Vietnam Journal of Mechanics, VAST, Vol. 31, No. 3 &4 (2009), pp. 159 – 165

# UNSTABLE BEHAVIOUR OF ROCKS

**Luong Minh Phong**
*CNRS-LMS, Ecole Polytechnique, Palaiseau France*

**Abstract.** This paper aims to introduce a new non-destructive testing technique in use for detecting the occurrence of material instability and a specific data reduction procedure to access damage accumulation. An input-output non-parametric procedure based on ultrasonic pulse propagation, and a non-linear analyser were chosen to portray the unstable behaviour of brittle rock material under static compressive loading. It can be used to monitor non-destructively and continuously the overall alteration or damage process so that damage mechanisms could be quantitatively estimated by a dimensionless parameter the so-called non-linearity ratio.

## 1. INTRODUCTION

In recent years, there has been an increased need for the non-destructive evaluation and testing for civil engineering projects, particularly interesting in inspection and monitoring of geotechnical structures. With the wide application of digital signal processing techniques, the acoustic emission AE and ultrasonic waves are used to evaluate the alteration state or the mechanical performance of a material.

The ultrasonic wave properties are measured during propagation through rocks to find out their mechanical properties. Several authors (Lockner *et al.,* 1977; Sobolev *et al.*, 1978) have reported that cracking noise occurred at about 60% to 99% of the ultimate load. It was recognised that these significant changes in rock mechanical behaviour are caused by micro-cracking. Laboratory measurements, indeed sensitive to the presence of existing micro-cracks in rock specimens, detect the failure process, only at the start of dilatancy (unstable cracking) or coalescence appearance. The early beginning of cracking (phase 3 of Bieniawski's model (1967a): stable cracking) cannot be determined by the velocities (Couvreur *et al.*, 1998). Modification of waveform during propagation through the material is a measure of the non-elastic components of deformation (Bourbié *et al.*, 1987). Attenuation may therefore be more sensitive than velocity to defects, but it is more complex to analyse (Lockner *et al.,* 1977).

This paper introduces a non-destructive technique based on ultrasound propagation characteristics to detect material instability occurred in brittle rocks. A special testing technique was used to detect the occurrence of non-linear characteristics of ultrasound propagation. An input-output non-parametric procedure based on ultrasonic pulse propagation and a non-linear analyser for data reduction analysis were chosen to portray the unstable behaviour of a specimen subjected to increasing static compressive loads. Based on a multidimensional Fourier transform, the non-linear analyser permits to separate linear and non-linear parts and to monitor non-destructively and continuously the overall alteration or damage process of brittle rock so that damage mechanisms could be quantitatively estimated by a dimensionless parameter the so-called non-linearity ratio.

## 2. TESTING METHOD

The salient feature of rock behaviour originates from their internal micro-cracking, announcing subsequent failure. This feature is advantageously exploited in this ultrasonic non-destructive evaluation, relying on the mechanism of ultrasound propagation through rock materials.

Techniques using ultrasonic waves are especially appealing because of the direct connection between the characteristics of the wave propagation and the damage states of a solid (Achenbach, 1990). The present analysis only considers, in the framework of small perturbations, the propagation mechanism of a small wave through an elastic plastic solid presenting locally an unstable behaviour.

Within the theory of plasticity, several postulates that guarantee the mechanical stability of frictional materials have been suggested based on either energy or wave propagation considerations. Mechanical stability is taken as the capability of geomaterials to sustain a given stress state. For a non-associated plastic flow rule, localisation can also appear during hardening. This type of instability, referred to as pre-failure flow instability. Note the instability of a material can occur when the propagation of a small perturbation in the form of stress wave in a certain direction is impossible (Mandel, 1964). Based on the assumption that a stable material is able to propagate a small perturbation in the form of wave, Mandel proposed a necessary and sufficient condition for stability. He showed that a wave propagates in a material with an elastic plastic matrix A, along the direction $\alpha$, if and only if all the eigenvalues $\lambda$ of the matrix B are real and positive. This phenomenon is used as a highly sensitive manifestation of geomaterial instability (Luong, 1993, Luong, 2001 and Luong *et al.*, 2007).

Volterra analysis is used here to deal with unknown non-linear systems. Although attempts have been made to identify the governing equation of SDOF systems (Marmarelis, 1989), it is more usual to identify high order transfer functions characterising the non-linear behaviour of the mechanical system. The system dynamic response $y(t)$ as a function of excitation $x(t)$can be expanded in a Volterra series in the following way (Thomas, 1995):

$$y\left(t\right)=\sum_{i=1}^{\infty}y_i\left(t\right)=\sum_{i=1}^{\infty}\int\limits_{-\infty}^{+\infty}...\int\limits_{-\infty}^{+\infty}h_i\left(\tau_1,...,\tau_i\right)\prod_{k=1}^{i}a\delta\left(t-T-\tau_k\right)d\tau_k \tag{1}$$

These series result from the summation of multidimensional convolution products between excitation and Volterra kernels $h_i(\tau_1,\dots\tau_i)$. The terms $y_1$ of the series correspond to the linear component of the response, whereas the other terms correspond to the non-linear components (Vinh and Tomlinson, 1990; Liu and Vinh, 1991). Working out the Volterra kernels allows the characterisation of the system by separating linear and non-linear parts of the dynamic response. Activation of non-linear phenomena gives rise to non-zero values in these high order kernels. For a non-linear system, appearance of a supplementary non-linearity (such as instability, micro-cracking, damage, etc.) increases the amplitude of original high order kernels. The proposed method aims to evaluate the significance of non-linear terms in the global response. If these non-linear aspects exhibit a sudden increase, it will be associated to the occurrence of material instability causing additional non-linear behaviour.

The determination of kernels gives access to the different terms of the series, and to their energies. The energy ${}_lE_m^i$ of the $i^{th}$ component of ${}_ly_i(t)$ for the $m^{th}$ excitation the form:

$$ {}_lE_m^i = \int_0^\infty {}_ly_i^{(m)}(t)^2\,dt \tag{2} $$

To quantify the non-linear contributions in the global response, ${}_lr_m$ the non-linearity ratio at point $l$ for the $m^{th}$ excitation is defined as follows:

$$ {}_lr_m = \frac{\sum_{i=2}^{N} {}_lE_m^i}{\sum_{i=1}^{N} {}_lE_m^i} = \frac{non-linear\ \ energy}{total\ \ energy} \tag{3} $$

According to Eq. (2), Volterra kernels can be introduced in the former equation. The non-linearity ratio is then written as:

$$ {}_lr_m = \frac{a_m^4{}_l\eta_2 + \ldots + a_m^{2N}{}_l\eta_N}{a_m^2{}_l\eta_1 + a_m^4{}_l\eta_2 + \ldots + a_m^{2N}{}_l\eta_N} \text{ with } {}_l\eta_i = \int_0^\infty {}_lh_i(t)^2\,dt \tag{4} $$

This function expresses the energetic part of non-linear components in the system response to an impulse excitation of magnitude $a$.

## 3. EXPERIMENTAL RESULTS

The proposed technique has been applied in laboratory on two different specimens of Vosges sandstone subjected to increasing levels of static compressive loading. This rock type was selected because it is homogeneous, weak, brittle, dilatant and not clayey. Such properties are definitely favorable in the framework of the research. The pulse transmission

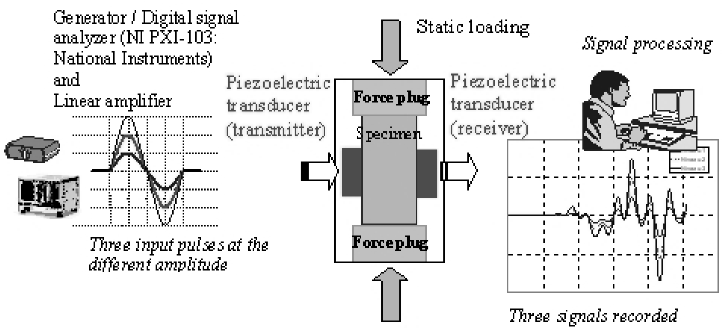
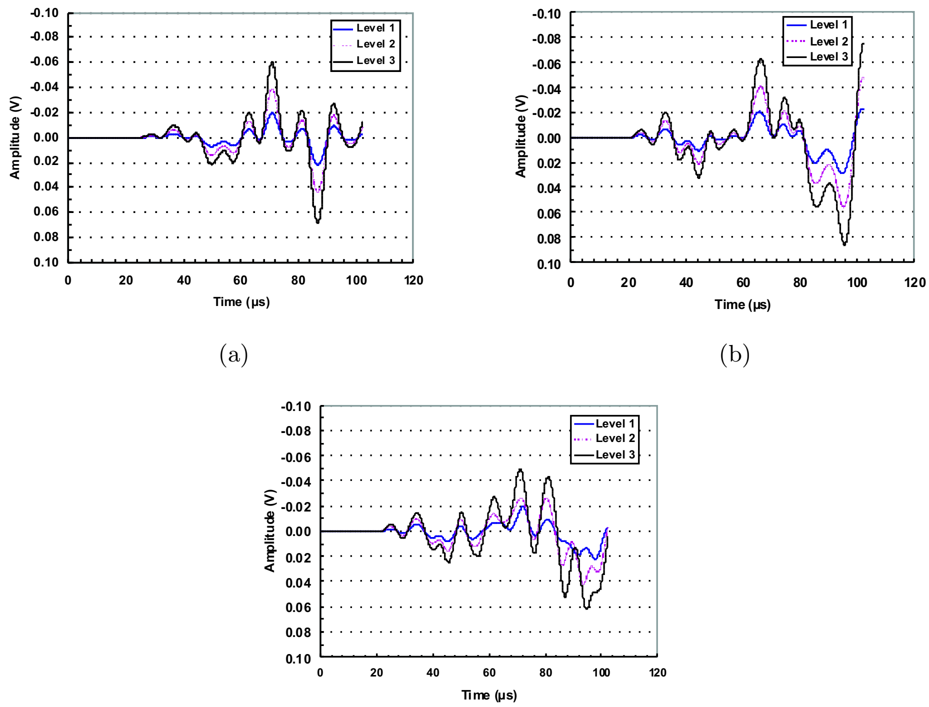



*Fig. 1.* Experimental device of the ultrasound propagation and signal processing



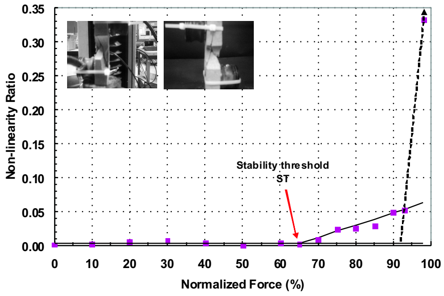

(a) (b)

(c)

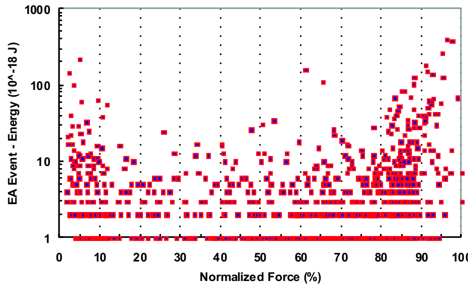
*Fig. 2.* Wave amplitude (volts) versus time (sec) of the three proportional: 2a) input ultrasonic pulses, 2b) and 2c) output ultrasonic pulses before the stability threshold and after the stability threshold

technique, using scan piezoelectric transducers V150 (100 KHz) and S140B (20 KHz), has been applied as a non-destructive testing. A coupling agent was used to improve the wave transmissibility through the interface between the transducers and the rock specimen. The pulse generator section produces an electrical pulse to excite a piezoelectric transducer, which emits an ultrasonic pulse. The pulse travels through the loaded specimen, to a second transducer acting as a receiver (Figure 1). The transducer converts the pulse into an electric signal that makes available for non-linear analysis. Three input pulses were used at three proportional amplitudes (Figure 2a). Response signal records at different static loads have indicated the evolution of the ultrasonic pulse travelling through the specimen that is subjected to increasing static compressive loads (Figures 2b and 2c). The experimental set-up continuously monitored the applied load, the axial and radial strains and the signals of ultrasonic waves.

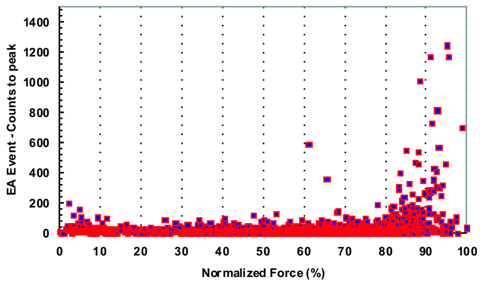
The data processing technique provides the variation of non-linear energy normalised by the total energy and non-linearity contrast as a function of stress levels (Figures 3a and 4). They have evidenced a material stability threshold "ST" that precedes significantly the occurrence of crack initiation so that either load-controlled or displacement controlled tests




(a) ST stability threshold




(b) AE energy




(c) AE counts to peak

*Fig. 3.* Graphical definition of the stability threshold ST (3a) and Distribution of localised AE events (3b,c) for sandstone $S_A$ (unit weight : 26.16 kN/m$^3$, porosity 17.5%, unconfined compressive strength : 38 MPa) subject to increasing compression loading

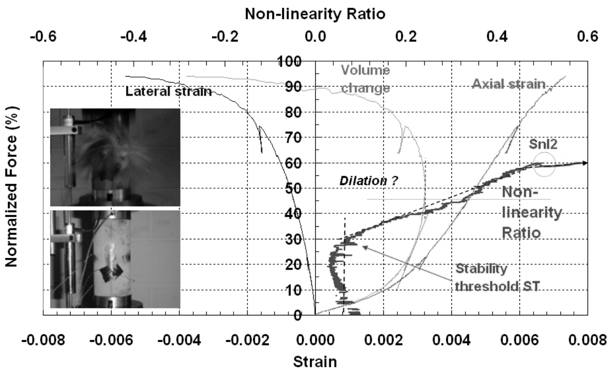



*Fig. 4.* Graphical definition of the stability threshold ST for sandstone $S_B$ (unit weight = 26.24 kN/m$^3$, porosity = 13.7%, unconfined compressive strength = 54 MPa) subject to increasing compression loading

can be used. The slope change of the non-linearity ratio suggests that the quasi-brittle rock specimen presents two quite different behaviours: the former is quasi elastic and stable, the latter may lead to a sudden failure (in stress-controlled condition) caused by the extension of the unstable zone that generates non-linear effects affecting the ultrasonic wave propagation mechanisms.

The acoustic emission AE is represented by points in Figures 3b and 3c. The gradual acceleration of acoustic emission AE nearly from the very beginning of loading was observed. The results also show that the lack of significant AE activity in the initial stages of loading makes it more difficult to detect the occurrence of crack initiation (ST). However, the unstable crack threshold (dilatancy threshold, Snl2) could be readily determined during the compression loading.

## 4. CONCLUSION

This highly sensitive detection technique of material instability could provide a very useful early warning for the security of work at high risk for environment.

This non-destructive evaluation of material instability could offer an efficient field monitoring before failure initiation in order to reduce risk of imminent failures by giving advanced and sufficient warning for remedial measures to be designed. The application of ultrasound scanning to inspection and monitoring of underground geotechnical structures relies on the fact that during the process of micro-cracking, the rock material may be locally unstable and hence modifies and partially obstructs the propagation characteristics of ultrasound pulses. One of the advantages of using NL monitoring technique is the possibility to observe damage processes during the entire loading history without any disturbance to the structures. Measurement can be performed from remote locations, adding another distinct advantage

## REFERENCES

[1] Achenbach J. D., *From ultrasonics to failure prevention, Elastic waves and ultrasonic nondestructive evaluation*, edited by Datta S.K. et al., North-Holland, Amsterd, 1990.

[2] Bieniawski Z. T., Stability concept of brittle fracture propagation in rock, *Engineering Geology* **2** (1967a) 149-162.

[3] Bieniawski Z.T., Mechanism of brittle rock fracture. Part II. Experimental studies, *Int. J. Rock Mech. and Min. Sci. & Geomech. Abstr.* **4** (1967b) (4) 407-423.

[4] Bourbié T., Coussy O. and Zinszner B., *Acoustics of porous media*, Paris, Technip, 1987.

[5] Couvreur J. F., Thimus J. F., Vervoort A. and King M. S., *Damage process of sedimentary rocks: Advanced processing of ultrasonic waves*, edited by Yunmei Lin., Advances in Rock Mechanics, World Scientific Publishing Co. pp. 59-66, 1998.

[6] Eberhardt E., Stead D., Stimpson B. and Read R. S., Identifying crack initiation and propagation thresholds in brittle rock, *Can. Geotech. J.* **25** (1998) (2) 222-233.

[7] Liu H. and Vinh T., Multidimensional signal processing for nonlinear structural dynamics, *Mechanical system and signals processing* **5** (1991) (1) 61-80.

[8] Lockner D. A., Walsh J. B. and Byerlee J. D., Changes in seismic velocity and attenuation during deformation of granite, *J. Geophys. Res.* **82** (1977) 5374-5378.

[9] Luong M.P., Infrared thermographic observations of rock failure, *Comprehensive Rock Engineering – Principles, Practices & Projects*, ed. by Hudson, J.A., Pergamon Press, Vol.4(26), pp. 715-730, 1992.

[10] Luong M. P., Ultrasound propagation in nonlinear microcracked medium, *Micromechanics of concrete and cementitious composites*, Presses Polytechniques et Universitaires Romandes, Lausanne, CH, pp. 105-116, 1993.
[11] Luong M. P., Non-destructive evaluation of the stability threshold of geomaterials, *Topics on Nondestructive Evaluation Series*, ASNT, ISBN 1-57117-091-X, Vol.6, pp. 257-262, 2001..
[12] Luong M.P., Non-destructive evaluation of the stable behavior of a quasi brittle sandstone, *Proc. $11^{th}$ Congress of the International Society for Rock Mechanics*, Taylor & Francis Group, London, ISBN 978-0-415-45084-3, pp. 365-368, 2007.
[13] Marmarelis V.Z., Identification and modeling of a class of nonlinear system, *Mathematical and Computer Modeling* **12** (1989) (8) 991-995.
[14] Prikryl R., Lokajicek T., Li C. and Rudajev V., Acoustic emission characteristics and failure of uniaxially stressed granitic rocks: the effect of rock fabric, *Rock Mech. Rock Engng* **36** (2003) (4) 255-270.
[15] Sobolev, G., Spetzler, H. and Salov, B., Precursors to failure in rocks while undergoing anelastic deformations, *J. Geophys. Research* **83** (1978) 269-274.
[16] Thomas J.J., Contrôle non destructif des matériaux et des structures par analyse dynamique non linéaire, *Thèse de Doctorat*, Ecole Polytechnique, Palaiseau, France, 1995.
[17] Vinh, T. and Tomlinson, G., Dynamique des systèmes non linéaires, *Séminaire de perfectionnement*, ISMCM, Saint Ouen, tome III, 1990.

*Received October 2, 2009*

## ỨNG XỬ KHÔNG ỔN ĐỊNH CỦA ĐÁ

Bài nghiên cứu này muốn giới thiệu một kỹ thuật mới dùng để phát hiện sự không ổn của chất liệu và một cách cụ thể để truy cập các thiệt hại tích lũy. Một thủ tục "đầu vào-đầu ra" không tham số dựa vào cách siêu âm truyền lan, và một thủ tục phân tích tài liệu không ổn đã được chọn để phát hiện việc không ổn của chất liệu đá cứng giòn dưới tải tĩnh nén. Nó có thể được sử dụng để theo dõi một cách không phá hủy và liên tục quá trình thiệt hại để có thể lượng ước cơ chế thiệt hại bởi một số gọi là tỷ số phi tuyến.