Acoustic Emission Mechanisms at Geomaterial Interfaces: Multiscale Insights for Developing an Early Warning Device for Relative Displacement-Induced Geotechnical Instabilities

by

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ABSTRACT

Geotechnical instabilities cause widespread damage to infrastructure and significant socio-economic losses worldwide. Although many such failures evolve progressively, their underlying deformation mechanisms remain challenging to interpret using conventional monitoring. Acoustic emission (AE) offers sensitivity to early-stage micromechanical activity; however, its effective use in geotechnical systems is limited by an incomplete understanding of AE generation at soil–structure interfaces. This thesis addresses this gap by systematically investigating the fundamental mechanisms governing AE generation during particle–continuum interface shearing, with specific relevance to relative displacement–induced instabilities, and by proposing a novel strip-based active waveguide design as an alternative to traditional tubular waveguides, whose response under controlled relative displacement–induced failure conditions is evaluated using laboratory and large scale model test studies.

A multiscale experimental framework was adopted, integrating macromechanical, micromechanical, and large scale model-scale investigations. At the macroscale, interface direct shear tests were conducted using a custom-developed Macromechanical Interface Direct Shear Test (Macro-IDST) apparatus to quantify the influence of particle morphology, continuum surface roughness, material hardness, normal stress, and displacement rate on coupled shear and AE responses. Granular materials included silty sand granular fill (SSGF), angular granular fill (AGF), and rounded glass beads (RGF), while continuum materials comprised steel and aluminum surfaces with controlled roughness. Results demonstrate that interfaces

involving angular particles and hard, smooth steel surfaces generate consistent and interpretable AE signatures, predominantly within the 20–30 kHz frequency band, closely linked to shear stress mobilization and failure processes. Increasing normal stress amplified AE energy, whereas increasing displacement rate shifted dominant frequencies toward higher bands and produced exponential increases in AE activity.

To isolate the sources of AE, particle-scale interface shear tests were conducted using an in-house developed micromechanical interface direct shear apparatus under fixed-particle and unrestricted-particle boundary conditions. This experimental framework enabled independent examination of sliding, plowing, particle breakage, wear, and rearrangement mechanisms. Sliding and plowing at the continuum material in the absence of particle degradation generated negligible AE, whereas particle breakage produced high-energy, AE in the 20–100 kHz range. Wear and rearrangement processes contributed sustained, moderate AE activity, reflecting cumulative energy release associated with frictional dissipation and particle mobilization. Collectively, these findings establish direct mechanistic links between individual micromechanical processes and their corresponding AE signatures.

Building on these insights, a strip-type, rough-surfaced active waveguide was designed, and design guidelines for its geometry and material selection were established based on the multiscale experimental findings. The waveguide response was evaluated through large direct shear (DST) tests under both homogeneous and composite soil configurations. These tests demonstrated that the host soil (silty sand) generated negligible acoustic emission, even under increasing normal stress and displacement rate, confirming that an engineered granular fill is essential for effective AE generation in an active waveguide system. Additional tests conducted under dry and submerged conditions revealed that the presence of water significantly dampened AE activity and reduced signal energy due to enhanced attenuation

and lubrication effects at the interface. Finally, a physical model test simulating the retaining wall failure, incorporating the proposed strip-based waveguide (TRL 5), performed under controlled relative displacement–induced failure conditions, validated the accuracy and sensitivity of the system in capturing early deformation precursors.