Doctoral Thesis

Characteristics of force jumps and energy release during shearing of granular material - acoustic emissions measurements and fiber-bundle models

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Publication Date:
2013

Permanent Link:
https://doi.org/10.3929/ethz-a-009943078

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CHARACTERISTICS OF FORCE JUMPS AND ENERGY RELEASE DURING SHEARING OF GRANULAR MATERIAL - ACOUSTIC EMISSIONS MEASUREMENTS AND FIBER-BUNDLE MODELS

A dissertation submitted to
ETH ZURICH

for the degree of
Doctor of Sciences

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2013
Abstract

The thesis presents experimental and theoretical studies of acoustic emissions reflecting individual events of abrupt elastic energy release during shearing of granular media. Modeling of these events is based on the fiber-bundle model (FBM) formalism. The FBM is capable of characterizing rupture and interaction of disordered material constituents and can be used to predict progressive failure in complex systems such as granular assemblies and Earth materials. Fast geologic mass movements, such as shallow landslides, rock falls, or snow avalanches, often occur without obvious warning signs. Heterogeneity of host materials, complexity of the underpinning mechanical processes and limitations to measurement techniques often hamper the prediction of such mass movements. Triggering of geologic mass movements is typically associated with the accumulation of internal failure and localized deformation events culminating in the formation of a slip plane, which eventually leads to an abrupt and often catastrophic mass release event. Local internal failure events may include rearrangement of the grain contact network, particle-to-particle friction, rapid liquid-air interface displacement, breakage of cementing agents or rupture of biological components occurring in natural geo-materials. Presenting an abrupt perturbation of the internal force network deformation-induced failure processes typically result in emission of elastic waves. For their characteristic frequency spectra in the kHz range such elastic waves are often termed acoustic emissions (AE). Based on investigations of failure-induced AE and measurable granular material stress-strain behavior we present a framework for the observation and prediction of shear zone formation in granular materials.

To study characteristic AE signature of micro-failure events in granular shear zones we extended and applied a conceptual fiber-bundle model (FBM). Individual building-blocks of the FBM, called fibers, represent either single grain contacts, elements of the granular force network or other load-bearing entities occurring in granular geo-materials. Using the FBM we can provide links between AE-generating grain-scale failure processes and shear zone formation.

In preparation for the theoretical and experimental studies, we initiated an exhaustive literature review to assess the current state-of-the-art of AE application for geologic material testing, and to pin down potential source mechanisms. We review important issues of acoustic signal propagation and attenuation, and outline potential strategies to apply the method on the field-scale for the assessment of slope stability. In acknowledgment of the great potential of FBMs for the modeling of grain-scale failure events associated with granular shear zone formation we adapted the FBM framework considering the peculiarities of granular materials. Analytical expressions of fiber rupture-induced energy release form the base for the simulation of acoustic events. Shear-frame experiments with glass beads as prototypical representation of granular matter were performed, including high resolution shear force and AE measurements. Experimental tests were in good qualitative agreement with predictions from the FBM and revealed a close connection between low-frequency acoustic emissions and small fluctuations of the shear stress. The simultaneous observation of continuously released high-frequency AE events suggests a relation of those signals to other source mechanisms, such as friction or rolling at individual grain contacts. We amended the FBM with an AE generation model that is rooted in the principle of failure-induced excitation of the granular force network and bridges the gap between macroscopic shear zone mechanics and failure-induced AE signals.
We found that the AE method combined with conceptual models of granular shear zone formation, such as the FBM, provides a promising tool for noninvasive and detailed interrogation of information rich mechanical failure processes in geologic media. We envision potential applications of AE for detailed and real-time early warning for imminent slope failure in sensitive areas, as a method of its own rights for geo-technical testing, or in industrial settings.
Zusammenfassung


Im folgenden letzten Teil der Arbeit erweitern wir das Fasebündel-Modell um ein mecha-
nistisches Modell zur Beschreibung von freigesetzten akustischen Emissionen. Damit kön-
nen wir eine vollständige Verbindung zwischen kleinskaligem Materialversagen, freigesetzten
akustischen Emissionen und dem mechanischen Verhalten von Scherfugen herstellen.
Messung von akustischen Emissionen in Kombination mit konzeptuellen Modellen, wie etwa
dem Faserbündel-Modell, bieten einen erfolgversprechenden Weg für die nicht-invasive und
detaillierte Abfrage mechanisch aussagekräftiger Versagensprozesse in granularen Materi-
alien. Die vorliegenden Resultate könnten daher Eingang in die Entwicklung von Früh-
warnsystemen für Hangrutschungen, geotechnische Testmethoden oder verfahrenstechnische
Messungen, finden.
Acknowledgements

Many people have contributed to this work in many different ways. First and foremost I would like to acknowledge my dissertation supervisor Prof. Dani Or. In my time as PhD I had the opportunity to profit from his extraordinary experience and scientific excellence. In addition to his scientific guidance Dani taught me priceless lessons for the organization and communication of research work. Considerable inputs to this work I received from Dr. Denis Cohen, who was involved in the supervision of this PhD project for almost three years. I am grateful for the time Denis and me spent in the lab, which gave me the chance to tremendously benefit from his work experience and expertise. I want to thank also the two external members of my PhD committee, Prof Hans-Jürgen Herrmann and Prof. Renaud Toussaint, who thoroughly revised my work leading to valuable and significant improvements of this thesis. Many of the colleagues I had the chance to work with during this last years, became close friends and partners for scientific and non-scientific discussions and debates. Out of this long list of brilliant minds and inspiring fellows I want to express gratefulness to my fellow-students and friends Gang Wang, Franziska Möbius and Jonas von Ruette. The four of us formed what one might consider a “generation” of PhD students at the lab of Soil and Terrestrial Environmental Sciences and without them the past four years would certainly have been much less enjoyable. I am thankful to Dani Breitenstein, who contributed with his outstanding technical skills to this project but more important became a good friend in the last years. I highly appreciated the scientific exchange with Dr. Peter Lehmann and the support in the lab by Christoph Meili. Further, I do not want to leave the fine company and support of Hans Wunderli, Massimiliano Schwarz, Andreas Papritz, Stan Schymanski, Jérôme Faillettaz, Ebrahim Shahraeeni, Frouke Hoogland, Madlene Nussbaum and all other members of the STEP group unmentioned. I am grateful for been given the chance to work in this vibrant research group and to meet so many interesting and sympathetic people. Also I want to acknowledge the opportunity to conduct my PhD within the framework of the “Triggering of Rapid Mass Movements” (TRAMM) project, which provided me the opportunity to interact with outstanding scientists from related fields and to participate in interdisciplinary activities throughout my time as a PhD student.

I want to express my utter thankfulness to my family who supported me ever since with their participation and caring: particularly to my parents who persistently encouraged and motivated me and to my passed away grandfather who long ago ignited my enthusiasm for science.

Finally and most of all, I would like to express my heartfelt greatfullness to Judit for her love, support, and patience during this years.
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1 Introduction

Granular media are ubiquitous at the Earth’s surface forming the landscape in which we live in and build on. The mechanical behavior of granular materials affect key land-surface features from steepness of mountains to the characteristic shapes of sand dunes. The gradual geomorphological changes of Earth’s surface over geological time scale are misleading as various mass release processes are abrupt and often pose hazard to life and infrastructure. Examples include abrupt triggering of shallow landslides, deep seated earth flows, or rock avalanches. Considering that a patch of land may have resisted extreme environmental conditions eventually for thousands of years before it fails in an abrupt mass release event, one becomes aware of the peculiar nature of such triggering events. The apparent randomness of those events is indicative of eventually undetected internal failure growth and weakening processes that is driven by repetitive or extreme precipitation, freezing-thawing cycles or other external straining mechanisms and may ultimately lead to mass release. Direct observations of internal progressive failure presents a considerable challenge for existing measurement techniques, consequently the mechanical state of Earth materials at any given time remains unknown. This renders the correct prediction of failure times and location an almost impossible task. Landslides and other geologic mass movements may present a severe natural hazard creating a societal demand for early warning systems and ability to predict such phenomena. This thesis aims for providing new methods for the observation and integrated modeling of progressive internal failure in granular geologic materials eventually culminating in catastrophic mass release. This work seeks to develop strategies for the early-recognition of shallow landslide triggering, a natural hazard that causes severe damage particularly in mountainous terrain.

Many mechanical properties of granular Earth materials are affected by features of their constituents: an immense number of dissimilar, mechanically-interacting particles. Although this similarity to thermodynamical systems holds a great promise for application of principles of statistical mechanics to granular systems, the use of thermodynamical concepts for the description of granular systems remains a delicate task. For many scientific and engineering scales of interest the effect of single particles or of clusters of particles is present in the material behavior. This often leads to intermittency, fluctuations and localization phenomena, all of which are hard to conciliate with classical concepts of thermodynamics. The formation of a shear zone in loaded granular material appears as a prominent example for the effect of particle-scale mechanisms on macroscopic mechanical behavior. This study was motivated by the notion that formation of a shear zone in granular material involves localized, abrupt changes of internal stresses and the transfer of forces amongst particles. Typically such grain-scale perturbations translate into elastic waves and propagate within the material. Measurements of those
elast...formation of shear zones. Existing acoustic emission technology allows to sample elastic waves in the kilohertz-range with high accuracy. Along this line the acoustic emissions method may be used for detection of shear zone evolution, which is the underpinning failure mechanism for most types of geologic mass movements, including shallow landslides. Amended with conceptual mechanical models, that aim at capturing essential features of shear band formation, the acoustic emissions method provides a promising path towards predictability of such abrupt geologic mass release events. The combination of the AE technique with conceptual models enables to account for discrete, progressive failure accumulation in granular materials and for the stochastic nature of grain scale mechanical interaction. The presented study is therefore located at the intersection between physics of granular media, geophysical material testing and geo-mechanics. The work presented in this thesis was driven by the following key objectives:

• to compile and summarize the state-of-the-art and to identify potential sources of acoustic emissions in granular materials, particularly in granular Earth materials,

• to develop a model framework that is able of capturing features of complex granular shearing process essential for generation of AE,

• to experimentally investigate characteristic frequencies and statistical features of AE generation under different mechanical conditions,

• to translate the acoustic emission-signature of granular shear zone formation into a mechanical context that allows track grain-scale failure mechanisms from generated acoustic signals.

A thorough review of the scientific literature revealed that the acoustic emissions (AE) method has been used in the context of geo-sciences mainly for rock mechanical problems [23, 28], and as a tool for small-scale seismological investigations [45, 32]. An impressive body of research describes the abundancy of information on material properties of geologic materials [52], structural damage [25], or progressive failure [2], that can be investigated by acoustic emissions measurements. Investigations on AE for landslide monitoring are motivated by a number of studies reporting the successful measurement of acoustic signals from unstable slopes [30, 5, 44, 13, 14] and during geo-technical testing procedures [21, 22, 29]. Methods and models used for the analysis of AE data in those studies were typically adapted from seismology, and AE applications in material testing. Specific analytical tools, that consider the peculiarities of elastic wave generation in granular and Earth materials have merely been put forward until now. This is possibly owed to a lack of information concerning acoustic source mechanisms and propagation in soil and other loose Earth materials. Many complex phenomena associated with elastic wave propagation in prototypical granular media have been unraveled in theoretical studies. Nesterenko and co-workers [36] found the emergence of soliton waves in regularly packed granular assemblies when their elastic interaction is governed by Hertzian potentials. This is the case when transient deformations are of the same order of magnitude as indentations between spheres stemming from confining stresses.
1 Introduction

The appearance of such solitary, non-dispersive waves in confined granular chains was demonstrated also in experiments [20] standing in consensus with Nesterenkos postulates. Complex elastic wave propagation may also arise from the non-continuous nature of granular materials even under the premise of linear-elastic grain interaction. Multiple scattering and diffraction of signals with wave lengths similar to the characteristic grain size leads to the emergence of a slowly-propagating wave front trailing coherent P- and S-waves. Referring to a similar phenomenon that is known from seismic earthquake records, such strongly scattered ultrasonic waves are referred to as coda [19, 18]. Coda signals are extremely sensitive to the granular contact network which makes them a potential tool to probe grain-to-grain dissipation or other internal features of the grain lattice. The appearance of soliton waves and the generation of coda signals are just two examples that serve to illustrate the complexity of elastic waves within granular materials. At the same time they underline the abundant information elastic waves may provide about their source mechanisms, and the media they travel in.

The mechanics of granular materials has been studied exhaustively in the context of statistical physics. Parallels with thermodynamic systems comprising a large number of molecules [15] intrigued researchers. In this “thermodynamic” vein equivalent state parameters like “granular temperature” were put forward. The thermodynamical concept of critical phase transitions revealed a new view on unjamming, i.e. the transition from a solid-like to a fluid-like behavior, of granular materials [26]. Characteristic appearance of exponential probability distributions in characteristic features of granular material, e.g. of particle contact forces [41, 27, 8, 31, 9, 40], may be interpreted under this perspective as expression of a finite range of interaction between particles and give credence to analogies with thermodynamical systems. Despite of the many examples of successful application of thermodynamical concepts, caution should be exercised since granular assemblies are seldom in equilibrium. The absence of thermal fluctuations in granular materials with large particles, compared to the molecule-scale, prevents such systems to explore their entire phase-space leaving them often in a out-of-equilibrium status (affecting, for example, the packing of grains [51]). Many localization and intermittency phenomena that are characteristic for granular assemblies may be seen as a consequence of this property: stick-slip behavior of granular media under shearing deformation [3] express repetitive and local unjamming events of the material, in numerical simulations of biaxial tests localized, abrupt release of stored strain energy was observed [50], and the concentration of shear strain into thin shear zones is a commonly known feature of granular materials [35, 37].

Particularly for stability of granular assemblies formation of shear zones is of prominent relevance. These are confined band-like regions within the granular material that accommodate high shear strains. Together with the shear straining shear bands typically undergo considerable density rarefaction leading to a volumetric expansion of the material, that is often referred to as dilation. Although shear banding occurs also in continuum materials [7], the underlying mechanisms are slightly different than in discontinuous materials. In granular media shear zone formation stands in close relation to rearrangements of the contact network, particularly of so-called force chains [38, 16, 46]. These are aligned arrangements of highly loaded particles in stressed granular media.
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that bear a large proportion of the applied load [4, 49, 40]. It has been shown that during the progressive formation of a shear band in granular material force chains undergo subsequent cycles of destruction and reformation [46]. For this crucial dependence of shear zone formation on the particulate nature of granular materials conceptual models of shear zone formation often present a promising alternative to continuum-mechanical approaches.

Fiber-bundle models were originally devised to simulate the rupture behavior of yarn strings [39], a prototypical disordered material. FBMs consist of a large collection of elastic elements that rupture at a stochastically assigned threshold stress. Macroscopic material behavior emerges from collective loading and rupturing of the bundle elements. Their versatility and the possibility to often analytically solve the complex, stress-controlled loading case [11] made FBMs to one of the prevailing tools for modeling rupture of disordered materials. The bundle behavior may be altered by adjusting the single element mechanical properties or by using different statistical distributions to determine fiber rupture. FBMs are capable to capture typical features of a wide range of materials [6, 34, 43] and may be adapted to different loading conditions [24, 42, 7].

Rupture of a single model element, or fiber, corresponds to the collapse of a single microscopic load bearing unit of the represented system. In many real materials such micro-failure events result in the generation of high-frequency elastic waves, or acoustic emissions. The acoustic emission method is often employed for the observation of such micro-scale failure events, providing a experimental complement to FBM and other conceptual model results [1, 47, 17]. Despite of their popularity for the application to disordered material breakdown there exist few examples of FBM application to granular material [17, 10].

Theoretical knowledge about statistics and mechanics of granular materials are linked in this work for the first time with the data-rich AE method to obtain novel insights into shear zone formation in Earth materials and for the gauging of dissipative processes in granular media. The work seeks to develop of a genuine set of tools to interpret and predict AE from shear zone formation in granular materials. The study exploits the capabilities of conceptual fiber-bundle models (FBM) to reproduce key attributes of granular shearing and to represent stochastic features of this process at relatively low computational costs. Coupling the FBM with a simple mechanistic AE generation model allows to simulate expected frequencies and energies of shearing-induced AE signals. The results of this work may bear relevance for granular shear processes on all scales. Deforming fault gouge and resulting seismic activity is known to exhibit features of a stick-slip process [33]. Geomorphological processes, such as landslides, are known to crucially depend on shear band formation [12]. Even dry friction may show curious similarities to granular shearing [48]. Prediction of any of those processes remains a challenge, creating a demand for new experimental techniques and modeling tools.

In the first part (Section 2) of this thesis a literature review is presented, including theoretical concepts of AE generation in granular geo-materials. Successful applications of the AE method to geophysical and geo-technical problems are summarized and model concepts for translation of AE signals into information on the mechanics of granular geo-materials are evaluated. In the following (Section 3) a conceptual fiber-bundle model
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(FBM) is introduced as a modeling framework for shear zone formation and associated AE generation. A systematic evaluation of acoustic emissions events from shear tests under different mechanical conditions is presented in Section 4, allowing new insights into different aspects of granular shear zone formation. In Section 5 the FBM introduced in the previous section is linked to a mechanistic AE generation model, providing a full description of granular deformation-induced generation of AE and its links to material behavior. The thesis concludes with a summary of the key findings from this work (Section 6).

Literature


1 Introduction


1 Introduction


1 Introduction


2 Sources and characteristics of acoustic emissions from mechanically stressed geologic granular media – a review

Published paper in Earth-Science Reviews, 2012, 112, 97-114

Abstract

The formation of cracks and emergence of shearing planes and other modes of macroscopic failure in geologic granular media often reflect a culmination of numerous grain scale mechanical interactions that generate high frequency (kHz) elastic waves, typically 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.
2 Characteristics of acoustic emissions from geologic granular media

2.1 Introduction

Non-invasive characterization of deformation processes and mechanical failures of geologic granular materials is of great interest for applications in material sciences, engineering, and natural hazard mitigation. 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 ($10^4 - 10^6$ Hz), rapid (few milliseconds), small magnitude body waves generated by the rapid release of stored strain energy from a delimited source region [143]. 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 thus 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 emission activity in engineering applications is routinely used for assessment of the structural integrity of key elements in civil infrastructure such as bridges [203] or deep excavations [243] and to test engineering materials such as concrete [128] and fiber-reinforced composites used in aerospace or automobile engineering [14]. In Earth sciences, AE activity has received considerable attention in the study of rock strength and fracture properties [143]. 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 could 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 [218]. 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 [119, 80] and reviews [213, 200, 25]. Studies on specific applications of acoustic emissions were published for example on crack formation and propagation in brittle materials [58], on brittle rock failure [242], concrete [169], or fiber-reinforced resins [14]. In geosciences Koerner and co-workers have measured AE from soils and sands to assess stability of slopes [145, 146, 121, 122, 123, 96]. Koerner et al. [122] 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 Figure 2.1.1). In the context of landslide hydrological processes, Cadman and Goodman [31]
were among the first to implement the acoustic emission technique as a tool for monitoring slope movement. 
Rouse et al. [193] measured significant acoustic emission activity following heavy rainfall events within a slope prone to landslide and attributed it to localized hydromechanically destabilization. In another field study, Chichibu et al. [38] found indication that AE activity increases at the onset of slope deformation induced by heavy rainfalls. Shiotani and Ohtsu [204] 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 using acoustic emission for slope stability detection relying on waveguides were made by Dixon and co-workers [53, 54]. The authors reported acoustic emission measurements in combination with steel waveguides embedded in a borehole by sand or gravel (“active waveguides”) in a field site to monitor slope instabilities. Sommerfeld and Gubler [208] and van Herwijnen and Schweizer [225] tested the application of AE for monitoring of a snow avalanche initiation zone and have identified a range of low frequency precursory AE indicative of imminent avalanche release. Recent developments in AE measurement using optical fiber offer exciting potential for large and distributed earth science applications in terms of monitoring and analyzing progressive mechanical failure [102, 201, 104, 230, 247, 105]. This applications enable monitoring of strains and AE-induced vibrations at rapid sampling rates (> $10^5 \text{s}^{-1}\text{m}^{-1}$) 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. [93] used acoustic emission signals to study internal force rearrangements in assemblies of glass beads. Gardel et al. [65] measured rapid force and velocity fluctuations due to grain collisions and frictional interaction with piezoelectric sensors in dense granular flows. Recently Carson and co-workers [35, 34] monitored particle size distribution of powders by acoustic emissions generated by grain-grain or grain-wall collisions. Allan et al. [4] recorded acoustic emissions at the wall of a mixer vessel during blending of pharmaceutical powders and were able to assign features of the elastic waves to material properties such as grain size or density [25]. Similar efforts were undertaken by Cody et al. [43] and by Jiang et al. [111] to understand random motion of granular material entrained by a gas flow inside a container. Complementary to empirical use of AE measurements, there are strong links between elastic waves produced by failure mechanisms and statistical models of failure such as the fiber bundle model [223]. Linking frequency-magnitude characteristics of measured acoustic events to the imminence of collapse offers a promising possibility for early warning applications.

Notwithstanding the number of studies addressing occurrence of AE and other forms of elastic waves in granular geologic materials, relatively little is known about mechanisms that generate such acoustic waves. Correspondingly, there is little coherent information regarding characteristics, frequency content, and amplitudes of elastic waves generated by micro-mechanical interactions in granular materials. Additionally the number of acoustic events, their occurrence frequency, and their temporal distribution in mechanically stressed granular material remains an open question. Perhaps the most critical
obstacle to the widespread application of acoustic emissions method for study and monitoring of mechanical interaction and states of geologic materials is a relatively short propagation distance of acoustic emissions in such media [124].

Despite several benchmark studies [122, 193, 152, 65, 231] on acoustic emissions in geologic granular materials, no overarching review of the topic that summarizes results and knowledge has been presented. Hence, the primary goal of this review was to introduce Earth scientists and geoengineers to the field of acoustic emissions and its potential (section 2). An important objective was to establish links between certain physical processes associated with shear, compression and other forms of mechanical loading of granular media and associated acoustic emission to capture failure progression. Different micromechanical mechanisms that may generate acoustic emissions in geologic materials will be reviewed to quantify number of events, occurrence rates, and intrinsic frequencies (section 3). Links between acoustic signals and conceptual mechanical models to enable interpretation of measured AE in deterministic and stochastic frameworks will be presented in section 4. We will present the fiber-bundle model as a potential tool for linking different types of progressive failure in granular materials with AE events (section 5). Finally the use of acoustic emissions for monitoring the imminent failure in field applications will be discussed (section 6). Advances in rapid and highly resolved AE acquisition systems may provide new insights into micro-mechanical processes associated with stress-strain relationship and thus complement existing geotechnical testing procedures. Additionally, AE seems as a promising tool for early detection of slope failure which otherwise may appear abrupt and erratic [53, 54].

### 2.2 Measurement of Acoustic Emissions

Acoustic emissions (AE) measurements are motivated by the propensity of certain materials to generate elastic body waves during deformation and abrupt grain-scale failure. Intermittent and rapid mechanical perturbations within a body may produce audible sound, as encountered in our daily experience with the crackling sound of paper crumpling, the snapping of timber, or the noise of a metal specimen during deformation.
Capturing acoustic emissions requires the detection of these mechanical waves within a body by measurements of small motions at its surface.

Many engineering applications such as material testing of aircraft structural integrity [210], monitoring of bridges and other civil structures [169, 203], engineering geology [246] or rock mechanics [143], make use of piezoelectric sensors for measurements of AE. Piezoelectricity is the property of certain materials to generate an electric potential when mechanically strained [119]. In an AE sensor, the piezoelectric crystal, often a man-made ceramic such as lead zirconate titanate, is protected by a wear plate that is in direct contact with the surface of the monitored structure, and transforms incident stress waves into an analog signal (see Figure 2.2.1) Piezoelectric sensors have become the standard method for capturing and analyzing acoustic emission stress waves and are commercially available from many manufacturers (e.g., BrueL&Kjaer, Physical Acoustics Corporation, Vallen Systeme, etc.).

Based on their operating principle we can distinguish two types of piezoelectric sensors: (a) Resonance-type sensors are designed to respond strongly to waves of a certain frequency range corresponding to the sensor resonance spectrum. Such sensors are highly sensitive to acoustic emissions close to their target frequencies. Waves with frequency outside that spectrum are captured with lower sensitivity. Consequently, full waveform analysis of Fourier spectra acquired by such sensors is limited by this inherently biased
response. (b) Broadband sensors are designed to acquire acoustic signals with a uniform response over a wide range of frequencies. Their sensitivity is typically lower, however all captured frequencies are represented relatively equally. Piezoelectric AE sensors typically operate in the frequency range from $10^4$ Hz to $10^7$ Hz. Although piezoelectric sensors are the most commonly used for AE measurements, we note that other types of sensors exist, such as piezoresistive sensors or laser interferometry based systems.

A relatively novel technique for measurement of vibrations and AE is based on fiber optical distributed sensors. Recent advances of fiber optic technology offer possibilities for real time monitoring of distributed acoustic emissions in civil structures using large sensor arrays [157, and references therein] or for application as hydrophone [28, 107]. Various techniques have been implemented for measuring acoustic waves by means of optic fibers. These methods capitalize on mechanical interaction induced by elastic waves and optical alteration of light propagating in the affected fiber optical cable [248]. Excited acoustic waves produce a periodic modulation of the refractive index and light propagation in the fiber is diffracted backward, giving rise to a frequency-shifted component by a phenomenon similar to the Doppler shift [102]. Bragg grated fibers [172, 116, 135] contain photosensitive notches at a specific spacing. If the length between notches varies due to extension or compression of the fibers, light reflection is modified. Strain measurements obtained in such way from fiber-optic cables embedded in concrete parts has been used to locate changes in the integrity of large civil structures [150]. Fast interrogation allows to obtain strain measurement sequences resolving the interaction of elastic waves with optic fibers at comparable frequencies as conventional AE sensors. A direct comparison between fiber-optic based AE measurements and piezoelectric sensors was performed by Chen and Ansari [37], showing that both methods are able to capture AE signals with a similar sensitivity.

For analysis of a transient acoustic emission signals it is necessary to introduce a threshold separating acoustic events, i.e. those parts of the signal that are associated with failure or other mechanical processes, from unavoidable underlying noise (Figure 2.2.1, left panel). Once the signal amplitude exceeds the threshold (that may be fixed or self adjusting to a present noise level), this denotes the start of an AE event. If during an event the signal remains below the threshold for longer than some pre-defined duration (often termed duration-discrimination time or rearm time) the event terminates. In that way AE events may consist of many signal oscillation cycles taking account of the fact that mechanical generation processes typically generate entire wave packages. Most commercial AE acquisition systems offer triggered monitoring operating after this principle. Signal threshold and the discrimination time normally have to be chosen by the user and may vary between different applications.

After determination of events further analyses can give more precise information about the captured AE signal: the event amplitude is the maximum amplitude reached during a AE event; the event duration is the time difference between the first and the last threshold crossing; the rise time is the time difference from the first threshold crossing to the event amplitude. More information can be obtained by capturing the complete transient waveform. An integration of the signal with respect to time gives a measure of the wave energy captured by the sensor. Such characteristic numbers are used
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for operational AE testing since they typically deliver enough information necessary to characterize AE events, without having to treat the entire signal. For a comprehensive review of parametric analysis of AE events see [80].

Capturing the complete transient waveform of individual AE events allows further analyses of AE events and offers the possibility to transform signals into frequency domain. We note however, that because of above mentioned frequency dependent sensitivity of many piezoelectric AE sensors, the frequency content of a signal is often subjected to natural, inevitable band-pass filtering. Despite these limitations due to the sensor intrinsic bias, frequency content of a signal in some cases allows inference of corresponding sources of elastic waves.

2.3 AE Sources and Signal Propagation

Various types of rapid mechanical deformation in geologic or artificial granular materials have the potential to generate acoustic waves, eventually involving particle interaction such as grain-to-grain impacts, bursts of elastic energy during contact point release, creation of interfacial energy during fracturing, or solid and liquid bond rupture. Following the triggering of an AE event, the elastic waves propagate away from the source location, born by the solid particle network or liquid within the porous material. Elastic wave-medium interactions and the properties of the granular medium may alter the wave (frequencies and amplitudes) and shape its propagation path. Acoustic wave alteration may be attributed to different types of phenomena, such as dispersion (wave velocity depends on frequency, e.g., Liu and Nagel [140]), attenuation due to viscous contact deformation [251], attenuation due to frictional dissipation [27], reflection at interfaces [108, 221] or other nonlinear effects [220, 222]. After alteration of the AE wave from propagation, it may undergo changes during detection by the transducer and conversion to analog or digital signal (as mentioned in the previous section). Otherwise the ultimate sink of the released energy is heat production [71].

2.3.1 Particle Interactions in Granular Geologic Media

Mechanical interaction of particles within granular material play a prominent role for elastic wave generation and propagation. We therefore start with a brief review of mechanical properties of grain contacts. The forces and deformations that occur at a contact point of two ideal spheres were first studied by Hertz [91]. Invoking several simplifying assumptions (most importantly smoothness of contact surfaces and absence of friction), Hertz derived the contact force $F_n$ as a function of the normal displacement $u_n$ at the contact point,

$$F_n = \frac{2}{3} \frac{E}{1 - \nu^2} R^* R_1^{1/2} R_2^{3/2},$$

where $R^*$ is the effective radius ($1/R^* = (1/R_1 + 1/R_2)$ with $R_1$ and $R_2$ the radii of the contacting particles), $E$ is the Young’s modulus, and $\nu$ is the Poisson’s ratio. Hertz’ [91] expression suggests a similitude of curved contacts with a non-linear spring: the stiffness of a two-sphere contact, i.e., the ratio between the contact deformation $u$
and the contact force $F$, is a nonlinear function of the deformation $F \sim u^{3/2}_n$. This nonlinearity has a number of implications for the mechanical and acoustical behavior of granular materials, some of which will be discussed next. The theory of Hertz [91] was subsequently extended by Mindlin and Deresiewicz [158] who considered micro slip of the contact and the dependence of contact forces on loading history in the presence of friction.

Hertz’ [91] contact model and its extensions (see e.g., [114] and references therein) determine primarily the normal and tangential elastic deformations at a particle contact. The dynamical behavior of granular materials are, however, strongly affected by non-elastic, dissipative forms of granular interactions [87, 99, 125]. Incomplete restitution of elastic energy during collisions and friction are two forms of energy dissipation that decrease kinetic energy of particles in motion. This phenomena, known as “granular cooling”, exemplifies the large dissipative capacity of granular materials [238]. In analogy with the thermodynamical description of molecular gases, the random kinetic motion of particles in granular material is termed “granular temperature” [75]. As a measure of available kinetic energy within an entrained assembly of particles granular temperature stands in a close relationship with collision-generated AE. In fact, there exist several attempts to quantify granular temperature within experimental systems using event rate or energy of acoustic emissions [43, 111]. Granular temperature, together with density and stress, is one of the properties that determine jamming respectively unjamming of particles, i.e. the spontaneous onset or loss of rigidity, within granular matter [134]. The concepts above suggest that yielding of granular materials under shear stress may be viewed as continuous fluctuations around a jamming-unjamming limit associated with localized increase in granular temperature. Numerical simulations of granular materials provide clear evidence of the link between bursts of kinetic energy and shear deformation [217, 235]. Potential usefulness of such phenomena for AE-based detection of shear failure will be discussed in the next section.

2.3.2 Sources of Acoustic Emissions in Granular Geologic Media

There is a wide array of failure mechanisms that may generate acoustic emissions in geologic granular media. Figure 2.3.1 presents the most prominent ones, such as rupture of plant roots, breakage of cohesive soils aggregates, crackling of soil particle cementation, friction between particles, release of contact force between particles or the rupture of capillary bridges. In the following we review mechanisms of AE generation in geologic granular material and introduce four classes of source mechanisms, that may vary in their relevance for different scenarios and representations of granular materials. Also we note that elastic waves in complex natural geologic materials are presumably not generated exclusively by one source mechanism but rather by a combination of processes. Simple theoretical considerations will be presented for several types of source mechanisms that may guide estimates of amplitudes, frequencies and other features of generated acoustic emissions.
Figure 2.3.1: Different representations of source mechanisms proposed for the generation of acoustic emissions in granular geologic materials: (1) liquid bridge rupture, (2) crack development, (3) release of force chains, (4) grain friction, (5) grain cementation fracture, and (6) rupture of soil fibers.
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2.3.2.1 Acoustic Emissions Induced by Grain Contact Networks Rearrangement

n of a striker with a granular bed [191] or a rigid surface [89, 35] often generate elastic waves. Rapid and energy-dissipative rearrangements of microstructure within granular materials, such as the instantaneous formation of contacts, may result in significant internal particle collisions and therefore play a role in AE generation. Studies have shown that even minor deformation of granular material may be associated with a large number of such rearrangements events [215, 136, 235]. In addition to grain collisions, we also consider the abrupt removal of existing contacts and associated rapid release of elastic energy as a potential source of AE. For most cases of slow progressive failure of geologic granular materials this presumably outweighs rapid grain collisions [144]. For understanding grain force release and associated AE generation it is prerequisite to investigate the distribution of contact forces within a granular assembly.

Granular earth materials, such as soil or sand, are typically polydisperse and disordered. Considering inherent hindrances to attaining most energetically favorable internal configuration when being externally loaded, a typical occurrence is the inhomogeneous distribution of loads amongst contacting particles. Within the force network (i.e., all particles and particle contacts that participate in internal stress redistribution) one may find that a small fraction of grains are bearing disproportionally high loads. Load bearing particles are usually aligned roughly in the direction of principal stresses and often called force chains. Force chains can be observed in experiments [17, 148, 187] as well as in numerical simulations [181]. Liu et al. [141] proposed the following distribution to account for inhomogeneities of contact forces in granular material $F$:

$$P(F) \sim \begin{cases} F^\alpha & \text{if } F \leq \hat{F}; \\ e^{-\beta F} & \text{if } F > \hat{F}. \end{cases} \quad (2.3.2)$$

Based on theoretical considerations Liu et al. [141] suggested a power law distribution of forces for the weak contact network (all contacts that bear less than the average force $\hat{F}$) with characteristic coefficient $\alpha$ and an exponential distribution for forces of the strong contact network (contacts that bear more than the average force), with exponential coefficient $\beta$. This relations were confirmed experimentally [148] and independently by numerical simulation [181]. In their Couette cell experiments Behringer et al. [17] were able to show continuous breakage and reformation of such force chains in granular material under shear deformation. These findings support the notion that acoustic emissions from grain contact rearrangement may be strongly enhanced by heterogeneous force distribution in disordered granular materials, especially through high force concentrations, associated with so-called force chains. The failure of such force chains results in abrupt release of relatively large amounts of elastic energy which by itself may generate elastic waves. The force distribution within the contact network constituted by such force chains, as given in Equation 2.3.2, may serve as a starting point for estimation of the amount of energy available for elastic wave generation.

A link between force chain associated rearrangements and acoustic emissions was underlined by Hidalgo et al. [93], who measured AE events from an uniaxially loaded assembly of glass beads. Hidalgo et al. [93] have introduced a statistical model based
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on the assumption that newly formed force chains appear with increasing load before force chain formation ceases at a saturation load. Increasing loading at the same time induces failure of individual chains and subsequent force redistribution is modeled using a variation of the so called fiber-bundle model (for a description of the fiber-bundle model see e.g., Raischel et al. [184], or sec. 6 of this paper). These authors have found a good match between magnitude-frequency distribution of observed acoustic events and statistical characteristics of modeled force restructuring events, giving further indication for the production of AE events by such force network rearrangement.

The onset of shear deformation in most granular materials is associated with the formation of a shear zone in the process of strain weakening (see e.g., Read and Hegemier [185], and references therein). Local deformation induces weakening of the affected zones which leads to further attraction of strain and facilitates the localization of a slip plane. Localization of strain along a shear plane or shear bands in granular geologic material has been treated by a number of authors [166, 13, 50, 67, 171]. Shear band formation is known to be preceded by characteristic patterns of grain rearrangements, namely the promotion of a strong contact network (force chains) bearing disproportionately high loads [182, 153], appearance of rolling [164, 5, 57] and sliding [215] particle contacts. Evidence also suggests a preferential orientation of the strong network along the major principal stress direction [66, 57]. Once a shear zone has been formed, episodic fluctuations of the average number of grain contacts (coordination number) and the local density within the shear zone would be accompanied by sequences of unjamming (shear flow within the mobilized layers of the material) and jamming (hampered shear) [32, 1, 5]. Fluctuations in average contacts per particle also illustrate the continuous destruction and reformation of contact points – an indication that shear zones once formed within a granular material have the potential for emission of elastic waves due to intermittent destruction and formation of contact points.

As pointed out in the previous section there are close relations between the granular temperature (i.e. the random kinetic energy of particles) and the jamming-unjamming transition respectively the onset of shear inside a granular assembly. Tordesillas [217] observed a localized increase of the fluctuating kinetic energy during shear band formation and severe bursts of this quantity during subsequent stick-slip motion in their 2-D simulations of biaxial tests. Comparable features of spontaneous grain network reorganizations were observed in a numerical simulation of a gradually tilted granular bed by Staron et al. [209], reporting an increase in the total kinetic energy of the sloping bed as precursors of large avalanches. In addition they observed a strong increase in contact reorganizations prior to large failure events. Welker and McNamara [235] conducted detailed numerical analyses of failure precursors during biaxial tests on granular media and reported small rearrangement events prior to failure. The signature of such rearrangements is again clearly visible as localized bursts of particle kinetic energy within the system. Additionally such precursor events involve sudden changes in the number of sliding contacts. In their work Welker and McNamara [235] have postulated that measurement of such precursory events and bursts of kinetic energy should be possible by means of acoustic emission method.
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2.3.2.2 Acoustic Emissions Generated by Motion of Liquid-Gas Interfaces

Chotard et al. [40] demonstrated that water evaporation from porous ceramic induced numerous AE events. Similar measurements, taken from tree trunks during water stress that induced cavitation within tree xylem vessels, produces rich acoustic emissions that were used to characterize the level of embolism in the xylem [224, 253]. Hung et al. [97] measured acoustic emissions induced by water flow through gravel to quantify seepage in dams. DiCarlo et al. [51] observed considerable elastic wave generation during imbibition and drainage of sand columns expressed as hydroacoustic signals (propagating primarily through the liquid phase).

These experimental studies demonstrate that rapid motions of gas-liquid interfaces in bulk liquid (i.e., bubbles) or in porous media (fluid displacement fronts) may produce significant and measurable AE. They provide indication that measured AE signals are related to abrupt fluid motion when invading or escaping individual pores (Haines jumps). Chotard et al. [40] attributed elastic wave generation to snapping air water interfaces associated with gas phase invasion. Chotard et al. [40] propose that either rapid acceleration or deceleration of liquid-gas interfaces or subsequent oscillations of the liquid body may be responsible for triggering acoustic waves. Many fluid displacement processes in granular porous media that appear macroscopically continuous may result from numerous microscopic discontinuous rapid interfacial jumps [161]. Given the abrupt nature of pore filling and emptying events induced by macroscopic wetting front displacement during shearing of wet granular media, it seems reasonable to include such jumps into the family of potential acoustic emission sources. In this review we shall concentrate primarily on one process involving rapid motion and reconfiguration of liquid interfaces, that is probably most closely related to shear deformation of wet granular material: namely the rupture of capillary bridges and liquid clusters between particles as depicted in images taken with a high-speed camera in Figure 2.3.2. Characterization of the primary forces at play in this phenomenon is key to understanding AE generation, hence, these will be reviewed in the following.

The surface tension and the internal fluid pressure contribute to a tensile stress that a liquid bridge exerts on the attached particles (given the liquid is the wetting phase). If such a bridge is stretched due to mechanical deformation it ultimately breaks at some critical elongation distance (see Figure 2.3.3) and the elastic interfacial energy stored in the deformed bridge is rapidly released as the newly formed bodies of water seek a configuration of minimum interfacial energy. The released energy (deduced from the bridge geometry) provides an upper bound for the energy of triggered acoustic emission.

Invoking Fisher’s assumption [61] for approximating the shape of a liquid bond between two spheres as toroids and the well known Young-Laplace equation (relating the capillary pressure with the inverse radii of curvature and the surface tension) yield an analytical description of the static bridge force. This functional expression includes interface contact angle $\theta$, the liquid surface tension $\gamma$, the harmonic mean $R^*$ of the grain diameters $R_1, R_2$ $(1/R^* = (1/R_1 + 1/R_2))$, the normalized liquid volume $V^* = V/R^3$ and the separation distance $\delta$ [175]. Generally speaking, the capillary force decreases
with increasing grain separation distance $\delta$. Integration of the bridge force over the separation path determines the rupture energy $W_{\text{rup}}$ released during liquid bond rupture [205]. Willet et al. [236] proposed the following semi-empirical expression for the scaled rupture energy:

$$\frac{W_{\text{rup}}}{\gamma R^2 \theta^2} \approx \frac{2 \sqrt{\frac{\gamma R^2 \theta^2}{\pi^2}}}{0.45 - 0.08 \theta + 0.3 \theta^2}$$

(2.3.3)

The rupture energy defining the maximum available energy for AE generation is relatively small: Rupture of water ($\gamma = 0.072 \text{ N/m}$) bridges between mm-sized glass beads ($\theta \approx 0$) according to Equation 2.3.3 releases energies in the $\mu$J-range ($10^{-6}$J).

Analyses of dynamical deformation of capillary bridges performed by Chen and Tsa-mopoulos [36], Mollot et al. [163] or Zhang et al. [250] have shown by numerical simulations (as confirmed in experiments) that the rupture process involves the formation of a thin liquid thread between the two separating liquid bodies that elongates and finally breaks. The time of formation and breakage of this slender fluid thread is only weakly depended on the experimental conditions. Zhang et al. [250] provide a typical timescale in the range of 1–20 msec for the rupture of a liquid bridge.

In granular or porous media, small amounts of liquid may form complex bond networks between grains and form clusters of particles held together by capillary forces [159, 79, 197]. Deformation of wet granular material usually perturbs the bridge network and eventually leads to rupture of cohesive liquid bonds [62, 159]. Richefeu and Radjai [190] performed numerical simulations of direct shear tests with wet granular material and observe a decrease of liquid bonds between grains within the shear zone.
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Figure 2.3.3: (a) Liquid bridge rupture during shear deformation in wet granular material. (b) Decay of tensile (negative) contact force with distance between two spheres [190].

during deformation particularly when the material undergoes dilation, i.e. volumetric expansion at the onset of shear. According to the results of Richefeu and Radjai [190] the coordination number for tensile bonds decreases by almost one within the first four grain diameters of shear deformation. In other words each grain within the shear zone experiences in average one liquid bond rupture at the onset of shear. Liquid bridges between single grains in general prevail at low degrees of saturation where most of the pore space is occupied by air. With increasing water content large connected clusters of liquid form as coalescence of many bridges, which ultimately inhibit occurrence of liquid breakage. This regime is often termed “funicular” [90, 159] and favors liquid displacement by means of flow above violent breakage events. Correspondingly it would be reasonable to expect less AE activity due to liquid-gas interface displacement at higher degrees of saturation.

2.3.2.3 Acoustic Emissions Generated by Grain Friction

Frictional processes are often associated with vibration, elastic waves or audible sound [2] in certain engineered systems [101, 100, 174] and in geologic materials [195, 239, 241, 240]. Friction induced elastic waves or vibrations are often associated with the following processes: abrasion and deformation of asperities at the contact surface [240, 156], wear and grinding of debris between the surfaces [110], abrupt localized acceleration due to unlocking of the contact asperities and rapid reduction of frictional force [180]. Yabe et al. [241] have shown generation of elastic waves with frequency contents in the kHz range from frictional sliding of two granite surfaces pressed against each others with a pressure of 10 MPa. Measurements of the surface roughness before and after those tests revealed considerable wear of asperities and a smoothening of the rock surfaces as a consequence of sliding experiments. Estimations of the elastic wave source radius suggest that the coherent breakage of asperities at a certain location is responsible for single acoustic emission events. Slider experiments at relatively lower confining pressures (∼ 100 kPa) were conducted by Zigone et al. [252] or McLaskey et al. [156] and gave
indication that elastic waves are generated by single asperity failure. Comparison to synthetic waveforms indicate sudden force release events of $1 - 100$ mN in magnitude to trigger acoustic emission events.

Friction is often described by the Amontons-Coulomb law, in which the force opposing relative tangential motion of two contacting bodies is proportional to the normal stress at the contact plane. A constant sliding friction coefficient $\mu$ is typically introduced to express the relation between normal and friction forces [24]. Experimental evidence suggest limitations to the Amontons-Coulomb relation as the friction coefficient $\mu$ appears to depend on a number of different factors, such as relative velocity of the contact pair, surface wear or temperature [101]. This may result in considerable fluctuations of the friction force despite constant normal load. The dependence of $\mu$ particularly on sliding velocity eventually leads to the formation of different friction regimes such as creep motion, stick-slip sliding (stalled motion interrupted by phases of intermittent slip) or steady sliding [92]. Experiments showed that magnitudes of friction force jumps $\Delta f$ at a constant normal force often possess a power-law probability distribution of the form $P(\Delta F) \sim 1/\Delta F^\alpha$, $\alpha$ being a constant factor. Experimental evidence of such power-law features in dry frictional systems was found by Ciliberto and Laroche [41, 42], Buldyrev et al. [30], or Duarte et al. [56]. At the same time statistics of AE monitored friction between surfaces on a large span of length scales resemble a power-law behavior [234, 137, 195].

Obtaining a functional form of $\mu$ (including its dependence on temperature, sliding velocity etc.) for heterogeneous material represents a major challenge. There are several statistical-conceptual models relying on individual representation of asperities and humps of the contacting surfaces or arrested pieces of debris, with simple failure and interaction laws. Characteristic ongoing fluctuations around a critical state (e.g. the verge of sliding and arrested motion) are often referred to as self-organized criticality [11, 12] and can be represented well with such models. Examples are the Robin-Hood model of self-organized criticality [244] that was used by Buldyrev et al. [30] to reproduce characteristic force jumps during friction tests (using a pin-on-disk tribometer) or variants of the fiber-bundle model [184] for the description of creep [127]. We emphasize that failure of individual structural elements and fluctuations of the friction force, both of which are central features of SOC models, are assumed to be the main mechanisms to generate elastic waves during friction.

It is widely recognized that frictional interaction at particle contacts occurs during deformation of granular material. The importance of grain-to-grain friction was demonstrated in various numerical [215, 46] and experimental [18, 176] studies. It has been shown by Tordesillas and Muthuswamy [219] that microslip events (i.e., frictional slip events of single grain contacts) exert a large influence on the collapse of force chains as they typically affect the weak contacts delivering support for highly loaded grains. Thornton [215] demonstrated with numerical simulations that more than 10% of all contact points are sliding in a granular packing that undergoes shear deformation. Wang et al. [231] performed triaxial tests on samples of loose sand and attribute high rates of observed acoustic emissions primarily to the frictional interaction of sand particles.
2.3.2.4 Acoustic Emissions During Crack Formation

The formation and growth of cracks is a hallmark of brittle failure, which is probably the most common type of material damage monitored by acoustic emissions. An overview of different models of crack formation and fracture progression was given by Vanel et al. [226]. In granular earth materials cracks occur within solid cohesive grain bonds or during abrasive wear or splitting of single particles. Fracturing of grains usually requires high confining loads, that may however be provided even at moderate loading conditions due to inhomogeneous force distributions and stress concentrations at particle contact points. Elastic waves generated during fracturing of brittle solids strongly depend on the crack mode (tensile crack, shear crack or mixed mode crack) and the failure plane orientation, but are also dependent on material elasticity. Sophisticated tools, such as moment tensor analysis, facilitate prediction of amplitudes, frequencies and wave modes emanating from crack opening events in brittle media such as concrete or rock [212, 117, 47, 80]. Moreover, certain statistical features of fracture growth are relatively well understood and provide a sound basis for analysis of acoustic emissions due to brittle failure.

Changes in chemical or physical conditions (pH, temperature, water content) in soils may promote precipitation of different solute species from soil water. An example is the development of Al- or Fe-oxide crusts. In arid climates the extensive precipitation of Ca-compounds can lead to grain cementation [103]. Figure 2.3.4 shows scanning electron microscope images of such grain cementations. In addition to inorganic grain cementation, biological activity (plants, fungi, microbes) may promote formation and enmeshing of soil particles giving rise to aggregation and secondary structures [216]. Growing roots and soil microbes release primarily polysaccharides and polyuronides that have gel like consistency under hydrated conditions, but become stiff and rigid as soil dries [170]. Plant roots play a prominent role for mechanical soil reinforcement [76]. Schwarz et al. [199] and Cohen et al. [45] have recently shown the complexity of rupture of root reinforced soils. Breakage or slippage of individual roots respectively the accumulation of such events represent important failure mechanisms preceding hydromechanical collapse of natural soils (e.g., during landslide release). Considering the fact that straining wood or other fibrous plant tissues is often associated with generation of AE (e.g., Grosse and Ohtsu [80] chapter 12 and references therein), we expect strong root associated acoustic activity of mechanically stressed root-reinforced soils.

The generation of AE by the breakage of grain cementing agents was demonstrated by Wang et al. [231], who observed significant increase of high frequency (100 – 10000 kHz) acoustic emissions during triaxial tests of cemented sands as compared to tests using loose sand specimens. Wang et al. [231] is probably one of the few studies that reported measurements of elastic waves associated with grain bond failure. Nevertheless, a significant amount of scientific work was undertaken to analyze elastic waves from other natural composite or porous materials such as sandstone, gypsum or snow. Although the behavior of those materials could be markedly different than that of cemented soil, certain insights concerning AE could be gained from these studies. Acoustic emissions in sandstone were measured during loading e.g., by Mlakar et al. [160] (uniaxial stress tests),
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Figure 2.3.4: ESEM micrograph of cemented grains: (a) (from Golchert et al. [74]) shows the formation of sodium chloride precipitates at the contact points of granular material. (b) (from Ismail et al. [103]) illustrates calcite crusts cementing grains.

Zhang et al. [249] (hydrostatical compression) and Baud et al. [15], Liakopoulou-Morris et al. [137] (triaxial tests). Experiments concerning mechanical loading of sandstone have frequently used rates of AE events to distinguish different stages of deformation (matrix crackling, grain crushing) as well as to determine the type of ongoing collapse (localized or diffuse failure). Read et al. [186] studied the dominant acoustic frequencies during loading of Darley Dale sandstone and showed that this parameter changes such that high frequency signals (500kHz) occur preferably prior to peak stress while the post failure signals are associated with a lower characteristic frequency (100–200 kHz), also it was observed that the AE amplitudes significantly increase after exceeding peak stress. Read et al. [186] associated this frequency shift with the transition from isolated cracks to coalescence and development of system-wide fractures. Zang et al. [246] distinguished the failure of grain bonds and from frictional sliding of already released grains by analyzing duration and energies of acoustic emissions. High energy events with a duration shorter than 1 msec were generated by fracturing whereas low energy events with longer duration were associated with deformations along existing crack surfaces. Stress jumps during the ductile deformation of gypsum rock samples were monitored by means of acoustic emissions by Brantut et al. [26], who attributed AE signals inside loaded samples to shear band formation and crack propagation.

Acoustic emissions events were observed in snow samples by McClung [155] during progressive deformation. Largely enhanced intensity of the AE rate for fast shear delivered indication towards local shear plane formation while imposing slow shear, giving little acoustic emissions, resulted in snow creep. To describe snow avalanche generation from crack propagation at constant loading McClung [155] makes use of the J-integral introduced by Rice [189]. Palmer and Rice [173] apply the same principle to the propagation of fractures in overconsolidated clay soils, leading them to the conclusion, that the crack propagation zone, i. e. the portion of the material having a stress field disturbed by the fracture, in such material might attain considerable lengths of 0.5 – 2.5 m.

In addition to cracks forming between grains, AE may also emanate from breakage of grains themselves. Relative to bond rupture, crushing of grains typically requires higher
stresses but also releases higher amounts of energy. Karner et al. [118] found that for isotropic loading of loose quartz sand, so in the absence of any grain bonding agents, plastic deformation and significant grain comminution sets in at roughly 100 MPa. Measurements of acoustic emissions during their experiments showed that the rate of AE events shows a significant increase already at a hydrostatic pressure of 40 – 60 MPa, when the material displays still elastic material behavior. With increasing magnitude of compressive stresses the contact network becomes more and more rigid and the primary sources of AE are asperity breakage and grain microcrackling. Hydrostatic compression does typically not admit large rearrangements of the contact network the development of pre-fracture microcracks and wear of asperities inside the high force network might be considered as potential sources of such AE. The concentration of contact forces in a small amount of grains within the total force network (force chains, see Section 2.3.2.1) and the concentration of grain-to-grain forces on a relatively small contact area might cause localized development of fissures and microcracks even at moderate loading. Guimaraes et al. [83] points out the importance of the coordination number for the probability of grain fracture. At low coordination numbers loads on individual particles are concentrated on just a few contact points, which increases the probability of fracture. Analyses based on Hertz contact theory show that stresses around a contact point are not compressional only, but at the circumference of the contact circle tension stresses occur that can induce fracturing of the material in this region (see Figure 2.3.5). These Hertz fractures are described in greater detail by Frank and Lawn [63] or Wilshaw [237]. In addition to the AE that are generated from the micro-crack development around a contact region, Hertz fractures can also serve as nucleation points for further fracture propagation. Depending on their initial size relative to the particle Hertz fractures can either lead to splitting of grains or induce detachment of small chips from particle surfaces (see Figure 2.3.5).

2.3.3 Frequency Ranges and Energies Associated with Acoustic Emissions

Energies and frequency spectra of AE strongly depend on their generation mechanisms. While AE energies can be bracketed for most AE source mechanisms, calculating signal frequencies at the source is typically very demanding. Elastic wave frequency spectra depend, amongst others, on the time scale of energy release, resonance frequencies of involved structures and material properties. In the following we provide a review of maximum available energies and source frequency spectra for different classes of failure associated AE in geologic materials. In some cases we will also give time scales \( \tau \) associated with mechanisms implying a loose connection to the inverse of generated AE frequencies \( f \) \((\tau \sim 1/f)\).

Using Hertz’ contact mechanics the energy required for deformation \( U \) is equivalent to the amount of mechanical work and can be obtained from path integration of contact force (given by Equation 2.3.1). It depends primarily on Poisson’s ratio \( \nu \), Young’s Modulus \( E \) and the effective radius \( R^* \) of the contacting particles as well as on the maximum contact point deformation \( u \):

\[
U = \frac{4}{15} \frac{E}{1-\nu^2} \sqrt{R^*} u^{5/2}.
\]
2 Characteristics of acoustic emissions from geologic granular media

Figure 2.3.5: Grain rupture: (a) Occurrence of localized tensile forces at the fringe of the contact zone between two particles can lead to fracturing of this zone (modified after Zhang et al. [249]) (b) SEM picture of a sand grain with chips being split of its surface by Guimaraes et al. [83].

We note that for perfectly elastic conditions this would also be the amount of work stored in a deformed contact. The elastically stored energy can attain large values in the presence of force chains as the affected contacts might undergo strong deformation. The contact deformation energy may be released abruptly during failure of force chains. However it has been shown that the fraction of deformation energy that is dissipated by elastic wave generation is in the range of a few percents only [98, 99].

An estimate of the time scale of a particle-wall collision may be deduced from Landau and Lifshitz’ energy balance arguments assuming perfectly elastic behavior (see sec. 9 of Landau and Lifshitz [129]). Contact time $\tau$ of such an idealized collision is expressed as integral function of the initial impact velocity $v_0$, and the final displacement $u_0$:

$$\tau = \frac{2}{v_0} \int_0^{u_0} \frac{du}{1 - \left( \frac{u}{u_0} \right)^{5/2}}$$  \hspace{1cm} (2.3.5)

Note that the release of a particle-wall contact (e.g., due to destruction of a force chain) under the given assumptions represents the unloading motion of a corresponding collision and therefore takes $\tau/2$. The above approximation predicts that for a $1 \times 10^3$ m glass sphere colliding at a velocity of $0.05 \text{ m s}^{-1}$ into a wall, the impact time would be $13 \times 10^{-6}$ s. Following the calculation of Landau and Lifshitz [129] it can be found that low impact velocities lead to short contact times, while high impact velocities increase the time that particles are in contact. Cody et al. [43] implied similar assumptions for the estimation of frequencies from grain-wall impacts for fluidized granular material. Using $0.05 \times 10^{-3} - 0.5 \times 10^{-3}$ m mm glass beads colliding with velocities of $0.01 - 1 \text{ m s}^{-1}$, Cody et al. [43] estimate an upper bound for the expected frequency spectrum of about $300 \times 10^3 \text{ Hz}$. 
AE energies for liquid bridge breakage are bound by the rupture energy given in Equation 2.3.3. In their numerical and experimental analyses of liquid bridge dynamics Zhang et al. [250] found that the breakage time of such a liquid bridge depends only weakly on experimental conditions and is in the range of $1 \times 10^{-3} \sim 20 \times 10^{-3}$ s. Interestingly Gauglitz and Radke [69] estimate a similar time scale for the reformation of a liquid bridge in a capillary during snap-off of a gas bubble. Additionally, Lorencau et al. [147] observed that the collapse of a gas-liquid interface at the onset of liquid invasion into a glass pipe typically takes about $20 \times 10^{-3}$ s. We note that the dynamics of liquid bridges is much slower than the solid particle interaction and my therefore have a significantly distinct frequency spectrum.

Friction of two rough surfaces often display force fluctuations with frequency magnitude distributions of the form $1/\Delta f^\alpha$. Buldyrev et al. [30] showed that the frequency spectrum of friction generated AE is strongly determined by this characteristic distribution. Striving to model AE frequencies for tribometer experiments they found that this $1/\Delta f^\alpha$-noise is typically overlaid by the contacting bodies resonance frequencies (for resonance phenomena in tribometer experiments see also the review of Akay [2]). Correspondingly for granular material resonance frequencies are assumed to be determined mainly by contact stiffnesses and particle masses. A microstructural model for AE energies generated during frictional processes was recently proposed by Fan et al. [59] and relies mainly on friction and wear of surface asperities.

From experiments with sandstone samples it is known that fracture of bonds is associated with high frequency acoustic emission. Corresponding measurements were performed by Zhang et al. [249], Read et al. [186], Zang et al. [246, 245], Baud et al. [15] and many others. Read et al. [186] also analyzed the AE spectra generated during deformation of sandstone and found frequencies in the range of 100 kHz.

AE spectra from different source mechanisms are summarized in Table 2.1. From the table it can be seen that grain bridge rupture is assumed to generate very low frequency elastic waves, while grain collisions and force chain release events emit vibrations in the range of 10 kHz. Highest frequencies are eventually generated from frictional sliding and fracture.

### 2.3.4 Wave Propagation in Granular Media

The properties of a measured AE signal (amplitude, spectral content) and its attenuation are critically dependent on source distance and propagation characteristics. Elastic waves propagation in granular materials are influenced primarily by the grain elastic modulus, structural properties, such as porosity or coordination number, and energy dissipation mechanisms. The loss of AE wave energy is attributed to the growing wave front area as a signal radiates away from the source (geometrical spreading), wave scattering, mode conversion and incomplete transmission at internal boundaries and inhomogeneities of the material (apparent attenuation) and the conversion of wave energy into heat (material losses) [232].

The speed of an elastic wave $c$ within a particular medium is of paramount importance for the understanding and modeling of dynamic behavior of materials. Evaluation of the
Table 2.1: Literature review of wave frequencies from different AE source mechanisms:

<table>
<thead>
<tr>
<th>AE mechanism</th>
<th>time</th>
<th>literature source</th>
<th>test procedure</th>
<th>char. freq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>grain collision</td>
<td>$10^{-6}$–$10^{-5}$s</td>
<td>Jiang et al. 2009 [111]</td>
<td>AE measurements of wall grain collisions in a fluidized granular flow</td>
<td>$20 - 80$ kHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cody et al. 1996 [43]</td>
<td>accelerometer measurements of glass bead-container wall collisions in a fluidized granular bed</td>
<td>$10 - 20$ kHz</td>
</tr>
<tr>
<td>fluid interface displacement</td>
<td>$10^{-3}$–$10^{-2}$s</td>
<td>Hung et al. 2009 [97]</td>
<td>AE from water flow in natural soils</td>
<td>$0.8 - 10$ kHz</td>
</tr>
<tr>
<td>frictional sliding of grains</td>
<td></td>
<td>Gardel et al. 2009 [65]</td>
<td>sliding of grains against a silo wall during discharge</td>
<td>$&lt; 10$ kHz</td>
</tr>
<tr>
<td>grain/rock fracture</td>
<td></td>
<td>Read et al. 1995 [186]</td>
<td>3-axial testing of porous rock</td>
<td>$100 - 600$ kHz</td>
</tr>
</tbody>
</table>

Hertzian contact theory shows, that wave propagation velocity in dry granular media is proportional to the $1/6$-power of the applied confining pressure [139, 140, 138, 109, 72]. The origins of a discrepancy between this theoretical prediction and experimental observations, indicating a $1/4$-power dependency is a matter of ongoing debate (for a summary see Somfai et al. [207]). Nevertheless, theory and experiments clearly show that confining stresses in granular materials exert a crucial influence on propagation of acoustic signals. Measurements by Domenico [55] show that the compressional wave propagation velocity in glass beads ranges from $813$ m/sec to $1571$ m/sec for confining pressures of $270 - 3400$ kPa. In unconfined sand the propagation velocity can be as low as $280$ m/sec [140]. Somfai et al. [207] pointed out that despite occurrence of large differences in contact forces due to force chain formation, the stiffness of the contact network, and thus the propagation speed of elastic waves, exhibit a much higher degree of homogeneity. Consequently, elastic waves propagate relatively uniform even through a granular assembly that contains a highly non-homogeneous force network.

Descriptions of acoustic wave propagation through heterogeneous porous or granular media [68, 52, 10, 73] usually make use of the effective medium theory, tacitly assuming that wavelengths (given by the ratio between wave speed $c$ and frequency $f$) exceed the size of particles. Signals, with wavelengths of the order of less than a few grain sizes experience strong scattering at the interfaces between particles. The seismological term “coda wave” has been introduced into the field of granular acoustics by Jia [108] to describe this phenomenon (in contrast with coherent wave propagation). A strong apparent attenuation of coda waves may lead to highly reduced propagation distances compared to coherent waves. Jia [108] found a strong susceptibility of such short-wavelength acoustic signals to the internal organization of granular material, as even the
change of one contact along the travel path of a coda wave may alter the characteristics of the signal. Tournat and Gusev [221] showed that a high frequency (and correspondingly short wave length) acoustic signal is decomposed into a highly scattered coda part and a low-frequency coherent part by demodulation along its propagation path through a packing of glass beads. This wavelength-specific decomposition leads to an inherent cut-off of high frequency waves, undergoing strong scattering and therefore quickly attenuating, in heterogeneous media.

Experiments have shown that the presence of water, filling pore spaces between grains, strongly influences wave propagation properties of the medium [167, 227, 168, 133, 70, 149, 78]. Capillary bridge forces may provide additional contact stiffness leading to better acoustic propagation, but on the other hand, motion of contact lines and viscous damping may promote attenuation of elastic waves. Significant contributions to the understanding of elastic wave propagation in water-filled granular media were made by researchers focusing on marine sediment acoustics [20, 211, 8, 29, 131]. Various models exist to describe elastic wave propagation in porous material under partially [154, 142] and fully saturated conditions [20, 19, 29]. The significance of pore water can be seen in various experimental studies such as by Brunet et al. [27], reporting changes of elastic wave attenuation in confined sand after the addition of even small amounts of water or the study of Velea et al. [227], showing strong variations of the wave velocity with changing water saturation.

For their tremendous capacity of granular matter to dissipate energy, as it was discussed in chapter 3.1, granular materials are very efficient attenuators of elastic waves. Apart from strong apparent attenuation of short wavelength acoustic signals, resulting in the coda-wave phenomenon, elastic waves undergo damping also due to material losses [86, 196], i.e., dissipation through heat production. Jackson and Anderson [106] point out that the effects of matrix inelasticity and frictional dissipation at grain boundaries are important sources of material loss in dry porous rocks. In their review on elastic wave attenuation in air-dry and wet sand Wang and Santamarina [232] state that for small strains ($\gamma \leq 10^{-5} - 10^{-6}$) (strains caused by acoustic waves have a similar order of magnitude [27]) frictional dissipation at grain contacts may become irrelevant and thermoelastic losses presumably deliver the largest contribution to attenuation. In their study the authors also underline the importance of liquid in granular materials for elastic wave attenuation. In water saturated materials, such as marine sediments, viscous losses due to liquid displacement and liquid-solid interaction deliver further contributions to attenuation [19, 115, 211]. For a recent review of attenuation experiments in marine sediments see Holmes et al. [95].

Elastic wave attenuation can be quantified by different measures [23], probably the most commonly used is the dimensionless quality factor $Q$ and the attenuation coefficient $\alpha$ with dimensions dB/m. Both, the quality factor and the attenuation coefficient are strongly dependent on the frequency of a signal. While $Q$ can be interpreted as the relative energy loss per one wave cycle [120], $\alpha$ is defined as logarithm of the ratio of two amplitudes measured at different distances from the source. Conversion between those two measures of attenuation can be performed, using the wave velocity $c$ and the
Table 2.2: Literature review of elastic wave attenuation in different earth materials under dry and wet conditions.

<table>
<thead>
<tr>
<th>Literature source</th>
<th>Material</th>
<th>Wat. cont.</th>
<th>Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nyborg et al. 1950</td>
<td>Sand</td>
<td>Dry</td>
<td>1-7 dB/cm at 10 kHz and 5-13 dB/cm at 26 kHz</td>
</tr>
<tr>
<td></td>
<td>Silt loam soil</td>
<td>Air dry</td>
<td>1-22 dB/cm at 10 kHz and 5-26 dB/cm at 26 kHz</td>
</tr>
<tr>
<td>Koerner et al. 1981</td>
<td>Sand</td>
<td>Dry</td>
<td>0.09 dB/cm at 0.5 kHz and 10.0 dB/cm at 16 kHz</td>
</tr>
<tr>
<td></td>
<td>Clayey silt</td>
<td>Variable</td>
<td>1.9 dB/cm at dry and 1.0 dB/cm at saturation</td>
</tr>
<tr>
<td>Oelze et al. 2002</td>
<td>Various soils</td>
<td>Variable</td>
<td>0.1 dB/cm-kHz at dry and 1.0 dB/cm kHz at saturation</td>
</tr>
<tr>
<td>George et al. 2009</td>
<td>Silt</td>
<td>Variable</td>
<td>0.2 $Q^{-1}$ at saturated and 0.02 $Q^{-1}$ at unsaturated conditions (at 20 kHz excitation)(^1)</td>
</tr>
<tr>
<td></td>
<td>Loamy sand</td>
<td>Variable</td>
<td>0.4 $Q^{-1}$ at saturated and 0.01 $Q^{-1}$ at unsaturated conditions (at 20 kHz excitation)(^2)</td>
</tr>
<tr>
<td>Leong et al. 2004</td>
<td>Mudstone</td>
<td>Dry</td>
<td>203 - 216 dB/m</td>
</tr>
<tr>
<td></td>
<td>Residual soil</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ Q^{-1} = \frac{c}{\pi f^\alpha} \]  

(2.3.6)

In unconsolidated loose granular materials attenuation can be as high as 25 dB/cm [167], which means that elastic waves are attenuated within a few centimeters of propagation in an extreme case. Table 2 gives an overview of various experimental studies concerning elastic wave attenuation within geologic granular materials and underlines the strong variability of this property on influencing factors. There is a general trend that attenuation decreases with decreasing frequency [132], increasing confining stresses [86] and decreasing fluid saturation [232, 78].

### 2.4 Statistics of Acoustic Emissions in Granular Geologic Materials

Given the large number of grain interactions and associated AE generated during these microscale failures we may use statistical characterization of acoustic emissions for non-invasive assessment of the mechanical state (and its evolution) of the stressed sample. Certain statistical signatures of precursor may provide information of reaching a global, macroscopic critical state.

\(^1\)corresponds to \(\approx 0.12\) dB/cm at saturated and 0.03 dB/cm at unsaturated conditions  
\(^2\)corresponds to \(\approx 0.26\) dB/cm at saturated and 0.001 dB/cm at unsaturated conditions
Experiments on rocks and other brittle materials such as concrete, wood, fiberglass, or paper, have shown that acoustic emissions generated during progressive failure display power-law frequency-amplitude distributions [162, 198, 94, 143, 64, 9, 113, 194] of the form

$$\log N(>A) = a - b \log A, \quad (2.4.1)$$

where $N$ is the cumulative number of events greater than amplitude $A$, and $a$ and $b$ are constants. The exponent $b$ varies usually between 1 and 2 and may depend on rock type and degree of heterogeneity [162], shear stress and confining pressure [198, 6], or temperature in fractures produced by thermal stresses [233]. Power-law scalings like Equation (2.4.1) have also been found for waiting time and energy distributions [192] with $b$ values in the range of 1.2–2 for energy and 1–1.3 for waiting times. The scaling in Equation (2.4.1) is identical to the Gutenberg-Richter relation for earthquakes [84] with $b$ taking on values around 1. These power-law behaviors are indications of scale-free dynamics and are typical of large complex systems with many degrees of freedoms often interpreted in the context of criticality and phase transitions [202].

Power-law distributions of AE may fluctuate with time, or equivalently with progressive failure or deformation. To better understand earthquake mechanics, pioneering laboratory studies on rocks have measured variations in the $b$-value of acoustic emissions associated with slip events between rock surfaces [234] and with brittle rock fracturing [77, 143]. In general, the value of $b$ decreases with stress or deformation as the system approaches global failure. This indicates a greater proportion of large failure events. Lockner [143] associated changes in the $b$-value to various stages of crack nucleation and growth. Lavrov and Shkuratnik [130] attributed the decrease of $b$ with increasing stress to the coalescence and fracture of larger cracks, indicators of progression towards a macroscopic scale and thus towards global failure. Main et al. [151] explained the decrease in the $b$ value observed in earthquakes [229, 112] using a fracture mechanics model for increasing stress intensity factor at tensile crack tips with progressive failure. Similar observations of changes in the power-law exponent have been made for concrete [33], wood and fiberglass [81], and kevlar and fiber-matrix composite vessels [9, 113] when approaching global failure. These experiments prove that under controlled laboratory conditions, detectable $b$-value changes linked to AE activity can be used as an indicator of precursor events prior to global failure. In field studies in rock mines [126, 16], recordings of AE have shown spatial and temporal variations in $b$ values associated with microcrack formations, differences in rock type, and thermal unloading. Other than for earthquakes and rock mines, observations of changes in the power-law exponent in natural systems are rare: [204] recorded fluctuations in the power-law exponent during slope failure but failed to find a consistent trend; [7] observed a marked decrease in the power-law exponent of the distributions of signal energy recorded by geophones a few hours before the collapse of a rock cliff.

Statistics of acoustic emissions have also been used to infer properties of granular materials. For example, [39] measured AE frequency-size distributions during cyclic triaxial compression experiments with sand as a function of differential stress. They noted wider distributions with higher amplitudes at higher differential stress which they
attributed to failure of larger normal and frictional contact forces between grains. [93] measured acoustic emission activity during uniaxial compression of glass beads and observed power-law frequency-amplitude statistics which they associated with failures of force chains. Distributions of normal and shear forces in force chains, however, are exponential above the mean [141, 181, 165, 148, 21].

Statistics of AE offers instantaneous and noninvasive insights into the mechanical state of geologic materials (composed of numerous mechanical elements) during deformation. For brittle geomaterials, the link between AE statistics and the failure process is relatively well established, as it is often related to characteristic power-law behavior. This link, however, remains to be developed and exploited for granular materials. Identifying signatures of acoustic emissions in granular materials that vary statistically during loading and progressive failure may be the most effective way of monitoring natural systems such as soils on slopes in an effort to devise advance warning systems for imminent slope failure.

2.5 Linking AE with Models of Progressive Failure

The discrete nature of acoustic emissions lies in their association with failure of individual elements, such as a grain bond or a force chain. When an element breaks, the load carried by the element must be redistributed to the remaining intact elements. This load redistribution may lead to secondary failures of elements and triggers avalanches of failures before the load is distributed to a sufficient number of intact elements to return to a (marginally) stable state. If a failure cascade involves all load-bearing elements of the structure, global collapse occurs marking the final stage of progressive failure behavior. Progressive material degradation should also cause avalanches of acoustic emissions. Indeed the accumulation of AE events during failure progression episodes was observed by researchers working on the mechanical stability of geomaterial and a number of studies were mentioned in previous sections. Models capable of describing progressive failure hold great value for the interpretation of acoustic emissions towards identification of predictors for global failure.

A conceptual framework holding such a promise is the fiber bundle model (FBM) which idealizes and represents a disordered material as a bundle of parallel, linear elastic fibers [49, 206, 88, 3]. In the classical FBM all fibers have the same elasticity while the stress at which they fail is different for all fibers and is assigned randomly according to a characteristic probability distribution function. When a bundle of such fibers is loaded in tension it exhibits progressive failure behavior: following an increase in stress, the currently weakest fiber breaks and its load is redistributed to the remaining fibers possibly triggering larger burst avalanches. Increasing stress will gradually break the fiber bundle. Although each fiber is linear elastic, the bundle behaves as a non-linear material. Also, frequency-size distribution of avalanches exhibits a cumulative distribution that is power-law with an exponent of 5/2 [88, 183, 179]. While simple versions of the fiber bundle model can be described analytically, numerical calculations are used to formulate variants of the model that incorporate more complex rules (for a more
Figure 2.5.1: Fiber bundle model for slope stability monitoring: (1) plant roots and (2) force chains in granular earth material resemble fiber bundles. Similarly their fracture emits acoustic emissions.

comprehensive review of the fiber-bundle model see Raischel et al. [184] or Pradhan et al. [177]). Although the FBM in its original formulation reproduces purely tensile loading it can be easily adapted to account for creep rupture or shear failure of disordered materials [127]. By specifying a healing condition for broken fibers the model can also mimic residual strength and stick-slip behavior [85] as it occurs in geomaterials at high strains. Using a healing-fiber FBM. Reiweger et al. [188] modeled shear failure of weak snow layers accounting also for resintering of broken ice crystals within the shear zone. Failure mechanisms that govern the collapse of geologic granular materials and that may be represented using FBMs are shown in Figure 2.5.1: Progressive plant root failure were described as representation of a FBM recently by Cohen et al. [45]. Force chains typically form in stressed granular material and their ongoing destruction and reformation is a characteristic feature of shear deformation. Simulation of this process using a FBM seems therefore promising and might allow to model force chain associated AE [93]. Theoretically a close correspondence between individual fiber failures and associated acoustic emission events are expected. Bursts of fibers during avalanching may release considerable elastic energy generating large acoustic emissions. Some of this energy may be lost in the formation of a new cracked surface and in heat. Bosia et al. [22] and Pradhan and Hemmer [179] have estimated energy released during stress loading of a fiber bundle model and predict power-law growth of the cumulative energy and power-law distribution of burst energy. In modeling fatigue using the so-called dynamic FBM, Turcotte et al. [223] predict that the cumulative energy as a function of time scaled to the failure time is also power law. These models are in accord with acoustic emission measurements obtained on tensile tests of fibrous materials [9, 82, 113, 33].
The fiber bundle model predicts that the distribution of event magnitudes evolves during progressive failure [178] owing to the exponential cutoff of the power-law distribution at high event magnitude. In practice, this change of the shape of the failure distribution has been used to analyze acoustic emission data from failing rocks and fit the change to changes in the power-law exponent $b$ [7]. Cohen et al. [44] presented a comparison between the data of Amitrano et al. [7], with the FBM showing the good fit of the model to the data (Figure 2.5.2). Hence, the FBM has the potential to identify precursor events of global failure through identification of changes of the event and energy distribution of fiber bursts. The same method could be applied to acoustic emission of deforming granular materials although this mechanism has yet to be identified for such materials.

### 2.6 Acoustic Emission Applications in Earth Sciences

Table 3 provides an overview of studies reporting the use of AE in granular geologic materials and selected work on other types of granular matter. We mentioned earlier that the first systematic assessment of the AE method for geotechnical applications is attributed to Koerner, who published amongst others a study on AE monitoring of granular [121] and cohesive [122] soils subjected to loading. Koerner recognized the possibilities of AE in field applications and mentioned the importance to find solutions for massive wave attenuation [123] in soils.

Attempts to circumvent limitations imposed by strong acoustic signal attenuation in soils involve deployment of waveguides (see Figure 2.5.1) especially for field applications. Using metal rods as acoustic wave guides [38] demonstrated that ground displacement...
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in natural slopes generate significant AE. The authors report further that AE signals in some cases were measured days before displacement was visible on the land surface. Similarly [193] detected AE (frequency band ranging from $1 \times 10^3$ Hz to $7 \times 10^3$ Hz) events using metal waveguides in landslide prone slopes. In their experiments the authors measured a change of the signal characteristics during heavy rainfalls. Although metals have the advantage of being very rigid and therefore easy to deploy, typically there is a strong mismatch of acoustic impedances between them and earth materials. This can lead to undesirable, strong signal reflections at the interface between the waveguide and the host material. [204] have addressed issues related to efficient waveguide design for landslide early warning, in which they evaluated the performance of PVC and composite materials as AE waveguides. [53, 54] propose the use of “active waveguides”, i.e. conventional waveguides that are placed in a borehole and backfilled with coarse sand or gravel that generates secondary signals during deformation. Overcome the issue of acoustic emission attenuation, active waveguides are, however, not designed as a low attenuation link between soil and sensor but to generate acoustic emissions themselves during deformation of the host material.

An attractive natural waveguide could rely on tree roots embedded in soil as a basis for soil failure monitoring (see Figure 2.5.1). Wave attenuation in wood is much lower than in soil. We pointed out in Section 2.3.2.4 that tree roots constitute a network of natural fibers eventually involved in progressive failure of a natural slope. However the rupture of roots may not be the only source of AE within trees, as also externally produced elastic waves may take advantage of the low attenuation properties within the tree root system leading to detectable root AE. The root system of a tree states a natural network of waveguides that is present in every forested slope. We note however, that tree roots reinforce their surrounding soils and thus may provide a biased picture of locations of landslide initiation (that might develop preferably in areas not reinforced by tree roots).

Recent advances in fiber optic technology and its application to measurement of strains and AE in geological media offer an exciting array of possibilities for overcoming attenuation and deployment of distributed AE sensing networks [157]. [201] enumerate a list of successful field-scale applications of fiber-optic temperature measurement, which necessitates the very same principles as strain or vibration measurements, and demonstrated usefulness and potentials of the fiber-optic technology for hydrological and geophysical investigations. Successful application of fiber-optic based strain measurements in a geotechnical context were reported by [48, 104, 230, 247, 105]. Although technical specifications vary among techniques and manufacturers, fiber-optic AE measurements may resolve events at meter scale along kilometer long fiber optic cables at very high temporal resolution.

Several studies have attempted to complement standard geotechnical lab tests with different forms of acoustic and vibration monitoring. Examples of AE monitoring during oedometric compression, triaxial tests, cone penetrometer tests, and shear tests can be found in Table 2.3. A large amount of work has been done for studying different forms of active acoustic emissions in geo-materials: in a review paper on the use of bender elements, i.e. piezoelectric shear wave transducer, Lee and Santamaría [131] summarize techniques to extract soil mechanical properties from measurement of shear wave that.
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Table 2.3: Experiments from the literature involving measurements of acoustic emissions in earth material and other granular media.

<table>
<thead>
<tr>
<th>Author</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dixon et al. 2003 [53], Dixon et al. 2007 [54]</td>
<td>Field measurements of an unstable slope using AE</td>
</tr>
<tr>
<td>Chichibu et al. 1989[38]</td>
<td>Field measurement of AE in an unstable slope, waveguide application</td>
</tr>
<tr>
<td>Rouse et al. 1991 [193]</td>
<td>Measurements of microseismic emissions in a landslide prone slope during heavy rainfall</td>
</tr>
<tr>
<td>Fernandes et al. 2010 [60]</td>
<td>AE from oedometer tests with sand</td>
</tr>
<tr>
<td>Tanimoto et al. 1981 [214]</td>
<td>AE during triaxial testing of soils specimens</td>
</tr>
<tr>
<td>Wang et al. 2009 [231]</td>
<td>AE during triaxial tests with loose and cemented sand</td>
</tr>
<tr>
<td>Chodyn and Zuberek 1992 [39]</td>
<td>AE from triaxial tests with sand and from borehole in sand pit</td>
</tr>
<tr>
<td>Villet et al. 1981 [228]</td>
<td>AE from cone penetration tests in soils</td>
</tr>
<tr>
<td>Huck and Koerner 1981 [96]</td>
<td>AE from hydraulic fractures in soil and rock</td>
</tr>
<tr>
<td>Chotard et al. 2006 [40]</td>
<td>AE from water flow during seepage</td>
</tr>
<tr>
<td>Mair et al. 2007 [152]</td>
<td>AE from fault gouge between two rock surfaces</td>
</tr>
<tr>
<td>Yabe et al. 2003 [241]</td>
<td>AE from frictional sliding of two rock surfaces</td>
</tr>
<tr>
<td>Karner et al. 2003 [118]</td>
<td>AE from grain fracture during isotropic loading of sand</td>
</tr>
<tr>
<td>Hidalgo et al. 2002 [93]</td>
<td>AE measurements from static glass bead assembly</td>
</tr>
<tr>
<td>Gardel et al. 2009 [65]</td>
<td>Piezoelectric force measurements during dense granular flow</td>
</tr>
<tr>
<td>Jiang et al. 2007 [111]</td>
<td>AE from granular gas random motion</td>
</tr>
</tbody>
</table>

are artificially generated by piezoelectric pulser within the sample material.

2.7 Conclusions

The implementation of the acoustic emission (AE) method for passive monitoring and characterization of micro scale mechanical failure events in geological material hold a great promise for process understanding and potential early warning systems. The method can be used to observe progressive failure of granular geologic material in lab experiments and to monitor the triggering of landslides or other earth material movements in field applications, complementary to existing techniques.

We have reviewed elastic waves in granular geologic material released during progressive failure and suggest that their generation is primarily due to grain contact rearrangement (i.e. grain-to-grain collisions and rapid removal of contact points), liquid bridge rupture, frictional sliding and crack formation in grain cementing agents and particles. We found reasonable support for the assumption, that all those mechanisms generate elastic waves within the AE frequency spectrum. Generated acoustic emissions are altered and strongly attenuated while propagation through granular materials. For widely used AE sensing technology based on individual piezoelectric sensors, the
usefulness of different acoustic waveguides was demonstrated by a number of studies reviewed in this work. In addition to artificial structures, we propose the assessment of tree roots as natural waveguides, as we are not aware of studies published on this issue. Fiber-optic based sensors present an attractive alternative to point measurements and thus may pave the way to large distributed monitoring networks circumventing issues of signal attenuation limitation AE application over practical field scales of interest.

Amongst statistical methods applicable on AE data records, b-value analysis is maybe most prominent. The b-value is the slope of empirical power-law distributions of occurrence frequencies and changes are known to stand in closed relation with progressive failure of disordered material. We have discussed benefits and potential applications of conceptual statistical models such as the fiber bundle model (FBM) in combination with the AE method to analyse and predict progressive failure evolution in granular geologic materials. Conceptual failure models are able to reproduce pre-failure accumulation of acoustic events and may help to identify changes of AE statistics at imminent failure. Additionally AE measurements bear a great potential to be linked to deterministic discrete element models of granular materials which up to now remain often the only way to investigate grain network changes of micro-mechanical processes within granular materials.

Literature


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2 Characteristics of acoustic emissions from geologic granular media


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3 Fiber Bundle Models for Stress Release and Energy Bursts during Granular Shearing

Published paper in *Physical Review E*, 2012, 86, 061307

Abstract

Fiber bundle models (FBMs) offer a versatile framework for representing transitions from progressive to abrupt failure in disordered material. We report a FBM-based description of mechanical interactions and associated energy bursts during shear deformation of granular materials. For strain controlled shearing, where elements fail in a sequential order, we present analytical expressions for strain energy release and failure statistics. Results suggest that frequency-magnitude characteristics of fiber failure vary considerably throughout progressive shearing. Predicted failure distributions were in good agreement with experimentally observed shear stress fluctuations and associated bursts of acoustic emissions. Experiments also confirm a delayed release of acoustic emission energy relative to shear stress buildup, as anticipated by the model. Combined with data-rich acoustic emission measurements, the modified FBM offers highly resolved contact-scale insights into granular media dynamics of shearing processes.

3.1 Introduction

Shearing of granular media is of relevance to many natural and engineering processes such as earthquakes, landslides or the mixing of powders and building materials. A common feature to all of these processes is their non-smooth mechanical behavior, reflecting the collective response of many load-bearing elements. Reaction to loading may involve difficult-to-predict failure of elements, progressive contact network destruction, and ongoing formation of new contacts. Under strain-controlled loading cyclic destruction and formation of force network elements may result in fluctuations of shear stresses. Stress-controlled loading in contrary induces abrupt and jumpy changes of material deformation. Notwithstanding the apparent symmetry between the two scenarios, there are fundamental differences, rooted in the capability to redistribute stresses only amongst mechanical elements of a granular assembly. Hence, in stress-controlled systems disordered materials exhibit avalanches of element failure, marking abrupt stress redistribution-driven rupture events that may cascade through many elements simultaneously [3]. Conversely, under strain-controlled loading rupture events happen sequentially. Resulting discrete force jumps [26, 12, 21] provide a virtual “force microscope”
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for the observation of granular media deformation, as they reflect intrinsic properties of the material (grain size, particle roughness, force distribution, characteristic force correlation length) [21] and the nature of loading or characteristics of jamming [10]. Such fluctuations may also reflect localized precursors or markers for larger breakdown events [36, 40]. Discrete force-release events may serve as potential tools for linking grain-scale contact restructuring events with macroscopic mechanical behavior of the material [9, 40]. In this work we report theoretical derivations and experimental results linking shear-induced stress jumps with bursts of strain energy release within the material measured by acoustic emissions. A simple process model offers a means for deducing information on load-bearing elements and material constitutive behavior from force jumps and associated energy release events.

Load-bearing elements in granular materials occur at different scales, ranging from single grain contacts, to force networks comprising many particles. Distribution of contact forces in granular material obeys typically an exponential frequency-size distribution over a wide range of magnitudes, as was demonstrated in experimental [4, 17] and numerical [18, 38] studies. Various conceptual models [22, 8, 42] were proposed in this context to capture inhomogeneous stress distribution and exponential falloff of high magnitude contact forces. Highly stressed contacts often align in the direction of the principal stresses forming a network of so-called force chains. These pillars, comprising strongly loaded grains, contribute significantly to internal stress transmission within granular media and occur both in statically confined [28, 23] and sheared [26] assemblages. Continual destruction and reformation of force chains during shearing contribute to fluctuations of grain network forces and lead to measurable jumps in macroscopic shear stresses that represent the integrated mechanics of the granular assembly [1]. Force chains in slow granular flows may persist over several grain diameters of shear displacements [5]. Nevertheless, direct observations of grain contact forces and failure-associated rearrangements of the force network remain a challenge and have been obtained with great effort only for special configurations such as small, static assemblies [23] or two-dimensional systems [24].

Considering the challenges of observing force redistribution at the grain scale, a promising tool involves capturing of failure-associated strain energy release events by measurements of acoustic emission (AE) or microseismic (MS) signals [25]. These are rapid, transient and typically small magnitude, elastic waves generated within deforming granular assemblages, solids, and composite materials. They are characterized by frequencies in the range of 100 Hz to 1000 kHz. Providing access to abrupt restructuring events of the force network [34, 41], AE and MS present a rich surrogate for previously unobservable quantities.

Fiber bundle models (FBMs) have been developed for modeling rupture and internal failure events within disordered materials. FBMs were used already for a wide range of phenomena, such as tensile failure of fiber-reinforced-composite materials [27], creep failure of glued interfaces [31, 20], formation and release of force concentrations in compressed granular materials [16], and representation of energy release events in materials close to breakage [37, 30]. FBMs describe the response of many mechanical elements (fibers) to an external load. Individual fibers are typically assigned identi-
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Figure 3.2.1: Rupture sequence due to straining of a single fiber from FBMs with different disorder types, having thresholds $t^*_i$ drawn from a statistical distribution $p_t$ (a). For quenched disorder (b) each fiber retains the same threshold ($t^*_0$) after failure, while for annealed disorder (c) new values ($t^*_0$, $t^*_1$, $t^*_2$, $t^*_3$, ...) are drawn consecutively. Insets of panels (b) and (c) show shearing of regular and disordered granular assemblies as potential applications of different FBM types.

cal constitutive (stress-strain) behavior but fail at different threshold strengths selected randomly from a statistical distribution. During load application weak fibers break first and stronger ones survive longer. Under displacement-controlled loading conditions this leads to fluctuations of the resulting force. Although originally devised for tensile loading conditions, there are examples of FBMs for compressive failure [16, 19], material damage from bending [35], shearing deformation [33], and combined modes of failure [6, 7]. FBMs simulating granular shearing were reported by Hidalgo et al. [16], Dalton et al. [10] and Geng et al. [12]. Most of the present studies on FBM are centered on constitutive stress-strain behavior and failure avalanches under stress-controlled conditions. Failure-induced discrete energy release events, however, have not received much attention in the literature so far, despite their great potential as a key to link modeled fiber rupture with experimentally observed shear-induced grain rearrangement [37].

This study presents analytical solutions for strain energy release and failure statistics from different types of FBMs under strain controlled deformation. In addition to the classical FBM, a recently presented type of FBM [13, 14] is used, capitalizing on strong conceptual analogies between element behavior and granular material force network reformulation. We compared simulation results against force and AE measurements from shear-frame experiments. Based on this comparison the FBM provides insights into the physics of shearing-induced force network changes, their statistical features, and how they determine the material mechanical behavior.

3.2 Energy release from strained fiber bundles

In its standard form, the FBM [11] consists of a large number of individual fibers with initial length $l_0$ and linear elastic behavior, attached to stiff plates at both ends. The
fiber bundle is loaded by moving the plates relative to each other. Fibers are assigned constant and uniform Young’s modulus $E$ and cross section area $A$, ensuring simple and direct conversion between fiber stresses, strains, and elongations. For simplicity, we assume that fiber bundle shear strain can be converted straightforwardly into normal strain of fibers. Critical deformation of a fiber is given by a unique rupture strain $t^*$, which is assigned stochastically from a probability distribution with density function $p_t$ and cumulative density $P_t$. Different probability distributions have been used for the determination of rupture thresholds (e.g., normal, exponential, Weibull) and lead to a wide range of stress-strain relations [32]. When a fiber breaks at its threshold strain $t^*$, the total stress of the bundle drops by the magnitude of $(Et^*)$ and under the given assumptions the stored strain energy of the fiber, $u^*$, is released:

$$u^* = \frac{EA}{2} t^*^2.$$  \hfill (3.2.1)

### 3.2.1 Simple fiber bundle model

For the simple FBM, the total mechanical work $W$ on a bundle to attain a loading strain $\varepsilon$ is obtained by integration of stresses within the fraction of intact fibers $1 - P_t(t)$ over the loading history:

$$W = EA \int_0^\varepsilon t \ [1 - P_t(t)] \ dt$$

$$= \frac{EA}{2} \varepsilon^2 [1 - P_t(\varepsilon)] + \int_0^\varepsilon \frac{EA}{2} t^2 p_t(t) dt.$$  \hfill (3.2.2)

The integration variable $t$ marks the threshold of all fibers that fail at a certain strain. For the simple FBM this quantity reflects the past loading strains applied to the bundle. Integration by parts yields the second line of Equation (2), illustrating that $W$ is partitioned into strain energy stored in the intact fibers (first term) and strain energy lost due to fiber failure over the loading history (second term). The integrand of the second term expresses the rate of strain energy release at a given bundle loading strain:

$$\frac{dU}{d\varepsilon} = \frac{d}{d\varepsilon} \int_0^\varepsilon \frac{EA}{2} t^2 p_t(t) = \frac{EA}{2} \varepsilon^2 p_t(\varepsilon).$$  \hfill (3.2.3)

This expression for the standard FBM describes the ongoing change in released strain energy $U$, and is closely related to the progressive loading and failure of the bundle. The released strain energy represents a dissipation mechanism that constantly removes energy from the mechanical system by means of fiber rupture events. For displacement-controlled loading, $U$ depends on the applied bundle strain $\varepsilon$ and the probability density $p_t$ of fiber strengths. The continuous release of strain energy from the bundle is maintained throughout the strain path by fibers, having a rupture threshold exactly corresponding to the current loading strain.
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Figure 3.2.2: (a) Modeled shear stress $\tau_{FBM}$ (Halász and Kun [13], their Equation 4) and (b) energy release rate $dU_{FBM}/d\varepsilon$ for simple ($k_{\text{max}} = 0$) and annealed disorder ($k_{\text{max}} = \infty$) fiber bundles using Weibull probability functions for fiber thresholds with scale and shape parameters set to $\lambda = 1$ and $m = 1, 2, 5$, correspondingly. Panels on the right-hand side show experimental data for comparison: (c) measured shear stress ratio $\tau/\sigma_N$ and (d) acoustic energy released during discrete events per unit displacement $dU_{AE}/d\varepsilon$. Insets show exemplary close-ups of a shear test data record: Measured shear stress ratio $\tau/\sigma_N$ (upper panel) exhibits distinct jumps resulting in the saw tooth shape of the stress curve. Discrete acoustic bursts ($U_{AE}$) were observed at strains coinciding with stress jumps (lower panel) underlining a close link between both. Vertical gray lines are drawn to guide the eye and indicate significant stress jumps.

3.2.2 Quenched disorder fiber bundle model

Recently Halász and Kun presented a new type of FBM [13, 14] where fibers are reintroduced following rupture and thus may experience several cycles of loading and failure. Reminiscent of the continual destruction and reformation of grain contacts and force chains, their FBM provides a starting point for simulation of shearing of granular material. The maximum number of rupture events a fiber can undergo beyond the standard FBM is given by the parameter $k_{\text{max}}$, ranging from 0 to $\infty$. After breaking $k_{\text{max}}$ times, a fiber is permanently removed from the bundle. Post rupture mechanical behavior of fibers can be adjusted to represent different types of material behavior. Here we consider two types of fiber replacement rules: quenched disorder implies the restoration of a broken fiber with the same rupture threshold (Figure 3.2.1b); annealed disorder consists in the replacement of failed elements with a new threshold drawn from the original probability distribution $p_t$ (Figure 3.2.1c).

Similar to the standard FBM, fibers in the quenched disorder FBM break at a loading
strain if it is equal to their rupture threshold ($\varepsilon = t$), but also if $\varepsilon = 2t$, $\varepsilon = 3t$, up to $\varepsilon = k_{\text{max}}t$. A fiber that has failed $k$ times and is about to break again at $\varepsilon$, will experience a strain of $\frac{\varepsilon}{k+1}$. To obtain an expression of the rate of energy release induced by ruptures, we consider the probability density that a fiber will fail the $(k+1)$-th time when incrementing the strain infinitesimally, $p_t^{(k+1)} = \frac{1}{k+1} p_t^{(k)}$ (see Halász and Kun [13], their Equation 7). Thus, the rate of energy production at loading strain $\varepsilon$ for the bundle is

$$\frac{dU}{d\varepsilon} = \frac{EA}{2} \varepsilon^2 \sum_{k=0}^{k_{\text{max}}-1} p_t^{(\frac{\varepsilon}{k+1})} \frac{1}{(k+1)^3}. \tag{3.2.4}$$

For the quenched disorder, the rupture threshold remains a constant property of a load-bearing element as may be the case in shearing of a perfectly regular grain array or in dry friction between two regular wavy surfaces (Figure 3.2.1b).

### 3.2.3 Annealed disorder fiber bundle model

In many real granular systems, successive rupture thresholds of a single element do not necessarily remain identical (Figure 3.2.1c). Changes of element critical strains and related frequency-magnitude statistics of failure events may result from strain localization, shear band formation, or dilation effects; all of which also affect progressive development of macroscopic material behavior. In the annealed disorder FBM, successive rupture thresholds change randomly from a constant statistical distribution. To determine the rate of rupture-induced energy production from such annealed granular systems, it is necessary to consider the entire history of the bundle. This requires evaluation of the probabilities of each admissible strain threshold combination throughout the loading path. The rate of energy production for such a system is

$$\frac{dU}{d\varepsilon} = \frac{EA}{2} \varepsilon^2 p_t(\varepsilon) + \frac{EA}{2} \sum_{k=1}^{k_{\text{max}}} \int_0^\varepsilon \ldots \int_0^{\varepsilon - \sum_{i=1}^{k-1} t_i} p_t(t_1) \ldots p_t(t_k) p_t(\varepsilon - \sum_{i=1}^k t_i) \left(\varepsilon - \sum_{i=1}^k t_i\right)^2 dt_1 \ldots dt_k. \tag{3.2.5}$$

The first term on the right-hand side is the energy released from all primary fiber ruptures and is thus identical with the expression for the standard FBM (see Equation 3.2.3). The following terms describe energy release from the sum of all subsequent rupture events. The probability of those events is obtained by combining the probabilities of earlier rupture events $p_t(t_1), \ldots, p_t(t_k)$, with the probability $p_t(\varepsilon - \sum_{i=1}^k t_i)$ that a fiber fails again at the current loading strain $\varepsilon$. This results in a $k$-fold integration, constrained by the restriction that the sum of past thresholds must not exceed the currently applied bundle strain. The magnitude of a potential energy release from an element at a current load $\varepsilon$ is exclusively determined by the last threshold. Note that Equation 3.2.5 may be solved analytically only for special cases. Approximate solutions, however, may be obtained by numerical integration of the terms to estimate energy release for any desired type of FBM (see Figure 3.2.2).
Figure 3.2.3: Probability $p_U$ of rupture energies $U$ (annealed disorder FBM, Weibull distribution, $\lambda = 1$ and $m = 2$) from fibers that break the first, second, third, and fourth time at a total strain $\varepsilon = 2$ (a) and $\varepsilon = 5$ (b). With ongoing strain the contribution to the overall energy changes, but also the range of attainable energies and the shape of the resulting distributions. Note that first rupture of fibers contributes the largest energies and correspondingly stands out as a single peak at the high-energy end of the curve.

The annealed disorder FBM is capable of reproducing a wide range of different characteristic material behaviors, even for the same distribution for $p_t$ after each fiber failure. In this study we focus solely on the application of the Weibull [39] probability distribution $p_t = \frac{m}{\lambda} \left( \frac{U}{\lambda} \right)^{m-1} \exp \left[ - \left( \frac{U}{\lambda} \right)^m \right]$ for fiber failure thresholds. Figure 3.2.2a,b provides a comparison of the stress-strain behavior and the fiber rupture-induced energy release rate for annealed disorder fiber bundles using three different Weibull probability distributions. Weibull distributions can be adapted to match characteristic reliability features of elements. The functional parameter $m$ stands in close relation to the failure rate of a sample; this is the relative amount of elements that fail within an upcoming straining step. If element failure is less likely in earlier strain steps and becomes more probable at higher strains, one speaks of an increasing failure rate, a feature that may be represented by $m > 1$. The opposite case, that elements have the greatest propensity to fail at the beginning of their lifetime, corresponds to $m < 1$. $m = 1$ indicates a constant failure rate. Correspondingly, modifications of the Weibull shape parameter $m$ may result in different macroscopic properties of the fiber bundle: elastic-plastic behavior with shear strengthening ($m = 1$) as observed in loose granular materials; elastic-plastic behavior with shear strengthening and successive weakening towards a residual shear strength ($m = 2$) that occurs in dilatant dense granular materials; and oscillatory behavior of the constitutive curve ($m = 5$) which occurs in materials with complex shear band dynamics, such as metal foams [2]. Figure 3.2.2b demonstrates also that the constitutive stress-strain behavior stands in close relation to the rate of strain energy release.

Energy production in the annealed disorder FBM at loading strain $\varepsilon$ is determined by an entire population of fibers with different thresholds $\tau^*$, similar to real granular materials. This stands in contrast to the simple FBM under strain-controlled loading, where energy is produced only by fibers with identical thresholds at a time. To find out
the frequency-magnitude distribution of released energy in the annealed disorder case it is therefore prerequisite to know the probability \( p_{\tau} \) of different rupture magnitudes. \( p_{\tau} \) may be obtained by combining the fraction of fibers that broke due to their earlier thresholds \( (t_1, \ldots, t_k) \) at \( \varepsilon - \tau \) with the probability \( p_t(\tau) \) that they will break once more at \( \varepsilon \), due to their current threshold \( \tau \). The fraction of fibers that break the very first time at \( \varepsilon \) has to have a fixed \( \tau = \varepsilon \), appearing in the full distribution as a single peak:

\[
p_{\tau}(\tau; \varepsilon, p_t) = \delta(\varepsilon) p_t(\varepsilon) + \sum_{k=1}^{k_{\text{max}}} p_t(\tau) \int_{0}^{\varepsilon-\tau} \cdots \int_{0}^{\varepsilon-\tau-\sum_{i=1}^{k} t_i} p_t(t_1) \cdots p_t(t_k) \, dt_1 \cdots dt_k, \quad 0 < \tau < \varepsilon \quad (3.2.6)
\]

where \( \delta \) is the Dirac \( \delta \) function. From this frequency-magnitude relation of currently pending ruptures we may obtain the statistics of associated energy bursts by simple substitution. From Equation 3.2.1 we saw that \( \tau = \sqrt{2u} \), hence the distribution of rupture energy is

\[
p_U(U; \varepsilon, p_t) = \frac{1}{\sqrt{2u}} \left[ \delta(\varepsilon) p_t(\varepsilon) + \sum_{k=1}^{k_{\text{max}}} p_t(\sqrt{2u}) \int_{0}^{e-\sqrt{2u}} \cdots \int_{0}^{e-\sqrt{2u}-\sum_{i=1}^{k} t_i} p_t(t_1) \cdots p_t(t_k) \, dt_1 \cdots dt_k \right], \quad 0 < \tau < \varepsilon. \quad (3.2.7)
\]

The total rupture energy distribution is the sum of first, second, etc., rupture energy probabilities. The largest magnitudes come from the fibers that break the first time as their rupture threshold corresponds to the full loading strain (Figure 3.2.3a). However, the probability of such an event quickly diminishes with ongoing deformation, whereas the relevance of higher-order rupture events increases. Figure 3.2.3 demonstrates that fibers that break the second time contribute significantly to the total energy at a bundle strain of \( \varepsilon = 2 \). The total energy at an even later stage (\( \varepsilon = 5 \)) is mostly born by fibers undergoing their fourth failure.

Progression of deformation not only increases the likelihood of higher-order ruptures for the annealed disorder case but also gradually changes the shape of the statistical distribution of force jumps and associated energy release events (see Figure 3.2.3). The distribution for rupture associated large energy release events progressively approaches an exponential distribution. Noteworthily, this ongoing change of rupture-related probability distribution is observed, although the distribution \( p_t \) of consecutively assigned fiber thresholds remains identical throughout the entire straining process.

### 3.3 Comparison with shear frame experiments

For comparison with our model results, strain rate-controlled \((0.033 \times 10^{-3} \text{ ms}^{-1})\) shear-frame experiments were performed with glass beads (SiLi Beads, Type S soda lime beads,
Figure 3.2.4: Probability densities of (a) stress release event magnitudes $\Delta \tau_{\text{FBM}}$ (see Equation 3.2.6) and (b) energy burst sizes $U_{\text{FBM}}$ (see Equation 3.2.7) of an annealed fiber bundle (Weibull distribution, $\lambda = 1$ and $m = 2$) at different strains ($\varepsilon = 1, 2, 3$) in comparison with data from two shear frame experiments performed under identical conditions. Stress jump data $\Delta \tau_{\text{norm}}$ (a) and AE event energies $U_{\text{AE, norm}}$ (b) were sampled during a later phase of shearing ($4\varphi < \varepsilon_{\text{Sampl.}} < 12\varphi$) where mechanical behavior was relatively free of transitional effects. Experimental results are rescaled to the range of attainable FBM thresholds and energies (at $\varepsilon = 2$) correspondingly. A shift of the stress jump data of $-1$ was performed to allow for a comparison of model results against the larger-than-average branch of the empirical distribution.
3 Fiber-bundle models for granular shearing

diameter \(1.0 \times 10^{-3} \text{–} 1.4 \times 10^{-3} \) m) at a constant confining stress \(\sigma_N\) of \(45 \times 10^3\) Pa. Shear forces were measured by two force gauges with high temporal resolution (1610 s\(^{-1}\)). The total sample volume was \(0.15 \times 0.15 \times 0.15\) m\(^3\), yielding a shear plane of 0.0225 m\(^2\). Using this geometric specifications of the test device, measured forces were converted into shear stresses. The ratio between shear stress and constantly applied normal stress expresses effective friction within the shear zone, and is referred to as “shear stress ratio” in this study. Experimentally measured shear stresses displayed distinguishable jumps in all experiments superimposed on the gradual trend of the stress-strain curve (see Figure 3.2.2c) and indicative for shear associated grain rearrangements. Stress jumps were defined as a decay of the transient stress data over more than 150 Pa, that is interrupted not longer than 0.002 s – a criterion that serves to rule out the effects of noise. It was found that stress jumps in our shear tests have an average magnitude of 1300 Pa (corresponding to a shear stress ratio of 0.029). Data show that larger events of stress jumps were often preceded by small fluctuations of the stress curve. Those may reflect minor, localized changes in the grain network precursory to a full rearrangement event. A few of these minor force fluctuations can be seen in the inset of Figure 3.2.2c, e.g., preceding the last force jump in the displayed record. To capture energy released from grain rearrangement events, acoustic emissions were measured. For this purpose a piezoelectric accelerometer \((\text{Measurement Specialities ACH-01})\) [25] was buried within the sample material, in close vicinity to the shear zone. A fixed threshold was applied to the continuous acoustic signal to extract discrete events. The time integral of recorded signal amplitudes within one of these events is a common proxy for the energy coming with an acoustic pulse [25]. For simplicity we refer to this quantity as “event energy” being aware of the fact that it is no energy in strict physical terms. To obtain a measure \(\Delta U_{\text{AE}}/\Delta \varepsilon\) that is equivalent to the FBM energy release rate, observed energies from AE events were summed up within small (0.5 grain \(\varepsilon\)) deformation intervals and divided through the interval width (see Figure 3.2.2d). The efficiency of AE in capturing force jump events is illustrated in the insets of Figure 3.2.2c&d, showing an example record of acoustic bursts. A comparison with synchronous stress jumps highlights capabilities of the AE method and its usefulness for detection of grain network rearrangement events. Quantitative inspection of the match between acoustic and mechanical data, revealed that 75%–85% of all observed force jumps were associated with an AE event. The overall stress-strain behavior of the glass bead assemblies displays typical characteristics of densely packed granular materials. We find an immediate and initially almost linear increase of the shear stress ratio as a response to imposed deformation. With growing plastic deformation, the stress-strain curve bends towards its maximum, indicating imminence of the peak shear stress. Subsequent decay of measured shear stress and continual volumetric expansion indicate progressive formation of a shear zone within the material [29, 15]. Together with the increasing shear stress, growth of the AE energy release rate was observed, culminating in a maximum that is slightly delayed with respect to the peak stress.

A good qualitative agreement between experimental data and the annealed disorder FBM was obtained without passing the model through any calibration procedure. Essential mechanical features of granular shearing are captured by the model, based on the following assumptions: (a) repetitive regeneration of the force network under shear-
Fiber-bundle models for granular shearing, (b) elements receive a new randomly chosen failure threshold in each rupture cycle and (c) an increasing failure rate of force network elements. The first two assumptions deliver justification for the selection of an annealed disorder FBM with $k_{\text{max}} = \infty$. The last assumption implies that failure becomes more likely the more an individual element is strained. This is implemented in the model with by using a Weibull distribution with shape parameter $m = 2$ for fiber rupture thresholds. This is in agreement with the notion of force chains that undergo repetitive cycles of formation, straining, and destruction. Based on this assumptions only, the FBM is able to reproduce the shear stress development of a densely packed granular material (Figure 3.2.2c), such as the glass bead assemblies in our shear-frame experiments. AE measurements provide a unique opportunity to look into shear-induced failure of the granular force network and to compare this with simulated fiber failure from the FBM. Good qualitative agreement between modeled energy release rate (Figure 3.2.2d) and measured energy from AE events indicates that principal features of granular network reorganization are captured by the FBM. The modeled delay of fiber associated energy release matches a similar phenomenon of AE energy in our experiments. In the FBM this effect can be explained by greater energy released from more stable fibers rupturing later during shearing coupled with enhancement of failure-driven energy production by second, third, etc., ruptures of elements.

The empirical frequency-magnitude distribution of experimentally observed stress jump statistics reveals a clear separation of the full sample into two parts (see Figure 3.2.4a). Frequency-magnitude distributions of observed events display a lower-than-average branch exhibiting exponential behavior. Separated from this by a distinct minimum of the curves, a second branch appears, representing events that are higher than the average. As mentioned earlier, minor force fluctuations presumably from smaller, single grain rearrangement events were often classified as force jumps. We assume that the right, low-magnitude branch of the empirical distribution reflects such events. The high-magnitude, left branch of the curve is supposed to represent full force network restructuring events associated with strong stress jumps. No such separation was observed in the empirical AE event energy distribution. The presented FBM allows one to capture failure from one type of source mechanism only. Therefore we focus here on large magnitude force jumps, presuming they originate from the same mechanical sources as observed acoustic events. Figure 3.2.4 presents a comparison between rescaled empirical probability distributions, extracted from experimental data, and FBM generated distributions of force jumps and energy release magnitudes. For the above mentioned reasons, we performed a shift of stress jump data in order to focus our analysis on high-magnitude stress jumps only. To allow a direct comparison of measurements with uncalibrated model results experimental data sets were rescaled to the full range of attainable FBM values at a bundle strain of $\varepsilon = 2$. Figure 3.2.4 illustrates that characteristic shapes of both measured quantities are reproduced by the FBM under the given premises. Model results suggest that both distributions approximate an exponential falloff of high magnitude events, evolving from an initially different shape (see also the comparison of probability densities in Figure 3.2.3). Stress jump data shown in Figure 3.2.4a stem from an early stage of shearing and underline the non-exponential
shape of larger-than-average failure events statistics, as predicted by the FBM. The developing dominance of the exponential distribution with progressing shear deformation is as well in agreement with experimental observations reported in [17, 12]. According to the FBM, failure-associated energy release events converge to the exponential shape faster than the corresponding stress jumps – a feature that can also be confirmed from the data displayed in Figure 3.2.4.

3.4 Concluding remarks

We presented analytical expressions characterizing force fluctuations in granular material and energy bursts using a fiber bundle model and compared those against measurements obtained from shear tests with glass bead assemblies. Strain-controlled shearing and associated one-by-one failure of elements allows one to trace individual rupture events, providing a “microscopic” view into the evolution of the load-bearing structure. In the FBM, failure probability of single force network elements was expressed by means of a Weibull distribution function. Assumptions concerning the failure rate of single elements translate into different shapes of Weibull distribution and may result in a wide array of typical shearing behavior of granular assemblies. We were able to qualitatively reproduce experimental data by imposing simple assumptions concerning force chain life cycles, without any foregoing calibration procedure. Although the probability distribution of element failure remained constant throughout deformation, the presented model results show a complex shape of failure-associated energy production. Model results suggest a delay of energy release with respect to shear stress build-up – a feature that was confirmed by experimental acoustic emission data. Modeled statistical distribution of stress jumps and associated energy release reproduce a gradual transition to an exponential falloff of high-magnitude events after initiation of shearing. Development of statistical features result from a continuously changing contribution of first, second, third, etc., failure events to frequency-magnitude distributions of failure only. Force jump frequency-magnitude distributions from our experiments showed a distinct separation into a high-magnitude and a low-magnitude branch. We explained this with the presence of two different source mechanisms. A cursory comparison of model results to statistics of high magnitude events, presumably associated with force network restructuring events, shows good qualitative agreement also for an early stage of the shearing process. Bursts of strain energy were measured during shear tests by means of acoustic emissions. Statistical features of the energies captured by AE sensors within single bursts were found to confirm FBM results. Experimental falloff of both curves for fully developed shear zones were predicted by the model, and are in agreement with qualitative inspection of our AE data and observations reported in the literature [17].

The model involves various simplifying assumptions. Concerning load application, we assume displacement-controlled shearing process, implying no avalanches of element rupture. We cannot guarantee that this is strictly fulfilled during our tests, even when imposing a constant strain rate on the material. Finite stiffness of the particles and of our shearing device creates the possibility for force redistribution amongst grains. Addi-
tionally, the presented FBM does not consider attenuation of released strain energy and the partial capture of release events (an unavoidable characteristic in most experimental systems), both of which may affect translation of energy bursts into AE events. It is reasonable to assume, however, that elastic wave attenuations and related phenomena do not play a dominant role in the relatively small-sized samples used for this study.

The analytical expressions presented in this study shed light on the evolution of rupture event statistics under imposed strain, and may serve to outline potential strategies for early recognition of shear failure. A comparison with experiments supports model results and highlights the potential for coupling FBMs with advance AE measurement methods capable of capturing large amounts of individual and abrupt failures and re-structuring events, thus supplementing macroscopic shearing information with a detailed grain scale picture.

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3 Fiber-bundle models for granular shearing


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4 Shear induced force fluctuations and acoustic emissions in granular material

Manuscript submitted to Journal of Geophysical Research – Solid Earth

Abstract

We conducted a series of strain-controlled experiments to study the characteristics of a shear zone forming in dense flow of confined dry granular media. The primary objective was to link force fluctuations due to jamming and force network reformation with episodic release of elastic energy as passively monitored by acoustic emission sensors. Under constant deformation rate, the shear stress exhibits a characteristic saw-tooth behavior reflecting the strong influence of micro-mechanical processes on the macroscopic stress-strain behavior. Measured shear stress jumps were highly correlated with low-frequency (< 20 kHz) acoustic emissions events. The high-frequency (30 kHz–80 kHz) acoustic signals appear to be directly linked to continual grain-scale interactions (e.g., friction, rolling). A conceptual mechanical fiber-bundle model (FBM) for representing the dynamics at the shear zone of large granular assemblies was capable of reproducing the dynamics of stress jumps and associated elastic energy release events. The combination of AE measurements and FBM framework offers new insights into the behavior of shear failure and enhances capabilities for resolving grain-scale mechanical processes and for predicting rapid mass movement such as shallow landslides and debris flows.

4.1 Introduction

The ubiquity of granular materials and their complex dynamic behavior attracted considerable interest for various natural and industrial applications. The dynamic mechanical behavior of granular materials is shaped by self-organized formation of load-bearing grain networks [29, 31], and intermittent jamming of dense flow with abrupt transition to solid-like behavior [27]. Both examples reflect the peculiarities of granular mechanics, where grain-to-grain interactions affect meso- and continuum-scale phenomena. An intriguing facet of granular mechanics complexity is the formation of shear zones under loading. Development of a shear band involves slip between grains and rearrangement of the granular structure - both are dissipative mechanisms that result in the appearance of macroscopic material plasticity [47]. The force network within granular materials typically comprises of aligned, highly loaded grains, oriented approximately along the principal directions of the stress field. During progressive shear zone formation these so-called force chains [40, 47] may undergo consecutive cycles of formation, loading and destruction. Such abrupt events associated with force chain destruction introduce strong
perturbations of the granular structure, typically resulting in considerable fluctuations of the total supported load [39], intermittent jamming and non-smooth mechanical behavior. Strain energies released during abrupt reformation events are often manifested in generation of elastic waves [26, 22, 28, 15, 1]. Due to their high frequencies (kHz-range) those phenomena are often referred to as acoustic emissions (AE) [34]. For granular shearing deformation such elastic waves may carry a considerable amount of information concerning grain network restructuring events and force chain collapse [48].

Here we use a fiber-bundle model (FBM) to link observed acoustic emissions with discrete failure events in granular material under shear deformation. FBMs rely on the straining and stochastically determined failure of individual load-bearing elements (called fibers for historical reasons). The occurrence of fiber failure presents an inherent dissipation mechanism that releases energy in discrete events and causing yielding of the bundle. In addition to the material stress-strain behavior the model directly provides predictions of bursts triggered by such energy release events. Adjusting the mechanical rules of fiber behavior FBMs are capable of mimicking repetitive formation and destruction of load-bearing elements [12, 42, 35], as it is characteristic of grain contacts and force chains in granular material.

For the application to granular shear zones, single fibers could represent force chains, or grain contacts. Mechanical failure of force chains critically depends on grain geometries, sizes, surface roughness and other properties that are notoriously difficult to obtain. A lack of knowledge concerning complex particle geometric and material properties is compensated for through statistical distributions [12, 20, 35] in the FBM. Under certain conditions FBMs are equivalent to damage accumulation models that are used in continuum-mechanical approaches to account for plastic effects and yielding [48]. The FBM can build up on a large body of work concerning statistical properties of force chains and other elements in granular materials. Liu et al. [29] were amongst the first to show that strong contact forces in loaded granular assemblies follow an exponential frequency-magnitude distribution, a feature that was confirmed experimentally [30, 38, 4], and in numerical simulations of granular assemblies [44, 32]. Exponential falloff of contact force distributions stands in close relation to force chains, as experimental visualizations of grain contact forces in two-dimensional assemblies demonstrated impressively [31, 51]. Exponential distributions of grain contact forces were found valid also for examples of three-dimensional granular assemblies [50]. Under deformation, the probability distributions of contact force magnitudes may change considerably. Evolving force distributions often bear the signature of contact anisotropy [25] or reflect the un-jamming transition in dense granular flows [10]. The statistics of contact stresses reflect the static structure of a granular assembly but are not necessarily linked to strengths of force chains. Strain-controlled deformation tests may provide such information. In this loading procedure forces resulting from an imposed strain are measured. The breakage of an element within the assembly leads to an abrupt decay in the resulting force. No force redistribution occurs and correspondingly no secondary element failure or avalanches. In the ideal case this procedure samples failure events in a sequential manner. Force jump distributions from such tests were reported to result in log-normal distributions [11, 41]. A large variety of tests with granular materials resulting in repetitive fluctuations of
measured stresses can be found in the literature: Deformation-induced force fluctuations on a single grain were characterized by [14, 9]. Force jumps were also observed for larger structures that were either dragged through granular material [24, 5, 33] or placed to resist granular flow [2, 18].

A variety of other processes may resemble granular shearing and exhibit characteristic stress fluctuations, such as dry friction [23, 49], sliding of gel [53] or atomic-force-microscopy [54]. The occurrence of stress jumps is also observed in deforming fault gouges [37] (layers of fine granular material forming in faults). Such layers may have crucial control over the frictional properties of a fault region by mediating sliding behavior and occurrence of earthquakes. The formation of a granular shear zone is a key process for the evolution of landslides and other geologic mass movements. Here a shear zone develops in material regions that can be considered pristine with respect to deformation. Early detection of the conditions promoting subsurface shear plane development is a prerequisite for the prediction of shallow landslides. These often hydrologically-triggered mass release events are notoriously difficult to predict and thus improved understanding of events preceding shear zone formation are critical to enhance predictability and early warning.

The objective of this work was to link measurable internal abrupt events of strain energy release to internal force jumps and associated grain-scale mechanical processes. We investigated stress jumps and associated acoustic signals that occur during granular shearing for different loading conditions and material properties. Changes in force and acoustic signals characteristics during deformation were studied. We expanded and implemented a special type of FBM with reforming fibers [35] to simulate the temporal development and statistical features of micro-structural rearrangements and internal failure events. We have used measurements to evaluate the performance of the proposed FBM framework and its capacity to link mechanical and acoustical characteristics.

Following a brief overview of the modified FBM, we describe the experimental shear test setup and methods of data analysis. Results of the experiments give corroborating evidence for a close relation between grain network restructuring events, stress jumps, and acoustic emission bursts. Further analysis indicates remarkable stable levels of elastic energy release associated with force jumps despite large variations in experimental conditions. Implications of our findings on the understanding of micro-mechanical aspects of granular shearing are then summarized and discussed in the concluding section of this work.

4.2 Annealed fiber-bundle model

To investigate the lumped mechanical behavior of large assemblies of individual stochastic force elements, we use the fiber-bundle model (FBM). This is a simple mechanical model comprising a large number of independent elastic mechanical elements, referred to as fibers, that conceptually mimic load-bearing grain contacts or force chains. Although the FBM [13] was originally conceived to reproduce failure in disordered materials under tensile loading, the scope of this model was extended to accommodate shearing [45, 8]
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and other types of mechanical loading. In this work we build up on a novel type of FBM [16, 17], in which fibers are reinserted into the bundle after failure with a new (annealed disorder) rupture threshold [43]. For the purpose of arriving to a mathematical description of the bundle behavior it is instructive to group fibers, according to the number of rupture events they have undergone at a certain strain level. The contribution of unbroken fibers to the bundle stress may be obtained from the fiber elastic modulus $E$, the area of the shear plane $A$ and the present strain of the unbroken fibers (in this case is identical to the global bundle strain $\varepsilon$ ). The term $[1 - P_t(\varepsilon)]$ describes the fraction of intact fibers within the bundle:

$$\sigma_0(\varepsilon) = AE \varepsilon [1 - P_t(\varepsilon)] \quad (4.2.1)$$

The contribution of fibers that have ruptured once is

$$\sigma_1(\varepsilon) = \int_0^\varepsilon p_t(t_1) [1 - P_t(\varepsilon - t_1)] AE(\varepsilon - t_1)dt_1 \quad (4.2.2)$$

which again includes a term describing the elastic modulus $E$ times the fiber deformation ($\varepsilon - t_1$) after the first rupture. The combined probability $p_t(t_1) [1 - P_t(\varepsilon - t_1)]$ provides the fraction of fibers that fulfill the conditions to have failed once at $t_1$ and to be intact ever since. $t_1$ may take any positive value that is smaller than the current bundle strain. The summation of all those cases is performed mathematically by integration. Mechanical action of further groups of fibers may be described in a similar manner. The total stress-strain relation is obtained by summing up over all groups of fibers that broke zero, one, two, ... , $k_{\text{max}}$-times ($k_{\text{max}}$ being the maximum number of restorations) and was provided by [16]:

$$\sigma(\varepsilon) = AE\varepsilon (1 - P_t(\varepsilon)) + \sum_{k=1}^{k_{\text{max}}} \int_0^\varepsilon \int_0^{\varepsilon - t_1} \cdots \int_0^{\varepsilon - t_1 - t_2 - \cdots - t_k} p_t(t_1)\cdots p_t(t_i) \left[ 1 - P_t(\varepsilon - \sum_{i=1}^k t_i) \right] E(\varepsilon - \sum_{i=1}^k t_i)dt_1\cdots dt_k \quad (4.2.3)$$

The annealed disorder FBM provides links between the mechanical behavior of a disordered material, single element failure events and associated release of strain energy. A measure of this deformation driven energy production is the energy release rate, as introduced by [35]. This quantifies the deformation driven energy production and describes the cumulative failure-associated energy per unit strain interval. Following the same logic as for the stress-strain relation, the energy release rate may be considered as being constituted from first, second, ... , $k_{\text{max}}$ failure events. The energy released by rupture of all previously intact fibers $\frac{dU_{t,0}}{d\varepsilon}$ may be written as

$$\frac{dU_{t,0}}{d\varepsilon} = \frac{1}{2} E\varepsilon^2 p_t(\varepsilon). \quad (4.2.4)$$

Here the quantity of interest can be obtained as a product of the elastic energy stored in a fiber at strain $\varepsilon$ and the probability of rupture at this strain. Fibers that have ruptured
already once before the breakage event under consideration yield an energy release rate of

\[
\frac{dU_{t1}}{d\varepsilon} = \frac{1}{2} E \int_0^\varepsilon (\varepsilon - t_1)^2 p_t(t_1)p_t(\varepsilon - t_1) \, dt_1, \quad (4.2.5)
\]

The expression above contains the strain energy of fibers that have been restored once after their rupture at strain \( t_1 \). To find the fraction of fibers that fulfill this criterion and rupture the second time just at the strain \( \varepsilon \) it becomes necessary to introduce the terms \( p_t(t_1) \) and \( p_t(\varepsilon - t_1) \). The corresponding expressions for fibers that rupture the third, fourth, etc. time at strain \( \varepsilon \) can be obtained in an analogue way. Summation over all those expressions yields an analytical formulations for the energy release due to fiber rupture:

\[
\frac{dU_t}{d\varepsilon} = \frac{1}{2} E \varepsilon^2 p_t(\varepsilon) + \frac{1}{2} E \sum_{k=1}^{k_{max}} \int_0^{\varepsilon - \sum_{i=1}^{k-1} t_i} \int_0^{\varepsilon - \sum_{i=1}^{k-1} t_i} \cdots \int_0^{\varepsilon - \sum_{i=1}^{k-1} t_i} p_t(t_1) \cdots p_t(t_k) \, dt_1 \cdots dt_k.
\]

The energy release rate \( \frac{dU_t}{d\varepsilon} \) (units of force) may also be defined as rate of energy dissipation due to fiber failures. This equation stands in close relation to the total shear stress of the bundle and may also be interpreted as half the sum of all shear force fluctuations within a straining increment. Fig. 4.2.1 summarizes how the two key quantities, shear stress and energy release rate, are obtained from a simple fiber bundle. Focusing on key features of force chains and up-scaling individual element behavior into shear plane mechanics, the model is capable of reproducing the main mechanical features of granular shearing [35]. From Eqs. 4.2.3 and 4.2.6 we deduce that the fiber rupture probability \( p_t \) affects the bundle constitutive behavior. Within the framework of annealed fiber-bundle models it is also possible to derive analytical expressions for the size distribution of stress fluctuations \( \tau \) and associated energy release events \( U \) [35]. The derivation works after an analogous principle as for the above described expression and gives an expression that is closely related to the equations above:

\[
p_t(\tau; \varepsilon, p_t) = \delta(\varepsilon)p_t(\varepsilon) + \sum_{k=1}^{k_{max}} p_t(\tau) \int_0^{\varepsilon - \tau - \sum_{i=1}^{k-1} t_i} \cdots \int_0^{\varepsilon - \sum_{i=1}^{k-1} t_i} p_t(t_1) \cdots p_t(t_k) \, dt_1 \cdots dt_k \quad 0 < \tau < \varepsilon,
\]

\[
p_U(U; \varepsilon, p_t) = \frac{1}{\sqrt{2U}} \left[ \delta(\varepsilon)p_t(\varepsilon) + \sum_{k=1}^{k_{max}} p_t(\sqrt{2U}) \int_0^{\varepsilon - \sqrt{2U}} \cdots \int_0^{\varepsilon - \sqrt{2U} - \sum_{i=1}^{k-1} t_i} p_t(t_1) \cdots p_t(t_k) dt_1 \cdots dt_k \right] \quad 0 < U < \varepsilon^2.
\]

Here \( \delta \) is the Dirac impulse function, that has to be introduced for considering all events that come from the first rupture of fibers.

Fig. 4.2.2 provides a comparison of FBMs with different distributions and parameters. The parameter \( k_{max} \) was set to infinity in all cases. Here we used the Weibull distribution and the log-normal distribution as characteristic functions of fiber strengths. Both are left-skewed distribution functions of positive values only. The Weibull distribution [52] is
often applied to characterize individual life times in biological populations or mechanical element failure rates in engineering systems and can be written as

\[ p_t(t) = \frac{m}{\lambda} \left( \frac{t}{\lambda} \right)^{m-1} e^{-\left(\frac{t}{\lambda}\right)^m}, \quad (4.2.9) \]

where \( \lambda \) is a scaling parameter and \( m \), the shape parameter, is related to the failure rate, i.e. the probability that an element will fail at a certain stage of the straining process. If \( m < 1 \) a population of element has a decreasing failure rate so rupture is most likely at the beginning of their lifetime. When \( m = 1 \) failure rate is constant and when \( m > 1 \) elements have an increasing failure probability the longer an element survives. Such simple considerations may guide the choice of Weibull-parameters for the case of force chain failure: Setting the shape parameter to a value larger than one (in our case \( m = 2 \)) means to imply a failure rate that increases with strain. The underlying assumption here is that force chains are more susceptible to buckling with gradually increasing straining. This is in agreement with observations documented in the literature [6, 46]. The log-normal distribution is a two parameter function of the form

\[ p_t(t) = \frac{1}{\sqrt{2\pi} \sigma x} e^{-\left(\frac{\ln x - \mu}{2\sigma^2}\right)^2}, \quad (4.2.10) \]

with \( \sigma \) the standard deviation that determines the shape and mean \( \mu \) that acts as a scaling parameter. The log-normal distribution has been reported to stand in a close relation to force chain failure respectively stick-slip fluctuations in slowly sheared granular media. Both distributions seem capable of reproducing different characteristic material behavior. The qualitative behavior resulting from the two compared distributions is relatively similar for the given selection of parameters. We thus conclude that the general behavior of the FBM is not critically dependent on the form of the fiber threshold distribution function. A similar observation was made by Dalton et al. [12] leading the authors to the conclusion that certain system features reflect the load-redistribution feature of the process rather than particular input parameters.

Eqs. 4.2.3 & 4.2.6 contain the FBM strain \( \varepsilon \) as the independent variable, implying a strain-controlled loading of the bundle. In a disordered material this means that elements are loaded independently. For the strain-controlled case, the mechanical load is not redistributed or accumulated as it happens in stress-controlled loading; hence no failure avalanches are observed during this loading procedure. In materials consisting of elements with different failure strengths, strain-controlled loading results in an ordered failure according to fiber thresholds. Consequently, this loading procedure results in a sequential interrogation of element rupture strain. In addition to bulk material behavior this reveals essential information about individual element strengths and rupture energies.

A cursory inspection of the stress-strain (Eq. 4.2.3) and the energy release rate (Eq. 4.2.6) curves (see Fig. 4.2.2) reveals that their maxima do not coincide: In the example shown, the rate of energy release reaches its maximum respectively saturates after the modeled shear stress. This is the case for all presented distributions and parameter choices. The
Figure 4.2.1: (a) A simple annealed disorder FBM consisting of four fibers representing a small granular system. (b) Mechanical behavior of the four fibers (gray lines) that undergo successive phases of loading and rupture. For each cycle a new rupture threshold is determined. The black line displays the resulting shear stress of the full bundle, bearing the signature of single fiber failure events. (c) Energy bursts associated with fiber rupture events (gray impulses) and resulting energy release rate (black steps).
Figure 4.2.2: FBM results for Weibull and log-normal distribution of fiber strength (as shown in the inset): modeled stress-strain relations (a) and energy release rate (b). Results are obtained from evaluation of expressions 4.2.3 & 4.2.6 and represent a fiber bundle of infinite size.
FBM also predicts that the rate of failure associated energy is entering a phase of deceleration, when the material reaches the maximum stress. These dynamics evolve when the system departs from a pristine state where all fibers of a bundle are unstrained. At this stage the probability of fiber rupture is constantly growing and both the energy release and the stresses increase steadily. In a “mature” bundle fibers are at random strain levels due to previous rupture events. The probability of rupture events within the bundle saturates and leads the system into a steady-state. For all the presented annealed disorder FBMs, both quantities have finite values at large strains, a behavior that reproduces the presence of a residual shear strength in many granular materials.

An important point to remember is that the annealed disorder FBM is a conceptual representation of granular shearing rather than a full physical description of the process. Although parameters (e.g., Young’s modulus of fibers, $E$, Weibull scaling factor, $\lambda$, etc.) can be adjusted to better match observed stress and energy release magnitudes, this does not match the objectives of the presented work. Here, our aim is at a qualitative comparison (with no parameter adjustment) between model results and experimental data, emphasizing the appropriate simulation of characteristic bulk response rather than fitting the model to data.

4.3 Material and Methods

4.3.1 Experimental Setup and Procedures

For the experiments we used a linear shear apparatus (see Fig. 4.3.1) designed for direct shear tests on $0.15 \times 0.15 \times 0.15 \text{m}$ samples of granular material. The set-up allowed to perform strain-controlled direct shear tests with a wide range of displacement rates and normal loads. Normal load application was provided by a pneumatic cylinder. Designing the lower part of the sample container slightly larger than the upper (fixed part compartment) we were able to drive the sample material to relatively high strains. The deformation was applied with a linear drive (PERO linear spindle motor, PERO GmbH, Sickte, Germany) pulling the lower frame at a constant rate. Shear forces were measured at a rate of $1.61 \times 10^3 \text{Hz}$ with a resolution of $30 \text{Pa}$ using two force gauges.

The shear frame can be used simultaneously with two acoustic emission systems operating on different frequency ranges. A 1-D accelerometer (Measurement Specialities ACH-01) with a sensitivity of $0.92 \times 10^{-3} \text{V ms}^{-2}$ with a linear frequency response in the range $<20 \text{kHz}$ was placed in the upper frame $0.05 \text{m}$ above the imposed shear zone in a way that it captured motion normal to the shear plane. A piezoelectric sensor (Vallen VS30-V; peak sensitivity is $0.63 \times 10^{-3} \text{V Pa}^{-1}$) sensitive to frequencies in the range of $30 \text{kHz}$–$80 \text{kHz}$ was positioned in the close vicinity of the accelerometer with its cone of sensitivity facing towards the shear zone. To prevent grain friction against the AE sensor casing causing unwanted noise, transducers were wrapped in rubber-sheets to acoustically shield them from the surrounding material. For the low frequency accelerometers excitation occurred primarily through vertical vibration of the entire sensor. We therefore assume that no relevant noise is generated by single grains contacting and eventually scraping against the sensor case. Both AE sensor systems delivered con-
4 Shear induced force fluctuations and AE in granular material

Figure 4.3.1: Photography of the shear test apparatus, with inset showing a sketch of the test setup.

Continuous waveforms of transient motion respectively pressure changes. We assume that source mechanisms of acoustic emissions produce distinct wave packages exceeding the ubiquitous electric and ambient noise level, and use a threshold to extract such events from the transient waveform. Acoustic events were analyzed towards their maximum magnitude, their duration and the energy they carry (for further description of event extraction from continuous acoustic waveform see Michlmayr et al. 2012 [34]). The accelerometer has a flat response spectrum with a relatively constant sensitivity over a wide frequency spectrum. This allows to convert the voltage signal into measures of accelerations, respectively energy. Caution has to be exercised for the conversion of high frequency signals into mechanical quantities: A number of resonance peaks affect the sensor response. Depending on their frequency waves may be translated differently into voltage signals. The resulting estimates of the energy captured by the AE sensor are biased through this effect. Shear tests were performed on three different types of dry glass beads (*SiLi beads type S*, Sigmund Lindner GmbH, Warmsteinach, Germany) each with a narrow grain size distribution, at different normal loads and at displacement rates in the range of $10^{-2} - 10^{-1}$ grain diameters per second. A full factorial set of experiments was conducted with a single or multiple repetitions for each factor combination resulting in 17 tests. The exact design of experiment is listed in Tab. 4.1. Soda lime beads have a Young’s modulus of $63 \times 10^9$ Pa and a bulk density of $1.44 - 1.51$ kg m$^{-3}$. Depending on the mean bead diameter, the shear frame chamber may hold approximately $2.50 \times 10^6$, $0.36 \times 10^6$ and $0.05 \times 10^6$ glass particles with diameters of 0.001 m, 0.002 m, and 0.004 m, respectively. The average number of beads that are participating in shearing is estimated to be in the range of $0.121 \times 10^6$, $0.035 \times 10^6$, and $0.010 \times 10^6$, under the assumption that shear zones in granular materials have a width of about 8 grain diameters [40].
Table 4.1: Design of experiment

<table>
<thead>
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<th>factors</th>
<th>classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>grain diameter</td>
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</tr>
<tr>
<td></td>
<td>$2.0 \times 10^{-3} - 2.4 \times 10^{-3} \text{ m}$</td>
</tr>
<tr>
<td></td>
<td>$1.0 \times 10^{-3} - 1.3 \times 10^{-3} \text{ m}$</td>
</tr>
<tr>
<td>normal load</td>
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</tr>
<tr>
<td></td>
<td>$45 \times 10^3 \text{ Pa}$</td>
</tr>
<tr>
<td></td>
<td>$60 \times 10^3 \text{ Pa}$</td>
</tr>
</tbody>
</table>

4.3.2 Data analyses

The high temporal resolution of shear stress measurements allowed to capture fluctuations of stress magnitudes exhibiting a typical saw-tooth shape, as can be seen in Fig. 4.4.1c. Using simple criteria on magnitude and re-occurrence time of such fluctuations, stress jumps were extracted from the continuous shear stress record. For each stress jump the magnitude, that is the difference of stresses before and after the release event, and the time lapse since the last release was determined. Latter presents the inverse of the event occurrence rate, i.e. the number of events within a time increment.

Waveforms from acoustic emissions of low and high frequency sensors were processed separately to extract discrete, failure-associated events from continuous data streams. The high frequency AE signals were processed using a Vallen AMSYS-5 acoustic emission measurement system (Vallen GmbH, Germany). Sensor raw data were enhanced through a 34 dB pre-amplifier and underwent analogue 30 kHz high-pass filtering placed before the A/D converter. After conversion into a digital waveform a fixed threshold of $80 \times 10^{-6} \text{ V}$ was used to extract acoustic events in a real-time data processing, where voltage peaks that occur in intervals shorter than $30 \times 10^{-3} \text{ sec}$ were grouped into one event. Low frequency acoustic signals were captured using an Audiomatica Clio 10 acoustical measurement device. The amplified and digitized waveforms were provided as WAVE (48 kHz, 16 bit) audio file format [36] for post-processing. To remove trends of the base level voltage, data streams were filtered by subtraction of a 1 s-moving-average from the raw data. For event extraction a fixed threshold was applied to the waveform. Data peaks that occurred in sequences shorter than $15 \times 10^{-3} \text{ sec}$ were considered to belong to the same event. The event energy was obtained by summation of the squared voltage values occurring during one event and conversion in physical units of energy using the characteristic sensor sensitivity. Summing up the energy values from all events that occur within a time or strain interval delivered the energy release rate. Using this analysis we could extract significant events with from the transient signal waveform. Event magnitude were often found to be several orders of magnitude larger that the underlying noise floor, confirming our initial assumption that unavoidable disturbances and random effects (e.g. from single grains scraping against the sensor) do not lead to significant loss of data quality.
4.4 Results

4.4.1 Time series of shear stress and AE events

Shear stress as a function of strain exhibits a characteristic shape consisting of linear elastic deformation at the onset of shearing, followed by plastic shear strengthening, and subsequently a gradual reduction of the slope up to the maximum (see Fig. 4.4.1a). This stress peak ranges in general between 60% and 80% of the applied normal load, $\sigma_N$, and can be observed typically after 2–4 mm of shear deformation. Both values were in agreement with comparable experiments [19]. Along with the shear stress, the energy measured by the low-frequency acoustic sensors increases. Fig. 4.4.1b shows the energy captured by the low-frequency transducer during subsequent strain intervals (i.e., energy release rate). The results exhibited significant variations and scatter, yet the peak of energy release consistently trailed the peak stress of the stress-strain curve.

The general form of the stress-strain curve was overlaid by characteristic saw-tooth shaped fluctuations (Fig. 4.4.1a,c), or stress jumps, that varied in magnitude and recurrence time with progression of granular shearing. Focusing on the shape of a single stress jump, several characteristic features were observed. Single stress release events were generally preceded by initially elastic straining of the grain lattice, indicated by a linear build-up of the stress-strain curve. With gradual straining, plastic deformation became dominant leading to a decrease of stress-strain curve steepness. During this late phase of a stress jump cycle, often minute stress fluctuations were observed indicating the imminence of a larger release event. Stress build-up ends by an abrupt jump that reflects a major restructuring of grain force network. At the same time the elastic energy stored in the force network element is also abruptly released. Synchronous records of two different acoustic emission systems typically display a strong response of AE activity along with observed stress fluctuations. Although stress jumps and associated mechanical processes excited AE waves in both high- and low-frequency ranges, clear differences between these types of acoustic emissions were found. Stress jumps were generally associated with direct generation of single low frequency AE events (see Fig. 4.4.1d). Also, smaller shear stress fluctuations preceding such jumps often released enough energy to cause measurable low-frequency AE events. AE signals with a high frequency content, in contrast, were generated constantly within the material during shear (see Fig. 4.4.1e).

4.4.2 Event average occurrence rates and magnitudes

The number of stress jumps per strain step, the stress jump rate, shows a non-trivial dependence on grain size (see Fig. 4.4.2a). Large (4 mm) glass beads generally produced least stress jumps relative to the intermediate (2 mm) and small (1 mm) glass beads. Typical rates were in the range of 10–60 events/mm. Results also show a significant influence of the applied normal loads: experiments with lowest normal loads delivered more stress jumps; higher normal loads appear to reduce the number of stress release events. In contrast, the average magnitude of stress jumps (Fig. 4.4.2d) shows a different picture; the values were high for the 4 mm beads and smaller for the small and medium size bead. We found that increasing the normal load directly increased the magnitude of
Figure 4.4.1: (a) Shear stress ratio $\tau/\sigma_N$ against displacement $\varepsilon$ of shear tests with 1 mm glass beads at a normal load of 30 kPa, 45 kPa and 60 kPa. A gray rectangle indicates the data section magnified in the right panels. (b) Measured energy release rate $dU_{<20\text{kHz}}/d\varepsilon$. (c) Magnification of the shear stress ratio $\tau/\sigma_N$ from a shear test with 45 kPa normal load exhibits a succession of stress fluctuations: typical phases of such a stress release event consist in a relatively linear build-up phase (i), that increasingly becomes interrupted by smaller precursory fluctuations (ii) and finally is concluded by a major release event (iii); (d) synchronous record of low frequency (0–20 kHz) acoustic event energies $U_{<20\text{kHz}}$ and (e) high frequency (30–80 kHz) acoustic event energies $U_{>30\text{kHz}}$. 
the average stress jump. As discussed above, low-frequency AE (< 20 kHz) events were closely related to stress release events. This indicates, that elastic waves are triggered by rapid rearrangements of the granular force network in response to shear deformation. It is therefore no surprise that average low-frequency AE event rate (Fig. 4.4.2b) and mean magnitude (4.4.2e) partly resemble the above discussed stress jump characteristics. Event occurrence rates of low-frequency AE events were found to be in a similar range as values for stress jumps. Similarities in the response of low-frequency AE and stress jumps in terms of their event rates and magnitudes for the different grain sizes underscores the relation between stress jumps and AE generation. In our data we found a tendency for small particles to generate a large number of relatively weak AE events, while larger grains produce less frequent but stronger events. The energy that was captured during low frequency AE events was in the range of 0.2–2 mJ. This is several orders of magnitudes lower than what can be expected as total energy release from stress jump events.

The high-frequency AE events, i.e. signals with frequencies in the range of 30 kHz–80 kHz (Fig. 4.4.2c & 4.4.2f), displayed features that deviate from those of stress jumps. Typical event occurrence rates were in the range of 70–700 mm$^{-1}$, which is roughly one order of magnitude higher than the average values of stress jumps and low-frequency AE. Data of those events were in general consistent with analyses of stress jumps and low-frequency AE. Only for the high-frequency AE we found that normal loads were positively correlated with the average number of events.

Although the foregoing analyses suggested that stress jumps associated with the imposed shearing directly result in low frequency AE events, we have not been able to establish a clear correlation between the magnitudes of both processes (see Fig. 4.4.3). Comparison of stress jump magnitudes with the energy of consequently captured AE events shows strong scatter of the data and does not expose any linear relation between the both. It can however be gleaned from Fig. 4.4.3 that stress jumps in many cases were split in a group of high- and a group of low-magnitude events.

4.4.3 Empirical frequency-size distributions of stress jumps and AE events

Additional insights into the link between stress jumps and AE events were gained from the analyses in Fig. 4.4.4 that display the frequency-magnitude distributions of recorded stress jump and AE events. The distributions of stress jumps showed a characteristic shapes consisting of multiple peaks A similar phenomenon was found for distribution of grain stresses in deforming granular assemblies by Howell et al. [21, Fig. 18]. Generally, an increase of either grain size or the normal load shifted the peaks to the right, i.e. to higher magnitudes. A simple principal shape was found for the statistics of low frequency AE events. A common feature of many observed distributions was the presence of a characteristic fall-off of large event probabilities. We find the distributions of low-frequency AE persistent even under different experimental conditions. Particularly under different normal loads the displayed distributions showed far less variability than their stress jump counterparts.

Fig. 4.4.5 exhibits the strong tendency of high frequency AE size distributions to
Figure 4.4.2: Average event occurrence rate $F_{\Delta \tau}$ (a) and event magnitudes $\Delta \tau$ of stress release events (d). Average event occurrence rate of low frequency acoustic emission events $F_{<20kHz}$ (b) and the corresponding event energies $U_{<20kHz}$ (e). Average event occurrence rate of high frequency acoustic emission events $F_{>30kHz}$ (c) and energies $U_{>30kHz}$ (f). Panels show results for different grain sizes and normal loads.
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Figure 4.4.3: Empirical correlation between stress jumps and associated acoustic events for different test conditions.
obey power laws. Estimation of the exponent from measurement data was performed with a goodness-of-fit based method [7] and yielded values around 2.0. Fitted power-law exponents were found to slightly depend on the normal load applied to the sample. Tests with less confining stress result in power-law coefficients up to 2.5.

### 4.4.4 Elastic energy release rate - AE analyses

We defined the sum of energies that are captured from events during a strain interval divided by the width of this interval as the acoustic energy release rate. This measure characterizes the total amount of energy that is released in discrete failure events within a strain interval. Earlier we looked at links between individual stress jumps and AE events (Sec. 4.4.1) and response of both phenomena to different experimental conditions (Sec. 4.4.2). Here we address questions concerning the strain-driven AE energy release rate under different experimental conditions. We observed that the average number of acoustic events and their magnitudes were dependent on the applied normal load and
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Figure 4.4.5: Occurrence frequency of recorded high-frequency AE events for shear tests with 1 mm (a) and 4 mm (b) glass beads. Straight lines indicate the steepness of fitted power-laws (for normalized data). Values range between 2.2 and 2.5 for tests under 30 kPa normal load (light gray lines). Tests with 60 kPa confining stress result in values from 1.9 to 2.1.

on the grain size. Hence, we may expect that also energy release rates were affected by both experimental conditions. Fig. 4.4.6 depicts the evolution of observed low-frequency energy release rates.

The analysis of Sec. 4.4.2 shows that high occurrence rates in the records of low frequency AE and stress jumps were often associated with a low mean magnitude of events and vice-versa. The signature of this phenomenon could also be found in measured energy release rate, where a compensation of event occurrence rates against the average magnitude partly blurred the effect of different test conditions. Fig. 4.4.6 shows, that observed low-frequency AE energy rates, particularly in the later stages of our experiments were only weakly affected by normal loads. Furthermore, we find no effect of grain size (data not shown).

The energy release of the high frequency AE measurements follows a slightly different trace as can be seen in the comparison between the two graphs in Fig. 4.4.6. For most test conditions we find an immediate increase and a fast saturation of the energy release rate after the onset of straining. In some cases this happens even before the peak stress is reached. For the high frequency AE signals a clear dependency on normal load could be found in contrast to energy captured by low frequency accelerometers.

4.4.5 Comparison of shear experiments with FB-modeling results

The stick-slip FBM [16, 17, 35] provides a relatively simple means to establish and test hypotheses for the observed behavior of granular material under shear deformation. The model framework allows to convert elastic properties and failure distribution of the single load-bearing element into collective material strain response. Fig. 4.4.6 shows that the characteristic stress-strain behavior of our granular sample material were well captured by the model. Except for a simple scaling to match the location of the observed peak
Figure 4.4.6: Energy released by low-frequency (0–20kHz) AE per unit strain (a) 1 mm, (b) 2 mm, and (c) 4 mm glass beads under different normal loads. Solid curve is FBM result. No fitting to experimental results was attempted.
stress, we perform no systematic calibration of the model to the experimental data. The observed energy release rates (see Fig. 4.4.6b) shows that the maximum of energy release per unit strain occurred after the peak stress, at least for low frequency AE. This feature is predicted by the model as seen in Fig. 4.4.6. Model results suggest that the peak stress of a granular assembly coincides with the energy release turning point. This means that the energy release rate accelerates up to the maximum shear stress, after which it slows down towards its maximum. Because of significant scatter in the AE energy, it is difficult to confirm this phenomenon experimentally, but the finding is consistent with analysis from other disordered systems [3] where an acceleration of observed failure rates culminates in the final breakdown. Fig. 4.4.4 depicts comparison between modeled and observed frequency-size distributions of stress jumps and AE events. The characteristic distributions of high magnitude force jumps were in good agreement with modeled predictions. The observed low-magnitude events appear to obey different statistical distributions as they appear clearly separated. The FBM cannot reproduce this observed feature that may be an expression of different failure mechanisms triggering stress jump events in our tests. Scrutiny of predicted energy release size distributions (see the inset of Fig. 4.4.4b) reveals that the model can capture an exponential cut-off at high magnitudes. The distribution of lower magnitude events deviates considerably from our model predictions.

4.5 Discussion

Experimental and theoretical links between stress-strain curves and energy release rates during shearing of granular assemblies and similarities in their statistical features underline the strong links between stress jumps and low-frequency acoustic emission events. From the results of our shear-frame tests we found significant indications that both phenomena originate from the same source mechanism, namely abrupt rearrangements of the force-chain network. Simultaneous occurrences of low-frequency acoustic signals and jumps of shear stresses were found in all analyzed data. Similarities between the average number of observed events and their magnitude characteristics (Fig. 4.4.2) provide further support for the hypothesis that mechanical force jumps and triggering of acoustic events occur together.

Comparing average event rates with the corresponding mean magnitudes of stress jumps, one finds that high event rates often occur in conjunction with low average magnitudes: we find that shearing that leads to a large number of events (low normal load, smaller grain sizes), also yields smaller event magnitudes as seen in Fig. 4.4.2. This phenomenon can be observed also in the average features of low-frequency acoustic signals, and leads to a partial compensation between event occurrence rate and average magnitude. The energy release rates of those acoustic events yield a fairly weak signature of the experimental conditions particularly on the level of captured energy in later stages of our tests (Fig. 4.4.6).

We observed clear differences in the statistical distribution, recurrence frequencies, and response to different test conditions between low-frequency and high-frequency acoustic
emission events. In contrast with the episodic and distinct occurrence of low frequency acoustic events, we observed a continual generation of high frequency signals during shear deformation (see the example in Fig. 4.4.1e). More high-frequency elastic waves were found generally under larger normal loads and for smaller particle sizes. The magnitude of these energy release events is primarily influenced by the normal load (Fig. 4.4.2). High-frequency acoustic events come with relatively persistent frequency-size distributions even under changing experimental conditions (Fig. 4.4.4). Frequency magnitude distributions could be fitted by power-laws, with power-law coefficients in the range from 2.0 to 2.5. For higher characteristic frequencies, it is likely that such events are triggered by grain-to-grain interactions in contrast with low frequency AE events that are associated with grain network rearrangement. The most prominent grain-scale failure in dense granular packings is frictional slip, a known AE generating mechanism in granular media [34]. Assuming that the two types of acoustic signals represent failure mechanisms at different scales, insights into the dissipation behavior of granular assemblies may be obtained. Low-frequency AE events indicate source mechanisms with an energy release that is in total only weakly dependent on normal load and particle sizes. Their close relation to observed stress jumps supports the assumption that they are generated by grain lattice rearrangement events. High-frequency AE, presumably associated with grain-to-grain interactions, display a pronounced dependence on normal loads and grain sizes.

FBM predictions show reasonable qualitative agreement with observations in many aspects. As shown earlier [35] the model was capable of reproducing the characteristic stress-strain behavior of granular materials under direct shear deformation. Previous studies have shown that FBMs are closely related to continuum mechanical brittle damage accumulation approaches [48], where fiber rupture is analogue to the opening of a micro-crack. Here the failure of a fiber represents the failure of a load bearing element in a granular shear zone, in particular force chain buckling. Accounting for the repetitive breakage and reformation of force chains in granular shear zones fibers are restituted after their failure in the FBM. The force jump during fiber failure is compared against observed force fluctuations of our strain-controlled shear tests. Modeled energy release represent energy bursts in the granular shear layer leading to observable elastic wave generation. The focus of the FBM on statistical features of stress fluctuations and associated energy bursts, the model retains the salient features and avoids a critical dependence on data concerning particle shapes, geometric and material properties. The model thus relies on statistical information concerning force chain strengths and dynamics. The analysis shows (as did the work of [12]) that resulting distributions are rather influenced by inherent load redistribution and fiber restoration than by the precise shape of the input functions.

Based on the comparison of FBM predictions with data from our experiments we suggest that the FBM in its presented form represents mechanical interactions dominated by the action of force chains. Formation of shear zones, dilation and residual shear strength are all phenomena that are at least indirectly linked to such mesoscopic structural elements. They would not occur if the mechanical interactions were determined by friction between single grains only. Using a purely phenomenological match
between model and material behavior we found a good qualitative agreement of different statistical quantities and certain measures of dissipative energy release. It is instructive to discuss several discrepancies between model and observations that illustrate certain features of the process:

• The separation of observed stress jump statistics into two distinct parts was not captured by the model. We interpret this feature of the observed data as an expression of failure localization marked by precursory stress fluctuations before a full stress jump. Such avalanche behavior points towards coupled breakage and local load redistribution in the failure region even under strain-controlled loading. The presented FBM is not capable of accounting for this effect.

• Acoustic events at high-frequencies do not obey predicted exponential distribution functions. A good fit to the data is obtained by power-laws. The source mechanism for these AE events may be governed by processes other than the repetitive force chain failure. We suggest continual frictional interaction between grains of the assembly as potential source mechanism. Friction is known to yield force fluctuations that can be described with power-laws. Moreover, we found that high-frequency signals were continuously generated also between successive force jumps.

• All acoustic signals experience considerable attenuation in porous media with signal damping as they propagate away from their source. Events that are generated farther away from the sensor would manifest smaller amplitudes than similar events near the sensor. Consequently the frequency-size distribution is expected to be biased. We suspect some of these effects contributing to differences between model and measurements in this study.

Key features of failure-associated acoustic emissions were predicted successfully by the model including the delay between the maximum shear stress and the maximum acoustic energy release rate. The model suggests a continuous acceleration in acoustic energy release rate before exceeding the peak shear stress, an observation that may guide the usage of the acoustic method for shear failure monitoring.

Despite the benefits offered by the simplicity of the annealed disorder FBM, caution should be exercised in the application of this model to granular shearing. The current model considers only one mechanism of energy dissipation in granular material: failure of the force-chain network. Distinct features of different types of acoustic signals, as presented earlier in this work, suggest the presence of other mechanical phenomena, that withdraw strain energy from the mechanically active part of a granular assembly. Fig. 4.4.5 underlines shortcomings of the model that was not able to reproduce features of high-frequency AEs. Note, that the FBM reproduces mechanics of a shear zone comprising of infinite number of mechanical elements. The resulting continuous stress-strain and energy release rate curves, stands in stark contrast to fluctuations, that dominates the observations. The aim of our experiments was to promote the production of stress jumps by using relatively large particles. Such jumps would most likely average out in larger more realistic shear zones approaching the smooth behavior predicted by an infinitely large fiber-bundle

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4.6 Summary

We performed shear frame experiments with spherical glass particles of different grain sizes, measuring fluctuations of the shear force and acoustic signals in two different frequency bands. Observations demonstrated that shear-induced changes in the grain contacts network produced a high number of acoustic emission events in low and high frequency bands providing a rich interrogation tool for shear zone mechanics. Low frequency signals were strongly correlated with measurable jumps of the shear stress, suggesting that they are triggered by larger episodic restructuring of the strong force network (force chain buckling). Evidence suggests that that high frequency AE are correlated with grain-to-grain interaction such as frictional slip. Reproducing qualitative features of granular shearing by a conceptual annealed disorder FBM inspires confidence that the coupling of the data-rich AE method and our conceptual model provides a powerful method to investigate mechanical and energetic aspects of granular shear deformation. Granular shear zones play an important role in many geophysical processes, such as landslides, rock falls and other geologic mass movements or in fault mechanics and earthquake triggering. The findings of this work provide a new framework for investigating and predicting the rich mechanical interactions at granular shear zones and failure mechanisms involved. The proposed framework consisting of acoustic emission measurements and a conceptual shear zone model may open new possibilities for early warning of notoriously hard-to-predict shallow landslides and even for larger scale for the monitoring of tectonic shear zones.

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Manuscript in preparation

Abstract

Grain jamming, contact friction, grain collisions and other small-scale mechanical interactions arising during shear deformation result in complex force network fluctuations with episodic and abrupt release of stored elastic energy. These release events are characterized by the emission of elastic waves at the frequency range of kHz, often termed acoustic emissions (AE). The close association between grain-scale mechanics and AE generation motivated the use of AE as surrogates for the mechanical state of complex materials and granular flows. The primary objective of this study was the characterization of AE generation mechanisms stemming from grain-scale mechanical interactions. Basic mechanisms for the generation of individual elastic waves are considered, including frictional slip between particles, and mechanical excitation of particle configurations during force network restructuring events. The intrinsic frequencies and energy content of generated AEs bear the signature of source mechanisms and of structural features of the grain network. The resulting quantitative insights provides new capabilities for non-invasive interrogation of micromechanical interactions and linkage to a stochastic representation of shear zone mechanics. Statistic features of failure events and associated energy release linked to shearing were predicted with a fiber-bundel model (FBM). This conceptual model framework describes granular matter by a large number of independent mechanical elements, called fibers. The release of energy related to abrupt and episodic failure propagation in the FBM are exploited to predict energy available for AE generation and its statistical features. Acoustic measurements in simple shear experiments on a granular micro-model reveal distinct characteristics of AE from different source mechanisms. Results of the FBM-AE generation model where in reasonable agreement with direct shear experiments that were performed on large granular assemblies. The results underline the potential of using AE as a diagnostic tool to study micro-mechanical interactions and to obtain predictions concerning granular failure and mobilization.

5.1 Introduction

The link between mechanically-entrained granular media and generation of audible sounds has been part of our experiences since we learned to handle rattlers in our early childhood. Such sounds remain familiar parts of our daily experiences: from the faint trickling of sand in an hourglass to the crunching sounds generating during driving or
walking on a gravel road. Such deformation-induced sounds result from abrupt and episodic grain scale mechanical interactions that release stored strain energy in the form of elastic waves. These mechanical interactions may include collisions of particles, sliding at grain contacts or larger rearrangements within the granular contact network. Different shearing-induced micro-mechanical processes may produce elastic waves with distinguishable frequencies and varying energy content. Perceptible sound is created when such vibrations are transmitted from solid or liquid surfaces into the surrounding air. A common process that induce abrupt mechanical interactions, associated with elastic wave production, is macroscopic shear deformation of granular assemblies.

Non-smooth grain-scale interactions affects the macroscopic behavior of grain assemblies in a number of well-known, yet curious phenomena: the localization of shear deformation in narrow shear bands [49, 31, 8], the non-linear properties of sound wave speeds [20, 18, 51], or the inhomogeneous distribution of loads amongst particles under the influence of a stress field [21, 30, 22, 25]. Many of those phenomena are based on non-smooth mechanical laws that govern granular material behavior on the particle scale. Two prominent examples of non-smooth grain-to-grain interaction are frictional slip and particle collisions. The mechanical behavior of granular materials is dominated by the self-organization of grains under loading and the formation of force networks. Such force networks typically consist of pillars of aligned, highly loaded grains, the so-called force chains [50, 34] often oriented along the principal directions of the mean stress field. During progressive shearing, individual force chains undergo numerous cycles of formation, straining and failure [46]. Repetitive cycles of particle network rearrangements and the concentration of stresses into force chains result in a number of episodic features at the meso-scale. Examples include intermittent jamming-unjamming events, stick-slip phenomena or rapid fluctuations of the shear stress [1, 10]. For conditions of strain-controlled deformation, granular assemblies typically exhibit fluctuations of stresses [27] (these conditions are contrasted with stress-driven deformation that leads to episodic strain jumps). Such stress jumps reflect the effects of non-smooth grain-scale processes on macroscopic material behavior. In addition they present sources of elastic vibrations and waves. Similar processes of strain accumulation and sudden release are key to the abrupt occurrence of earthquakes, the triggering of landslides, and the onset of granular flows. The quantitative description of such processes hinges on properly deciphering grain and force network mechanics.

The abrupt failure of a force network, grain collisions or friction at particle contacts invariably involve the rapid release of stored elastic energy accumulated during straining. Deformation-induced rearrangement of the grain network, frictional particle interaction and non-elastic particle collisions present efficient mechanisms for energy dissipation [17, 26], namely the ultimate conversion of mechanical energy into heat [11]. Force fluctuations and resulting elastic wave generation (as visualized by Bardenhagen et al. [2] or Owens et al. [32]) may therefore offer a means for gauging energy dissipation, and for tracking different pathways of strain energy release. Evidence suggest that the signature of different source mechanisms may be contained in the frequencies and energy of generated elastic waves [5, 9].

The deformation of granular assemblies involves a large number of failure events at
different intensities. Interactions among numerous mechanical elements (grains, force chains), introduce many degrees of freedom that are confounded by inherent variability in grain properties and geometrical packing detail. A potentially useful modeling framework for gaining insights into the statistical behavior of such systems with many interacting elements is offered by analogy to fiber bundle models (FBM). The FBM is a conceptual tool capable of representing mechanical interactions and transition processes in disordered materials, such as granular shear zone formation [29, 28]. FBMs are based on the interaction of a large number of elements that obey simple mechanical rules and that fail at a stochastically determined threshold strain. Conceptual parallels between elements of the FBM and force chains justify the use of this relatively simple tool for simulation of complex mechanical processes in granular material. FBMs also provide predictions of failure and associated release of strain energy, this is at the same time the energy available for AE generation. Hence, FBM-based prediction of AE energies provide a promising starting point to establish links between material mechanics and failure associated AE generation [15, 48, 29, 28]. Elastic waves that are generated during failure waves radiate from the source location and undergo altering on their propagation path. If not gauged at the source location (which can hardly be realized in an experiment) such effects may induce considerable bias in inferences based on measured AE events.

The objective of this study was to exploit the close links between the grain-scale mechanical interactions in sheared granular materials and associated AE characteristics. We present various mechanisms giving rise to abrupt release of strain energy. We endeavor to investigate how prototypical granular structures release stored strain energy in the form of elastic waves and look at the frequency spectra generated by such energy release events. Knowledge of the response of prototypical granular structures to mechanical excitation enables the development of bounds for typical frequency ranges as they may occur in real granular assemblies. The outcome of our analysis is compared to AE event data obtained from shear frame experiments using cohesionless glass bead assemblies. An important practical goal was to establish links between granular material properties, respectively loading procedure and characteristics of generated acoustic emissions. From numerical solutions of the FBM we obtained the statistical description of mechanical failure events and associated AE energies. These results serve to investigate sources of granular material plasticity and granular material principal mechanical behavior. In this upscaling we also consider contributions of signal attenuation and geometric restrictions of signal acquisition as they occur in real measurement scenarios. Simulation results will be presented in the result section and are compared against observations from shear tests and measured acoustic event statistics. A concluding section presents consequences of obtained results with respect to the objective to use AE from granular material for plasticity and material behavior assessment. Potentials and limitations of the presented methods will be discussed and further possibilities will be outlined.
5.2 Modeling Grain-Scale AE Generation

5.2.1 Characteristic frequencies and energies of AE generation

In the following we introduce details in the role of particle impacts and contact friction as mechanisms for elastic wave generation in granular materials. The resulting elastic wave frequencies are shaped also by geometrical and material properties of the excited structure. In a second step we provide a mechanistic description of prototypical grain configurations and analyze their characteristics with respect to elastic vibrations. The analyses of grain-scale mechanical interactions are illustrative and remain largely conceptual, nevertheless these results may be sufficient for constraining the expected spectral ranges of resulting elastic waves.

5.2.1.1 Particle Collisions

During large deformation of granular materials changes of the grain lattice are inevitable and often involve destruction and reformation of contact networks. The establishment of a new contact by two grains involve a grain collision. The approaching speed of the two grains determines the energy for the resulting impact. Considering elastic deformation with no shear forces at the contact (the assumptions of Hertz contact mechanics [14]) the energy involved in deformation is given as:

\[ U = \frac{8}{15} E^* R^*^{1/2} d^{5/2} \]  \hspace{1cm} (5.2.1)

where \( R^* \) is the harmonic mean of particle radii, \( E^* \) the harmonic mean of the Young’s moduli and \( d \) is the indentation depth. A collision of particles against one another introduces a mechanical impulse on the granular structure. If the impact is sufficiently short it corresponds to a broadband excitation, i.e. all frequencies are equally present in such an impulse. For the estimation of the impact duration, we again invoke Hertz mechanics to obtain [19]:

\[ t_c = \frac{4\sqrt{\pi}\Gamma(2/5)}{5\Gamma(9/10)} \left( \frac{m^*}{16/15^{1/5}E^* R^*} \right) \]  \hspace{1cm} (5.2.2)

Here \( \Gamma() \) is the gamma-function, and \( \nu \) is the material Poisson ratio. Based on Equation 5.2.2 the impact duration for two glass beads \( (m = 11 \times 10^{-6} \text{kg}, E = 65 \text{GPa}, \nu = 0.23) \) during collision at an approach speed of 0.05 m/sec is estimated to be 13 \( \times \) 10^-6 sec. An impact of this duration may be considered a broadband pulse up to a cut-off frequency of 77 \( \times \) 10^6Hz [3], which is the inverse of the collision time \( t_c \). The collision between two curved bodies receives additional complexity due to the fact that the volume affected by the body deformation increases during the process resulting in stiffening of the contact. Seeking a simple description of the force development we invoke an approximation made by Hunter [16], that showed that the process can be described reasonably well by a sinusoidal-curve.
5 Mechanisms for AE generation during granular shearing

5.2.1.2 Frictional slip

Shear deformation of granular media involves considerable amount of frictional slip events between pairs of grains [43, 23, 52]. Studies have shown that dry friction between two rough bodies is a result of the interlocking of surface asperities [35]. Sliding of the two bodies requires deformation or rupture of those asperities. Repetitive sequences of surface interlocking and release during frictional slip constitute dynamic friction force. This apparently constant force consists in fact of microscopic fluctuations around a mean value. Statistical rules for this force fluctuations can be obtained from microscopic features of the surface topography. The self-similarity of surface asperities can be converted into a frequency-magnitude spectrum of force fluctuations. Along this lines force fluctuations are predicted to decay with $1/f^2$ [54], where $f$ is the recurrence frequency of an event. Following the argumentation of Zaitsev [54], we will use the $1/f^2$-frequency spectrum as hallmark of frictional slip between two grains. Microscopic force fluctuations are also responsible for friction-induced vibration and generation of elastic waves [4]. The relation between friction and generation of acoustic signals is widely acknowledged and has been explored already in numerous studies [40, 53, 24, 26].

5.2.1.3 Single grain excitation

The most simple geometrical body that can be constructed from equal spheres is a tetrahedron. This configuration consists of a single particle supported by three neighboring particles (see inset of Figure 5.2.1). That form the most basic building block of 3-D granular assemblies [47]. Due to their relevance for dense granular media we investigate the response of this structure with respect to mechanical excitation. To obtain the elastic properties of the four-grain configuration we invoke again the theory of Hertz [14] and find for the stiffness $k_{ij}$ of a sphere-to-sphere contact:

$$k_{ij} = \left(\frac{3F_n R^*}{4}\right)^{1/3} \left(\frac{E^*}{1 + \nu^2}\right)^{4/3},$$

(5.2.3)

Equation 5.2.3 shows that the contact stiffness depends on the contact force $F_n$, respectively on the compliance induced by $F_n$. In the following, we assume that contact deformation due to static loads is larger than during dynamic oscillations (similar assumptions were made by Somfai et al. [42]). Correspondingly we neglect changes of $k_{ij}$ during particle excitation and the resulting motion. For the dynamical analysis viscous damping was considered at the particle contacts. Damping coefficients $d_{ij}$ were set to a small finite number proportional to the corresponding contact stiffness, such that the condition of proportional damping [41] is fulfilled. This additional constraint on the the $d_{ij}$ allows a relatively simple calculation of a system frequency response function. The starting point for the analysis of particle vibrations is the equation of motion, that describes the balance of mass inertia, contact stiffness and contact damping. For the free particle of our tetrahedron this reads in index notation as

$$m_\alpha \ddot{r}_\alpha = -d_\alpha \dot{r}_\alpha - k_\alpha r_\alpha$$

(5.2.4)
The effective damping coefficients $d_x$ and effective stiffness $k_x$ are obtained by conversion from the grain contacts reference frame into global (Cartesian coordinates). Considering the three spatial coordinates ($r = \{x y z\}$) Equation 5.2.4 can be expressed equally as three equations. These differential equations are typically solved by assuming a harmonic solution function of the form $exp(\text{i} \omega t)$ [41]. The characteristic frequencies of such oscillation $\omega_r$ can also be obtained from an eigenvalue analysis of the equivalent undamped system. Including the effect of damping into the mechanical analysis a dispersion of the frequency spectra, i.e. response of the system at frequencies other than $\omega_r$ can be found. The complete frequency response of the damped system can be expressed as [41]

$$R_x = \frac{1}{k_x} \left( \frac{1 - (\omega/\omega_{r,x})^2}{(1 - \omega/\omega_{r,x})^2 + (2\zeta_x\omega/\omega_{r,x})^2}\right)$$

(5.2.5)

Here $\zeta_x = d_x/2\sqrt{k_x m}$ is the damping ratio at the resonance frequency $\omega_{r,x}$. Figure 5.2.1a shows resonance frequencies and magnitude of the frequency response $|R_x|$ (including damping) of a tetrahedral grain configuration under different confining stresses. Higher static loading results in stiffer contacts and correspondingly higher resonance frequencies $\omega_r$ of the structure (note that $\omega_r \sim \sqrt{k/m}$). In our example, that was chosen to represent experimental system, $\omega_r$ ranges between 30 kHz and 60 kHz. In addition to the pure frequency response function we considered the system's response to different excitation mechanisms. Idealizing a collision against the free particle (Figure 5.2.1b) as a half-sine-wave it can be seen, how resonances of the structure are excited. In Figure 5.2.1c we replaced the excitation force with $1/f^2$-fluctuations (duration 130 $\mu$s, overlaid with a Hamming window). Again the resulting vibration is dominated by the resonance of the tetrahedron-structure. However, the excitation mechanism leaves a clear signature in the frequency spectrum, such as the presence of considerable low-frequency contributions in the amplitude spectrum.

5.2.1.4 Excitation of force chains

Shear deformation of granular media may involve development of internal structures consisting of clusters involving a larger number of grains. The mechanical back-bone of granular assemblies is typically formed by numerous force chains. Motivated by the broad consensus concerning the relevance of such chains for granular material mechanics [50, 34, 45] we present a dynamical analysis of granular chains in the following.

The derivation of the frequency response is based on mechanical analysis of an idealized force chain as can be seen in the inset of Figure 5.2.2. We consider an assembly of spherical masses connected by springs. Analogous to Equation 5.2.4 this simple mechanical model may be expressed as matrix equation [42]:

$$M \ddot{x} = -H^T KH x - H^T DH \dot{x},$$

(5.2.6)

The diagonal matrix $M$ represents particle masses and the vector $x$ indicates particle positions. On the right hand side we have the contact stiffness matrix $K$ containing normal
Figure 5.2.1: (a) Frequency response of a tetrahedron-shaped grain assembly (as shown in the inset) under different confining loads. Characteristic frequencies are indicated by the straight lines. (b) The response of the tetrahedral structure to excitation from a collision-induced force pulse, as shown in the inset. (c) The amplitude spectrum of the calculated response to force fluctuations generated by frictional slip (the excitation force is shown in the inset).
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and tangential stiffness of all particle contacts. Conversion of this information between the reference frame of particle contacts and a global coordinate system is performed by the tensor $H$. $H$ is often called the contact matrix [37] and allows to transform vectors between the different reference frames (contact reference frame and particle reference frame). Viscous contact damping is included into the equation of motion by the damping matrix $D$ (again we selected the entries of $D$ such that proportional damping is satisfied). Rearranging the terms of Equation 5.2.7 yields:

$$\ddot{x} = -M^{-1}H^TKH\dot{x} - M^{-1}H^TDH\dot{x}.$$  (5.2.7)

Solutions of this system of second order differential equations describes the oscillatory motions that are represented by harmonic functions [42]. The eigenvalues and corresponding eigenvectors of the undamped system (represented by the term $M^{-1}H^TKH$) enable derivation of the characteristic oscillation frequencies. The number of characteristic frequencies corresponds to the number of degrees of freedom of the mechanical system, and are indicative of the natural resonance frequencies of the structure. The stiffness matrix, $K$ (containing bilateral stiffness of all grain contacts), can be determined according to Equation 5.2.3 from grain geometry, material properties and static contact force. For simplicity do not consider changes of this quantity from force changes during an oscillation cycle.

The model allows systematic study of the frequencies produced by a particular granular structures. Here we selected a prototypical example of a force chain and compute generated frequencies. Figure 5.2.2a shows frequencies from a three-dimensional idealized force chain that consists of eight particles. The figure shows how different normal loads change the characteristic frequencies and their maximum amplitude. It can be seen that oscillations for the considered example have characteristic frequencies $> 10$ kHz. A larger normal load on the force chain yields stiffer contacts and results in higher resonance frequencies. On the other hand we find higher damping of configurations in the frequency response curve under large normal confinement.

The frequency response in Figure 5.2.2a describes the spectral signature of the grain arrangement irrespective of any particular mechanical input. To consider effects of the above discussed excitation mechanisms we modeled the frequency response of the structure to a short force pulse (representing a particle collision) and a succession of $1/f^2$ force fluctuations (standing for friction generated vibrations). Figure 5.2.2b shows the broadband excitation generated by a particle collision modeled through a 13µsec sine-shaped force pulse. It can be seen that resonance modes above the cut-off frequency ($77 \times 10^6$Hz) are almost not present in the resulting amplitude spectrum. Only the lowest resonance frequencies are excited by the collision. Under friction excitation we also find a cut-off of high resonance frequencies. $1/f^2$-fluctuations transport most energy at the low frequencies; correspondingly it is the lowest resonance frequencies that are responding strongest to this excitation mode.
Figure 5.2.2: (a) An excited force chain (see inset) resonance frequencies under different normal loads. Eigenfrequencies of the structure are indicated by vertical lines. (b) The frequency response due to particle collision with a force chain. (c) Frequency response after friction excitation.
5.2.2 Statistical description of grain scale interactions - The Fiber Bundle Model (FBM)

Following up the analysis of individual AE event generation, we strive for an upscaling procedure that allows direct links between mechanical events and the resulting AE activity expected to occur in granular assemblies during shearing. As a first step, we quantify the numbers and intensities of grain-scale failure events associated with progressive formation of a shear zone. To bridge the information gap concerning inherent variability of material structure, geometry and properties - all of which crucially determine mechanical behavior - we use a fiber bundle model (FBM), a stochastic framework to describe transition phenomena in disordered material [15, 39, 6, 36]. FBMs consider mechanical interactions among a large number of elements, called fibers. In a simplest representation such fibers behave as linear-elastic elements breaking at a threshold load that is stochastically determined individually for each fiber. The standard FBM was developed to describe tensile loading of yarn strings [33, 7]. The model was subsequently modified and expanded to consider other loading scenarios, such as bending [44], compression [15] and shearing [38, 6]. Building up on a variant of the FBM presented by Halázs and Kun [13, 12], Michlmayr et al. [29, 28] reproduce characteristic features of granular shearing and associated acoustic signals. In their annealed disorder FBM, broken elements are replaced by new, unstrained fibers that receive a new random rupture threshold. Fibers in this model undergo series of rupture and reconstitution cycles, reminiscent of continual force chain reformation or repetitive frictional slip between grains. Different statistical distribution functions may be used for the assignment of fiber threshold values. The two parameter ($m$ and $\lambda$) Weibull distribution function appears particularly useful for this task, because of its simplicity and the inherent link to failure processes:

$$p_t(t) = \frac{m}{\lambda} \left(\frac{t}{\lambda}\right)^{m-1} e^{-(t/\lambda)^m} \quad (5.2.8)$$

Earlier work provides us with detailed analysis of its mechanical behavior and energy release associated with fiber rupture in the annealed FBM [13, 12, 29, 28]. Here we consider annealed fiber bundles consisting of $N$ elements, representing active particle contacts of a granular shear zone. The stress strain behavior of the bundle naturally depends on the failure-restoration history of its fibers. It can be written in rate form as

$$\frac{\Delta \tau}{\Delta \varepsilon} = NE \Delta \varepsilon - \sum_{i=1}^{Nf} t_i \quad (5.2.9)$$

where $E$ is the fiber elasticity and $N_f$ indicates the number of breaking fibers within the strain interval $\Delta \varepsilon$. The first term on the right-hand-side of Equation 5.2.9 accounts for the elastic straining of fibers while the second term describes stress decay due to rupture events. The energy that is released during fiber rupture events can be expressed (also in rate form) as

$$\frac{\Delta U}{\Delta \varepsilon} = \frac{1}{E} \sum_{i=1}^{Nf} \frac{t_i^2}{2} \quad (5.2.10)$$
Looking at the elements of the FBM as conceptual representation of grain contacts and force chains the expression above represents the energy released during failure and associated with AE generation. As presented in the previous section, AE may be generated by different mechanisms during granular shearing. These different source mechanisms may be incorporated in the FBM by grouping fibers based on their rupture threshold.

A key assumption in this application is that the “fibers” with the highest rupture threshold (here in the top 10% interval $0.9t_{\text{max}} < t \leq t_{\text{max}}$) represent excitation of force chains. Smaller events are associated with individual grain collisions and contact friction. Smaller rupture events ($0 < t < 0.9t_{\text{max}}$) stand for the oscillation of a single grain ($t_{\text{max}}$ indicates the maximum possible threshold at a given bundle deformation). The two primary quantities of interest, namely the bundle stress $\tau$ and the energy release rate $\Delta U/\Delta \varepsilon$ can be compared against force and AE measurements of real granular systems and therefore present the two key quantities we obtain from our model. Since both measures can be expressed only in a rate form, we performed step-wise calculation of the bundle behavior according to the following procedure:

1. attribute initial rupture thresholds to all $N$ fibers,
2. increase the strain up to the threshold $t_{k}^{i}$ of the weakest fiber of the bundle,
3. after rupture a fiber receives a new random threshold $t_{k+1}^{i}$, the straining of the fiber is reset to zero, the next failure of this fiber will take place at $\sum_{q=1}^{k+1} t_{q}^{i}$.
4. repeat 2 and 3 to continue straining of the fiber bundle.

Previous studies [28] have shown that an annealed disorder FBM can reproduce complex granular shear zone formation considerably well: Figure 5.2.3 shows the shear stress $\tau$ on a fiber-bundle consisting of $N = 10^5$ elements (thresholds $t$ are drawn from a Weibull distribution with $m = 2$ and $\lambda = 1$). Similar to the results presented in earlier work [28] we find stress-features characteristic for granular materials under shear deformation: that is the build-up of shear stress with increasing plasticity at the onset of shearing (phase a–b in Figure 5.2.3), followed by the peak shear stress and relaxation into a residual stress regime (phase b–d in Figure 5.2.3). Simulations of the energy release rate $\Delta U/\Delta \varepsilon$ are in agreement with analytic results presented earlier [28]. The results show a delayed increase in energy release rate relative to the increase in shear stress. The episodic nature of energy release events exhibits larger fluctuations than the integrative stress fluctuations that also reflect the state of intact fibers. The insets of Figure 5.2.3 show the statistics of failure event energies at different phases throughout the straining process. A comparison of both empirical distributions shows how an increasing amount of large events shapes the energy release as deformation advances.

### 5.2.3 Attenuation of AE signals, a sensor’s field-of-view

To model elastic wave signal attenuation as it travels from the source location to the sensor we employed a simplistic geometrical decay model. We neglect other attenuation mechanisms, and consider the total elastic energy in a wavefront $E$ to remain conserved
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Figure 5.2.3: Stress strain curve of the annealed disorder FBM consisting of $N = 10^5$ fibers. The insets show statistics of rupture associated energy release at the beginning (a–b) and at the end (c–d) of the straining process.

at any distance from the source location $r$. The spherical divergence of the wave with distance from the source is associated with decay of the energy density $E_0$ according to:

$$E_0 4\pi r_0^2 = E 4\pi r^2$$

(5.2.11)

$$E = \left(\frac{r_0}{r}\right)^2 E_0.$$  

(5.2.12)

Here we assume that the elastic energy is concentrated at the propagating wave front that has the shape of an expanding spherical shell. Depending on the propagation distance, the original amount of emitted energy $E_0$ decays with the distance from the source as $r^{-2}$. The acoustic picture that an AE sensor obtains from a process generating distributed AE - such as granular shearing - is strongly affected by this geometric attenuation. Signals generated away from the sensor are more attenuated and appear weaker (low amplitude). This simple geometric damping was included in into our conceptual shear zone model as shown in Figure 5.2.4. Here we assume that elastic wave generation takes place at a plane $\Sigma$ only, which represents the shear zone. A sensor is located at a distance $r_0$ facing this plane. Selecting a random location on $\Sigma$ for each failure event we may attribute a propagation length to each failure event. From that we can calculate the relative geometric damping (as compared to a similar event at distance $r_0$) that generated AE undergo before hitting the sensor.

Figure 5.2.5 shows the effect of the above described mechanisms on a FBM-generated distribution of energies generated within a plane. Here we considered two different fiber-bundles with similar geometries. The bundles differed in their number of fibers allowing to study the effect of different grain sizes on AE energy production in a granular shear zone. The Figure shows empirical distributions of event energies at the source,
5.2.4 Shear frame experiments

Shear deformation of large granular assemblies were measured using a linear shear frame device (previously described in Michlmayr et al. [28]). The sample container consisted of two frames with dimensions of 0.15 m × 0.15 m × 0.15 m. The lower frame is supported by linear roller bearings to allow horizontal motion in one direction. Displacement is applied by a linear drive (PERO linear spindle motor, PERO GmbH, Sickte, Germany) pulling the lower frame at a constant rate. A normal load was applied to the sample material using a pneumatic cylinder. Force sensors attached to the upper frame allowed
to measure shear forces during the displacement procedure. Forces were recorded at high temporal resolution (1620 sec⁻¹) allowing to resolve rapid stress fluctuations with magnitudes > 30 Pa. For measurements of elastic waves, two types of acoustic transducers were placed within the sample material during the shear tests. A 1-D accelerometer (Measurement Specialties ACH-01) with a sensitivity of 0.92 × 10⁻⁴ V m sec⁻² and a linear frequency response in the range < 20 kHz was placed in the upper frame 0.05 m above the imposed shear zone in a way that it could captured elastic waves normal to the shear plane. Additionally for measuring high-frequency acoustic emissions in the range of 30 kHz–80 kHz we used piezoelectric sensors (Vallen, VS75-V, for frequency response see inset of Figure 5.3.2). All sensors were placed close to the shear zone inside the material. To extract discrete events from the continuous waveform captured by the different sensors a constant threshold was applied. Signals that exceed this threshold are assumed to be associated with with mechanical failure events within the material. Digitalized signals are provided in units of voltage. Note, that frequency-dependence of the sensor response, pre-amplification, and A/D-conversion makes the recovery of physical quantities from digital signals a delicate task. In this work we desisted from this exercise and provide signal amplitudes and derived energy measures in units of voltage respectively as non-physical energy units.

For the shear tests different types of spherical, narrow-graded soda-lime glass beads (SiLi beads type S) were used. The material has a density of 2.5 kg m⁻³ and a Young’s modulus of 63 × 10⁹ Pa. Tests were performed with different grain sizes: 3.8 mm–4.4 mm, and 1.0 mm–1.3 mm. We obtained the number of particles in the shear layer by assuming that one grain occupies a square of the size of its diameter. This leads us to estimate the grains in a layer of the size of the shear plane as 1225, and 19600 respectively. These numbers were taken over in the model. The sample material was air dry. To perform experiments glass beads were filled into the shear frame in three layers, that were compacted each with a number of hammer blows. Acoustic sensors were placed within the sample material during this procedure. After leveling the sample material at the surface it was covered with a 2 mm-thick rubber pad to provided a homogeneous
distribution of applied normal loads. Tests were conducted at different normal stresses: 30 kPa, 45 kPa, and 60 kPa. The displacement rate during experiments was held constant at 0.033 mm sec\(^{-1}\).

Data streams were synchronized before further analysis. Frequency spectra from low-frequency acoustic emission events were obtained by Fast-Fourier transformation. To avoid aliasing-effects in frequency spectra a Hamming window was applied to the data frames.

5.3 Results

5.3.1 AE from shear stress release events

5.3.1.1 Examples of signal waveforms

The formation of a shear zone in granular materials and associated micro-mechanical failure events manifest in development of shear stresses and simultaneous generation of AE signals. To investigate links between the mechanical and acoustic facet of shearing results of the direct shear tests were evaluated for illustrative examples of the principles. A consistent link between such stress jumps and the release of low-frequency AE signal has been shown in a previous study [28] and was confirmed by the data shown in Figure 5.3.1. We found that under the given test conditions shear stresses exhibit considerable fluctuations around an average value. Fluctuations typically consisted of (i) an accumulation phase, where shear stress builds up constantly, (ii) a plastic phase, that features decaying stress accumulation including smaller stress tremor and release events, and (iii) the actual stress release event, which was characterized by an abrupt and considerable jump of shear stress. Visual inspection of the results indicates that the measured stress jumps and acquired low frequency AE signals are highly correlated in their occurrence times. In some of the cases stress tremor and precursory jumps during plastic material deformation triggered minor low-frequency AE events. The three last force jumps of the example in Figure 5.3.1 show such tremor-induced low-frequency AE events.

High-frequency AE signals (Figure 5.3.1c) in our example occurred clearly at a higher rate than their low-frequency counterparts. An obvious connection to stress jumps was not given, since signals were captured during all three phases of a stress jump cycle. From the presented example we found indication towards an increase of AE intensity (i.e. rate and magnitudes) at the imminence of a stress jump. Immediately after a stress release event generation of high-frequency AE events obviously remained quiescent for a short period of time. Although we observed continual generation of high-frequency AE signals, the data record of Figure 5.3.1 delivered indication for intensity changes of the acoustic activity that match the cyclic accumulation and release of shear stresses.

5.3.1.2 Typical frequency ranges of observed AEs

Key mechanical considerations for quantifying AE events generated by grain-scale interactions were presented in Section 5.2.1. To experimentally evaluated predicted frequency
Figure 5.3.1: (a) Stress jumps during a shear experiment with 4 mm glass beads under a confining stress of 60 kPa with concurrent record of (b) low-frequency AE signals and (c) high-frequency AE events. The inset of the middle panel shows the location of AE measurements. Different phases of a characteristic stress jump cycle are illustrated for a single failure event marked by gray boxes.
5 Mechanisms for AE generation during granular shearing

Figure 5.3.2: (a) Measured average frequency spectrum captured by the low frequency AE system (acceleration amplitude spectrum) and (b) by the high frequency AE system (pressure amplitude spectrum). The inset of panel (b) shows the response function of the high frequency sensor in the spectrum of concern in dB re 1mV/bar.

ranges we analyzed signals collected during direct shear tests of glass beads and sand grains. The inversion of AE signals into the frequency domain using standard Fourier transformation allowed comparison of measurements with modeling results. Measured spectral amplitudes were averaged over many AE data sets to remove influences of spurious events. Figure 5.3.2 shows the average spectra of 29 low-frequency events. The right panel of Figure 5.3.2 displays the average spectrum of 29 high-frequency measurements collected concurrently. All signals were observed during the latter phase of shearing experiments with 1 mm glass beads and a confining load of 45 kPa. We found a general decay of the spectral amplitude for high frequencies in both spectra. This general trend is interrupted by a number of local peaks: at 5 kPa for the low-frequency spectrum, and at 54 kPa respectively at 111 kPa in the spectrum of high-frequency measurements. To rule out a bias from the sensor’s own resonance frequencies we compared our measurements with sensor frequency-response functions. The response spectrum of the AE sensor type (see the inset in Figure 5.3.2) did not exhibit any resonance frequencies at the observed frequency peaks, which suggests that those features represented properties of the material and the AE generation mechanisms.

5.3.1.3 Features of AE response to stress jumps

The illustrative data record of Figure 5.3.1 suggests that stress jumps are associated with two types of measured AE during direct shear tests. To improve our understanding of these observations we compared the average AE activity of both sensor systems at the imminence of stress release events (see Figure 5.3.3). For this analysis we performed coherent averaging over the stress jumps of a single shear test and associated records of AE events. This process involves collection of multiple consecutive stress jump cycles that originally occurred sequentially in time, and averaging over the force and AE signals for
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Figure 5.3.3: (a) Coherent averaging over stress release cycles under different test conditions (“mean” stress jump). (b) Concurrent low-frequency (accelerometer) AE, and (c) high-frequency AE activity. The normal load in all experiments was 45 kPa.

Each jump (stacking the sequences with a single origin). This analysis delivered us the mechanical (Figure 5.3.3a) and acoustic (Figure 5.3.3b-c) picture of the “mean” stress jump of experiments with different grain sizes. We observed clear differences between the magnitude of stress jumps amongst the three materials. We found that tests with 4 mm grains produced the highest stress jumps compared to other materials. For all cases considered, the averaging procedure produced a smooth force curve prior to the release event contrasting precursory stress tremor that has been observed during phase ii of the previously presented data example (see Figure 5.3.1a). The disappearance of precursory fluctuations after coherent signal averaging reflects the random nature of this phenomenon. The corresponding activity of low-frequency AE confirmed a strong link of those signals to stress jumps as it was pointed out already in Section 5.3.1.1: the analysis showed that almost every low-frequency event was observed together (at a strain difference of less than 0.005 mm) with a stress release event, irrespective of the experimental conditions. The results of Figure 5.3.3c show the average high-frequency AE activity in relation to stress release events. From our earlier analyses (see Figure 5.3.1c) we found that those signals occurred also during stress accumulation and not only during stress-release events. This was confirmed by Figure 5.3.3c. Also, we were able to reveal a significant increase of high-frequency AE activity at the imminence of stress jumps. Particularly in materials with smaller grains significant high-frequency AE activity was observed prior to stress jumps.

5.3.2 Modeling AE statistics

The analyses in the previous sections supported our initial assumption that different micro-mechanical interactions within a granular shear zone produce distinct AE signals. For example, we attribute large rearrangements of the granular lattice to the rupture of force chains. In our experiments such events appeared as fluctuations in the macroscopic shear stress and triggered distinct low-frequency AE signals. Smaller failure events eventually at the level of single grains could be detected by the high-frequency AE
Figure 5.3.4: Size distribution of strong fiber rupture events as generated by the signal-attenuation FBM: (a) Comparison between results from a large bundle with corresponding low-frequency AE events from 1 mm grain assemblies. (b) A small bundle represents a physical system with large (4 mm) grains. Again low-frequency AE energies are compared against energies from strong fiber rupture. A proxy for AE energy is obtained from time integral of recorded signal amplitudes and has units of V sec (we are aware that in a physical sense this is no energy measure and refer to it as “energy unit”).

events, however did not leave a visible signature on the global stress picture.

For integration into the FBM this means that low-frequency AE signals are associated with large stress jumps and often correspond to rupture of strong fibers. High-frequency acoustic events are represented by the breaking of a weak fiber in our model. For comparison with experimental observations we included attenuation of the released energy, as described above (Section 5.2.3). A comparison of attenuated strong fiber energies with low-frequency AE energies is presented in Figure 5.3.4. We found reasonable qualitative agreement between observations and model predictions. Difficulties to recover physical units from digitized signals, as mentioned in Section 5.2.4, led us to express AE event energies in terms of arbitrary (non physical) energy units. Such an arbitrary measure for the energy of an AE event is obtained from the integration of the a sensors digitized voltage signal (units of [V sec]). A quantitative comparison with FBM energies is therefore not possible. Nevertheless the coherence of the results between the two test cases compared in Figure 5.3.4 (1 mm and 4 mm glass beads) supports our confidence in the capabilities of the coupled signal attenuation-FBM to predict observed AE phenomena.

5.3.3 Modeling force chain rupture

By separation of fiber-bundle elements into two groups, namely strong and weak fibers, we were able to address different granular failure mechanisms with this model. Here, rupture of strong fibers was associated with stress jump-induced low-frequency AE events; weak fiber failure in the FBM represented minor failure events and was therefore associated with high-frequency AE. For testing model predictions of those different failure
types we compared modeled and measured energy release rates. The energy release rate is a measure of the failure-associated energy that is set free during a strain increment.

In Figure 5.3.5a the total predicted energy release is split according to the type of fiber it is associated with. Energy production from weak fiber failure develops differently from energy release from strong fibers. Weak fibers release most energy at the early stage of deformation. Only later the energy production is increasingly taken over by strong fibers. To test this model predictions we compared them against different AE measurements. Based on earlier work [29, 28] we can assume that AE present a physical measure of the dissipated strain energy in our experimental system. Our comparison shows that modeled results stands in agreement with characteristic features of measured high- and low-frequency AE energy. The dynamics of energy production from different fiber types are reflected also in the curves that indicate captured AE energy. Figure 5.3.5b reveals that the measured energy release rate of high-frequency AE signals resembles FBM predictions of weak fiber-associated energy production. The delayed onset of energy release from strong fibers can also be found in the energy trace of low-frequency AE signals.
5.4 Discussion and Conclusions

Elastic waves generated during shearing of granular materials provide a rich source of information related to grain scale rearrangements and failure precursors. To obtain a better understanding how material properties, and different triggering mechanisms shape resulting acoustic signals we studied prototypical cases of grain scale-induced elastic wave generation. We focused primarily on grain collisions and particle-to-particle friction as triggering mechanisms of acoustic signals. Based on mechanical considerations we propose a distinct acoustic signature of both processes. Together with the particular triggering mechanisms we assumed that the resonance frequencies of excited granular structures determine the spectral characteristics of elastic waves. We investigated the effect of those excitation mechanisms on different granular structures. Here we consider excitation of a single particles in a tetrahedral compound and of a confined granular chains - so-called force chains. Such force chains are known as the primary load bearing elements that dominate the mechanics of granular shear bands. We invoked eigenvalue analysis of the mentioned prototypical granular structures to localize typical resonances in a frequency range of $10^4$–$10^5$ Hz. Here we studied important AE source mechanisms in an exemplary manner, forgoing detailed knowledge about detailed structural and material properties. We did not consider altering of the frequency content due to wave dispersion, that is a gradual change of the wave shape along its propagation path. However, predictions from our model were in good agreement with frequency ranges of AE events observed during granular shearing of glass bead assemblies. Analyses revealed the presence of distinct peaks in the frequency spectra of experimental results that were in the range of predicted resonances.

Measurable acoustic emissions at different frequency bands were found to be closely related to episodic and abrupt stress release events observed during granular shearing. We were able to demonstrate a direct link between low-frequency AE events and distinct stress fluctuations, presumably expressing large rearrangements of the granular lattice and associated force chain excitation. High-frequency AE activity increased before such rearrangement events typically announcing observed stress jumps. The trace of individual high-frequency events could not be found in the shear stress data. Failure events that emit such high-frequency AE signals are presumably too small to induce measurable changes of the total shear stresses.

To model quantitative features and statistics of failure events that occur during granular shear deformation we used a fiber-bundle model. In this conceptual shear zone representation material behavior is constituted by a large number of individual elements, termed fibers, that fail independently at a statistically determined rupture threshold. This relatively simple model provides us with predictions of failure statistics and the material stress-strain behavior. Earlier work showed that this FBM can reproduce key features of granular shearing and presented analytical solutions of the model [29, 28]. Here we used the FBM to resolve different failure mechanism and their energetic trace throughout the deformation process: failure of the strongest fibers in the bundle was associated with force chain excitation; rupture of weak fibers was assumed to stand for excitation of smaller structures. Also we introduced a simple propagation model that
relies on the geometric attenuation of an elastic wave propagating through the granular assembly. Comparison of modeled failure magnitude distributions with statistics of low-frequency AE events shows a good agreement and legitimates our model.

An important advantage of the FBM lies in the simplicity to predict failure associated energy release. Energy loss from fiber rupture can be related directly with acoustic emissions, heat release, or other forms of energy dissipation. Here we attributed AE generation mechanisms to different rupture events. By comparison with AE data we could show that the FBM predicts characteristic energy release from high-frequency and low-frequency AE events (representing large and small rearrangement events respectively).

5.5 Summary

The study develops a novel quantitative framework linking grain-scale mechanical interactions with release of stored strain energy in the form of elastic waves. The mechanistic links enable interpretation of measurable acoustic emissions (AE) and their potential attribution to typically unobservable internal mechanical interactions during shearing of granular assemblies. In the core of the analysis are several prototypic AE generation mechanisms that are incorporated within a fiber bundle model that captures the stochastic nature of many interacting grains. By simple segregation of large energy release events (associated with formation and destruction of force chains) from small events (associated primarily with grain friction), the framework was capable of providing qualitative predictions in reasonable agreement with measurements. Evidence suggests that instantaneous observations of low (< 20 kHz) and high (> 30 kHz) AE events provide complementary information concerning formation of shear zone and stress release events. Together with a basic attenuation model the FBM allows a simulation of AE event statistics and their development throughout the shearing process.

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6 Summary

6.1 Key findings

This work presents the results of theoretical and experimental studies of high-frequency elastic waves, so-called acoustic emissions (AE), occurring during the formation and straining of granular shear zones. Expressing internal failure mechanisms AE are closely related to mechanical properties of granular materials. A review of the scientific literature and theoretical concepts of AE generation was presented and inspires great confidence in the AE method as a diagnostic tool for granular mechanics issues. To provide a theoretical framework for the translation of AE signals into an account of the mechanical status of the material a conceptual fiber-bundle model (FBM) was developed. Coupled with simple models of AE generation from granular force-networks, the FBM supports a full conversion of shear zone mechanics into acoustic signals. A large number of shear-frame tests with prototypical dry granular material was performed. Signals from AE sensors operating on different characteristic frequency bands, and shear force measurements with a high temporal resolution allow to test the developed model and provide further insights into the dependence of granular shear zone formation on mechanical boundary conditions.

Four main conclusions arouse from the presented work:

- A review of the current state-of-the-art clearly showed that AE provide a promising tool to support existing tests and to capture failure transition in granular geo-materials. In field-scale settings of the technique attenuation poses a major problem. High frequency AE signals are damped within a very short distance around the source region, which demands either dense coverage of AE sensors within the test site or signal enhancement strategies, such as acoustic wave-guides.

- Existing FBM approaches were adapted and extended to model key mechanisms of shear zone formation in granular material. The presented annealed FBM captures statistics of stress fluctuations resulting from localized failure and associated AE. The model predicts changes of the frequency-magnitude statistics and of the released acoustic energy with ongoing straining. These features could be supported by experimental data. Different failure mechanisms were attributed to single fibers of the FBM according to their strength. This allows to follow the energy trace of various failure modes throughout the straining process.

- AE provides means for gauging dissipative and failure processes during granular shearing. We found that measured AE in the frequency band above 30 kHz are presumably associated with grain contact failure such as frictional slip or rolling.
Signals in the lower frequency band (< 20 kHz) stem from contact network restructuring events that also reflect in measurable fluctuations of the shear force. Our analyses show that statistical features of such force jumps and associated acoustic emissions are affected by the experimental conditions, such as the applied normal load or the average grain diameter. The continual release of grain contact failure-associated high frequency AE indicates the importance of frictional processes for the dissipation of strain energy and resulting plastic behavior of granular materials. Also, the release of high-frequency AE signals was observed to stand in close relation to repetitive cycles of stress accumulation.

- A mechanistic model of generation and propagation of AE during shear zone formation was linked with the FBM and yields an integrated description of the mechanical-acoustical response of a deforming granular lattice. Characteristic frequencies of prototypical failure events in dry granular materials were identified and compared to measured AE frequency spectra. Presented results were used to establish links between the mechanical and the acoustical signature of grain-scale failure events, as they occur during shear zone formation.

We developed a genuine toolbox for the evaluation and analysis of failure generated AE in granular materials based on principles of statistical physics and mechanics. Statistical criteria for AE records were defined that indicate the formation of a shear zone giving the method relevance as a potential tool for geologic mass movement early-warning. Discovered ties between different dissipation mechanisms, underpinning granular material mechanics, and AE with distinct frequency spectra outline possible applications for studying constitutive material behavior.

### 6.2 Outlook

The FBM provides a conceptual framework to simulate defined modes of deformation or failure. The presented model is capable to describe the formation of a weak zone within sheared granular material. Other than models based on constitutive material laws the FBM does not support arbitrary load application; it is restricted to the loading procedure it was designed for. Rather than providing a full description of the material mechanics FBMs are to be seen as simulation tools to predict principle key mechanical and statistical features, of a particular loading process they were designed for. The annealed disorder FBM that was put forward in this thesis specifically addresses granular shearing, a highly complex and hard-to-predict process. Application of the rapidly evolving AE method provide an opportunity to cross the threshold to a non-destructive and non-invasive monitoring of granular shear zone mechanics. This may bear tremendous potential for the early-warning of natural hazard, but presents also a method in its own right for deciphering granular material behavior. The large-scale deployment of the AE method for natural hazard early warning is primarily hampered by massive signal attenuation. Earlier proposed wave-guides may serve to partly overcome this problem. Fast development of fiber-optics technology presents an alternative solution to the issue
of signal attenuation. Such measurements rely on mechanically induced alteration of
the optical properties of a fiber-optical cable. Elastic wave-generated distortion of the
cable produce a periodic modulation in its refractive index and light propagating in the
fiber is scattered. Resulting interference of the primary light wave with the scattered
wave can be measured. Based on this technology acoustic emissions may be detected
along transects equipped with fiber-optic cables at a high spatial resolution, holding a
great promise for advancing the AE method to applications on the field-scale. Another
challenge for further research is presented by issues related to signal propagation and
modification by the porous medium. From the literature it is known that elastic wave
propagation in granular materials entails a wide range of complex phenomena. The re-
sults of this work underscore at several points the importance of frequency alteration,
damping or distortion of AE signals on their path of propagation. The meaningful inte-
gration of those processes into the presented simulation framework remains as a challenge
for ongoing research.
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Scientific publications and presentations

Peer reviewed publications


CONFERENCE TALKS


3. Michlmayr, G., Characteristics of Acoustic Emissions During Soil Failure, ITES - Research Colloquia, 2010-12, Zurich, Switzerland.


POSTER PRESENTATIONS


