Damage assessment of cement-based geomaterial during loading by ultrasonic tomography

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Abstract. Damage assessment of cement-based geomaterials during loading was conducted in this work by using the through-transmission ultrasound. For this purpose a built up system of ultrasound consisting of 96 channels and the specific sensors allowing to measure at the same time three types of waves (a bulk wave and two shear waves) were used. The continuous measurements enable to assess the damage of material through the constructed image of ultrasonic velocity as well as the attenuation of each wave during loading. The difference tomography method using the differential arrival times or relative amplitudes with respect to the initial stage confirms its efficacy through this work. The results show that all three types of wave can be used to capture the progressive damage in material but the bulk wave seems to be more sensitive than the shear waves.

1. Introduction
Investigation of the damage phenomenon in geomaterial (rock, concrete, mortar) which plays an essential role on the sustainability of many structures such as buildings, tunnels, nuclear reactors or radioactive waste disposal galleries as mentioned a few is always a grand challenge not only on the theoretical aspect but also on the experimental and numerical points of view. Experimentally, this phenomenon is usually characterized in laboratory through some classical experiments like the uniaxial or triaxial compression test thanks to their possibility to reproduce the loading state that the material could be undergone during their life of service. During these tests, the specimen will be loaded monotonously or cyclically until failure while the damage can be interpreted from the result of the stress and deformation curve [1, 2]. It is widely accepted that damage in geomaterial is the consequence of the nucleation and propagation of a microcrack network which can coalesce to produce macrofracture at failure of specimen. These explanations are verified and confirmed from the observation by microscope realized on the specimen’s surface or on some cross sections obtained from the thin cuts. This efficient method owes however some disadvantages notably due to its destructive characteristic and hence less adopted in situ. Otherwise, the observation using thin cuts after loading cannot reflect exactly the process evolving during loading due to the change of sample’s statement. Recent tendency is focused on the application of the non-destructive technique as an independent method or associated with the destructive method to assess damage in geomaterial. The principal idea of these methods consists of measuring one or some physical properties (thermal or electrical conductivity, permeability, acoustic waves etc.) of material which could be sensitive with the
evolution of damage in geomaterial. Among different techniques, the measurement based on the ultrasonic wave has showed its efficacy as demonstrated in some contributions (see [1, 2] with references cited therein). A high sensitivity of ultrasonic waves with respect to the variation of the microstructure of material due to the presence of heterogeneity like inclusions, pores and eventually the evolution of the microcrack network was highlighted in these works. Particularly, by increasing the number of measure at different position on the surface of sample, the image of some acoustic parameter (velocity, attenuation) can be reconstructed through an inversion procedure. As for instance, this technique was used in [3] to image the progressive damage of granite subjected to uniaxial cyclic loading while in [4] it allows to investigate the process of shear and compaction band formation. It is noted however that in these contributions, usually only one type of wave (longitudinal or one shear wave) was chosen.

In this study, ultrasonic tomography was conducted to characterize damage in a cement-based geomaterial. By using a specific transducer which allows measuring at the same time three types of waves (a bulk wave and two shear waves), we will discuss the feasibility of this non destructive technique and also the efficacy of each type of wave to assess damage in geomaterial.

2. Experimental setup and tomographic reconstruction procedure

In this work, damage assessment by ultrasound of a cement-based geomaterials like mortar was conducted in associated with the uniaxial compression experiment. The considered material was fabricated using Portland cement CEMII 32.5 and standard sand with maximum grain size 2mm. The $40 \times 40 \times 80 \text{mm}$ specimens were produced from a mixing sand, cement and water with the ratio $s/c = 1/1$ and $w/c = 0.4$. During the axial loading, to assess the continuous process evolving in sample, the ultrasonic measurement was carried out continually thanks to a system comprising 96 channels developed by Diagnostic Sonar Ltd. This system including a generator, a group of multiplexers, preamplifiers for each channel and the card of acquisition allows recording the wave on all the receivers in a short chosen time (one second in this work). More precisely, three analogue hardware (NI-5752) 32 channel adapter modules connected with FlexRIO FPGA module to produce 96 channel 12 bit 50 MSPS acquisition module with digitally controlled swept gain. This digitizer is combined with other multi-channel preamplifier and pulser boards and three multiplexers 32 channel module. The multiplexers were used to gate the excitation 150V pulse to each of the transmitting transducer. The operation of this system ensures at a specific moment one transducer was chosen as transmitter while the remaining transducers were used as receivers. It means that any transducers in our system can be used as emitter or receiver. In this work, we decide to utilize the piezoceramic transducer (P-143.01 of PI Ceramic GmbH) with 150 kHz of central frequency. This piezoceramic transducer ($10 \text{mm} \times 10 \text{mm} \times 7 \text{mm}$ of size) composes three layers: the first layer is sensitive and can produce the longitudinal wave (qP-wave) while the second and the third layer are sensitive and can produce the shear waves (qSV and qSH waves respectively). Thus each of these sensors allows us to measure three modes of wave instead of using three separate transducers. The signals, preamplified with 30dB gain, were acquired at a sampling frequency of 50MHz with the resolution 12 bits and were stored in compressed form in the *.png file. From this database, the recorded waveforms can be extracted to realize the data processing. It is important to note also that, to maximize the acoustic contact, it requires a coupling material between the sample and sensors. During this work, honey is chosen due to its ability to support both longitudinal and shear waves. In figure 1 is captured the schema of the uniaxial compression test associated by a system of ultrasonic measurement. Twenty two acoustic sensors mounted on the surface of sample aim to image two vertical planes which pass the center vertical axis of specimen. More precisely, five sensors were glued on each lateral surface while on the top or bottom surface, only one sensor was placed due to the presence of the steel end platens. Before loading, all surface of sample were carefully prepared to ensure the good contact between sample and sensors. The measurements at the initial state were selected as standard references for successive measurements.
The data processing procedure consist of determining the time of flight (TOF) of recorded waveforms and particularly the differential traveltime for rays traversing identical paths at two states before and after loading \( \delta \tau = \tau^\sigma - \tau^{\sigma+\delta} \). In this work, these traveltimes were determined automatically. Concretely, the TOF was evaluated by using the automatic picking procedure based on the AIC method [5]. For the calculation of the relative arrival time, the recorded signals during loading were cross-correlated with those of the same raypaths measured at the initial state (referenced signals) by windowing the first portion of the arrival [6]. However, due to the fact that the accuracy of the determined TOF and differential traveltime affect importantly the result of tomographic image, potential inaccurate arrival time was checked and corrected manually during this work. Concerning the attenuation evaluation, the fast Fourier transformation was used to determine the magnitude of signals.

The travelt ime data of ultrasonic waves were used as input in the next step to reconstruct the tomographic images through an inversion procedure. In effect, these images present a set of the studied parameter (slowness, attenuation,…) which is considered to be constant in each grid cell (called pixel) of the discretized media. The principal idea of this discretization step is to replace the continuous model to the discrete model which allows establishing a system of equations for an inversion procedure. Indeed, following the well-known theory of traveltime in inhomogeneous, for a ray-path \( R_i \), the time \( \tau_i \) of wave propagating in the general media is defined as:

\[
\tau_i = \int_{R_i} \frac{1}{U} ds = \int_{R_i} V ds;
\]

(1)

where \( V \) is the slowness (inverse of the velocity \( U \)) at each location on the ray-path and \( ds \) is the incremental length along the ray-path \( R_i \).

Using the discretization step, the integral of travelt ime along a ray-path, measured by each pair of emitting and receiving transducers, can be reduced to the sum of the travelt ime within each grid cell through which the ray pass. Thus we can rewrite the equation (1) as:

\[
\tau_i = \sum_j \tau_{ij} = \sum_j R_{ij} V_j;
\]

(2)

where \( R_{ij} \) is the ray length of the \( i \) th ray in the \( j \) th cell, with slowness \( V_j \).
Similarly, if the interest focuses on the tomographic image of the slowness variation with respect to the initial state \( \delta V = V^\sigma - V^{\sigma=0} \), from the equation (2), we have these following expressions:
\[
\delta \tau = \sum_j \delta \tau_j = \sum_j R_{ij} \delta V_j; \tag{3}
\]
This equation was deduced by ignoring the influence of the ray-path perturbation, thus the different traveltimes is considered as a function of slowness variation (the perturbation theory as defined in [7]). Gathering the result obtained from all ray-path yields the following system of equations:
\[
t = L \chi; \tag{4}
\]
where \( t \) denotes the data vector representing the measured traveltimes (or the relative traveltimes), \( \chi \) defines the vector containing the unknown parameter of each grid cell and the matrix \( L \) is function of the ray-path segment \( R_{ij} \).

The inversion procedure consists to calculate the solution \( \chi \) of this system of equations which minimizes the error between the data, \( t \), and the theoretical traveltimes given by \( L \chi \). In general the matrix \( L \) (of size \( M \times N \)) is not square due to the fact that in most case there are many more data than unknowns (\( M>N \)). Otherwise this system of equations can be non-linear due to the dependence of matrix \( L \) on the model parameter. It is usually the case even in the isotropic media where the contrast of the model parameter of grid cells is high and hence the ray-path of each source-receiver can take the curve form instead of the straight ray. The methodology to reconstruct the ray propagating in media called ray-tracing method has been extensively discussed in the literature [8]. All the strategies based on the Fermat’s principle in which the traveltime from a source to a receiver must be the minima over all the possible ray-paths.

Consequently, the solution of the nonlinear system of equations (4) can be obtained through an iterative procedure:
\[
\chi_{k+1} = \chi_k + (J^T J + \lambda I)^{-1} J^T (t - L \chi_k); \tag{5}
\]
where \( J \) is the sensitivity (Jacobien) matrix representing the derivative of the theoretical traveltime with respect to the unknown parameter \( \chi \). Further, in equation (5) because the inverse problem is ill-posed, a small positive damping parameter \( \lambda \) (\( \lambda \in 0.001 \sim 10 \)) is introduced with \( I \) the identity matrix. The procedure is repeated until the convergence is reached.

Note that in this work, we suppose that the initial media is isotropic and homogeneous and hence we can use the straight ray hypothesis between each pair source-receiver to reconstruct the tomography. The same procedure can be used to construct the tomography of the attenuation due to its similarity from mathematical point of view. Indeed, the attenuation phenomenon is characterized by the attenuation coefficient \( \alpha \) which represents the relationship of the amplitude measured at the receiver \( A_i \) decayed exponentially with respect to the amplitude at the source \( A_0 \) and the distance of the raypath \( l_R \) as follow:
\[
A_i = \frac{1}{l_R} A_0 \exp(-\int_{l_R} \alpha ds); \tag{6}
\]
This equation (6) can be written in a similar form of equation (1) as:
\[
\tau_i = \int_{l_R} \alpha ds; \tag{7}
\]
where \( \tau_i = \ln(A_i) - \ln(A_0 l_R) \).

By applying the perturbation theory in equation (7), we can obtain without difficulty the following expression which has the analogue form as equation (3):
\[
\delta \tau = \sum_j \delta \tau_j = \sum_j R_{ij} \delta \alpha_j; \tag{8}
\]
where the amplitude difference of a ray-path \( \delta r_i = \ln(A_i^{\sigma=0}) - \ln(A_i^\sigma) \) is function of relative variation of the attenuation coefficient \( \delta \alpha = \alpha^\sigma - \alpha^{\sigma=0} \).

3. Result and discussions

As mentioned previously, the tomography can be presented in two forms: the first form image the absolute value of the studied parameter while the second form aims to capture the difference tomography with respect to the referenced state. In this study, the authors used the difference data (of slowness and attenuation coefficient) versus the initial state so that the evolution damage during loading could be observed.

We presented in figure 2 tomographic images constructed from the slowness difference of longitudinal wave measured at different loading stages. These tomograms show that even at low stress (about 20% of maximum stress at failure), a microfracture appears at the left high corner of sample where the slowness difference increases (velocity decreases correspondingly). This damaged zone becomes visible from 40% of maximum loading stage represented by a considerable increase of slowness difference. Moreover, this latter parameter changes significantly in the loading range from 40% to 80% of peak stress. Beyond this latter stage load, the maximum value of slowness difference increases slightly but the extension of damaged zone becomes remarkable. Particularly, when the stress approaches the material’s strength, the results show that a fracture ranging from the left high corner to the right bottom corner was created in the sample.

![Figure 2. Slowness difference tomography (s/\mu m) of longitudinal wave at different stages of loading with respect to the initial state.](image)

The same remarks can be noted for the images obtained from the shear wave as illustrated in figure 3. However, more artefacts were observed in these images in comparison with the tomograms of bulk wave and the damaged zone may be distinguished only from the loading stage corresponding to 60% of stress at failure. The results obtained at different stages of loading are less consistent than those of
longitudinal wave. In effect, taking insight the waveform of bulk and shear waves recorded during loading, we observed more noise and eventually greater reduction of amplitude in the shear wave represented by smaller signal to noise ratio in comparison with one of the bulk wave.

![Figure 3](image.png)

**Figure 3.** Slowness difference tomography \( (s / \mu m) \) of shear wave at different stages of loading with respect to the initial state.

In figures 4 and 5, we presented images of the attenuation difference of bulk and shear waves during loading of sample. In this case, no significant difference between bulk and shear waves can be observed but higher value of the relative attenuation coefficient was noted for the shear wave. As in the previous study case of slowness difference, a weakened zone on the left of the top surface of sample begins to develop at the loading stage \( \sigma / \sigma_{\text{max}} = 40\% \) illustrated by a sharply increased value of relative attenuation coefficient. This zone tends to extend toward the bottom surface near the right corner and accelerate when the stress pass 80\% maximum stress. At failure, the results showed a fracture created with an inclined angle with the axial axis of specimen. This type of failure is usually observed in uniaxially loaded samples and the damage phenomena is known as consequence of the nucleation, propagation of microcracks which coalesce at high density to create a fracture. The position of the damaged zone observed from the reconstructed images of the slowness and attenuation difference agree quite well with the real fracture created in sample as captured in figure 6. A small offset of the damaged zone from the real position in space can be explained by the potential artefacts included by the tomography technique.
Figure 4. Relative attenuation coefficient ($dB/m$) tomography of longitudinal wave at different stages of loading with respect to the initial state.

Figure 5. Relative attenuation coefficient ($dB/m$) tomography of shear wave at different stages of loading with respect to the initial state.
4. Conclusions
In this work, we present an application of the non-destructive method like ultrasound to assess the damage during loading of the cement-based geomaterial. Using a system consists of 96 channels with the specific piezoceramic transducer, we can capture the tomographic image of all types of waves and hence the continuous process evolving in the uniaxially loaded sample. The quite good agreement between the reconstructed tomograms and the visible fractured specimen after failure confirms the accuracy of the utilized inversion procedure and the efficacy of the ultrasound method to assess damage in geomaterial. However, the slowness tomography of longitudinal wave presents a clearer image with respect to the shear waves. Contrary, the tomograms of relative attenuation seem more stable with no significant difference for all types of wave. The question concerning the presence of artefacts particularly in the slowness images of the shear waves require more investigation notably to find a more robust arrival picking. Otherwise, the combination of the longitudinal and shear wave data could provide a complete answer of damage process in material and will be discussed in our near future work.

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