Stress transmission in compressed granular materials evaluated by acoustic emission techniques

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Abstract

The evolution of effective force chains percolating through a granular system under uniaxial compression can be investigated using the acoustic emission technique to obtain a better understanding of the global behaviour of granular media in terms of microscopic phenomena which occur at the level of discrete particles.
It is known from praxis as well as from the theory that percolation effects and a rearrangement of the granular materials can be observed under compression. Force lines can be observed transferring the load from one side to the other through the spheres. A rearrangement of the grains result in a spontaneous release of acoustic energy radiating waves similar to that observed in other brittle materials under load.
Different kinds of beads have been investigated to study this effect including beads out of glass and metal. A series of experiments showed that the type of the material, the diameter of the beads as well as other parameters as the setup and the recording equipment influences the results significantly. As shown earlier a correlation of the mechanical test parameters and the results of the AE analysis to computer simulations give a better understanding of the behaviour of coarse materials. In this paper the results of the acoustic emission tests are summarized.

1. Motivation

The acoustic emission technique (AET) is considered quite unique among the non- In collaboration between the *Institute for Computational Physics* (ICA1) and the *Institute of Construction Materials* (IWB) of the University of Stuttgart the evolution of effective force chains percolating through a granular system under uniaxial compression is investigated. It was the idea to prove the theory developed for these granular systems at the ICA1 by a series of experiments using acoustic emission (AE) analysis.
Recently, granular materials have been extensively studied under various conditions due to their scientific and technological importance. Huge experimental and theoretical efforts have been devoted to obtain a better understanding of the global behaviour of granular media in terms of microscopic phenomena which occur at the level of discrete. Subjecting a confined granular packing to uniaxial compression a rather peculiar constitutive behaviour can be observed: for small strains a strong deviation from the linear elastic response can be found implying that the system drastically hardens in this regime [Travers & Bideau et al. 1986; Makse & Johnson et al. 2000]. Linear elastic behaviour can only be achieved asymptotically at larger deformations when the system gets highly compacted. When the external load is decreased again the system shows an irreversible increase in its effective stiffness, furthermore, under cyclic loading hysteretic behaviour is obtained.

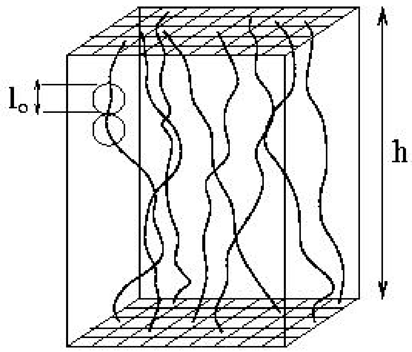

Fig. 1: Sketch of the used model.

Microscopically, inside a compressed granular packing, stresses are transferred by the contact of particles (Fig. 1). Particles lying between lines of the force network do not support any load and can even be removed from the packing without changing its mechanical properties. Increasing the external load, more and more force lines appear and they all undergo erratic changes until the system reaches a saturated state when all the particles hold typically the same load and the system behaves as a bulk material. The creation and restructuring of percolating force chains implies relative displacements of particles which can be followed experimentally by recording the acoustic waves emitted, however, up to now no such experiments have been performed systematically. Theoretically, this problem has been mainly studied by means contact dynamics simulations using spherical or cylindrical particles, and cellular automata [Radjai & Jean et al. 1996; Rintoul & Torquato 1996; Makse & Johnson et al. 2000].

2. Experimental setup

We performed experiments by compressing an ensemble of spherical particles in a cylindrical container monitoring the macroscopic constitutive behaviour and the acoustic signals. The cylindrical container was out of PMMA and filled with several thousand spherical beads. It has a thickness of 5 mm and a diameter of 140 mm (Fig. 2). To record the acoustic emission signals, eight broadband sensors sensitive in the frequency range of 50-250 kHz have been glued to the sidewall of the container. The Position of the sensors was chosen in a way that subsequently a 3D localization can be carried out using the sensor data of the acoustic emissions. A review of appropriate localization techniques along with some applications can be found in the literature [Grosse 2000].

In a first test series beads out of glass have been used. Additional materials as steel and polymers are discussed; the results of the further experiments will be presented later elsewhere. The data represented in the following section were obtained using either glass beads with I_0 = 5 mm or with I_0 = 8 mm, respectively, to test the theory with coarse material of different diameter.

Usually, the AE signal energy is relatively weak and a proper coupling of the sensors is required. To enhance the data quality in regard to the signal-to-noise ratio the space between the beads was saturated with water. The compressional wave velocity was measured using ultrasound in through-transmission (transmitter – receiver at opposite sides). Besides the material properties, the effective velocity depends on the diameter I_0 of the beads. The standard error of the mean was calculated out of 20 single measurements. For the combination water/glass-beads we found:

I_0 = 5 mm: v_p = 1966 (± 13) m/s
I_0 = 8 mm: v_p = 1430 (± 54) m/s

Replacing the water with glycerine the velocities were shifted to values between 2000 and 2200 m/s. This will give better results for the experiments, where the locations of the AE will be investigated.

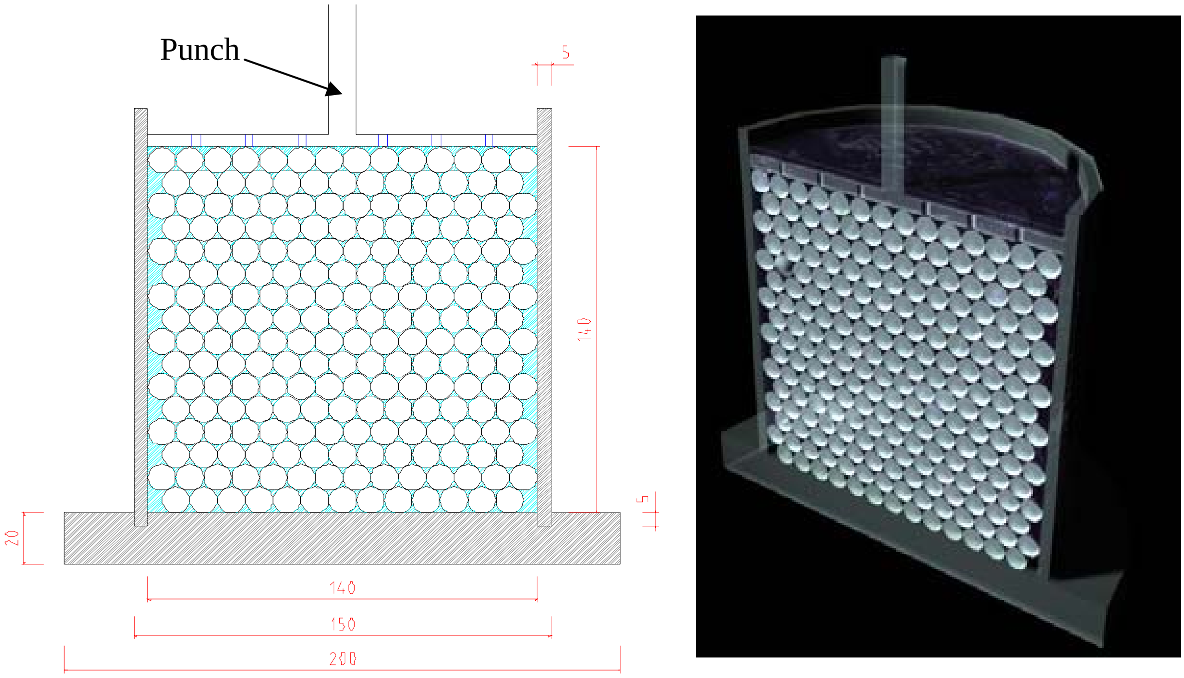

Fig. 2: Details of the PMMA container (dimensions in mm) filled with glass beads.

3. AE Experiments – preliminary results

A uniaxial pressure system (punch test) was used to apply monotonically increasing displacements at the top level of the glass beads. To reduce the pressure to be obtained by the side wall of the cylinder causing elastic deformations the punch was perforated to let the water flow to both sides of the punch. The actual force and the displacement, measured at the traverse of the loading machine, together with the AE signals were recorded simultaneously. An eight channel transient recorder was used as an analogue-to-digital converter to enable the storing of the AE waveforms and a signal-based data processing in further experiments. As a first approach to combine the AE data analysis with the simulation in the frame of percolating force chains theory a statistical evaluation of the acoustic emissions was done. Typically several hundred signals were recorded at all channels during the experiments.

To give a preliminary impression of the results, the experimental data of a test using glass beads with I_0 = 5 mm in the water filled container under load are represented in Fig. 3. The experiment was controlled with monotonically increasing displacement showing an interesting behaviour of the load. As predicted by the theory multiple rearrangements of the compressed glass beads ensemble occurred, what is indicated by a sudden release of the load. The release of load energy transformed into energy to rearrange the granular material is significantly higher at the end of the experiment than in the beginning. Evaluating the histogram plot in Fig. 3 it is obvious, that this release is accompanied by acoustic emission activities caused by the internally restructuring of percolating force chains. There is a good coincidence between the sharp decline of the load and the occurrence of high energy AE events. The AE data shown were automatically extracted by an algorithm determining the peak amplitudes of the burst signals versus time in form of energy histograms. This energy is defined as the integral of the AE signal amplitude following the onset time. The data recorded at all eight sensors are plotted into this graph to elucidate the time dependent evaluation of AE activity.

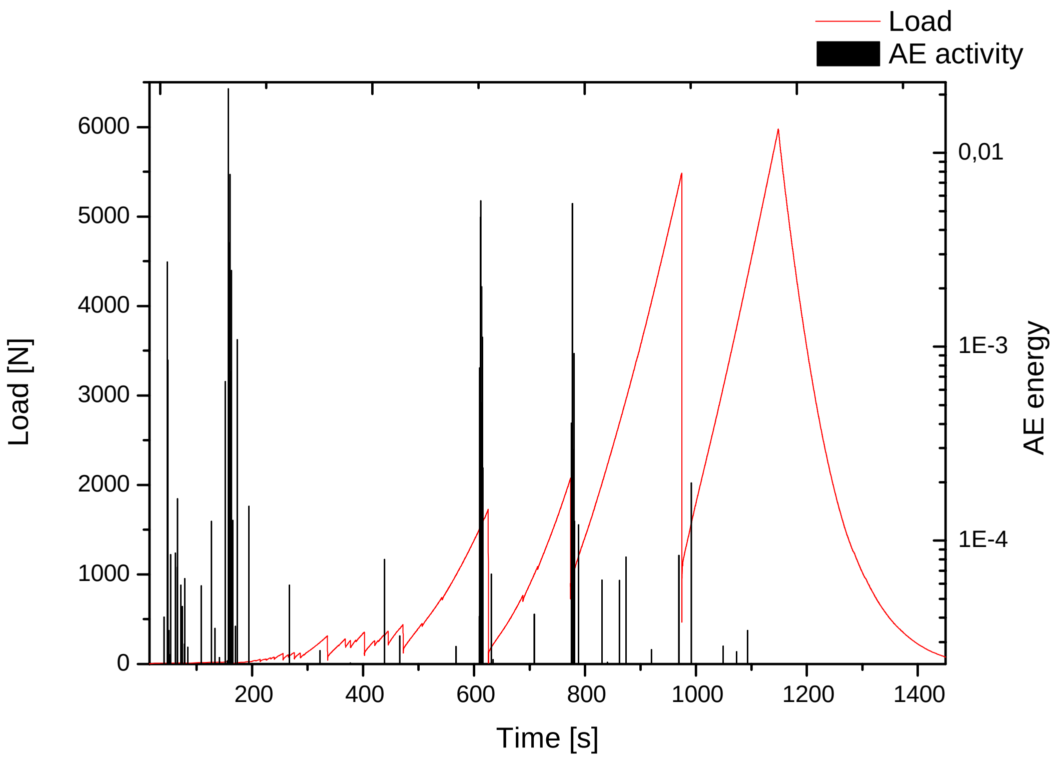

Fig. 3: Example of the AE measurements and mechanical data. The statistic of AE is plotted using the integral energy at all eight sensors along with the load (straight red line).

However, this experimental approach is straight forward and will be modified for further experiments. There are several points, which need some improvement including a more detailed signal analysis. This is especially true for the discrimination capabilities of signals to noise concerning parameter-based AE approaches. It was shown by Grosse [1996] that a statistical analysis of AE signals without localizing the events can be somehow misleading. Since signal energy seems to be a stable parameter it has to be examined if the energy measured at all sensors is about the same or if mean energy values are representing the acoustic effects in the material more precise. The statistical analysis procedures should be cross-checked by a signal-based analysis of AE activities including an examination of the influence of preset threshold values.

The configuration of a new state-of-the-art multi-channel AE system with high resolution and acceptable recording speed is undergoing. Additional experiments will be conducted using this new AE device investigating glass beads and beads out of other materials.

A more detailed description of acoustic emission data analysis and especially signal-based techniques can be found in Grosse & Reinhardt et al. [1997], Grosse & Weiler et al. [1997] or Grosse & Reinhardt et al. [2002].

4. Summary

Based on the analogy of force lines percolating through the system and fibres of a fibre composite Hidalgo, Kun and Herrmann proposed a novel theoretical approach, namely, an inversion of the Continuous Damage Model (CDM) of fibre bundles [Kun & Zapperi et al. 2000; Hidalgo & Kun et al. 2001] to describe the stress transmission through granular assemblies. The model provides a nonlinear constitutive behaviour in good quantitative agreement with the experimental results as shown in Hidalgo & Grosse et al. 2002. For a system of hard particles the model predicts a universal power law divergence of stress when approaching a critical deformation. The amplitude distribution of acoustic signals was found experimentally (Fig. 4) to follow a power law with exponent $\delta = 1.15 \pm 0.05$ which is in a good agreement with the analytic solution of the model. More results combining simulations, analytical models and experimental data are in preparation to be published soon. This will include also beads out of different materials as well as improved AE data.

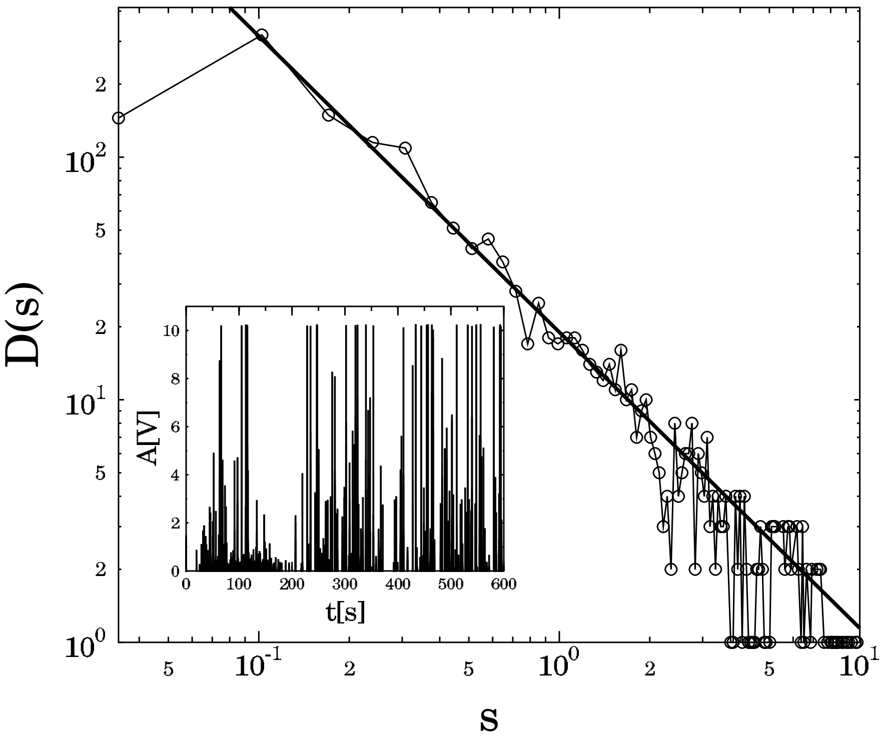

Fig. 4: A power law relation was found to give best fitted results according to the size distribution of the signals of the inset [Hidalgo & Grosse et al. 2002].

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References

Grosse, C. U., B. Weiler, H. W. Reinhardt: *Relative moment tensor inversion applied to concrete fracture tests*. J. of Acoustic Emission, 14, 3-4 (1997), S64-S87.

Grosse, C. U. , H. W. Reinhardt, F. Finck: *Signal-based acoustic emission techniques in civil engineering*. Accepted by J. of Mat. in Civ. Eng. (2002).

Grosse, C. U. , H. W. Reinhardt, T. Dahm: *Localization and Classification of Fracture Types in Concrete with Quantitative Acoustic Emission Measurement Techniques*. NDT&E Intern. 30, 4 (1997), 223-230.

Grosse, C. U.: *WinPecker - Programm zur vollautomatischen dreidimensionalen Lokalisierung von Schall-emissionsquellen*. DGZfP Berichtsband 72, 12. Kolloquium Schallemission, Jena. Berlin: DGZfP (2000), 191-204.

Grosse, C. U.: *Quantitative zerstörungsfreie Prüfung von Baustoffen mittels Schallemissionsanalyse und Ultraschall*. Ph.D. Thesis, University of Stuttgart (1996).

Hidalgo, R. C., C. U. Grosse, F. Kun, H. W. Reinhardt and H. J. Herrmann: *Evolution of Percolating Force Chains in Compressed Granular Media.* submitted to Phys. Rev. Lett. (2002).

Hidalgo, R. C., F. Kun, and H. J. Herrmann: *Bursts in a fiber bundle model with contiuous damage*. Phys. Rev. E 64 (2001), 066122.

Kun, F., S. Zapperi, and H. J. Herrmann: *Damage in fiber bundle models.* Eur. Phys. J. B 17 (2000), 269-279.

Makse, H. A., D. L. Johnson, and L. M. Schwartz: *Packing of Compressible Granular Materials*. Phys. Rev. Lett. 84 (2000), 4160.

Radjai, F., M. Jean, J.-J. Moreau, and S. Roux : *Force Distribution in Dense Two-Dimensional Granular Systems.* Phys. Rev. Lett. 77 (1996), 274.

Rintoul, M.D., and S. Torquato: *Metastability and crystallization in hard-sphere systems***.** Phys. Rev. Lett. 77 (1996), 4198.

Travers, T., D. Bideau, A. Gervois, J. P. Troadec, and J. C. Messager: *Uniaxial compression effects on 2D mixtures of `hard' and `soft' cylinders***.** J. Phys. A 74, 19 (1986), L1033.