Damaging and healing of earth materials as a multi-scale phenomenon

Roel Snieder
(Brenguier et al., Science, 321, 1478-1481, 2008)
S-waves in Niigata and earthquakes

- M5.3, Jan. 4, 2001
- M6.8, Oct. 23, 2004
- M6.8, Jul. 16, 2007

Δν (m/s)
S-velocity changes with seasons
Rainfall/\nu_s \text{ for soft-rock sites}
Velocity changes in Chili

(a) Similarity matrix \( \phi_{\tau_i} \) of station PATCX between 10–15 s and 4–6 Hz. Negative correlation coefficients appear white. The blue dots in the similarity matrix symbolize the daily velocity variations normalized before calculating daily ACFs. The relative velocity change \( \delta \epsilon \) is calculated from noise signal that was recorded at time \( t_i \). For all times \( t_i \), the comparison between stretched or compressed versions of a long-term averaged reference trace \( \phi_{\tau} \) and we taper the edges in order to avoid artefacts in the autocorrelation envelope in quiet periods are detected and set to zero. We make sure that the deleted time windows are at least two minutes long. The rare blue dots at velocity decreases larger than 1.5 per cent before 2014 April result from cycle skipping although it cannot eliminate it completely. Such in-lapse lag times, this two-step approach minimizes the problems of cycle skipping and stretching. The rare blue dots at velocity decreases larger than 1.5 per cent before 2014 April result from cycle skipping although it cannot eliminate it completely. Such in-lapse lag times, this two-step approach minimizes the problems of cycle skipping and stretching. The rare blue dots at velocity decreases larger than 1.5 per cent before 2014 April result from cycle skipping although it cannot eliminate it completely. Such in-lapse lag times, this two-step approach minimizes the problems of cycle skipping and stretching. The rare blue dots at velocity decreases larger than 1.5 per cent before 2014 April result from cycle skipping although it cannot eliminate it completely. Such in-lapse lag times, this two-step approach minimizes the problems of cycle skipping and stretching. The rare blue dots at velocity decreases larger than 1.5 per cent before 2014 April result from cycle skipping although it cannot eliminate it completely. Such in-lapse lag times, this two-step approach minimizes the problems of cycle skipping and stretching. The rare blue dots at velocity decreases larger than 1.5 per cent before 2014 April result from cycle skipping although it cannot eliminate it completely. Such in-lapse lag times, this two-step approach minimizes the problems of cycle skipping and stretching. The rare blue dots at velocity decreases larger than 1.5 per cent before 2014 April result from cycle skipping although it cannot eliminate it completely. Such in-lapse lag times, this two-step approach minimizes the problems of cycle skipping and stretching.
Seismic sensors array on a dam

Crest

Sensors Array

Bottom

Courtesy of Ichiro Kuroda

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Direction components in a dam
Days since Tohoku-oki earthquake
Mineralized fractures

(Credit: NASA/JPL-Caltech/MSSS)
Intrusion by a dike
Color-enhanced Scanning Electron Microscope (SEM) image of human tooth dentine (fracture surface) showing a crack in the surface. 70% of dentin consists of the mineral hydroxyapatite, 20% is organic material, and 10% is water. Magnification: x1200 when printed 10 cm wide.

Filename: K14SEM--tooth062.jpg

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Color-enhanced Scanning Electron Microscope (SEM) image of human tooth dentine (fracture surface) showing a crack in the surface. 70% of dentin consists of the mineral hydroxyapatite, 20% is organic material, and 10% is water. Magnification: x1200 when printed 10 cm wide.
Micro-structure of a rock fracture

Power spectrum of rock surface

(Brown and Scholz, J. Geophys. Res., 90, 12575-12582, 1985)
Healing of a fracture

Healing of a fracture

Pressure solution
Pressure solution of oolitic limestone
Analogue model for cracks

(Renard et al., Geofluids, 9, 365-372, 2009)
A healing crack in a gel

(Renard et al., Geofluids, 9, 365-372, 2009)
A healing crack in a quartz

(Renard et al., Geofluids, 9, 365-372, 2009)
Log(time) behavior in resonance

Log\(\text{(time)}\) behavior in resonance

![Graph showing resonance frequencies versus log(time) for different geomaterials.](image)

(Ten Cate et al., Pure Appl. Geophys, 168, 2211-2219, 2011)
Chapter 6. Laboratory tests of shaking induced velocity variations

Figure 6.1: Experimental setup: a) A pair of ultrasound transducers is attached to two cylindrical sand-gypsum samples. A sound transducer is mounted on the top of sample A. It generates a shaking every 30 min on sample A, which is coupled to sample B with lower amplitude. b) The samples are placed in a climate chamber at a temperature of 30°C.

The signals were band-pass filtered between 10 and 50 kHz, and after autocorrelation of the transmitter and receiver signal possible velocity changes were analyzed with the stretching method (chapter 2.5.1) in a time window of 2-4 ms.

6.2 Results

The observed velocity variations corresponding to cross-correlation values larger than 0.7 are shown in Fig. 6.2. This threshold affects only the data of sample A during shaking. On average, correlation values are very large with mean values of 0.991 for sample A and 0.999 for sample B. Additionally, the data was corrected for as a malposition line artefacts estimated over the first 15 minutes.

The velocity shows sharp decreases at both samples at the times of the shocks followed by a subsequent recovery (Fig. 6.2 a). The amplitudes of the decreases at sample A are larger than at sample B, which is expected from the field observations at station PATCX, as the amplitude of the shaking at sample A is also larger than at sample B. At both samples, it can be observed that the amplitude of velocity change is the largest for the first shock. After the first shock, the amplitude of velocity change for later shocks decreases slightly. As the sample was at rest for more than four days before the experiment, this behavior can be attributed to aging effects, as described in chapter 3.4.1.

(Gassenmeier, 2015, PhD thesis, Universität Leipzig)
Healing of rock samples

(Gassenmeier, 2015, PhD thesis, Universität Leipzig)
So rock healing clearly goes as log-time
Logarithm means there is no time-scale

\[ \ln\left(\frac{t}{\tau}\right) = \ln(t) - \ln(\tau) \]

any time-scale corresponds to an offset
Relaxation process for one relaxation time

\[ R(t) = e^{-t/\tau} \]

Relaxation process for one relaxation time

\[ R(t) = e^{-t/\tau} \]

Superposition of relaxation processes

\[ R(t) = \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} \frac{1}{\tau} e^{-t/\tau} d\tau \]

\( \frac{1}{\tau} \) follows from Arrhenius’ law
How to get log-time behavior?

\[
R(t) = \int_{\tau_{min}}^{\tau_{max}} \frac{1}{\tau} e^{-t/\tau} d\tau
\]
How to get log-time behavior?

\[ R(t) = \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} \frac{1}{\tau} e^{-t/\tau} d\tau = \int_{t/\tau_{\text{max}}}^{t/\tau_{\text{min}}} \frac{1}{u} e^{-u} du \]

\[ u = t/\tau \]
How to get log-time behavior?

\[ R(t) = \int_{\tau_{min}}^{\tau_{max}} \frac{1}{\tau} e^{-t/\tau} d\tau = \int_{t/\tau_{max}}^{t/\tau_{min}} \frac{1}{u} e^{-u} du \]

\[ u = t/\tau \]

\[ \frac{dR(t)}{dt} = \frac{1}{t} \left( e^{-t/\tau_{min}} - e^{-t/\tau_{max}} \right) \]
How to get log-time behavior?

\[
\frac{dR(t)}{dt} = \frac{1}{t} \left( e^{-t/\tau_{\text{min}}} - e^{-t/\tau_{\text{max}}} \right)
\]
How to get log-time behavior?

$$\frac{dR(t)}{dt} = \frac{1}{t} \left( e^{-t/\tau_{\text{min}}} - e^{-t/\tau_{\text{max}}} \right)$$

when \( \tau_{\text{min}} \ll t \ll \tau_{\text{max}} \)

$$\frac{dR(t)}{dt} = \frac{1}{t} \left( 0 - 1 \right) = -\frac{1}{t}$$
How to get log-time behavior?

\[
\frac{dR(t)}{dt} = \frac{1}{t} \left( e^{-t/\tau_{min}} - e^{-t/\tau_{max}} \right)
\]

when \( \tau_{min} \ll t \ll \tau_{max} \)

\[
\frac{dR(t)}{dt} = \frac{1}{t} (0 - 1) = -\frac{1}{t}
\]

\[
R(t) = B - \ln(t)
\]
Relaxation function

$R(t)$

$\tau_{\text{max}} = 10^4 \text{ s}$

$\tau_{\text{max}} = 10^3 \text{ s}$

$\tau_{\text{max}} = 10^2 \text{ s}$
Once a semester, I will engage in a professional or personal activity that frightens me a little but which makes me feel alive.