



Slope Stability Monitoring

“After heavy rainfall, cracks appear above a road cutting. What would you want to know before deciding what to do?”

Why slope monitoring matters

Monitoring supports safer decisions

Why slope monitoring matters

Monitoring supports safer decisions

- Detect early movement

Why slope monitoring matters

Monitoring supports safer decisions

- Detect early movement
- Inform risk assessment and mitigation

Why slope monitoring matters

Monitoring supports safer decisions

- Detect early movement
- Inform risk assessment and mitigation
- Protect people, infrastructure and the environment

Why slope monitoring matters

Monitoring supports safer decisions

- Detect early movement
- Inform risk assessment and mitigation
- Protect people, infrastructure and the environment
- Reduce damage and repair costs

Why slope monitoring matters

Monitoring supports safer decisions

- Detect early movement
- Inform risk assessment and mitigation
- Protect people, infrastructure and the environment
- Reduce damage and repair costs

Monitoring Methods

Geotechnical monitoring

Geodetic monitoring

Remote sensing

Combined methods give a fuller picture of slope behaviour.

Geotechnical Monitoring

Sensors within or on the slope measure movement and changes in ground properties.

Inclinometers

Measure subsurface tilt and horizontal movement.

Identify the depth where movement occurs.

Inclinometers

- Locate deformation within the slope

Inclinometers

- Locate deformation within the slope
- Track whether movement is accelerating

Inclinometers

- Locate deformation within the slope
- Track whether movement is accelerating
- Check movement against design limits

Inclinometers

- Locate deformation within the slope
- Track whether movement is accelerating
- Check movement against design limits
- Support warnings of potential instability

Inclinometers



Probe, readout device and cable

Protective casing guides the probe through the borehole.

Inclinometers



Changes in tilt over time reveal lateral ground movement.

Inclinometers - Installation



Position the borehole where movement is expected.

Install casing to the required depth.

Grout the casing so it moves with the ground.

Internal grooves guide repeatable probe readings.

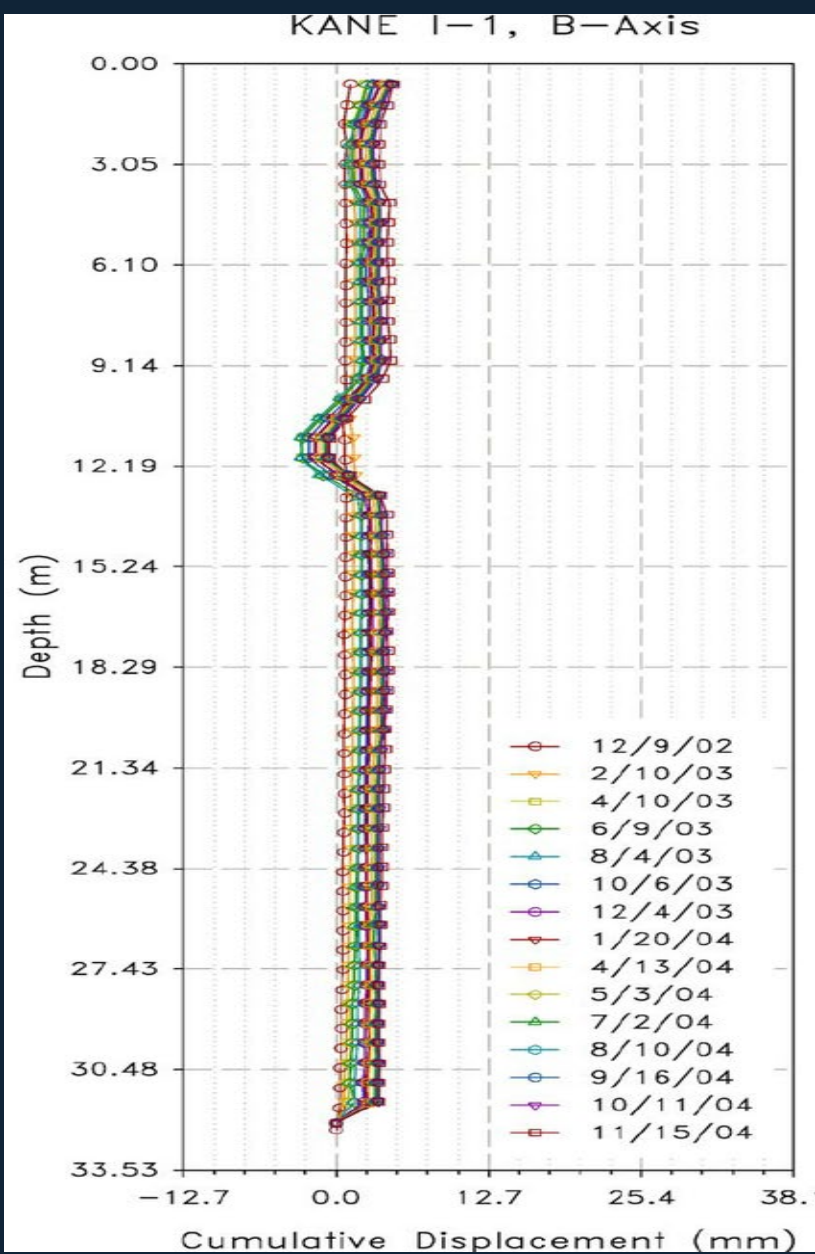
Inclinometers – Data Collection

Lower the probe to the base of the casing.

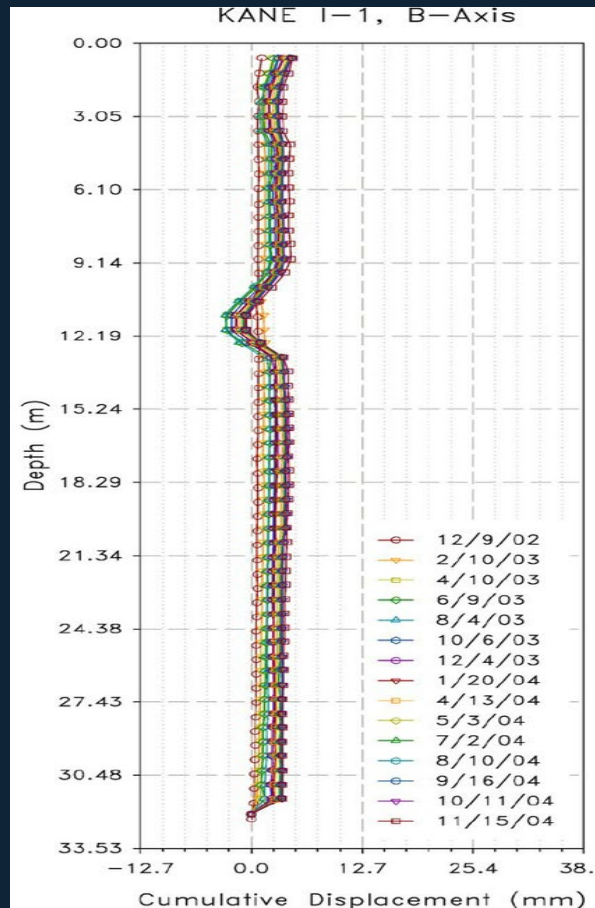
Record tilt at set depth intervals, usually 0.5 m or 1 m.

Measure along two perpendicular axes.

Compare readings over time to detect movement.



Inclinometers – Data Interpretation



Convert tilt readings into lateral displacement.

Compare profiles to track movement at each depth.

Concentrated displacement may indicate a shear plane.

Inclinometers – Advantages

Precise measurement of small subsurface movements

Monitoring at depth

Tracking of movement over time

Identification of the zone of movement

Inclinometers – Limitations

Borehole installation can be costly.

Large movements can damage the casing.

Manual readings leave gaps between measurements.

Piezometers

Measure pore water pressure in soil or rock.

Track pressure changes that may affect slope stability.

Piezometers

Piezometer tip or sensor

Tubing or cable

Data logger or readout unit



Piezometers - Installation



Install the piezometer at the required depth.

For standpipes, place filter sand around the tip.

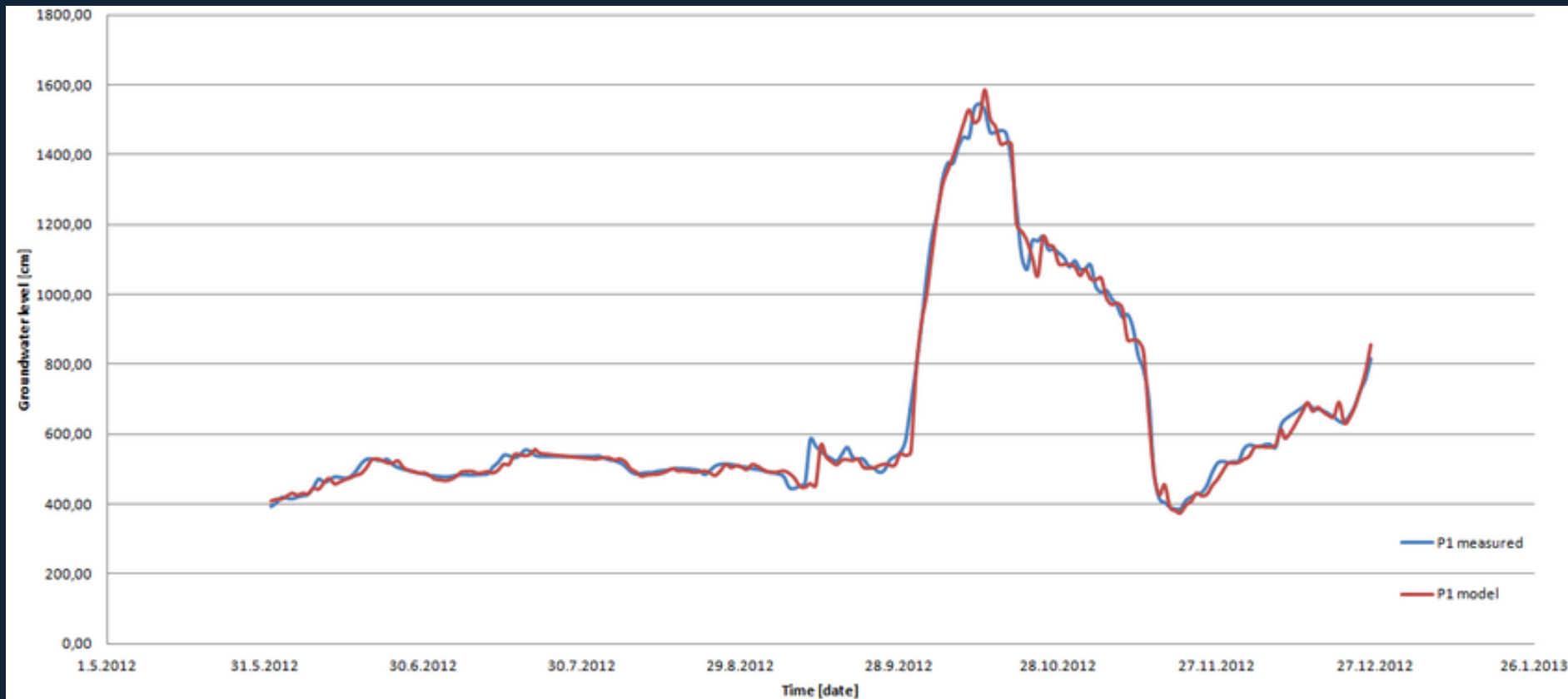
Use a bentonite seal to isolate the measurement zone.

Piezometers – Measurement

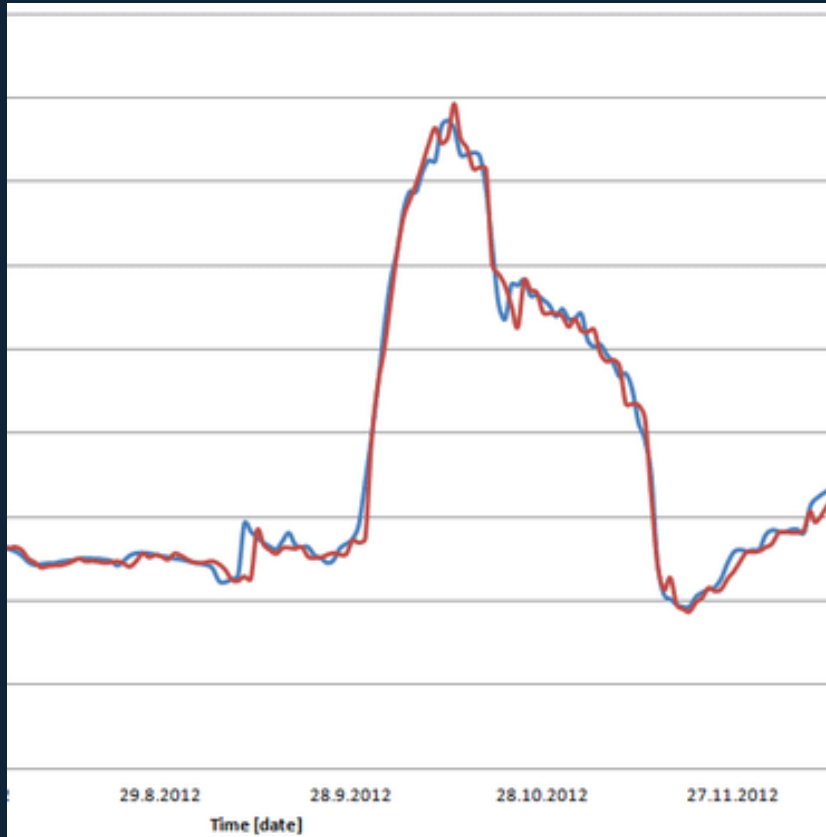
Standpipe: water level indicates hydraulic head and pressure.

Sensor-based: a pressure signal provides the reading at depth.

Piezometers – Data Interpretation



Piezometers – Data Interpretation



Manual systems: take periodic water-level readings.

Automated systems: log and transmit pressure data continuously.

Piezometers – Advantages

Warning of pressure rises, especially after rainfall

Continuous tracking with automated systems

Use across varied soils, rocks and depths

Sensitivity to small pressure changes

Piezometers – Limitations

Deep installations can be costly.

Manual systems need regular site visits.

Harsh conditions or ground movement can damage sensors.

Extensometers

Measure changes in distance between anchor points.

Track deformation at the surface or within the ground.

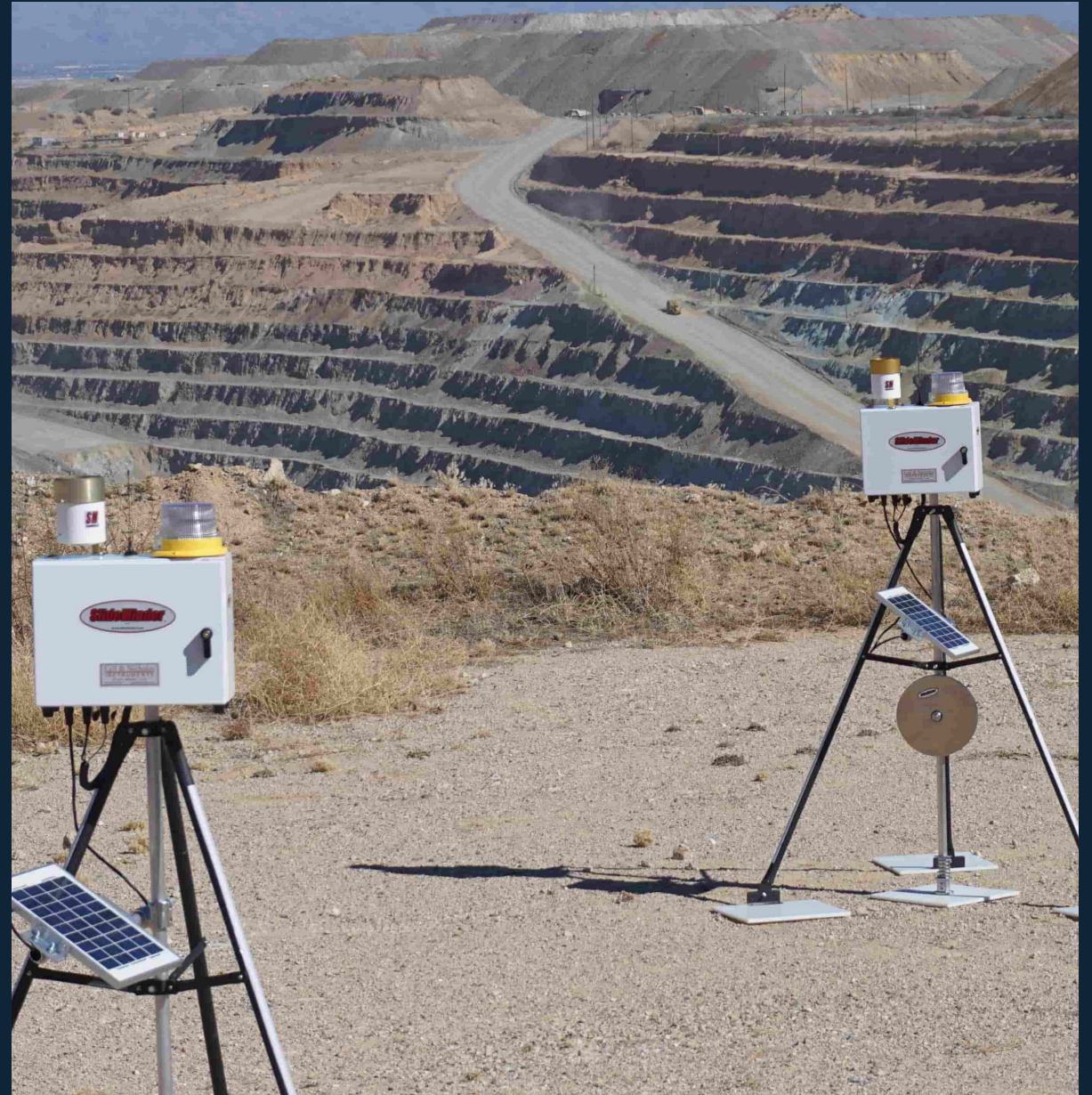
Extensometers

Anchor points

Measuring rods or cables

Displacement sensor or gauge

Data logger



Extensometers - Installation



Anchor measuring points at the surface or in boreholes.

Use anchors at different depths to locate movement within the ground.

Extensometers – Displacement Measurement

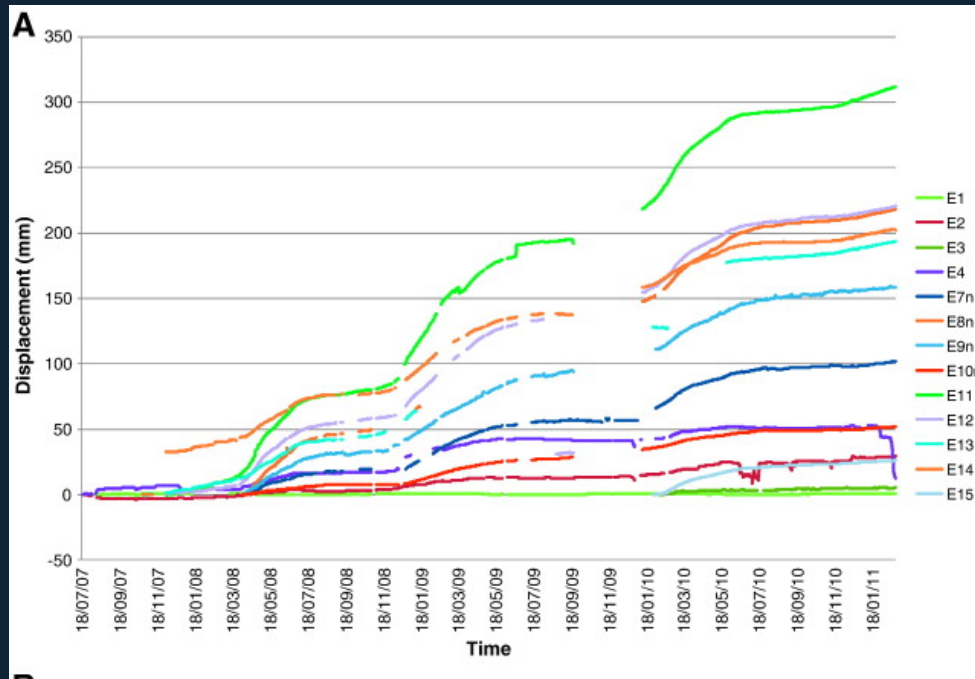
Ground movement changes the distance between anchors.

Rods or cables transmit movement to the sensor.

Compare measurements to quantify displacement.



Extensometers – Data Interpretation



Mechanical systems: read movement with a gauge.

Electronic systems: log displacement automatically for continuous monitoring.

Extensometers – Advantages

Detection of small movements

Depth information from multiple anchors

Early warning before movement becomes visible

Long-term tracking at the surface or at depth

Extensometers – Limitations

Deep installations can be complex and costly.

Large movements can damage sensors.

Each installation covers only specific locations.

Geodetic Monitoring

Surface measurements track slope displacement and deformation over time.

Total Stations

Measure angles and distances to survey targets.

Repeat surveys reveal movement of the slope or structures.

Total Stations

Telescope

Electronic distance
measurement unit

Control unit or computer

Prism or reflector



Total Stations

Measure distance and angles to a reflector.

Calculate its 3D coordinates.

Compare repeat surveys to detect movement.



Total Stations - Process



1. Reference targets

Place prisms on the slope or structure.

Establish stable benchmarks outside the moving area.

Total Stations - Process



2. Baseline survey

Set up the instrument at a stable, known location.

Record the initial 3D position of each target.

Total Stations - Process



3. Repeat measurements

Resurvey target coordinates at planned intervals.

Changes in position indicate movement.

Total Stations - Process

4. Interpretation and alerts

Analyse displacement trends and acceleration.

Compare readings with alert thresholds in automated systems.

Total Stations – Advantages

Precise measurement of small movements

Continuous monitoring with automated instruments

Remote data collection reduces site visits

Long-range monitoring of slopes and structures

Total Stations – Limitations

Clear sightlines to reflectors are essential.

Poor weather can interrupt measurements.

Manual systems require an operator.

Calibration and maintenance protect data quality.

GNSS

Global Navigation Satellite System (GNSS)

Track changes in the positions of receivers on a slope.

GNSS

Signals from multiple satellites locate each receiver.

Repeat position measurements reveal ground movement.



GNSS

GNSS receivers and reference station

Data logger and transmission system

Processing software

Power supply



GNSS- Process



1. Setup and baseline

Install receivers at critical slope locations.

Establish a stable reference station.

Record initial positions for comparison.

GNSS- Process

2. Data collection

Record slope and reference-station positions together.

Transmit readings for processing and comparison.

GNSS- Process

3. Displacement analysis

Compare current positions with the baseline.

Track horizontal and vertical movement, including gradual or sudden changes.

GNSS – Advantages

Precise positioning with correction techniques

Continuous data for early warning

Remote operation with fewer site visits

Receiver networks support long-term monitoring over large areas

GNSS – Limitations

Obstructions can block satellite signals.

Correction methods are essential for precise positioning.

Installation and data systems add cost.

Remote sites need reliable power and maintenance.

LiDAR

Light Detection and Ranging (LiDAR)

Laser measurements create detailed 3D models of the slope surface.

LiDAR

Laser pulses travel to the surface and back.

Travel time gives the distance.

A 3D point cloud forms the basis of a terrain model.

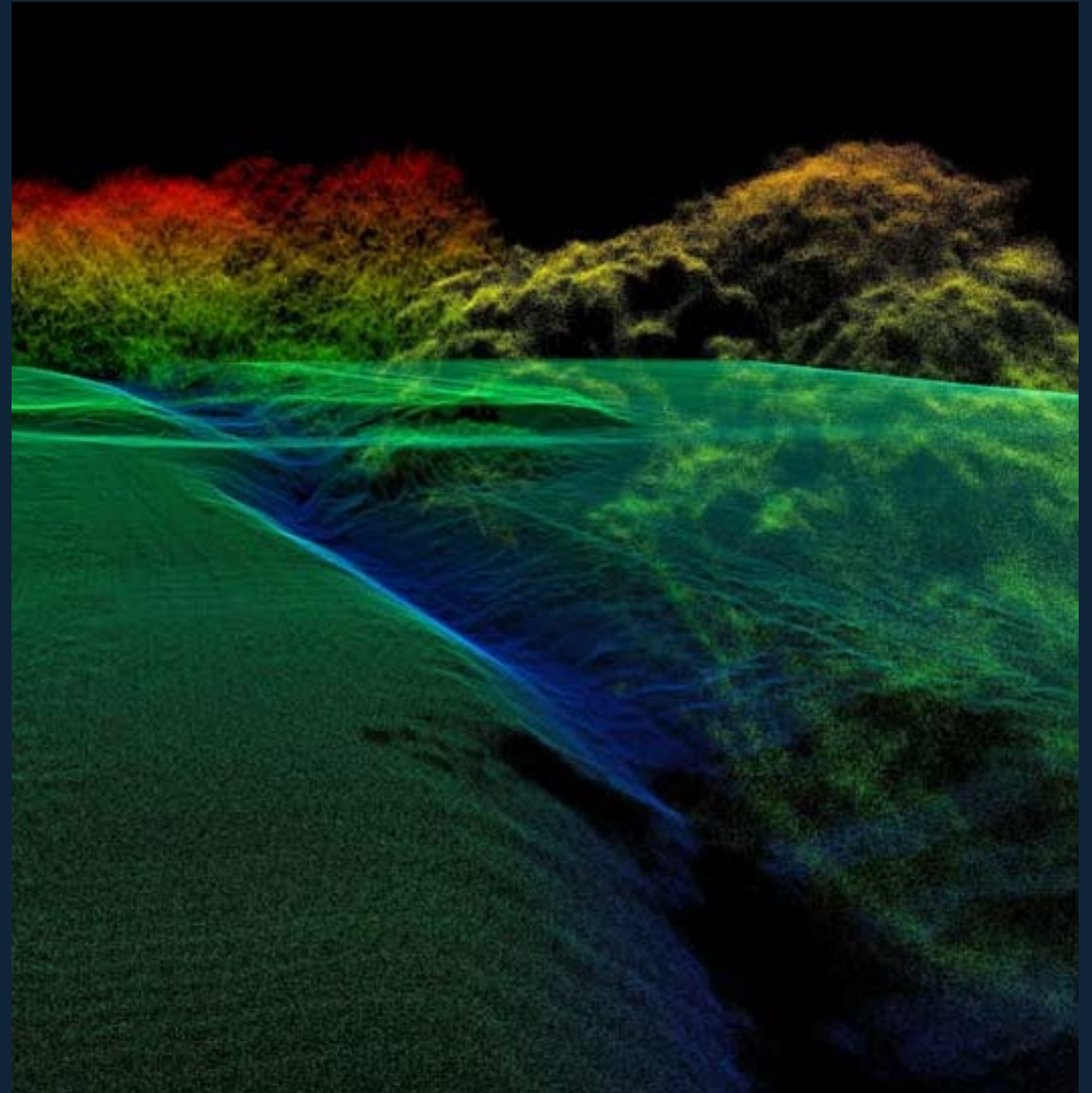


LiDAR - Process

1. Baseline survey

Scan the slope to create a 3D point cloud.

Build a terrain or elevation model for future comparison.



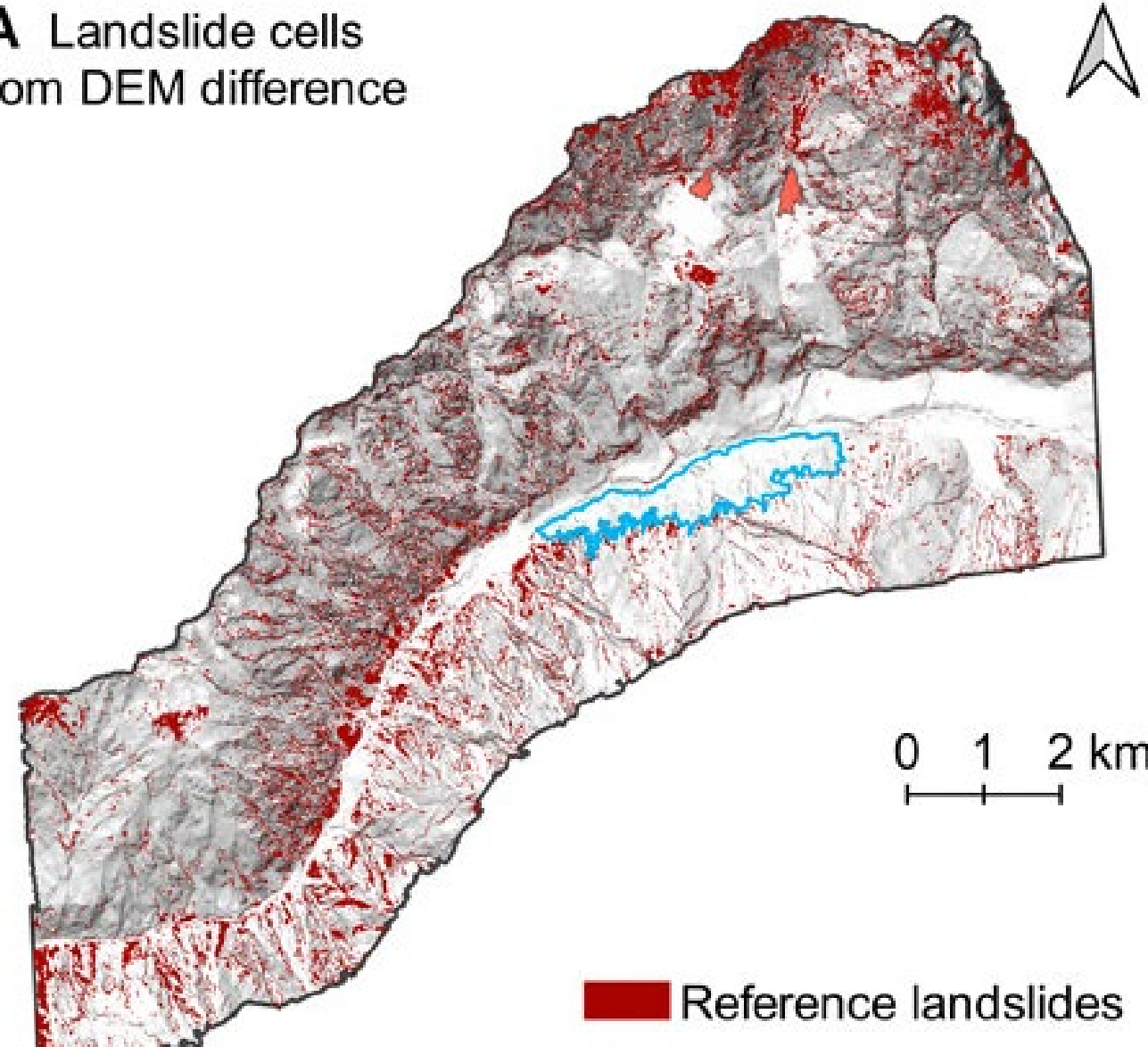
LiDAR - Process

2. Repeat surveys

Rescan at planned intervals or after significant events.

Compare models to reveal terrain changes.

A Landslide cells from DEM difference



LiDAR- Process

3. Change detection

Compare scans for displacement, erosion and deformation.

Identify areas of ongoing movement and potential instability.

LiDAR – Advantages

Detailed 3D surface models over large areas

Rapid data capture without contact with the slope

Repeat surveys reveal change over time

Airborne surveys can capture ground beneath vegetation

LiDAR – Limitations

Equipment and survey costs can be high.

Large datasets need specialist processing.

Survey intervals limit how quickly changes appear.

Weather and blocked sightlines can reduce coverage.

Remote Sensing Monitoring

Monitor large areas remotely, without installing sensors on the slope.

InSAR

Interferometric Synthetic Aperture Radar (InSAR)

Compare satellite radar images to detect ground deformation over time.

InSAR - Process

1. Radar images

A satellite sends radar pulses towards the ground.

Reflected signals form a SAR image.

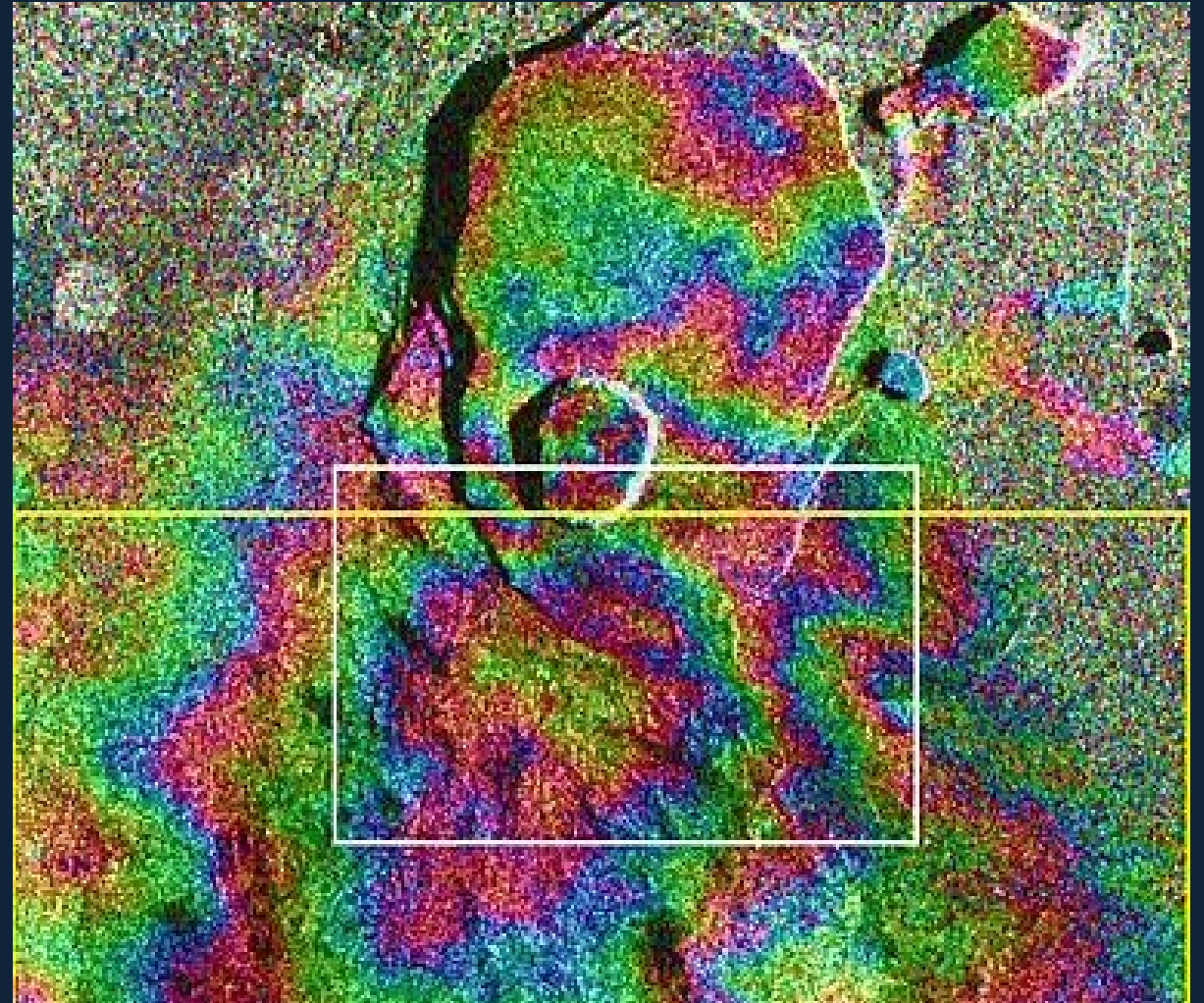


InSAR - Process

2. Interferogram

Compare radar images from different dates.

Phase differences reveal changes in the satellite-to-ground distance.



InSAR - Process

3. Displacement measurement

Use phase differences to calculate relative ground displacement.

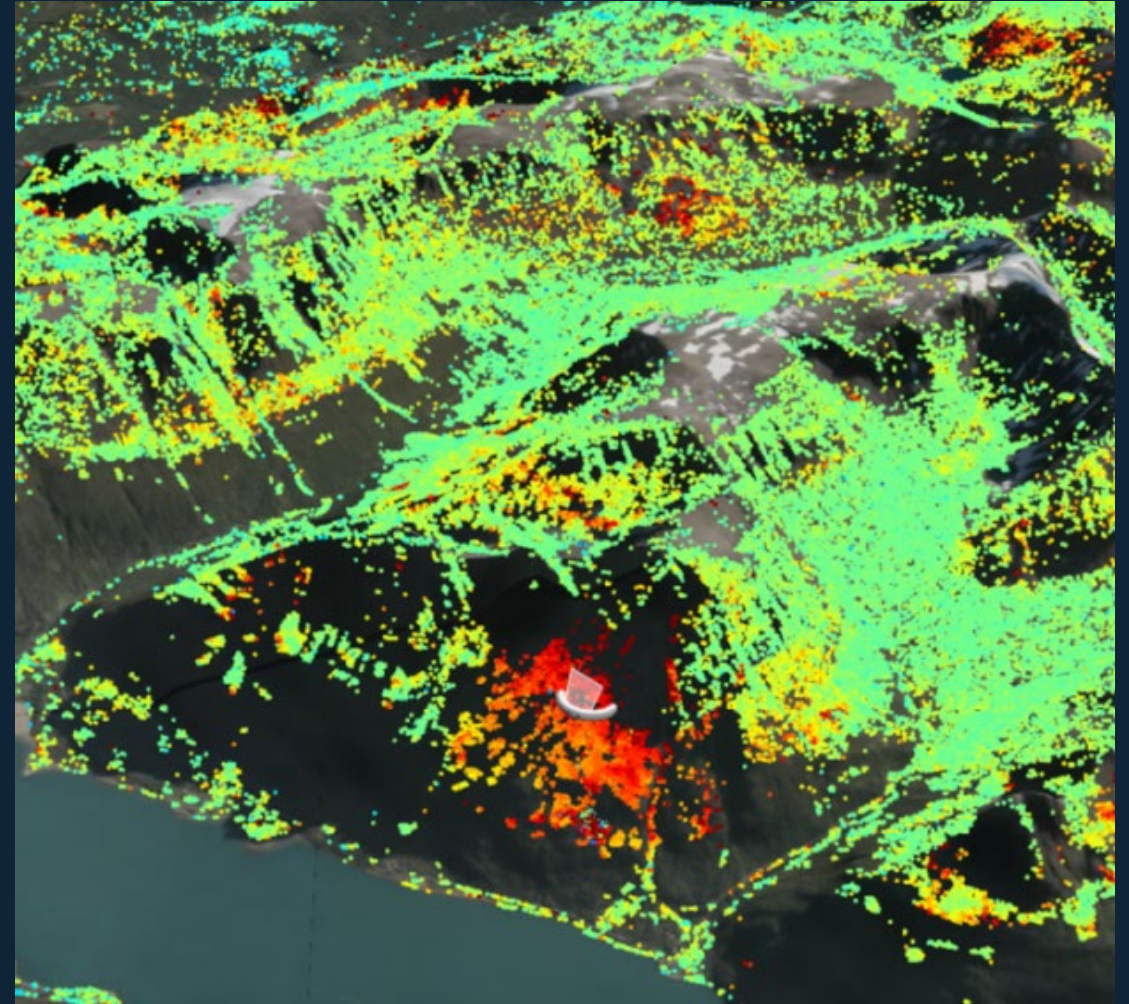
Compare repeated observations to track deformation.

InSAR - Process

4. Deformation map

Colour-coded maps show differences in displacement.

Locate areas of slope movement, subsidence or uplift.



InSAR – Advantages

Large-area monitoring without site access

Detection of slow ground movement

Time-series analysis of deformation

Radar observations by day or night, including through cloud

InSAR – Limitations

Atmospheric effects can introduce noise.

Satellite revisit times limit rapid-failure monitoring.

Surface measurements miss hidden subsurface movement.

Specialist processing and steep-terrain effects complicate interpretation.

Photogrammetry

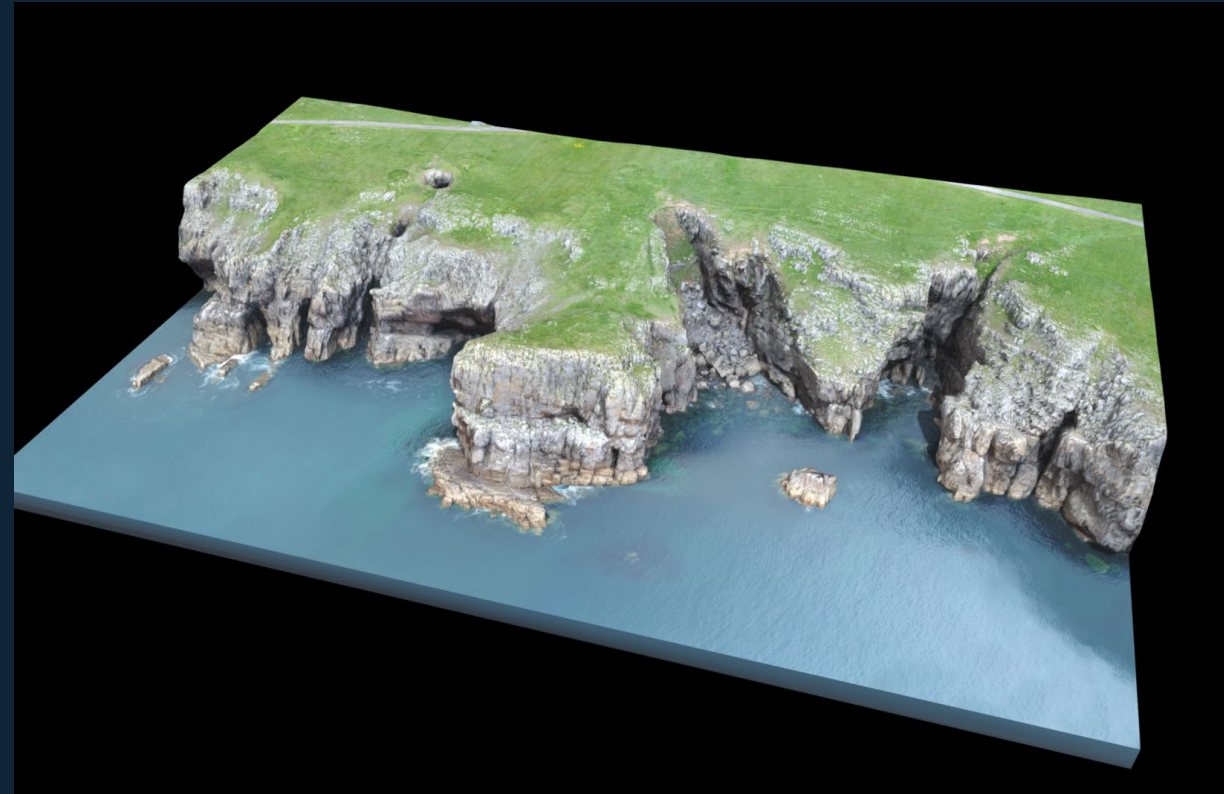
Overlapping photographs create a 3D model of the slope.

Repeat models reveal changes in the terrain.

Photogrammetry

Photographs from different viewpoints capture the same features.

Software uses these views to reconstruct the slope in 3D.



Photogrammetry - Process

1. Image capture

Use ground cameras, drones or aircraft.

Capture overlapping views of the slope, typically 60–80% overlap.

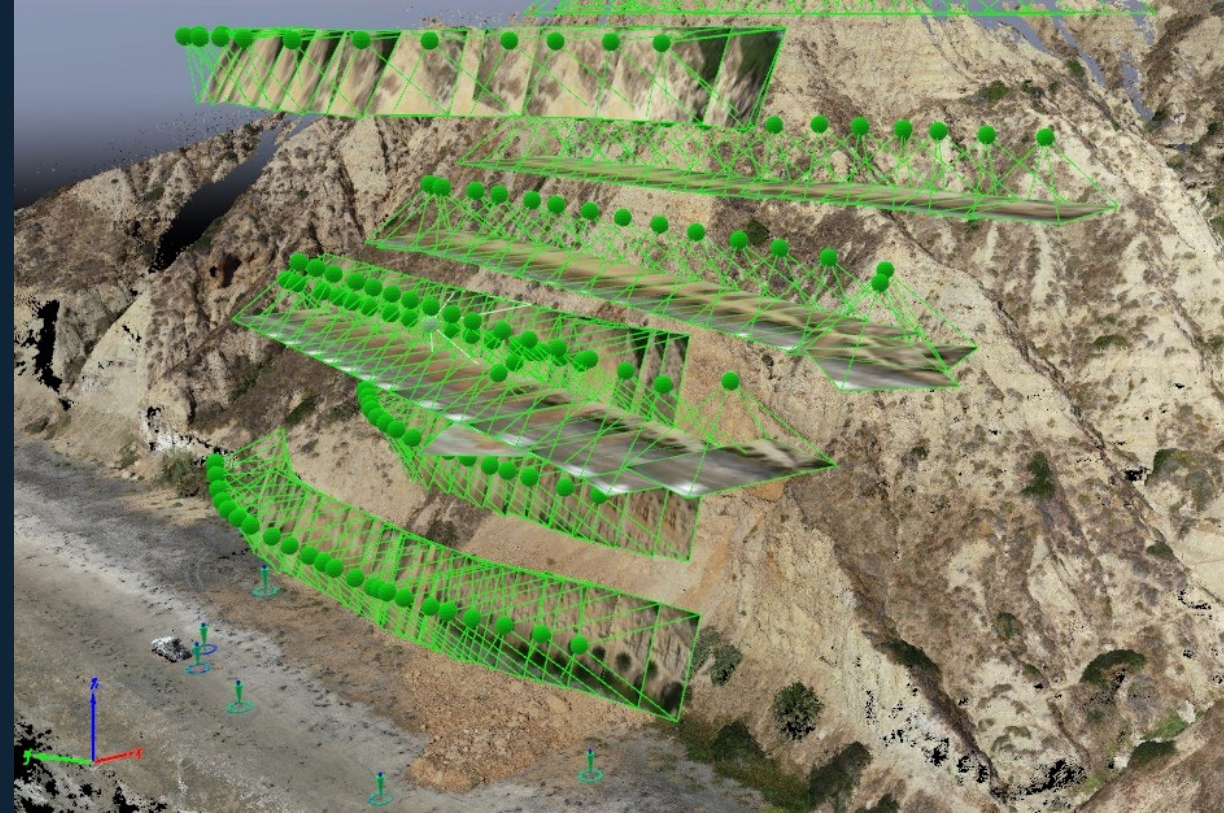


Photogrammetry - Process

2. Image alignment

Software matches common features, called tie points.

These matches establish camera positions and slope geometry.

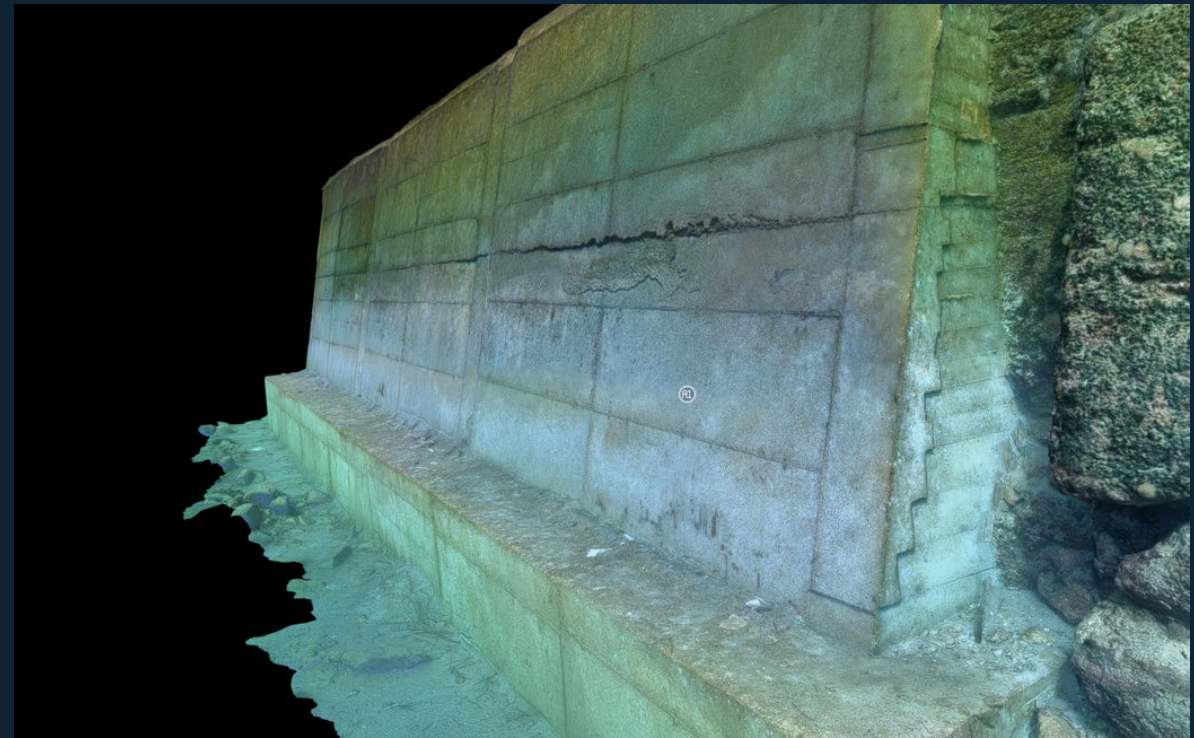


Photogrammetry - Process

3. Model generation

Create a 3D point cloud from aligned images.

Convert the points into a mesh or digital surface model.



Photogrammetry – Advantages

Detailed 3D models using cameras or drones

Scales from local slopes to larger areas

Rapid surveys without contact with the slope

Combines with LiDAR and GNSS data

Photogrammetry – Limitations

Weather, lighting and vegetation affect results.

Images capture the surface, not internal movement.

Accuracy depends on equipment and survey setup.

Processing expertise and repeat surveys add cost.

Developing Monitoring Strategies

Risk assessment

Prioritise slopes where failure threatens people or critical infrastructure.

Developing Monitoring Strategies

Baseline conditions

Establish the slope's initial geological, geotechnical and hydrological conditions.

Developing Monitoring Strategies

Choice of methods

Match monitoring techniques to slope conditions, risk and budget.

Developing Monitoring Strategies

Monitoring frequency

Choose continuous or periodic measurements to suit the slope's behaviour and seasonal risks.

Developing Monitoring Strategies

Data and interpretation

Analyse readings to assess stability and identify changes that cross alert thresholds.

Developing Monitoring Strategies

Early warning systems

Link critical thresholds to timely warnings, evacuation and mitigation measures.

Slope Monitoring: Defend and Challenge a Monitoring Plan





Slope Monitoring: Defend and Challenge a Monitoring Plan

A local authority is concerned about a steep slope above a rural road following several days of heavy rainfall. The slope is approximately 15 m high, with a road and a small number of residential properties below it.

A site inspection has identified:

- New cracks near the crest of the slope.
- A small area of bulging ground near the toe.
- Water emerging from the slope face.
- Reports from a nearby resident that a fence has moved recently.

The local authority has a limited monitoring budget and needs a plan to identify whether the slope is moving, how quickly it is moving, and whether the risk to the road and properties is increasing.

Your task: Propose a monitoring plan that would provide reliable information to support decisions about the slope's safety.