

Probing slow dynamics of consolidated granular multicomposite materials by diffuse acoustic wave spectroscopy

Nicolas Tremblay, Éric Larose, Vincent Rossetto

▶ **To cite this version:**

Nicolas Tremblay, Éric Larose, Vincent Rossetto. Probing slow dynamics of consolidated granular multicomposite materials by diffuse acoustic wave spectroscopy. Journal of the Acoustical Society of America, 2010, 127 (3), pp.1239. hal-00459719

HAL Id: hal-00459719
https://hal.science/hal-00459719

Submitted on 24 Feb 2010

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Probing slow dynamics of consolidated granular multicomposite materials by Diffuse Acoustic Wave Spectroscopy (DAWS)

Nicolas Tremblay and Eric Larose[a)]
Laboratoire de Géophysique Interne et Tectonophysique, CNRS & Université J. Fourier, BP53, 38041 Grenoble, France.

Vincent Rossetto
Laboratoire de Physique et Modélisation des Milieux Condensés, CNRS & Université J. Fourier, BP 166, 38042 Grenoble, France.

(Dated: February 24, 2010)

The stiffness of a consolidated granular medium experiences a drop immediately after a moderate mechanical solicitation. Then the stiffness rises back toward its initial value following a logarithmic time evolution called *slow dynamics*. In the literature, *slow dynamics* has been probed by macroscopic quantities averaged over the sample volume, for instance by the resonant frequency of vibrational eigenmodes. This article presents a different approach based on Diffuse Acoustic Wave Spectroscopy (DAWS), a technique that is directly sensitive to the details of the sample structure. The parameters of the dynamics are found to depend on the damage of the medium. Results confirm that *slow dynamics* is, at least in part, due to tiny structural rearrangements at the microscopic scale, such as inter-grain contacts.

PACS numbers: 4325Ts, 4335Yb,4340Le , 4335Zc

I. INTRODUCTION: WHAT IS SLOW DYNAMICS ?

Depending on the magnitude of the solicitation applied to it, a consolidated granular medium, like sedimentary rocks or concrete, can asymptotically react either in the elastic (reversible) regime, or in the brittle regime where irreversible fractures develop. A few years ago, several articles from Guyer, TenCate and co-workers [TenCate and Shankland (1996); Guyer *et al.* (1998); Guyer and Johnson (1999); TenCate *et al.* (2000)] reported on an intermediate regime where they observed non-linear elasticity. This regime is observed after imposing a strain of moderate amplitude (10^{-6}) that does not generate any macroscopic damage. They called its time-evolution *slow dynamics*: it starts with a drop of the elastic modulus, followed by a logarithmic recovery of the sample stiffness toward its initial value after the strain is released. The $log(t)$ recovery was found to be universal in granular solids of various composition [TenCate *et al.* (2000); Lacouture *et al.* (2003); Johnson and Sutin (2005)], humidity [Vakhnenko *et al.* (2004)] or level of damage [Van Den Abeele *et al.* (2001)]. Most of the time, the evolution of the sample stiffness is monitored through the frequency of vibrational eigenmodes, a technique named Non-Linear Elastic Wave Spectroscopy [Guyer and Johnson (1999)]. More recently, Lobkis and Weaver (2009) proposed to monitor the stiffness of the material using the Larsen effect between two piezo-eletric transducers. The resonant frequency f_L observed with a feedback loop was measured with a relative precision of the order $\frac{\delta f_L}{f_L} \approx 10^{-6}$, and was found to satisfyingly monitor the rigidity of the material. This latter technique offers simultaneously an increased sensitivity and a temporal resolution of a few ms, thus allowing to study *slow dynamics* over very short time-scales.

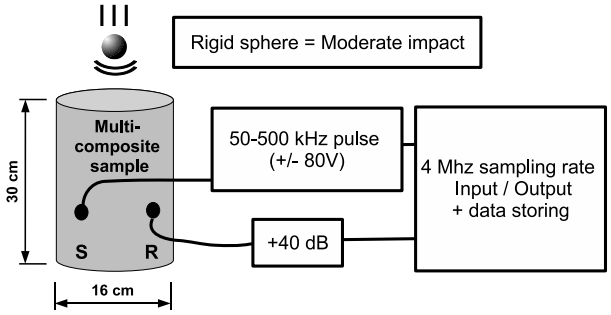


FIG. 1. Schematic view of the experimental setup for sample #1.

In this article, we develop an alternative method based on broadband diffuse ultrasound. We take advantage of coda waves that can be observed in multicomposite materials where multiple scattering effects (characterized by the scattering mean free time $t^\star$) dominate absorption effects (characteristic time τ_{abs}). Denoting by T the central period of the ultrasound, and by Δd the time between two ultrasonic records, the time scales in our experiment follow the hierarchy:

$$T < t^\star < \tau_{abs} < \Delta d. \qquad (1)$$

Similarly to Coda Wave Interferometry (CWI) [Poupinet *et al.* (1984); Roberts *et al.* (1992); Snieder *et al.* (2002)] and to Diffuse Acoustic Wave Spectroscopy

[a)]Electronic address: eric.larose@ujf-grenoble.fr

Composition (in weight)	Weight	density
cement: 17% fine sand: 31% gravel: 43% water: 9%	12.5 kg	2.2 kg/l

TABLE I. Sample composition

(DAWS) [Pine *et al.* (1988); Cowan *et al.* (2002)], we study weak changes of the diffuse waveforms in amplitude and phase. We compare waveforms recorded after a moderate solicitation to those recorded before it. The solicitation consists in the impact of a small steel ball falling onto the sample from a controlled height (one meter in general). The composition of the samples is displayed on table I.

II. EXPERIMENTAL SETUP

In the first experiment, we use a cylindrical sample of 16 cm in diameter and 30 cm in height (sample #1). Two ultrasonic transducers are used: one as a source and one as a receiver (labeled S and R, respectively, in Fig. 1); they are 10 cm apart. Note that the lateral part of the transducer is inactive and rigid, so that surface (Rayleigh) waves are neither excited nor recorded. In this sample, the scattering mean free time is of the order of $12\mu s$, the transit time is of the order of $60\mu s$, and the absorption time about $200\mu s$.

The lateral size of the active part of the transducers (0.7 mm) is much smaller than the wavelength (λ = 5 mm to 5 cm at working frequencies), which makes them very sensitive to multiply scattered waves. The transducers are glued onto the sample using a hot chemical glue (phenyl-salicylic acid) that solidifies with cooling (below 43°C). The ultrasonic experiment was performed several months after casting the samples. We send a 80V broad-band ultrasonic impulse with frequencies ranging from 50 to 500 kHz. The signal measured by the receiver is amplified, digitized and stored in memory. A typical record $h_d(t)$ is shown in Fig. 2. The impulse response contains a hardly visible direct arrival followed by a long lasting coda due to multiply scattered waves. The acquisition is repeated at various dates d ($d = 0$ starts the experiment), over about one hour. At date d_I, we drop a small metallic ball ($m = 30$ g) from a height $h = 1.38$ m onto the top face of the sample. The impact is about 15 cm from the source and the receiver. The elastic energy released to the sample is: $E_{kin} = mgh \approx 0.4$ J. Note that we observe no visible damage caused by this moderate impact.

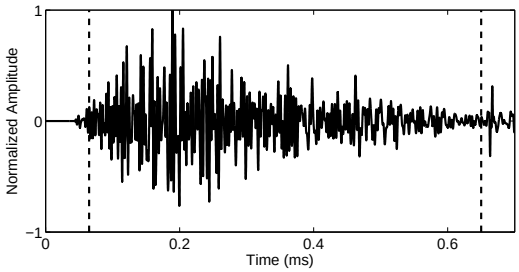


FIG. 2. Typical record collected through a concrete sample. The integration time-window is marked by the two dashed vertical lines: at 0.05 ms and at 0.65 ms. The initial impulse duration is about $10\mu s$.

III. DATA PROCESSING

From the set of ultrasonic data obtained during an experiment, we derive two quantities that depend on d. First, we measure the relative velocity change $\delta V_d/V$ within the material [Poupinet *et al.* (1984); Snieder *et al.* (2002); Lobkis and Weaver (2003)]. Second, we measure the remnant decorrelation K_d of the waveforms after correcting for the effect of the relative velocity change [Lobkis and Weaver (2003)].

A. Relative velocity change $\delta V/V$ (CWI)

Let us describe the two steps of our data processing in details. To measure the relative velocity change, we compare the phase of the waveforms acquired at the date d to the phase of the initial record ($d = 0$). Following Sens-Schönfelder and Wegler (2006), we interpolate and resample $h_d(t)$ at times $[1+\epsilon]\,t$; this corresponds to stretching the time-axis of the record by a factor $1+\epsilon$. Then we evaluate the correlation coefficient between h_0 and h_d:

$$X_d(\epsilon) = \frac{\int h_0(t) h_d([1+\epsilon]\,t) dt}{\sqrt{\int h_0^2(t) dt}\,\sqrt{\int h_d^2([1+\epsilon]\,t) dt}}, \qquad (2)$$

where the integration is performed over a time-window larger than the period T. This time-window is marked by two vertical broken lines in fig. 2. This calculation is repeated for various values of the parameter ϵ. The parameter ϵ maximizing X_d corresponds to the actual relative velocity change:

$$\epsilon_{max} = -\delta V_d/V. \qquad (3)$$

The evolution of $\delta V_d/V$ as a function of d is displayed in fig. 3 (top). Note that the ball impact occurs at date $d_I = 270\,s$ after starting the experiment. Before the impact, there is no relative velocity change, indicating that the medium is at rest. Immediately after the impact, the velocity is noticeably decreased. Since the density of the material is not changed, and since diffuse waves are mainly in the transverse (shear) polarization,

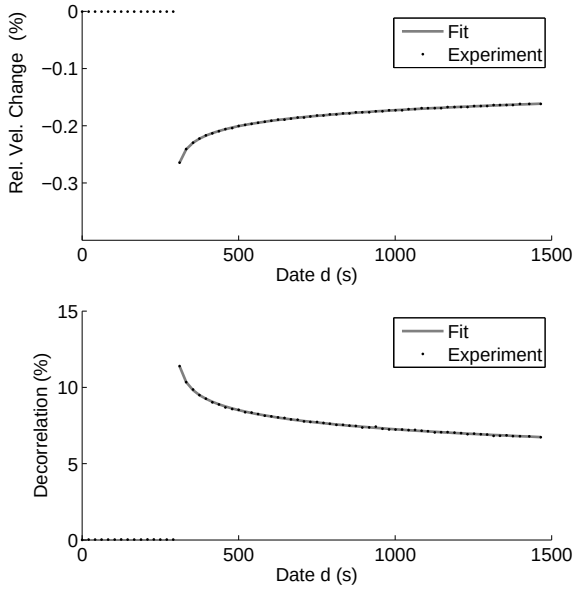


FIG. 3. Relative velocity change $\delta V/V$ (top) and decorrelation (bottom) versus the date d of the measurement. Impact is at $d_I = 270$ s. Thermal effects are negligible. A logarithmic fit is added to each experimental curve.

this velocity drop is principally due to a drop of rigidity of the material. Then, the material stiffness rises back toward its initial value.

B. Remnant decorrelation K (DAWS)

In a second step, we use the dilated records to evaluate the remnant decorrelation coefficient K_d between the waveforms, which simply reads [Pine *et al.* (1988); Cowan *et al.* (2002)]:

$$K_d = 1 - X_d(\epsilon_{max}). \tag{4}$$

The time evolution of K as a function of d is plotted in fig. 3 (bottom). Again, the record is very stable (no change) before the impact. After the impact, the ultrasonic waveform differs significantly from the reference, then the decorrelation from the reference waveform decreases over several hundreds of seconds. The decorrelation K defined in Eq. (4) cannot be solely associated to a difference of relative velocity changes for different waves (for instance between compressional and shear waves), contrary to the decorrelation studied by Lobkis and Weaver (2003). Also, the decorrelation can not be attributed to changes in the bulk of the grains, which would require much more energy than the one released by the ball. Here, it corresponds to a feeble change in the scattering properties of the concrete sample, for instance a small rearrangement of contacts between grains.

It is important to note that thermal changes are also well known to affect the average velocity within the sample [Lobkis and Weaver (2003); Snieder *et al.* (2002); Larose *et al.* (2006)], and consequently the decorrelation. Relative velocity changes due to temperature variations are found to be negligible in our experiment, as can be noticed by the flat curve in fig. 3, from t=0 to t=270 s. The decorrelation of the waveforms before the impact is actually near 0.1 %, and is attributed to the noise generated by the electronic devices. We neglect it in the following. Note also that the changes of intensity of the diffuse waveforms (say, the quality factor of the coda) was observed to show some recovery [TenCate *et al.* (2000)], but this effect is not studied here and is beyond the scope of the present paper.

IV. THE PHYSICAL PARAMETERS OF SLOW DYNAMICS

The time evolutions of both $\delta V/V$ and K fit logarithmic laws (with d and d_I in seconds):

$$\delta V_d/V = A' - m' \log_{10}(d - d_I), \tag{5}$$

$$K_d = A - m \log_{10}(d - d_I). \tag{6}$$

Such a logarithmic evolution, valid if $d \ll 10^{A/m}$ is referred to as *slow dynamics*. A and m are the fit parameters: A is the extrapolated decorrelation 1 s after the impact, and m the slope of the logarithmic decay. $10^{A/m}$ represents the recovery time (in seconds): the time the system needs to recover its initial state. In general, this recovery time is of the order of 10^4 to 10^5 s. Parameters A and m were found to depend on the experimental apparatus, but Eq. (6) was found to describe the dynamics in all cases. TenCate *et al.* (2000) mentioned a break away from the *log* recovery after 1000 s. . In our experiments, we should certainly expect an erosion of the *log* dynamics at some time. In particular, we must consider the possibility that part of the change in our experiments might be irreversible, and that the recovery might saturate. This could be ascribed to irreversible (but invisible) damages caused by the impact. As we could not monitor the sample longer than 1000s, we can not address this issue properly.

A. Slow Dynamics versus time in the coda

Let us now study the parameters A and m in more details. As a first test, we evaluate these parameters at different times t in the coda. To that end, we split the initial time window (see fig. 2) into five consecutive time windows of length 0.12 ms. The decorrelation K_d for these five windows is displayed in Fig. 4. A and m were found to increase with the time in the coda, confirming that late diffuse waves are much more sensitive to weak perturbation than early arrivals. Interestingly enough, the recovery time $10^{A/m}$ is constant within the whole record, which confirms that all time-windows (thus all wave paths) undergo the same *slow dynamics*

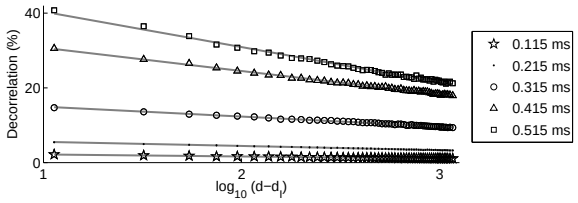


FIG. 4. Decorrelation versus the date of the measurement (in log scale) for various time windows in the coda. The central time of each window is displayed in the box. The recovery time $10^{A/m}$ is found to be constant in the whole record.

phenomenon.

B. Slow Dynamics versus frequency

To study the frequency dependence of *slow dynamics*, we filter the whole record into different frequency bands: we observe that A/m is constant in the 50-500 kHz frequency range. That the same dynamics was observed at different wavelength might suggest that there is no characteristic length in the re-arrangement of the material structure. This confirms the assumption commonly made by previous authors [TenCate *et al.* (2000)] that the changes occur at various scales following the probable continuous distribution of energy barriers.

C. Spatial dependence of Slow Dynamics

In the initial works on *slow dynamics* [TenCate and Shankland (1996); Guyer *et al.* (1998)], the medium was subject to a global excitation, and resulted in a global change of the sample stiffness. The excitation presented here is a local impact (as in [Lobkis and Weaver (2009)]). Determining whether the change induced by the ball impact is global (induced by the shock wave), or local is of some importance. To that end, we deploy a linear array of four sensors 10 cm away from the impact location and from the source transducer. Because the initial sample is not large enough, we use a different sample (#2) of similar composition but whose dimensions are now 1m× 1m × .25 m (see Fig. 5). The array has a spatial pitch of about 10 cm. The decorrelation K is found to strongly depend on the impact-receiver distance (Fig. 6). We therefore confirm the assumption issued by Lobkis and Weaver (2009): the changes induced by the ball impact are located in the vicinity of the impact, and the seismic (shock) wave emitted by the impact has negligible effect on the material stiffness at large distances.

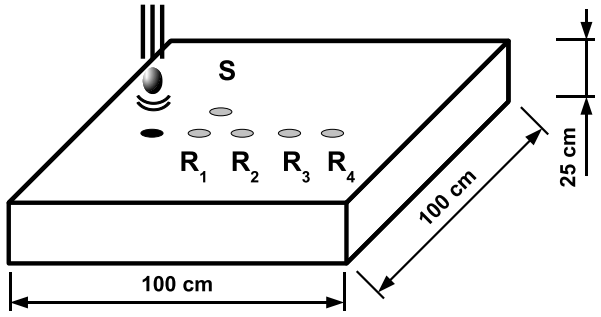


FIG. 5. Experimental setup for sample #2. Four receivers ($R_{1..4}$) are aligned with the impact location. The source S is 10 cm off the impact-receivers axis.

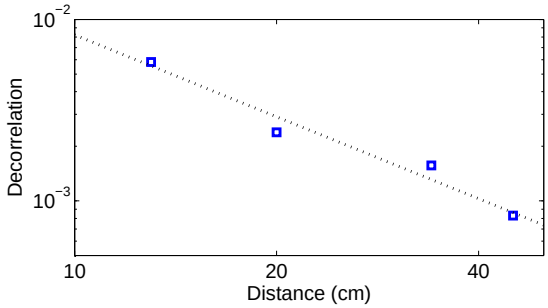


FIG. 6. Decorrelation of ultrasonic waveforms obtained a few ms right after the impact in log-log scale, at different distances from the impact. Squares are experimental data, dots represents a power law with the exponent -1.5.

V. TENTATIVE APPLICATION TO ON-SITE DAMAGE ESTIMATION

Last, we address the issue of damage estimation through DAWS. Consider two blocks of concrete of similar constitution (see tab. I) and of the same geometry (see sample #1): the first one is intact and the other one is damaged after undergoing a 30 MPa load. Both samples are tested using the same experimental protocol, and data processed in the same time window and frequency range. Resulting decorrelations K_d are plotted in fig. 7. Similarly to Van Den Abeele *et al.* (2001), we observe that damage increases considerably the amplitude of change in the material, and thus the absolute decorrelation A together with the speed of recovery m. Provided that the experimental protocol is rigorously similar from one site to another, this latter result suggests a possible route for on-site concrete damage assessment.

VI. CONCLUSION

In this article, we studied the *slow dynamics* behavior of concrete after a ball impact of moderate energy. We observed a drop of the acoustic velocity (probed by CWI [Poupinet *et al.* (1984)]) and a decorrelation of

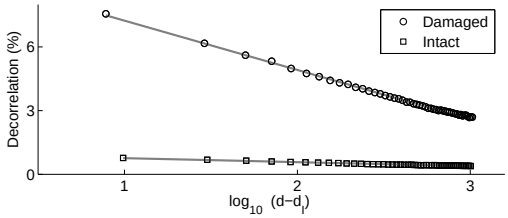


FIG. 7. Slow dynamics observed in undamaged and damaged concrete.

the diffuse waveforms (probed by DAWS). Then the material recovers over characteristic times ranging from 100 s to several 1000 s. In our experiments, the $log(t)$ recovery was observed at all time in the coda, and at different frequencies: this does not allow to exhibit any characteristic length, time, or energy. This feature is in agreement with a fractal structure of concrete. Slow dynamics is thus interpreted as a series of jumps of energy barriers having a continuous distribution. In principle, *slow dynamics* could be either due to a homogeneous change of mechanical characteristics of all constituents, or to local rearrangements of inter-grain contacts. As we observe a noticeable decorrelation of the diffuse waveforms that can not be solely ascribed to a homogeneous change of the material stiffness, we defend the second interpretation: slow dynamics is due to a collection of local changes in inter grain contacts, which simultaneously result in changes in scattering properties and in a decrease of the effective wave velocity. The rearrangements of inter grain contacts in our experiments are somehow analogous to those observed in solid friction [Lomnitz (1962); Pandit and Savage (1973); Karner and Marone (1998)]. As concrete is an example of consolidated multicomposite granular material, we also believe that our laboratory experiment shares analogy with the time evolution of shallow sedimentary geomaterials after an earthquake [Sawazaki *et al.* (2006); Brenguier *et al.* (2008)]. In our experiments, slow dynamics parameters A and m where found to be very sensitive to experimental apparatus, particularly to the impact energy and position. While keeping these features perfectly constant and the experiment perfectly reproducible, we observed that the slow dynamics parameters were also found to strongly depend on damage, which suggest that they could characterize the ageing of concrete structures. Since the experimental apparatus is light and easy to handle, it could have some practical interest in structural health monitoring, especially in civil engineering, or to perform down hole geomaterial characterization, provided that a reproducible and controlled impact could be delivered to the medium at depth.

The authors thank R. L. Weaver and P.A. Johnson for attracting their attention on *slow dynamics*. This work was funded by the ANR_08_JCJC_0066 *SISDIF* grant.

Brenguier, F., Campillo, M., Hadziioannou, C., Shapiro, N. M., Nadeau, R. M., and Larose, E. (**2008**). "Postseismic relaxation along the San Andreas fault at Parkfield from continuous seismological observations", Science **321**, 1478–1481.
Cowan, M. L., Jones, I. P., Page, J. H., and Weitz, D. A. (**2002**). "Diffusing acoustic wave spectroscopy", Phys. Rev. E **65**, 066605.
Guyer, R. A. and Johnson, P. A. (**1999**). "non-linear mesoscopic elasticity: evidence for a new class of materials", Physics Today **52**, 30–36.
Guyer, R. A., McCall, K. R., and Abeele, K. V. D. (**1998**). "Slow elastic dynamics in a resonant bar of rock", Geophys. Res. Lett. **25**, 1585–1588.
Johnson, P. and Sutin, A. (**2005**). "slow dynamics and anomalous fast dynamics in diverse solids", J. Acoust. Soc. Am. **117**, 124–130.
Karner, S. L. and Marone, C. (**1998**). "The effect of shear load healing in simulated fault gouge", Geophys. Res. Lett. **25**, 4561–4564.
Lacouture, J., Johnson, P., and Cohen-Tenoudji, F. (**2003**). "Study of critical behavior in concrete during curing by application of dynamic linear and nonlinear means", J. Acoust. Soc. Am. **113**, 1325–1332.
Larose, E., DeRosny, J., Margerin, L., Anache, D., Gouedard, P., Campillo, M., and VanTiggelen, B. (**2006**). "Observation of multiple scattering of kHz vibrations in a concrete structure and application to weak changes monitoring", Phys. Rev. E **73**, 016609.
Lobkis, O. I. and Weaver, R. L. (**2003**). "Coda-wave interferometry in finite solids: recovery of p-to-s conversion rates in an elastodynamic billiard", Phys. Rev. Lett. **90**, 254302.
Lobkis, O. I. and Weaver, R. L. (**2009**). "On the larsen effect to monitor small fast changes in materials", J. Acoust. Soc. Am. **125**, 1894–1905.
Lomnitz, C. (**1962**). "application of the logarithmic creep low to stress wave attenuation in th esolid earth", JGR **67**, 365–368.
Pandit, B. I. and Savage, J. C. (**1973**). "An experimental test of lomnitz's thoery of internal friction in rocks", JGR **78**, 6097–6099.
Pine, D. J., Weitz, D. A., Chaikin, P. M., and Herbolzheimer, E. (**1988**). "Diffusing-wave spectroscopy", Phys. Rev. Lett. **60**, 1134–1137.
Poupinet, G., Ellsworth, W. L., and Frechet, J. (**1984**). "Monitoring velocity variations in the crust using earthquake doublets: an application to the calaveras fault, california", J. Geophys. Res. **89**, 5719–5731.
Roberts, P. M., Phillips, W. S., and Fehler, M. (**1992**). "Development of the active doublet method for measuring small velocity and attenuation changes in solids", J. Acoust. Soc. Am. **91**, 3291.
Sawazaki, K., Sato, H., Nakahara, H., and Nishimura, T. (**2006**). "Temporal change in site response caused by earthquake strong motion as revealed from coda spectral ratio measurement", Geophys. Res. Lett. **33**, L21303.
Sens-Schönfelder, C. and Wegler, U. C. (**2006**). "Passive image interferometry and seasonal variations of seismic velocities at merapi volcano, indonesia.", Geophys. Res. Lett. **33**, L21302.
Snieder, R., Grêt, A., Douma, H., and Scales, J. (**2002**). "Coda wave interferometry for estimating nonlinear behavior in seismic velocity", Science **295**, 2253–2255.
TenCate, J. A. and Shankland, T. J. (**1996**). "Slow dynamics in the nonlinear elastic response of berea sandstone", Geophys. Res. Lett. **23**, 3019–3022.
TenCate, J. A., Smith, E., and Guyer, R. A. (**2000**). "Uni-

versal slow dynamics in granular solids", Phys. Rev. Lett. **85**, 1020–1023.
Vakhnenko, O. O., Vakhnenko, V. O., Shankland, T. J., and TenCate, J. A. (**2004**). "strain induced kinetics of inter-grain defects as the mechanism of slow duynamics in the nonlinear resonant response of humid sandstone samples", Phys. Rev. E **70**, 015602 (R).
Van Den Abeele, K., Sutin, A., Carmeliet, J., and Johnson, P. (**2001**). "Micro-damage diagnostics using nonlinear elastic wave spectroscopy (news)", NDTE Int. **34**, 239–248.