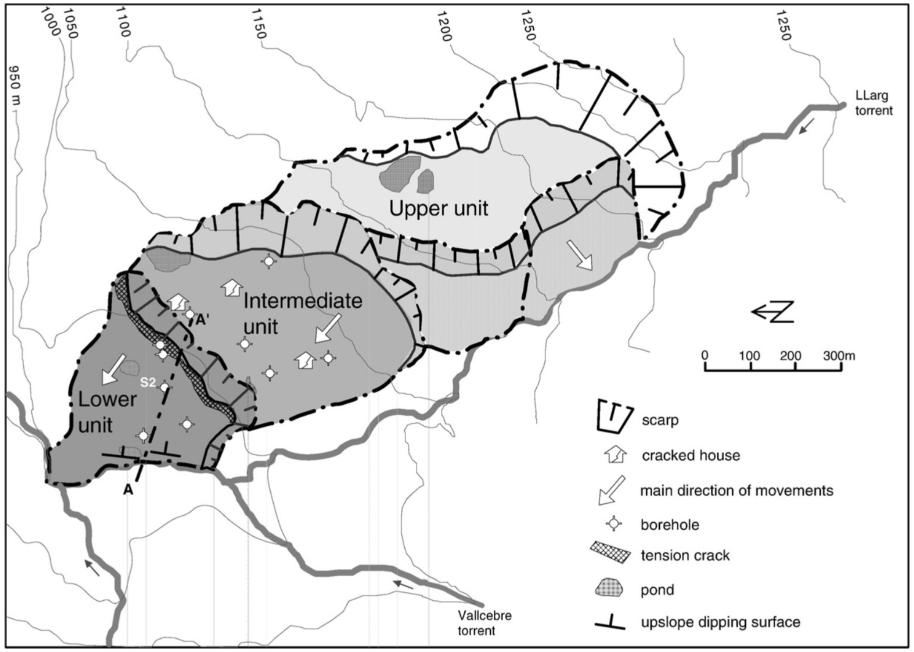
- Wire extensiometers



Corominas et al. 2000

Extensiometers

- Correlation between GWL changes and displacements registered with a wire extensimeter (Vallcebre landslide, Spain)



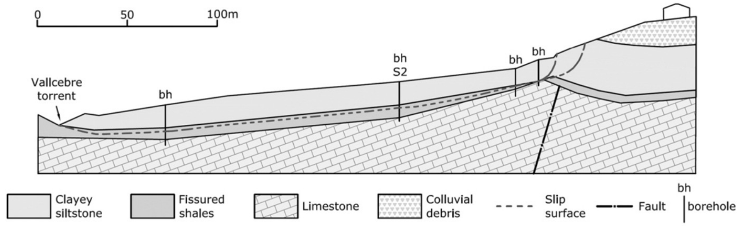


Fig. 12. Cross-section of the Vallcebre landslide lower unit (profile A-A′ in Fig. 11).

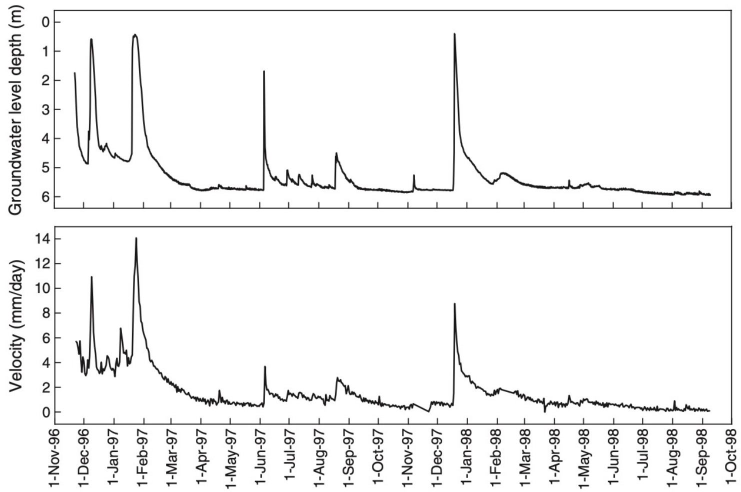
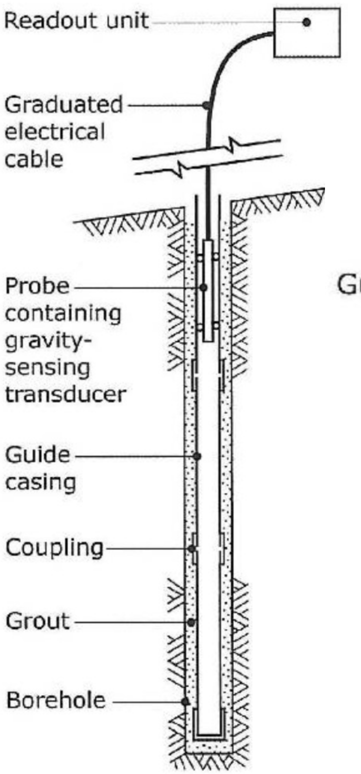


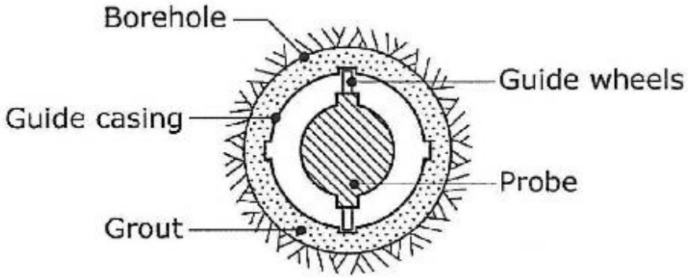
Fig. 14. The Vallcebre landslide: groundwater level depths and displacements registered at borehole S2.

- Ferrari et al. 2011

Inclinometers

- To measure displacements normal to the axis of a tube by means of a probe passing along the pipe



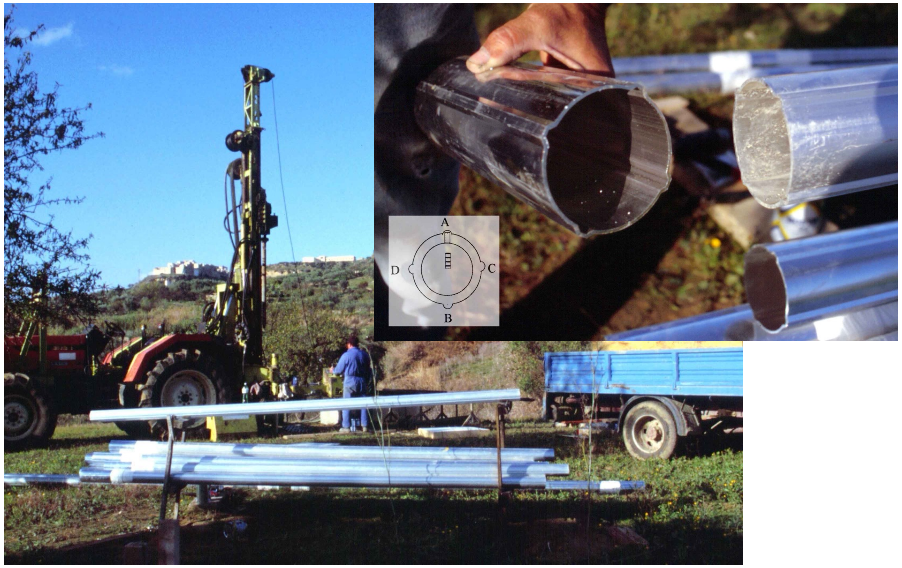


Dunnicliff et al. 2005

The probe has wheels that guide it into the tube

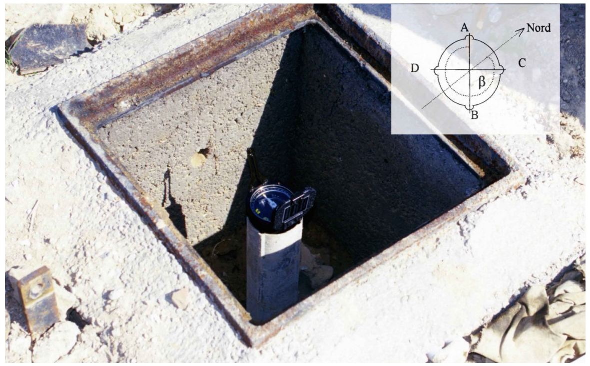
Inclinometers

- Installation of an inclinometer



Drilling and tube positioning

Grouting



Protection

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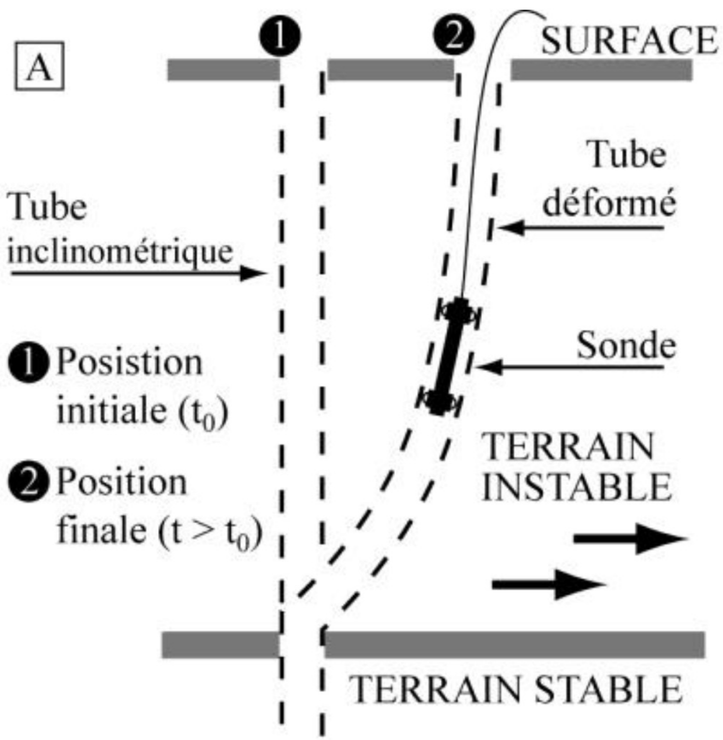
Inclinometers

- The probe is lowered through a graduated cable to the bottom of the hole and pulled to the ground, with stops at prescribed intervals, where the its inclination with respect to vertical is read.



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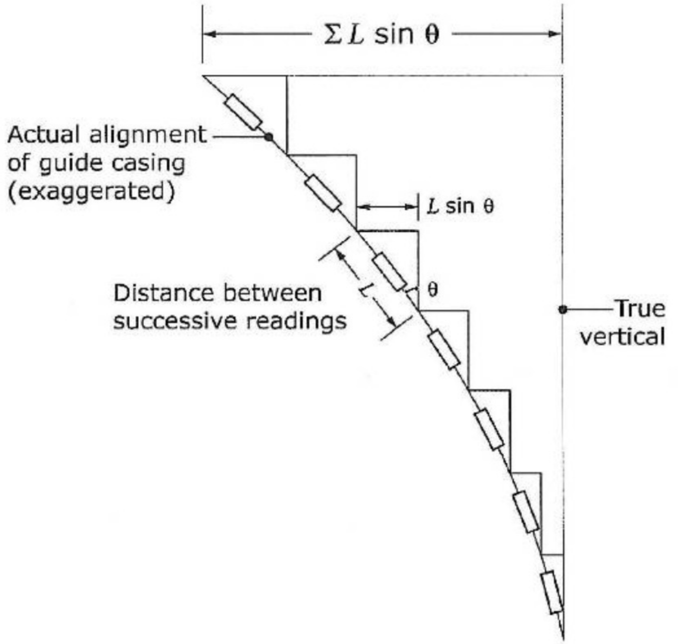
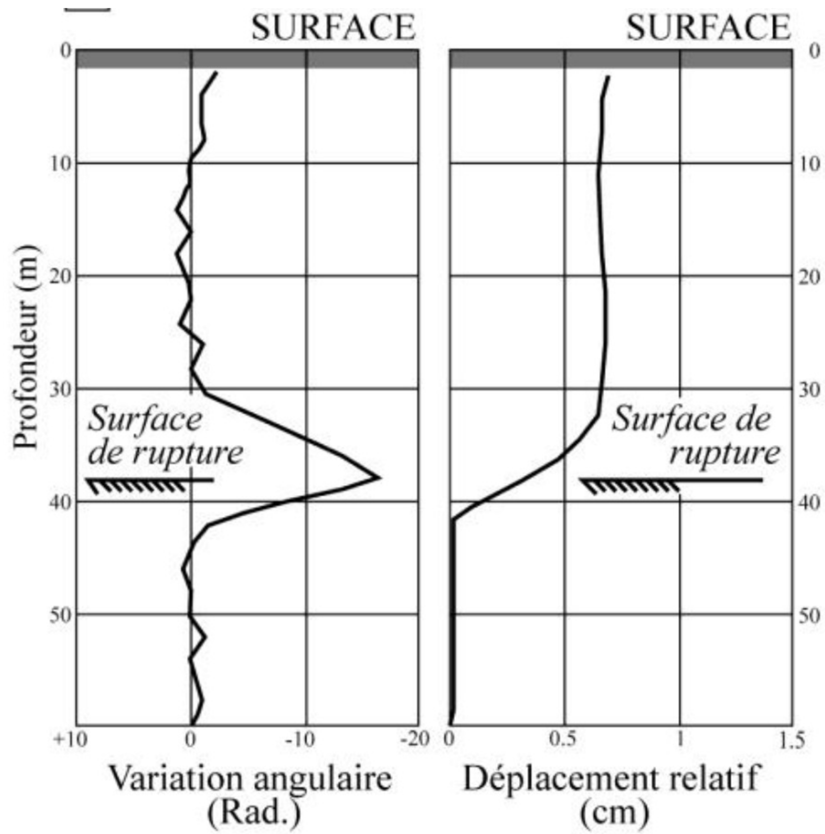
Inclinometers

- The inclination along depth is converted into a displacement normal to the vertical direction.





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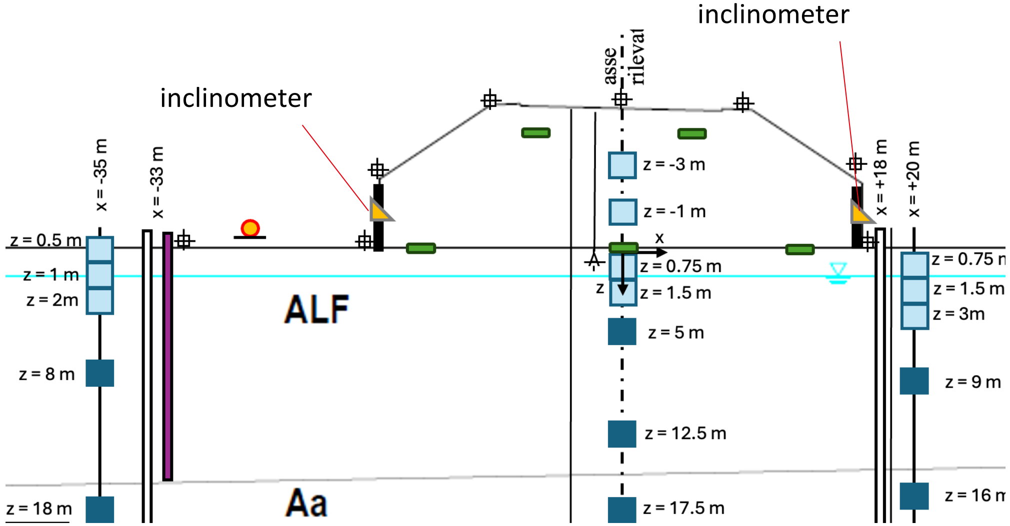
Inclinometers

Possible uses:

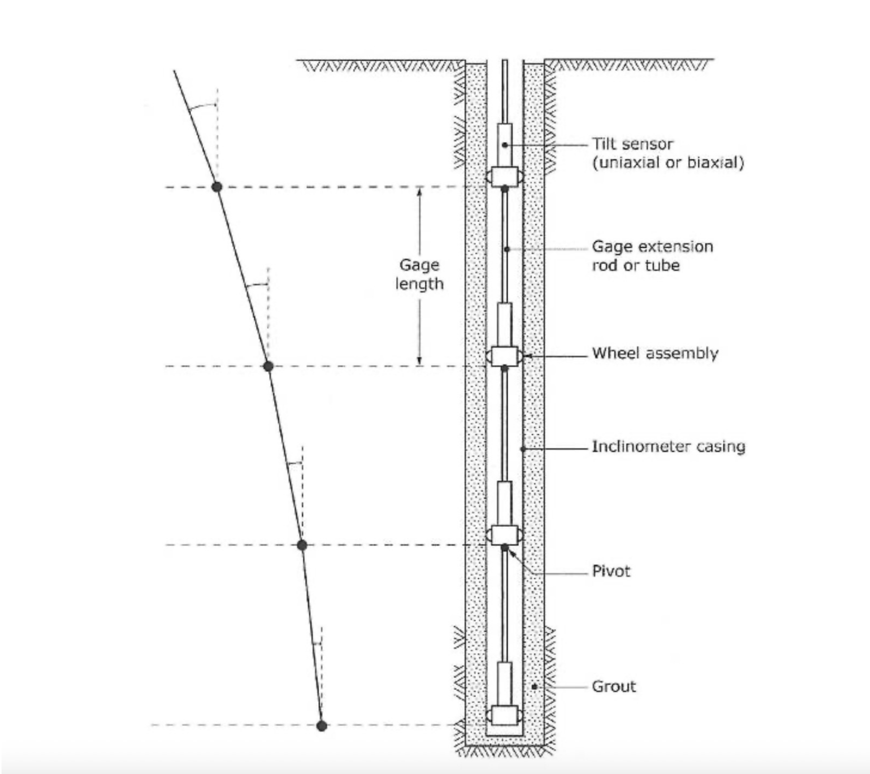
- The determination of the zone of a landslide movement; however, the probe inclinometers do not allow continuous recording of the displacements and cannot work after displacements of only a few centimetres;
- Monitoring of horizontal movements of earth dams, embankments in soft soil and along excavations or tunnels;
- Monitoring of deviations from vertical of bulkheads or retaining walls.

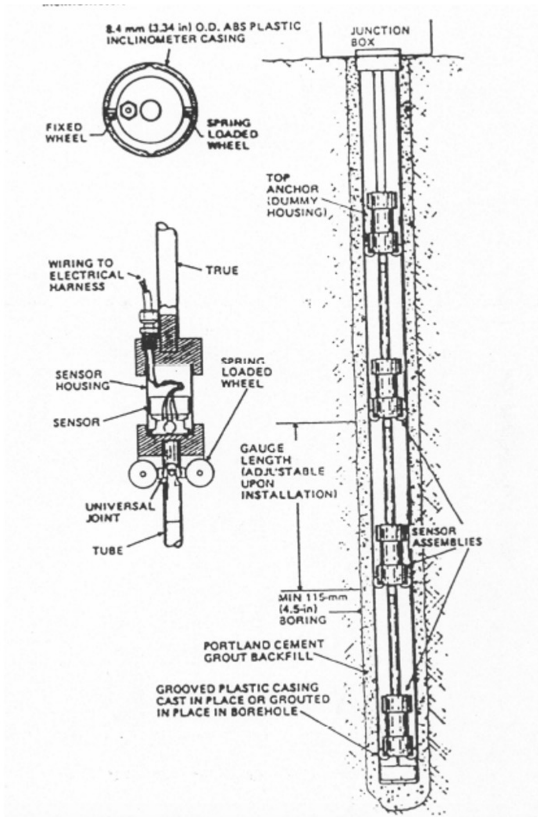


Inclinometers to read horizontal displacements of retaining walls in a road embankment

Inclinometers

- In-place (or fixed) inclinometers can be used when rapid measurements are needed or site is difficult to reach





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Inclinometers

- Repeating measurements at different dates can be used to assess the temporal evolution of displacements at different depths (until the tube is cut), and to assess possible multiple failure mechanisms.

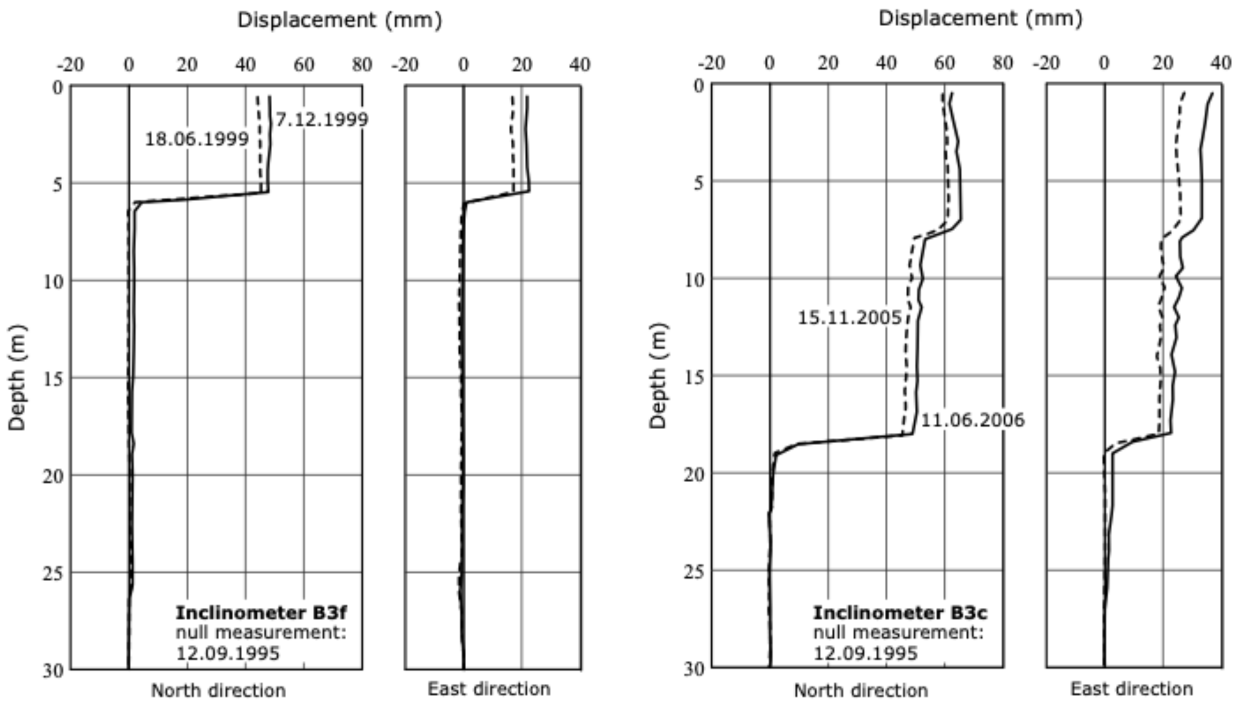

Figure 1: Example of inclinometer measurements for two different boreholes at the Steinernase landslide (Switzerland).

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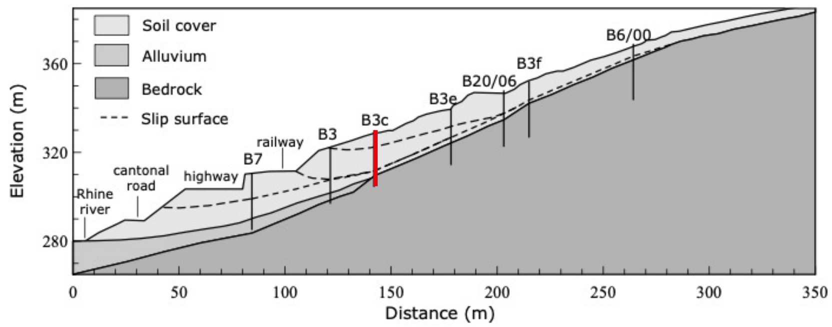


Figure 4: Cross-section along the centre of the landslide, indicating the multiple slip surface system as interpreted from inclinometer readings.

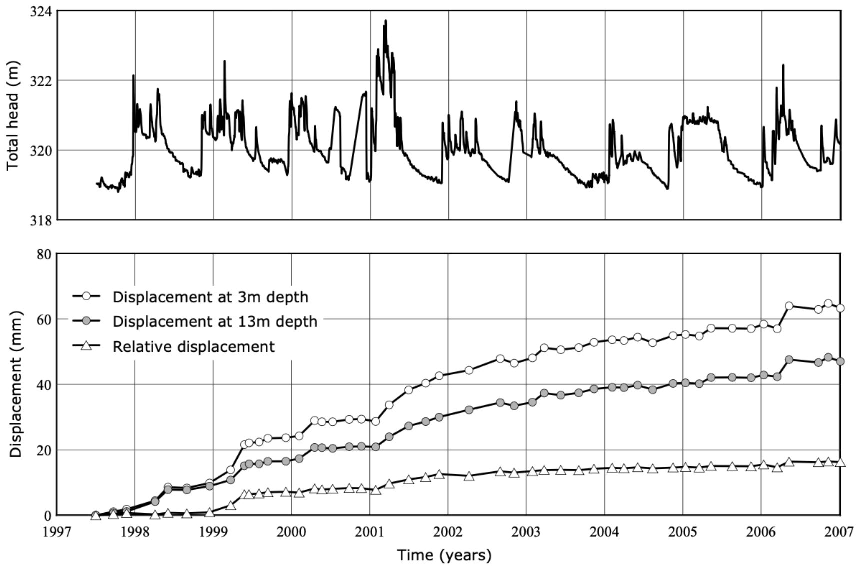
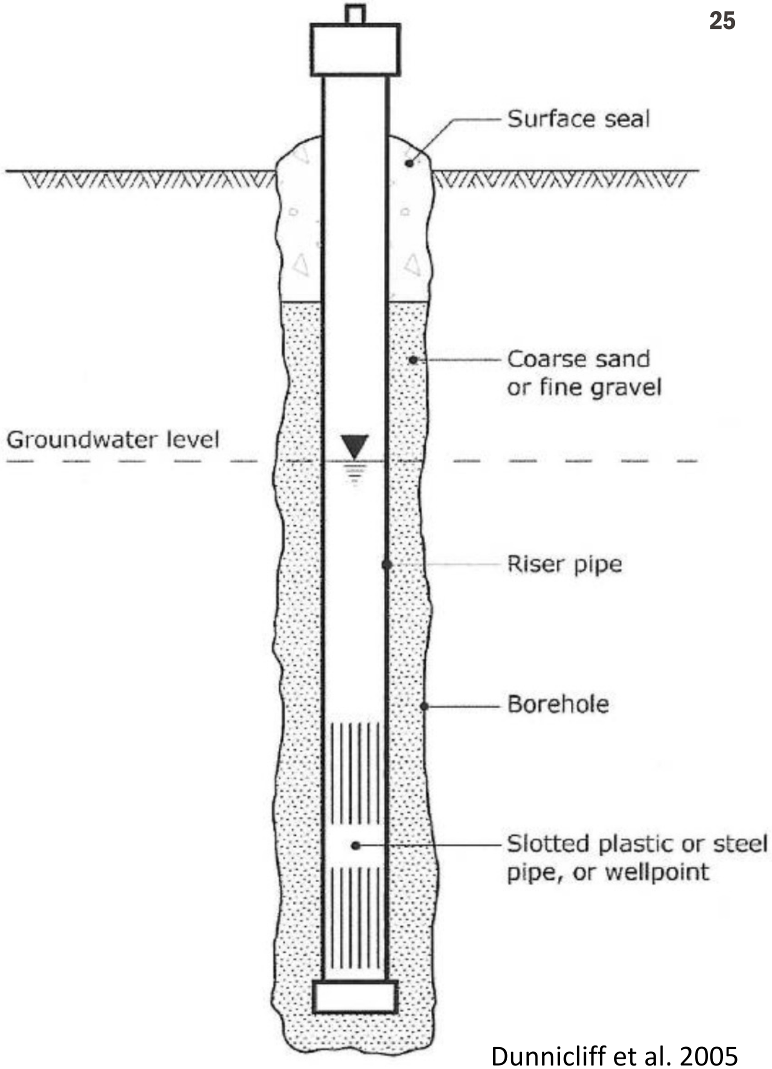


Figure 3: Total head at 10m depth and displacements at two different depths registered at borehole B3c.

Measurement of pore water pres.

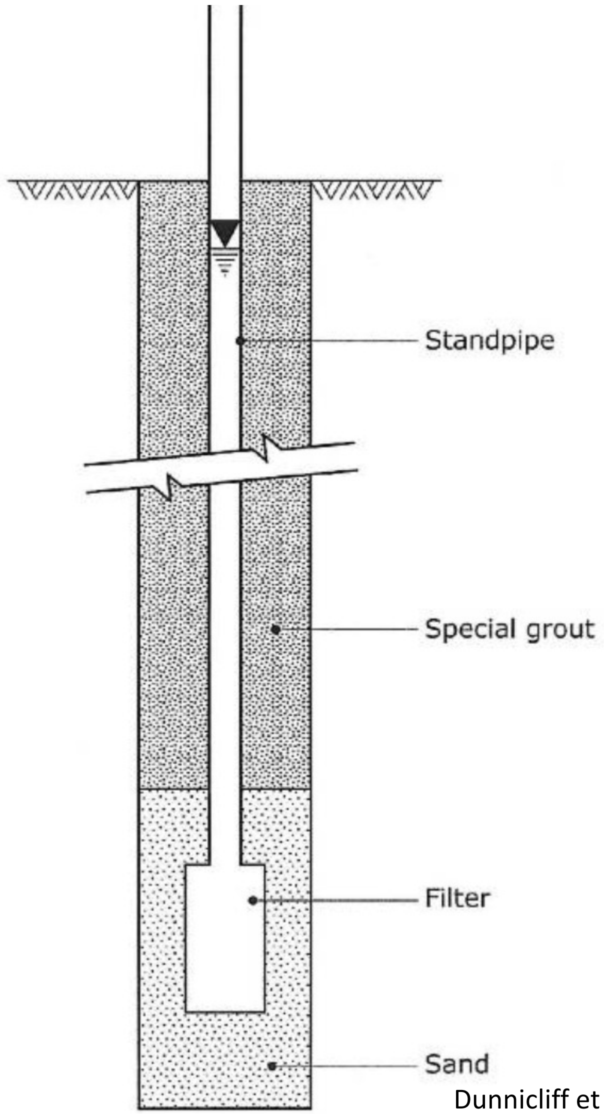
- **Observational wells**: pipe installed in a borehole slotted in the lower section.
- The space between the pipe and the borehole is filled with high-permeable materials (sand and/or gravel) so that water from all strata at all depths concur to establish the water level in the tube.
- The only seal is at the surface to prevent direct superficial water infiltration into the tube, while allowing air ventilation to avoid air-pressurization.
- Used to measure the position of the ground water level but cannot provide local values of pore water pressures.
- Suitable for coarse soils $k > 10^{-3}$cm/s



Dunnicliff et al. 2005

Measurement of pore water pres.

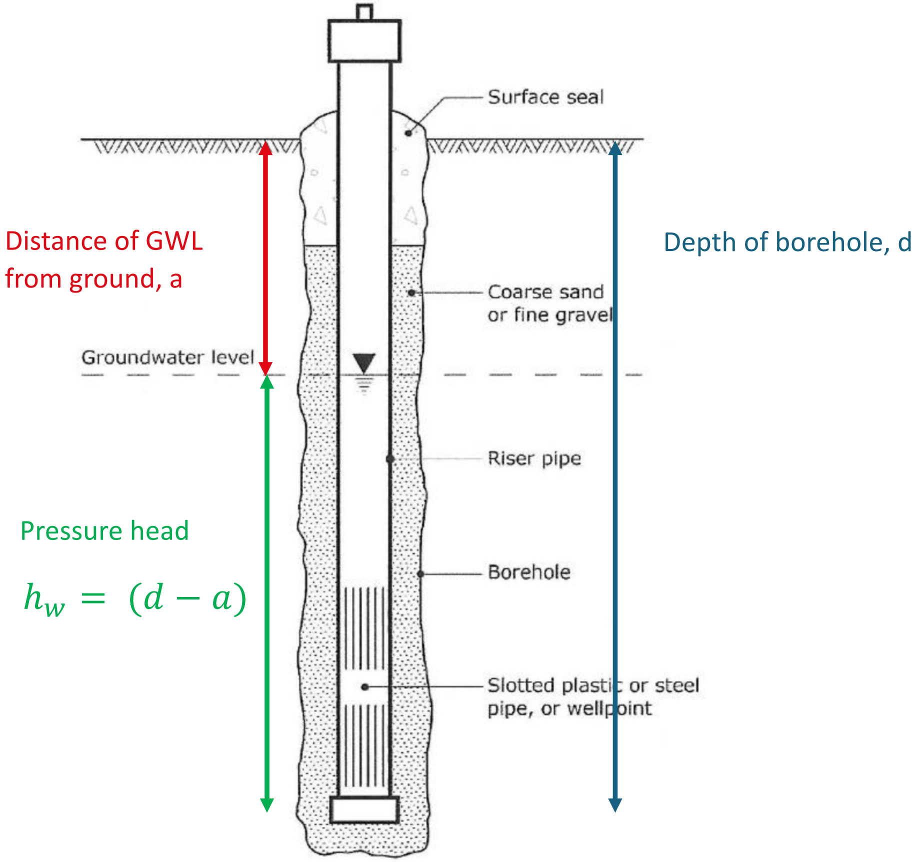
- **Open stand-pipe piezometers**: used to measure piezometric head in a specific layer.
- Grouting prevent water infiltration from other layers into the tube.



Dunnicliff et al. 2005

Measurement of pore water pres.

- **Measurements** are done by inserting a probe capable of detecting presence of water into the tube. The distance of the water level in the tube from the ground surface is reported and can be converted into a pressure head in the tube.



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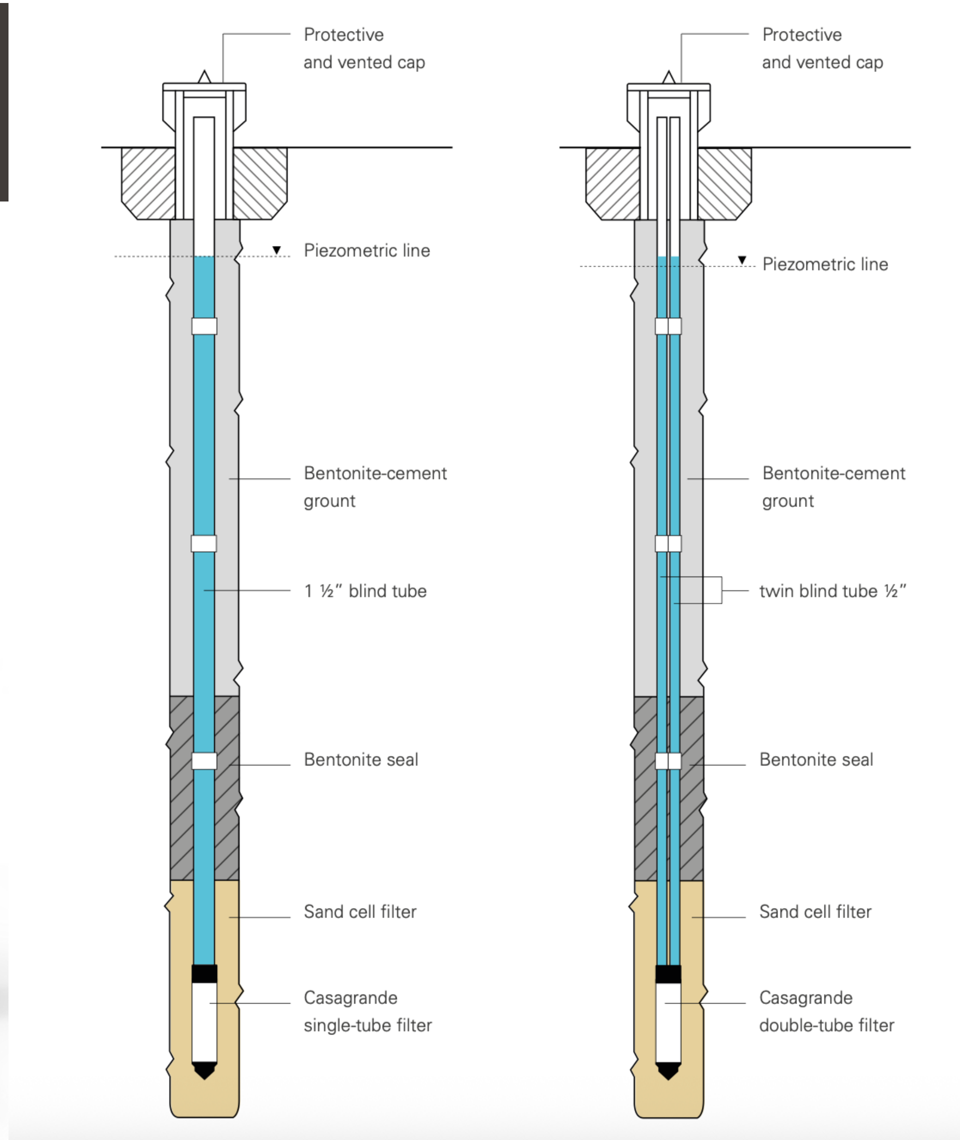
Measurement of pwp.

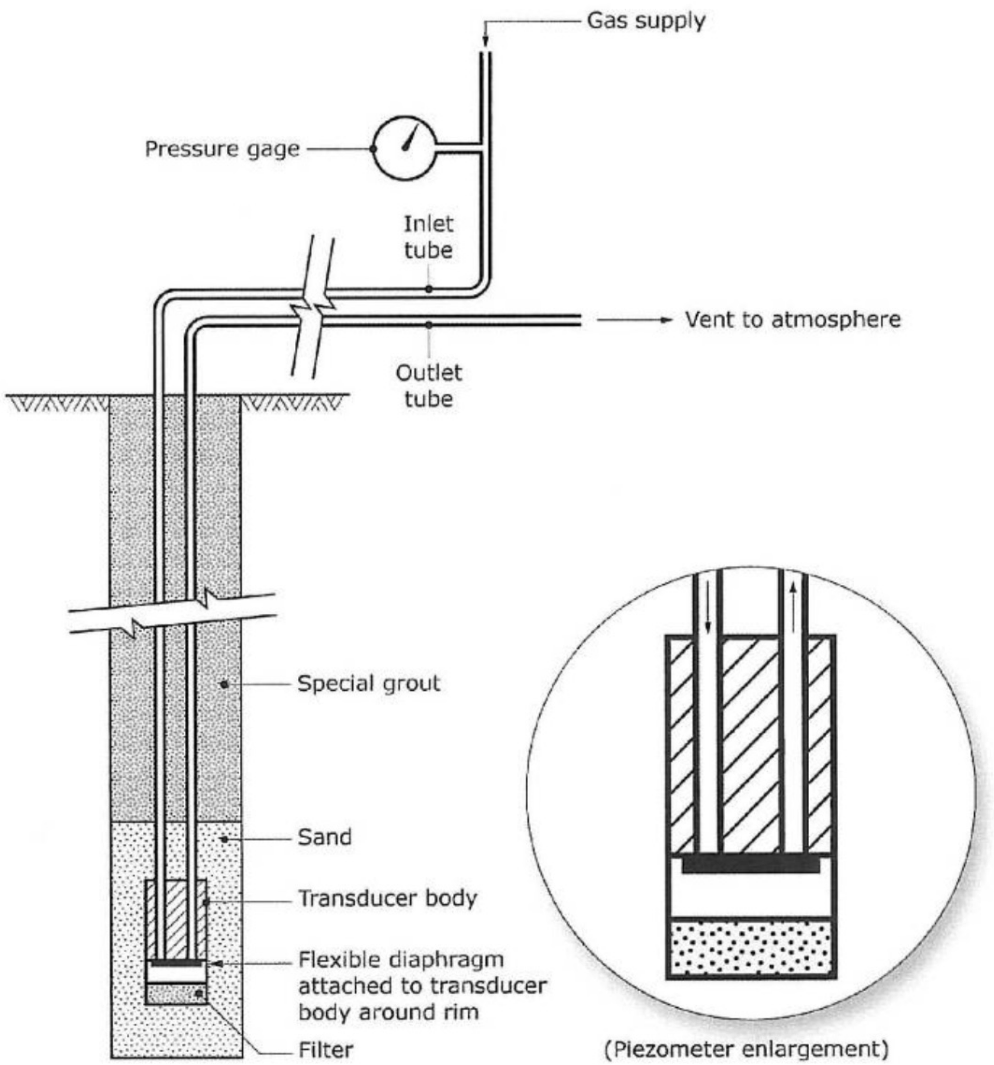
- **Casagrande's piezometer**: used to measure localized values of pore water pressure. Also in soils with low permeability.



- Sisgeo.com

Measurement of pwp

- **Pneumatic, vibrating wire and electrical resistance piezometers**: the water enters in a small cavity within the probe and the pressure is converted into a signal read by a data acquisition system.
- Suitable for automatic and continuous data acquisition, storage and sending.



Measurement of pore water pres.

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Vibrating wire piezometer

Resistance piezometer

Measurement of pore water pres.

- **Tensiometers** are used to measure negative pore water pressures (i.e. suctions)
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