GTI-Technical Note-3	Slope Stability Monitoring using Seismic Interferometry

In collaboration with the **Institute of Mine Seismology (IMS), Golden Taurus Ingeniería (GTI)** delivers cutting-edge **near real-time solutions** and services to the civil engineering sector, using advanced **Seismic Interferometry** for **continuous stability monitoring** of critical infrastructure, including tailings storage facility (TSF) monitoring and slopes that endanger roads, railways, and the built environment. This technology helps ensure safety and prevent potential disasters.

This note discusses the benefits of Seismic Interferometry for slope stability monitoring and contrasts this with conventional approaches.

1. Introduction

Slope instabilities pose significant threats to infrastructure, human lives, and the environment worldwide. Effective monitoring and early warning systems are crucial for mitigating these risks. Traditional methods have long been employed, but recent advancements in geophysical techniques, particularly **coda-wave interferometry (CWI)**, offer promising advantages. CWI is a form of seismic interferometry that analyzes the late coda portion of the reconstructed Green's Function by cross-correlation of ambient noise. The coda represents the multiply-scattered later arrivals that are more sensitive to changes in the medium by virtue of the longer pathlengths these waves have traversed and thereby also sample a larger volume.

2. Traditional Slope Stability Monitoring Methods and Their Limitations

Traditional methods for landslide and slope stability monitoring can be broadly categorized into in-situ measurements, remote sensing techniques, and some active geophysical surveys. While valuable, they often present certain limitations:

In-situ Methods (e.g. extensometers, inclinometers, pore pressure sensors, GPS):

- **Advantages:** Provide high-precision, direct measurements of displacement, deformation, and hydrological parameters at specific points.
- **Limitations:**
  - **Limited Spatial Coverage:** Offer only point estimates, making it challenging to characterize the complex, heterogeneous nature of a landslide body and its potential failure surfaces.
  - **Invasive and Costly:** Require drilling boreholes and installing instruments, which can be expensive, time-consuming, and disruptive to the site.
  - **Scalability Issues:** Not practical for monitoring large areas or widespread instabilities.
  - **Maintenance:** Harsh subsurface operating conditions, instruments can be prone to damage or malfunction, requiring regular maintenance.
  - **Data Interpretation:** Can be difficult to interpret the bulk behavior from isolated point data.

Remote Sensing Techniques (e.g. InSAR, LiDAR, photogrammetry, visual inspections):

- **Advantages:** Provide large-scale, non-intrusive monitoring of surface deformation and topographic changes. Can be useful for identifying visible signs of instability.
- **Limitations:**

- **Limited Subsurface Information:** Primarily focus on surface movements and cannot directly determine subsurface physical mechanisms or the depth of the failure surface.
- **Environmental Factors:** Can be affected by weather conditions (e.g. cloud cover, snow, rain) and vegetation.
- **Data Acquisition Infrequency:** Satellite-based methods often have long revisit times (days to weeks), making real-time or continuous monitoring challenging.
- **Costly for High-Resolution/Frequent Data:** Obtaining high-resolution or frequent data can be expensive.

3. Coda-Wave Interferometry (CWI) for Slope Stability Monitoring

Coda-Wave Interferometry is a passive geophysical method that utilizes the continuous background seismic vibrations (ambient noise) generated by natural processes (e.g. ocean waves, wind, atmospheric pressure changes) and human activities (e.g. traffic, machinery). By cross-correlating continuous ambient noise records between pairs of seismic stations, empirical Green's functions can be retrieved. These functions describe the arrival of seismic waves at one station as if an impulsive source is positioned at the other, the medium response between all possible pathways between these sensor-pairs is imprinted in the arrivals. Any change within the sampled volume becomes more pronounced at greater lag-times which represent longer inter-station pathlengths.

Phase changes in the late coda can be directly related to changes in material properties (e.g. stiffness, fluid saturation, fracturing), which are critical indicators of slope stability. A decrease in V_s, for instance, can indicate softening of the ground due to increased water content or the development of micro-cracks and deformation within the soil or rock mass, often preceding slope failure. A well calibrated system can even show sufficient sensitivity to detect day/night variation in medium velocity due to temperature changes.

This technology has been deployed successfully in the following contexts:

- Earthen dam walls (**Tailings Storage Facilities, TSFs**, in particular)
- Open pit wall stability
- Natural landslides
- Monitoring of active volcanoes

4. Advantages of Coda-Wave Interferometry

ANT offers several significant advantages over traditional slope stability monitoring methods:

Passive and Non-Invasive:

- **No Active Source Required:** Eliminates the need for artificial seismic sources, reducing logistical complexity, cost, and environmental impact.
- **Non-Destructive:** Does not disturb the ground, making it ideal for sensitive or inaccessible areas.

Continuous and Real-Time Monitoring Potential:

- **Utilizes Continuous Data:** Seismic stations continuously record ambient noise, allowing for the derivation of subsurface velocity-changes. This enables continuous or near real-time monitoring of subsurface changes.
- **Precursor Detection:** The ability to detect subtle changes in seismic velocity (e.g. a decrease in V_s) days or even weeks before a slope failure has been demonstrated, providing valuable precursor signals for early warning systems.

Cost-Effective and Easy to Deploy:

- **Economical:** Compared to active seismic surveys or extensive in-situ instrument deployments, CWI can be more cost-effective due to the passive nature of the data acquisition and the potential for using relatively inexpensive seismic sensors.
- **Easy Deployment:** Instruments are generally easy to deploy, and can be powered by AC or solar power, making it suitable for remote or challenging terrains.

Provides Subsurface Information:

- **Depth sensitivity:** Large seismic wavelengths mean changes at great depth can be detected. Typically surface deformation is a more advanced symptom of a failing slope, so changes at depth can provide advanced warning. Large wavelengths also mean a sparse network of sensors can monitor comparatively large structures.
- **Material Property Changes:** Directly sensitive to changes in shear-wave velocity, which is a key parameter indicative of material stiffness and integrity. This allows for the detection of internal deformation and weakening of the slope material, which is often missed by surface-only methods.

Robustness to Environmental Factors:

- **Less Affected by Surface Conditions:** Unlike optical remote sensing, CWI is largely unaffected by weather conditions (rain, snow, fog) or vegetation cover, ensuring continuous data acquisition.

Improved Time Resolution:

- With sufficient data quality and processing, CWI can achieve temporal resolutions of about 10 minutes, which is crucial for timely warnings.

Complementary to Other Techniques:

- ANT can be integrated with other geophysical methods (e.g. ERT, GPR) and traditional in-situ measurements to provide a more comprehensive characterization of the slope and its dynamics.

5. Conclusion

Coda-wave interferometry represents a significant leap forward in slope stability monitoring. Its passive, continuous, cost-effective, and subsurface sensitivity capabilities address many of the limitations inherent in traditional methods. By providing insights into dynamic changes in subsurface material properties, CWI offers a powerful tool for detecting early warning signs of instability, thereby enhancing the effectiveness of slope failure risk mitigation strategies and contributing to safer infrastructure and communities. CWI and particularly the localisation of changes detected, is an ongoing field of research and technological advancements continue to improve the applicability and robustness of this promising technique.

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