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## Th IS 12

# Monitoring and forecasting failure in laboratory using coda wave decorrelation

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## Summary

Gas extraction has caused pressure differences along the field, triggering earthquakes, which are causing a lot of damage and social unrest in the Groningen area. Predicting the degree of these stress changes, and as a result, the potential onset and exact location of failure and seismicity, is very challenging.

Therefore, developing good techniques that can monitor these changes is crucial for a better prediction and thus mitigation of failure and seismicity in the subsurface. Laboratory active acoustic-monitoring techniques are used to determine parameters that can forecast upcoming failure and seismicity.

We show the use of coda wave decorrelation as a monitoring tool using sandstones analogues for the Groningen reservoir. Failure of the rock sample is preceded by the formation of micro-fractures. These fractures change the scattering properties of acoustic waves. The decorrelation coefficient K, as the indicator of the amount of scattering and thus be used as precursor to failure. We show that by monitoring K we can forecast the upcoming failure of the rock samples in the laboratory.

## Introduction

The first seismicity associated with the gas extraction in Groningen (the Netherlands) was recorded in 1991 (TNO, 2020; Thienen-Visser and Breunise, 2015). Since this first event, the number of seismic events has increased over time with frequency and magnitude (Thienen-Visser and Breunise, 2015). Gas extraction has caused pressure differences along the field, causing reservoir compaction thereby triggering the seismicity. These induced seismic events are causing a lot of damage and social unrest in the Groningen area. Predicting the degree of these stress changes, and as a result, the potential onset and exact location of failure and seismicity, is very challenging.

Therefore, developing good techniques that can monitor these changes is crucial for a better prediction and thus mitigation of failure and seismicity in the subsurface. We use laboratory active acoustic-monitoring techniques to determine parameters that can forecast upcoming failure and seismicity.

To analyse physical properties of a medium, remotely and non- destructively, non-destructive testing (NDT) methods can be used (Hall, 2009). Geophysical methods can be used for monitoring seismic velocities, which provide insight in mechanical (rigidity, density, etc.) evolution (Schubnel et al., 2006). However, the sensitivity of seismic wave velocity to stress changes in rocks is low (Grêt et al., 2006; Nur, 1971; Grêt and Snieder, 2006; Barnhoorn et al., 2018) and detection of temporal variations is therefore difficult (Niu et al., 2003; Grêt et al., 2006). By analysing the direct arrivals, dispersion envelope, attenuation or the coda wave, stress changes in subsurface can also be monitored (Hall, 2009; Schubnel et al., 2006; Xie et al., 2018; Snieder, 2006; Grêt et al., 2006; Snieder, 2002; Grêt and Snieder, 2006; Barnhoorn et al., 2018).

The coda wave scatters throughout the rock multiple times and therefor samples a disturbed region more than a direct wave (Snieder, 2006; Grêt et al., 2006). Small rock structure changes may be undetectable in the signals of direct waves but are amplified by the repeated sampling and detected by the coda of the wave (Grêt et al., 2006; Snieder, 2006; Grêt and Snieder, 2006). Coda waves are used in many applications, such as monitoring of fault zones (Poupinet et al., 1984), volcano's (Snieder et al., 2006; Grêt et al., 2005), the integrity of concrete (Deroo et al., 2010; Niederleithinger et al., 2018), monitoring of temporal changes in the subsurface and in-situ stress (Grêt et al., 2006; Poupinet et al., 1984), but also monitor velocity changes in laboratory settings (Hadziioannou et al., 2009; Zotz-Wilson et al., 2019) and for localization of these changes (Snieder and Vrijlandt, 2005; Rossetto et al., 2011; Planès et al. 2014; Planès et al., 2015).

Zotz-Wilson et al (2019) has shown that coda wave decorrelation, using a rolling reference, can be used to monitor changes in the rock matrix for unconfined compression tested samples. In this study we extend this theory for confined experiments under pressure where we use $\sigma_1 > \sigma_2 = \sigma_3$. We will show the use of coda wave decorrelation as a monitoring tool using sandstones analogues for the Groningen reservoir.

## Theory

The method of coda wave decorrelation introduced by Larose et al. (2010) is based on the theory of Snieder (2006). The decorrelation coefficient, also described in Zotz-Wilson et al. (2019), is formulated as

$$K(t_s) = 1 - CC(t_s) = 1 - \frac{\int_{t_k-t_w}^{t_k+t_w} u_{p_{j-N}}(t)\, u_{p_j}(t+t_s)\, dt}{\sqrt{\int_{t_k-t_w}^{t_k+t_w} u_{p_{j-N}}^2(t)\, dt \int_{t_k-t_w}^{t_k+t_w} u_{p_j}^2(t)\, dt}},$$

where N is the number of measurements the reference wavefield $u_{p_{j-N}}(t)$ is lagging behind the to be correlated wavefield $u_{p_j}(t)$.

The decorrelation coefficient K is related to the changes in material scattering due to the addition of scatter(ers) (Planès et al. 2014; Planès et al., 2015).

The coda waves seem random due to the complex paths they take through the medium, but the changes they are subjected to are strongly related to the position and strength of the changes in the medium (Planès et al. 2014).

The scattering in a medium along the transport mean free path $l$ can be described using the cross-sectional area of a single scatterers $\sigma$ and the density of scatterers $\rho$ (Planès et al. 2014). The total scattering coefficient as described by Aki and Chouet (1975) is given by

$$g_0 = \rho\sigma = l^{-1}.$$

Following the theory in Aki and Chouet (1975), we can rewrite the coda decorrelation in terms of the scattering coefficient $(g_0)$ between a perturbed $(p)$ and unperturbed $(u)$ medium (Zotz-Wilson et al., 2020).

$$K(t) = \frac{v_0}{2} t \left|\Delta g_{0_{p-u}}\right|,$$

where $K(t)$ is the theoretical decorrelation coefficient, $t$ the time in the coda and $v_0$ the velocity in the medium. Using a rolling reference, the changes in the absolute value of $|g_0|$ are monitored as a rate of change (Zotz-Wilson et al., 2020).

## Method

A total of 8 uni-axially deformation experiments are performed at different confined pressures from 25 to 400 bar. Simultaneously to the loading of the rock, acoustic transmission measurements are done. This combined setup enables us to measure the wave properties under changing stress conditions. The tests are performed on Red Felser cores from Germany, which is an analogue to Groningen reservoir rock. The eight rock samples have a porosity between 22% and 25% and a fairly homogeneous composition. The core samples are cylindrical with a diameter of 30 ± 0.5 mm and 60 ± 2 mm length, such that the length/diameter ratio is 1:2.

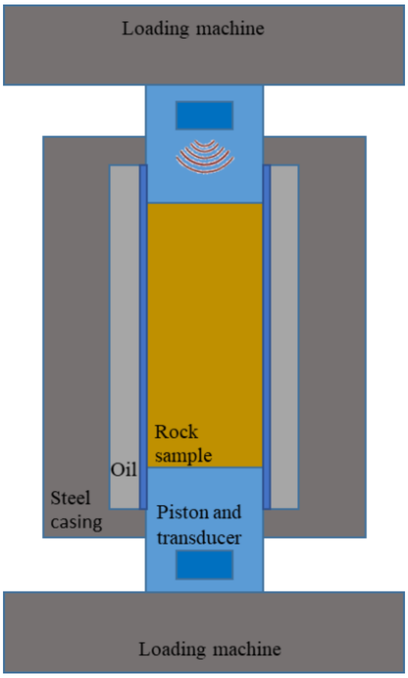

***Figure 1****: Scheme illustrating the experimental setup. Note: Not to scale.*

The experiments are performed with samples saturated with tap-water at room temperature. First, the samples are brought up to the confining pressure in steps of 10 bar/0.1 MPa, such that the axial stress always higher. The confining pressure is then set constant for the entire experiment. The samples are deformed at a constant strain rate of 0.005 $s^{-1}$ and the shortening of the sample is recorded with two linear variable displacement transducers (LVDT's).

The acoustic measurements are performed using two S-wave transducers, simultaneously to the deformation. The two axial transducers are integrated in the pistons in the loading system with a source at the top and receiver at the bottom. The transducers have a peak operating frequency of 1 MHz. The polarization of the shear source and receiver transducers was always aligned. The acoustic monitoring started immediately after starting the deformation. The acoustic signals are recorded every 10 seconds for 100 $\mu$s and are a stack of 256 (S-) waves increase the signal-to-noise ratio.

## Example

Following Zotz-Wilson et al. (2019), a rolling reference is used to monitor the changing decorrelation coefficient K. Changes in K correspond to the changes in the absolute value of scattering coefficient

$|g_0|$ as a rate of change. An increase in scattering density or scattering area by micro-fracture formation and/or fracture growth results in an increase in K. Opposite, a reduction in pore space, and/or compaction results in reduction of the scattering density or scattering area.

The first reference trace for the decorrelation is taken at 19% of the maximum stress, such that the experiments at different confining pressures have a similar starting point. The K decreases at the start of the experiment, indicating a reduction in scatterers. This reduction can be caused by elastic compaction of the rock and further closing of existing pore space. The majority of the pre-existing weaknesses is expected to be closed in the first 19MPa. The decrease is followed by an increase of K.

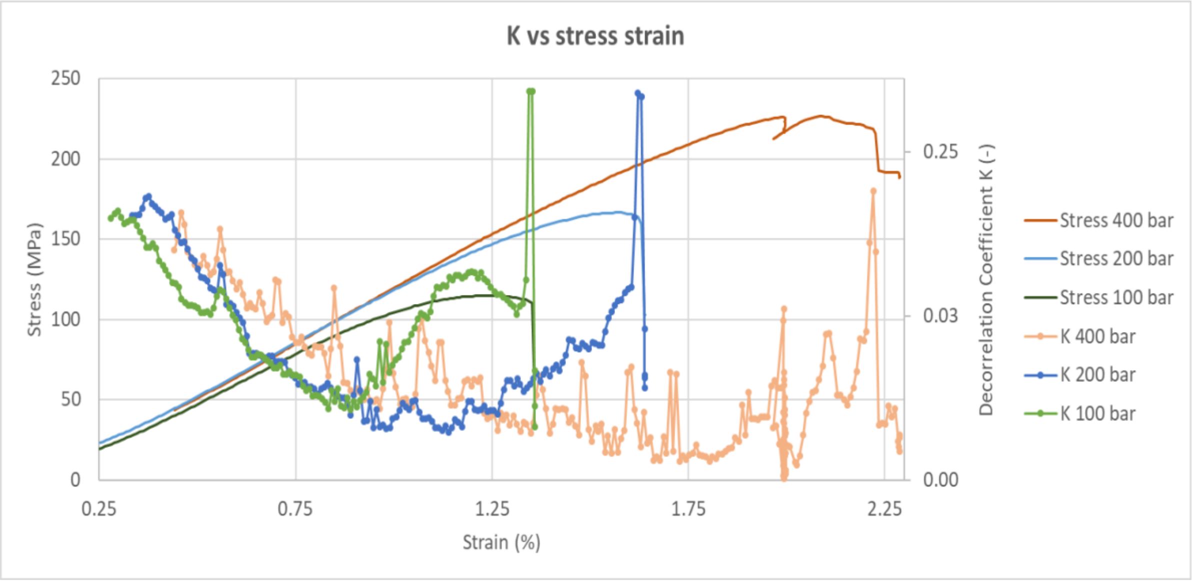

***Figure 2:*** *Figure showing the stress strain curve of the experiments at 100, 200 and 400 bar confining pressure. Accompanied are the decorrelation coefficients during the experiments.*

This increase correspond to the start of micro-fracture formation. Micro-fractures increase the total scattering surface within the rock sample. Close to the failure point (the maximum stress), K reaches a top and decreases a bit, to spike at the moment the rock sample collapses. Thus for monitoring and forecasting purposes we can say failure is coming when the decorrelation coefficient increases. The moment at which this first increase in decorrelation coefficient is noticed varies for every confining pressure (~70% and 80% of peak stress), but is early enough as a potential tool for failure monitoring and forecasting.

## Conclusions

In this study, we show that coda wave decorrelation, with a rolling reference, can be used to monitor the changing rock properties. Failure of the rock sample is preceded by the formation of micro-fractures. Detecting these fractures is therefore crucial to forecast failure. The coda is sensitive to small changes in the rock and is thus the ideal method for monitoring micro-fracture formation. During deformation of the rocks, the scattering properties of the wave change. The decorrelation coefficient K, as the indicator of the amount of scattering, is a good forecasting parameter. By monitoring the development of the K, predictions can be made about the current and future stress state of the sample. An increase of K is a clear indication of (micro-)fracture formation and that failure is imminent.

The experiments in this study are performed with the focus on the induced earthquakes in Groningen. These results show that monitoring in the laboratory are feasible and it is expected the use of coda wave decorrelation can be used for field-scale monitoring of the changing condition in Groningen. The conclusions of the laboratory experiments can be used in the remainder of the production in Groningen, but also other areas experiencing induced seismicity, such as areas with geothermal plants or (shale-) gas fracking. The advantage of the coda for monitoring is it ability of detecting small changes before any passive system record seismicity. It can be deployed at any time in the development of a field, due to the nature of measuring the rate change in scattering with a rolling reference.

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