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Sources and characteristics of acoustic emissions from mechanically stressed geologic granular media — A review

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ABSTRACT

The formation of cracks and emergence of shearing planes and other modes of rapid macroscopic failure in geologic granular media involve numerous grain scale mechanical interactions often generating high frequency (kHz) elastic waves, referred to as acoustic emissions (AE). These acoustic signals have been used primarily for monitoring and characterizing fatigue and progressive failure in engineered systems, with only a few applications concerning geologic granular media reported in the literature. Similar to the monitoring of seismic events preceding an earthquake, AE may offer a means for non-invasive, in-situ, assessment of mechanical precursors associated with imminent landslides or other types of rapid mass movements (debris flows, rock falls, snow avalanches, glacier stick-slip events). Despite diverse applications and potential usefulness, a systematic description of the AE method and its relevance to mechanical processes in Earth sciences is lacking. This review is aimed at providing a sound foundation for linking observed AE with various micro-mechanical failure events in geologic granular materials, not only for monitoring of triggering events preceding mass mobilization, but also as a non-invasive tool in its own right for probing the rich spectrum of mechanical processes at scales ranging from a single grain to a hillslope. We review first studies reporting use of AE for monitoring of failure in various geologic materials, and describe AE generating source mechanisms in mechanically stressed geologic media (e.g., frictional sliding, micro-crackling, particle collisions, rupture of water bridges, etc.) including AE statistical features, such as frequency content and occurrence probabilities. We summarize available AE sensors and measurement principles. The high sampling rates of advanced AE systems enable detection of numerous discrete failure events within a volume and thus provide access to statistical descriptions of progressive collapse of systems with many interacting mechanical elements such as the fiber bundle model (FBM). We highlight intrinsic links between AE characteristics and established statistical models often used in structural engineering and material sciences, and outline potential applications for failure prediction and early-warning using the AE method in combination with the FBM. The biggest challenge to application of the AE method for field applications is strong signal attenuation. We provide an outlook for overcoming such limitations considering emergence of a class of fiber-optic based distributed AE sensors and deployment of acoustic waveguides as part of monitoring networks.

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1. Introduction

Non-invasive characterization of deformation processes and mechanical failures of geologic granular materials is of great interest for applications in engineering, natural hazard mitigation, and material sciences. Mechanically induced elastic waves, often termed acoustic emissions or AE for short, provide a window into grain-scale processes not attainable with traditional monitoring techniques. AE are relatively high frequency (10–1000 kHz), rapid (few milliseconds), small magnitude body waves generated by the abrupt release of stored strain energy from a delimited source region (Lockner, 1993). Crack formation, grain rearrangement, friction between solid surfaces, and other grain-scale motion are typical processes generating AE.

Modern AE acquisition systems are capable of sampling rates exceeding tens of MHz and able to capture a massive number of discrete events emanating from a deforming geologic sample. AE monitoring can therefore complement other mechanical measurements of stress or strain by providing a measure of discrete mechanical interactions as singular events. The monitoring of acoustic emissions activity in engineering applications is routinely used for the assessment of the integrity of key structural elements in civil infrastructure such as bridges (e.g., Shigeishi et al., 2001) or deep excavations (e.g., Young and Martin, 1993) and for testing engineering materials such as concrete (e.g., Labuz et al., 2001) and fiber-reinforced composites used in aerospace or automobile engineering (e.g., Barre and Benzeggagh, 1994). In Earth sciences, AE activity has received considerable attention in the study of rock strength and fracture properties (Lockner, 1993). However, despite over half a century of acoustic emission research on geologic granular materials, the method has not enjoyed widespread application probably owing to the fundamental issues related to signal attenuation in porous media often requiring prohibitively large number of sensors for implementation at practical scales of interest. An array of important issues in granular mechanics could benefit from judicious application of acoustic emission method. For example, grain-scale micro-mechanical interactions resulting in the development of shear zones and localized deformations, grain rearrangements, or formation of force concentrations can potentially produce large numbers of AE whose characteristics and statistics could be used to identify granular deformation events. AE-producing granular interactions also determine how a granular material collapses when external stresses exceed the macroscopic strength of the material (Tordesillas and Behringer, 2009). The capacity of counting discrete events offered by AE data acquisition systems may provide a valuable measurement tool for investigations of progressive failure of granular materials.

Theoretical aspects and applications of AE have been summarized in various textbooks (e.g., Kino, 1987; Grosse and Ohtsu, 2008) and reviews (e.g., Swindlehurst, 1973; Scruby, 1987; Boyd and Varley, 2001). Studies on specific applications of acoustic emissions were published for example on crack formation and propagation in brittle materials (Evans and Linzer, 1977), on brittle rock failure (e.g., by Yamada et al., 1989), concrete (Ohtsu and Watanabe, 2001), or fiber-reinforced resins (Barre and Benzeggagh, 1994). In geosciences Koerner and co-workers have measured AE from soils and sands to assess stability of slopes (Lord and Koerner, 1974, 1975; Koerner et al., 1976, 1977; Huck and Koerner, 1981; Koerner et al., 1981a).

Koerner et al. (1977) also reported tests for the detection of mechanical failure in clayey or silty soils by measuring elastic body waves and have shown empirically that acoustic emissions are generated during failure of different geologic granular materials (see Fig. 1). In the context of landslide hydrological processes, Cadman and Goodman (1967) were among the first to implement the acoustic emission technique as a tool for monitoring slope movement. Rouse et al. (1991) measured significant acoustic emission activity following heavy rainfall events within a slope prone to landslide and attributed it to localized hydromechanical destabilization. In another field study Chichibu et al. (1989) found indication that AE activity increases at the onset of slope deformation induced by heavy rainfalls. Shiotani and Ohtsu (1999) evaluated statistical prediction methods to use AE signals for slope failure early warning. The authors addressed also the issue of strong AE signal attenuation within geologic materials and proposed different design options for waveguides, i.e. low-attenuation structures that help to reduce propagation losses of AE signals. Recent advances in application of acoustic emissions for slope stability detection using waveguides were made by Dixon and co-workers (Dixon et al., 2003; Dixon and Spriggs, 2007). The authors reported measurements of acoustic emissions in combination with steel waveguides in a borehole backfilled with sand or gravel ("active waveguides") in a field site to monitor slope instabilities. Sommerfeld and Gubler (1983) and van Herwijnen and Schweizer (2011b) tested the application of AE for monitoring of a snow avalanche initiation zone and have identified a range of low frequency precursory AE events indicative of imminent avalanche release. Recent developments in AE measurement techniques using optical fiber offer exciting potential for large and distributed earth science applications in terms of monitoring and analyzing progressive mechanical failure (Inaudi and Glisic, 2005; Selker et al., 2006; Iten, 2008; B.J. Wang et al., 2009; Zeni, 2009; Iten, 2011). These applications enable monitoring of strains and AE-induced vibrations at rapid sampling rates (>100 Ksamples/s/m) over several kilometers at sub-meter resolution.

Acoustic emissions were also used for experimental granular physics studies of grain-to-grain or sample scale mechanical interaction. Hidalgo et al. (2002) used acoustic emission signals to study internal force rearrangements in assemblies of glass beads. Gardel et al. (2009) measured rapid force and velocity fluctuations due to grain collisions and frictional interaction with piezoelectric sensors in dense granular flows. Recently Carson et al. (2008, 2009) monitored particle size distribution of powders by acoustic emissions generated

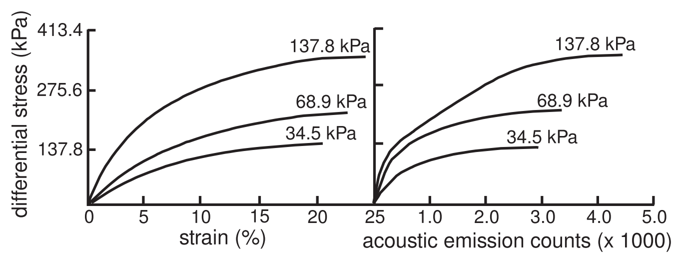

Fig. 1. Results from Koerner et al. (1977) that demonstrate the occurrence of acoustic emissions during shear deformation of soil. The graphs show the stress strain behavior of a clayey silt soil and the corresponding cumulative number of AE events. (Figure modified after Koerner et al., 1977).