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# **Statistical analyses of pressure signals, hydrogeologic characterization and evolution of *Excavation Damaged Zone* (claystone sites of Mont Terri and Tournemire)**

**Hassane FATMI<sup>1</sup>, Rachid ABABOU<sup>1</sup>, Jean-Michel MATRAY<sup>2</sup>,  
Christophe NUSSBAUM<sup>3</sup>**

<sup>1</sup> IMFT - Institut de Mécanique des Fluides de Toulouse,  
1 Allée du Professeur Camille Soula, 31400 Toulouse, France  
ababou@imft.fr; hassane.fatmi@hotmail.fr

<sup>2</sup> IRSN - Institut de Radioprotection et de Sécurité Nucléaire,  
Av. du Général Leclerc BP 17, 92262 Fontenay-aux-Roses, France  
jean-michel.matray@irsn.fr

<sup>3</sup> SwissTopo & Mont Terri Consortium,  
Fabrique de Chaux 65, 2882 St-Ursanne, Switzerland  
christophe.nussbaum@swisstopo.ch

**Keywords:** Signal processing and analysis; wavelets; correlation functions; Fourier spectrum; random process; statistical envelope; hydrogeology; claystone; specific storativity; porosity; compressibility; excavation; EDZ

**Abstract.** *We present statistical analyses of pore pressure and other signals, aimed at characterizing the properties of a geologic porous medium and, particularly, of the Excavation Damaged Zone ("EDZ") around underground galleries. The purpose is not only to identify the material properties, but also to quantify their evolution during excavation (creation of an EDZ). The methods are applied to two Underground Research Laboratories ("URL's") in claystone sites: Mont Terri in Switzerland (gallery Ga98) and Tournemire in France (gallery Ga03). This work is part of the LP 14 experiment, an international research program of the Mont Terri Consortium, aimed at assessing the isolation properties of claystone as a potential geologic repository for radioactive waste (LP 14 experiment: Long term Pressure experiment, phase 14).*

# 1 Introduction and objectives

We present methods for statistical analysis and hydrogeological interpretation of pressure signals in claystone formations. The purpose is to characterize the hydromechanical behaviour of the formation, and to study the evolution of its EDZ (Excavation Damaged Zone) during the excavation of galleries. We focus on galleries Ga98 and Ga03 in the sites of Mont Terri (Jura, Switzerland) and Tournemire (France, Aveyron), through data collected in the BPP-1 and PH2 boreholes, respectively. This work is part of ongoing studies on the isolation properties of deep claystone repositories for Mid-Level/High-Level and Long-Lived radioactive wastes.

The Mont Terri site, crossing the Aalenian Opalinus claystone, is an underground laboratory managed by an international consortium, namely the Mont Terri project (Switzerland). The Tournemire site, crossing the Toarcian claystone, is an Underground Research facility managed by IRSN (France).

We have analysed porewater and atmospheric pressure signals at these sites, sometimes in correlation with other data. The methods of analysis are based on the theory of stationary random signals (correlation functions, Fourier spectra, transfer functions, envelopes), and on multiresolution wavelet analysis (adapted to nonstationary and evolutionary signals). These methods are also combined with filtering techniques, and they can be used for single signals as well as pairs of signals (cross-analyses).

The objective of this work is to exploit pressure measurements in selected boreholes from the two compacted clay sites, in order to (i) evaluate phenomena affecting the measurements (earth tides, barometric pressures, etc.); (ii) to estimate some properties of the geologic formation (specific storativity, dynamic porosity) prior to excavation, and to compare them with those estimated by pulse or slug tests on shorter time scales; and finally (iii) to analyze the effects of drift excavation on pore pressures before, during, and after excavation.

## 2 Methods (overview)

To achieve the above objectives, we have analyzed atmospheric and pore pressure signals using various types of statistical methods, listed below<sup>1</sup>:

1. Auto-correlation function versus lag time, cross-correlation between two signals, and their input/output transfer functions (deconvolution).
2. Estimation of Fourier spectrum of each signal, and cross-spectral analyses (barometric effect in frequency space, *via* spectral gain of atmospheric/relative pore pressures).
3. Alternative cross-correlation analyses of porewater versus atmospheric pressure (Atmospheric Correction Factor, residual pore pressure, re-interpretation of barometric effect).

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<sup>1</sup> All methods were developed and implemented by the authors as custom-made MATLAB TOOLBOXES

4. Multi-resolution wavelet analysis (wavelet approximation and residual, selection of components at specified scales, cross-component analyses).
5. Statistical envelope of signals computed with Hilbert transform (Cramer-Leadbetter envelope); application: evolution of EDZ during excavation.

Before these methods can be implemented, it is necessary to first pre-process the raw signals obtained from data acquisition devices. In this work, the raw signals were pre-processed using a number of techniques, aimed at homogenizing irregular time steps, detecting outliers, and/or reconstructing missing data.<sup>2</sup> Furthermore, some of the methods enumerated just above also needed to be pre-calibrated or tested (e.g., cut-off parameters for spectral estimation filters). For all these reasons, a number of tests were developed to validate and illustrate the various processing tools (e.g. testing statistical envelopes for synthetic signals, or comparing Fourier/Wavelet decompositions).

### 3 Hydrogeologic characterization via barometric and earth tide effects (effective dynamic porosity and specific storativity)

The pressure signals were interpreted hydromechanically, in terms of compressibility effects, in order to assess the hydrogeologic characteristics of the claystone. In particular, the statistical analyses of atmospheric and pore pressures allowed us to detect and to characterize:

1. at diurnal time scales, the relationship between piezometric and atmospheric pressure (barometric efficiency in frequency space); and
2. at semi-diurnal time scales, the statistical influence of earth tides, identified with multi-resolution wavelets (whence specific storativity).

For the sake of brevity, we only summarize some of the results obtained from long term pressure signal analyses at Mont Terri's gallery Ga98 (PP1 and PP2). The effective dynamic porosity  $\Phi$  (in response to compressibility effects) was found to be quite low, on the order of 1% or even less on average (however, it peaks at 4% during the post-excavation phase). The effective specific storativity ( $S_S$ ) was found to be approximately  $3E - 07m^{-1}$  on average (except during excavation). These average values correspond to long term pressure signal analyses at the scale of several years (April 1997 – April 2005). The next section analyses in more detail, and on shorter time scales, the response to excavation (*pre-*, *syn-*, and *post-excavation* phases).

### 4 Excavation effects: evolution of pore pressure and storativity

We now focus on the time evolution of pressure signals during the passage of the excavation front, and on the inferred evolution of claystone properties

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<sup>2</sup>Fatmi H., R. Ababou, J.-M. Matray (2008): "Statistical pre-processing and analyses of hydrogeo-meteorological time series in a geologic clay site (methodology and first results for Mont Terri's PP experiment)". *Physics and Chemistry of the Earth: Special Issue on Clays in Natural & Engineered Barriers for Radioactive Waste Confinement (Internat. Conf. CLAY'2007, Lille, France) 33(2008) S14-S23.*

(such as  $S_S$ ) in the EDZ of gallery Ga98 at Mont Terri.<sup>3</sup>

Figure 1(a) presents a comparison plot of two time evolutions, namely: the absolute pore pressure  $P(t)$  measured in chamber PP1, and the distance  $D(t)$  between pressure chamber PP1 and the excavation front of gallery Ga98. Note that the smallest distance is 4 m, attained on the 4th of March 1998 (excavation works stopped for a few weeks after that). The pressure signal clearly indicates the emergence of a damaged zone (EDZ) as the excavation front approaches near the pressure sensor. The sharp rise of pore pressure coincides with the *syn-excavation* phase, which lasts about 11 days.

Figure 1(b) shows the resulting evolution of the specific storativity  $S_S(t)$  as a function of time, superimposed on the excavation distance  $D(t)$ . Specific storativity  $S_S(t)$  was obtained from multiresolution wavelet analysis (identification of the semi-diurnal "earth tide component" of the pressure signal); in addition, in order to better capture the fine evolution of  $S_S(t)$  during excavation, statistical envelope analysis was applied using the Hilbert Transform. There is clearly a sharp decrease of  $S_S(t)$  by 1 to 2 orders of magnitudes, for a few days, as the excavation front gets close to the pressure sensor (about 6 m).

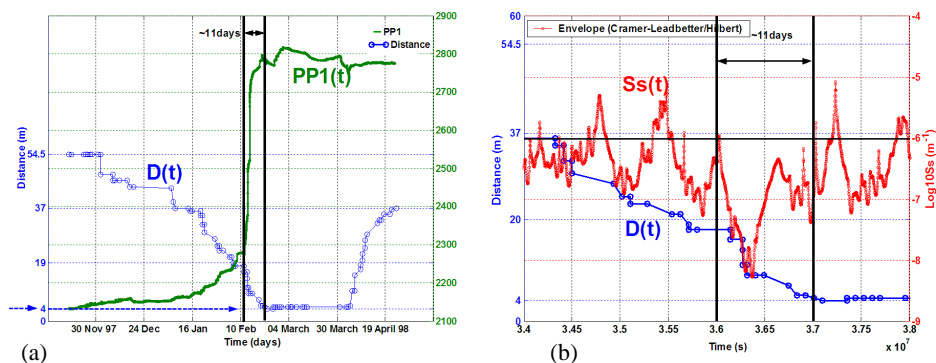


Figure 1: Effects of gallery excavation on pore pressure, and on specific storativity, at Mont Terri gallery Ga98. (a) Evolution of absolute pore pressure  $P(t)$  measured in chamber PP1 of borehole B-PP1, and distance  $D(t)$  between chamber PP1 and the moving excavation front. (b) Evolution of  $D(t)$  and evolution of specific storativity  $S_S(t)$  inferred from pressure signal analyses during excavation ( $S_S(t)$  is in  $m^{-1}$  units, and it is shown here on a log-scale).

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<sup>3</sup>For details, the reader may consult the following Ph.D. thesis (freely available on line): *Fatmi H. (2009), "Méthodologie d'analyse des signaux et caractérisation hydrogéologique: Application aux chroniques de données obtenues aux laboratoires souterrains du Mont Terri, Tournemire et Meuse/Haute-Marne". Doctoral thesis, Institut National Polytechnique de Toulouse, France, June 2009, 248 pp.*