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# EXAMPLE OF IDENTIFICATION OF THE IN SITU SOIL BEHAVIOUR UNDER MAJOR EARTHQUAKES BY A PROPAGATION S.H.S. TEST

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## SUMMARY

The determination of the in situ behaviour of a soil under large strains, as encountered in major earthquakes, requires firstly an adapted instrumentation; for this purpose the Seismic Harmonic System (S.H.S.) equipment is under development by Electricité de France (E.D.F.). It requires then a behaviour law adapted to very large strains; for this purpose a 3-parameters law has been recently proposed by Jouanna & Mabssout for extending the classical Hardin-Drnevich-Masing's hysteretic law to high shear strains. Finally an interpretation method is necessary for identifying soil parameters by an inverse process.

The present communication illustrates these three steps on a case study. After a presentation in section 1, the S.H.S. equipment, able to create harmonic displacements reproducing major seismic effects in the vicinity of a borehole, is presented in section 2. The modified 3-parameters behaviour law is presented in section 3 and applied to a propagation test between the well and a point at some distance of the well. The identification of the behaviour law parameters by an inverse process is then described in section 4, based on the comparison between the acceleration measured at some distance of the well and the harmonic displacement created at the well. The interpretation of such a propagation test, performed in a silty and clayey soil using the Seismic Harmonic System, leads to the values of the three soil parameters. In conclusion the importance of in situ and high strain tests is underlined in order to obtain the dynamic behaviour of a soil under major earthquakes.


## INTRODUCTION

The present paper illustrates the determination of the dynamic behaviour of in situ soils under large strains, equivalent to major earthquakes. The Seismic Harmonic System (S.H.S.) equipment, able to create harmonic displacements reproducing seismic effects in the vicinity of a borehole, is presented in section 2. Modelling a propagation test around the well is then presented in section 3, using a 3-parameters behaviour law able to simulate the soil behaviour up to the largest seismic shear strains. The interpretation of such a propagation test performed in a silty and clayey soil using the Seismic Harmonic System is then given in section 4, leading to the identification of the three parameters (Go, $\alpha$, $\beta$) of the in situ behaviour law. In conclusion the importance of in situ and high strain tests is underlined, in order to obtain the dynamic behaviour of a soil under major earthquakes.


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## 2. PRINCIPLE OF THE S.H.S EQUIPMENT AND EXPERIMENTAL DATA

### 2.1 Principle of the S.H.S equipment

The S.H.S. equipment [Jouanna & Montiel, 1988; Touret & al., 1992] consists in placing in a bore-hole a special casing moved by a down-the-hole probe which can transmit to the soil an alternative vertical vibration with a 1 Hz to 30 Hz fundamental frequency and which creates large vertical shear strains within the soil in the vicinity of the well. The diameter of the well is 100 mm in a preliminay prototype version and 160 mm in the industrial version. Tests performed with the preliminary equipment are illustrated in Figure 1. The displacement, acceleration and excitation force can be recorded on the excitation device placed in the well. Moreover, at the shallow depth, acceleration and temperature variations can be measured within the soil at some distance from the well by sensors placed in small holes drilled from the surface.

The cyclic vertical displacement at the well wall (point A) being the input, three types of outputs can be considered for obtaining information on the soil behaviour:

- In transmission tests, the output is the vertical acceleration recorded around the well (points B, C, etc.).
- In transfer function tests, the output is the vertical cyclic force applied on the excitation device.
- In thermal tests, the output is the temperature elevation recorded in the vicinity of the well during vibration.

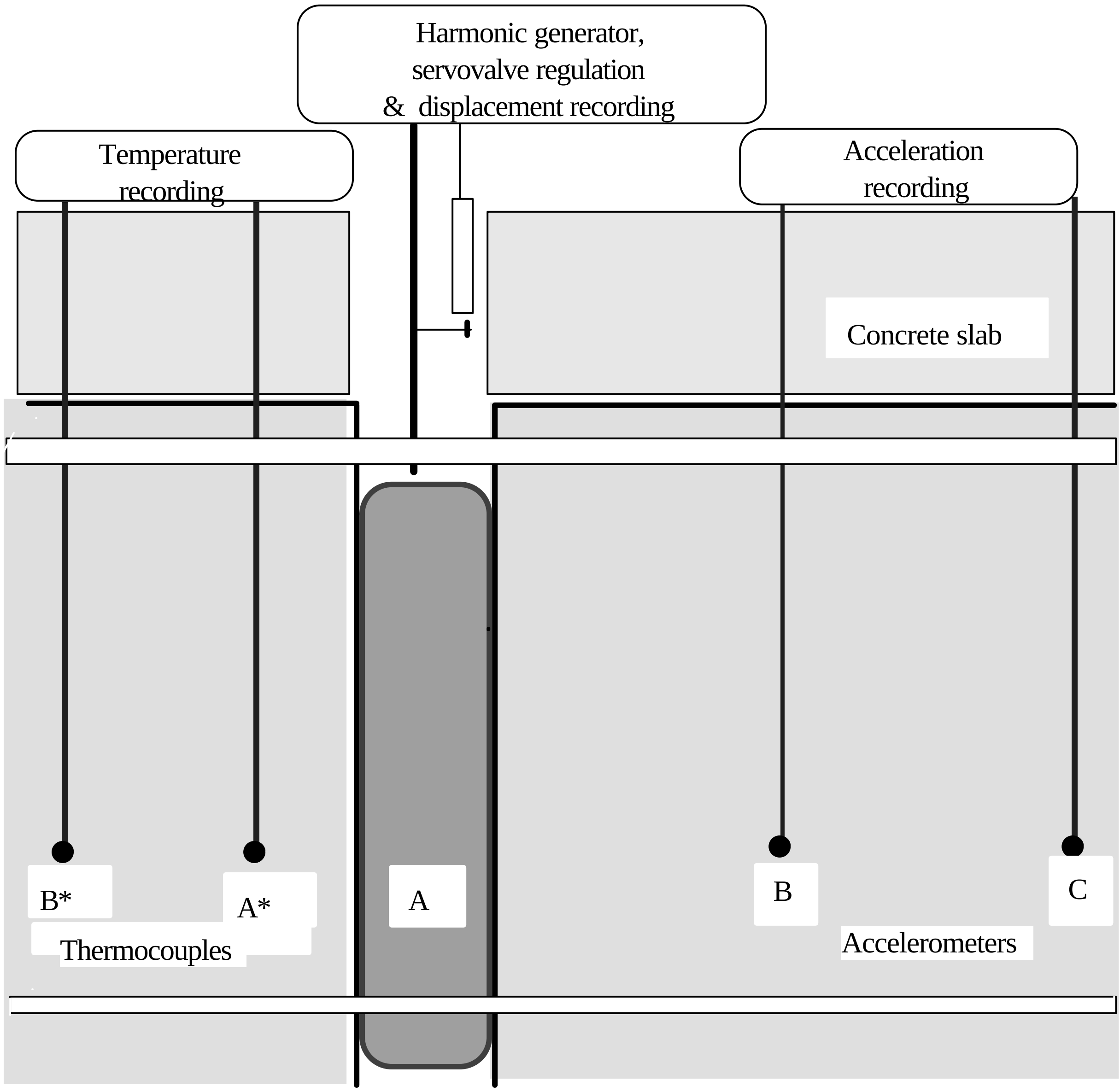
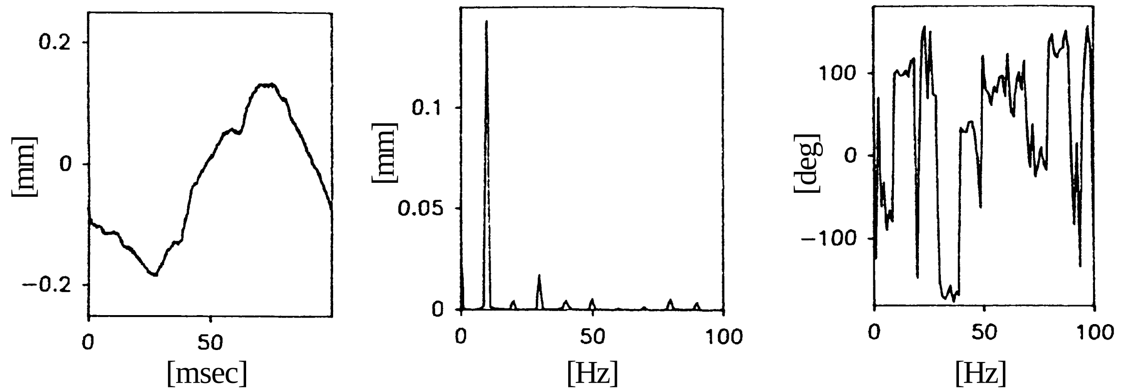



**Figure 1: Principle of the S.H.S. test**

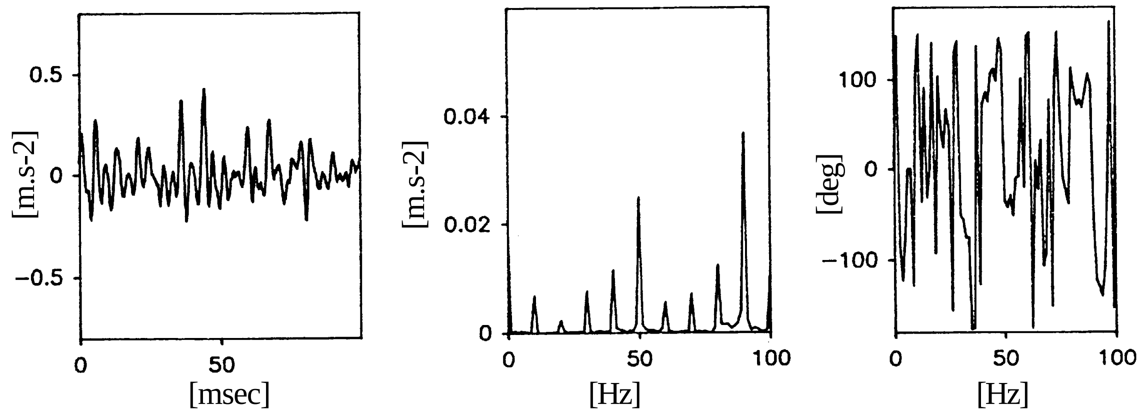
### 2.2 Experimental data

Typical recordings, obtained in the silty and clayey formation considered here, are given in the following figures at a fundamental frequency of 10 Hz. Figure 2 gives an example of the vertical displacement $w_A$ recorded at the well, with its Fourier transform (modulus and phase). Figure 3 gives an example of the vertical acceleration $\ddot{w}_B$ recorded at point B, with its Fourier transform (modulus and phase).




(a) Displacement $w_A(t)$ (b) Modulus of $w_A(f)$ (c) Phase of $w_A(f)$

**Figure 2: Recorded displacement $w_A$ at the well wall (5 cm from the axis)**




(a) Acceleration $\ddot{w}_B(t)$ (b) Modulus of $\ddot{w}_B(f)$ (c) Phase of $\ddot{w}_B(f)$

**Figure 3: Recorded acceleration $\ddot{w}_B$ at point B (25 cm from the axis)**

## 3. MODELLING A TRANSMISSION TEST BY A 3-PARAMETERS BEHAVIOUR LAW

In a transmission test considered here, the acceleration at a point in the vicinity of the well can be simulated using the fundamental dynamic law and a 3-parameters hysteretic law recently adapted to large shear strains as encountered in severe earthquakes.

### 3.1 Variables and notations

**Dimensionless variables**

$$r^* = \frac{r}{r_o} \; ; \; t^* = \frac{t}{t_o} \; ; \; w^*(r^*,t^*) = \frac{w(r,t)}{r_o} \; ; \; \ddot{w}^*(r^*,t^*) = \frac{\ddot{w}(r,t)}{r_o f_o^2} \; ; \quad (1)$$

$$\rho^* = \rho \,/\, \left(\frac{G_o t_o^2}{r_o^2}\right) ; \; \tau^*(r^*,t^*) = \frac{\tau(r,t)}{G_o} \; ; \; \gamma^*(r^*,t^*) = \gamma(r,t)$$

**Notations**

$r$ = distance (m) from a point to the axis of the well
$r_o$ = well radius (m)
$r^*$ = dimensionless distance to the well axis
$t$ = time (s)
$t_o$ = period of a cycle (s)
$t^*$ = dimensionless time
$w(r,t)$ = vertical displacement (m) of the soil at r and t
$w^*(r^*,t^*)$ = dimensionless vertical displacement of the soil at $r^*$ and $t^*$
$\ddot{w}(r,t)$ = vertical acceleration ($ms^{-2}$) of the soil at r and t
$\ddot{w}^*(r^*,t^*)$ = dimensionless vertical acceleration of the soil at $r^*$ and $t^*$
$f_o = 1/t_o$ = fundamental frequency (Hz)
$\rho$ = volumic mass ($kgm^{-3}$) of the soil
$\rho^*$ = dimensionless volumic mass of the soil
$G_o$ = shear modulus (Pa) of the soil, linear parameter of the behaviour law
$\tau(r,t)$ = vertical shear stress (Pa) at r and t
$\tau^*(r^*,t^*)$ = dimensionless vertical shear stress at $r^*$ and $t^*$
$\gamma(r,t)$ = vertical shear strain (/) at r and t
$\gamma^*(r^*,t^*)$ = dimensionless vertical shear strain at $r^*$ and $t^*$
$\tau_o(r) = |\tau(r,t)|_{max} = \tau_o(r)$ = maximum stress (Pa) in a cycle at distance r
$\tau_o^*(r^*) = \dfrac{|\tau(r,t)|_{max}}{G_o} = \dfrac{\tau_o(r)}{G_o}$ = maximum dimensionless stress at distance $r^*$
$\gamma_o^*(r^*) = |\gamma(r,t)|_{max} = \gamma_o(r)$ = maximum strain (/) in a cycle at distance r

### 3.2 Constitutive relations

In the close vicinity of the well, the approximation of a radial situation around the borehole can be assumed, leading to the following momentum balance equation:

$$\frac{\partial\tau^*(r^*,t^*)}{\partial r^*} + \frac{\tau^*(r^*,t^*)}{r^*} = \rho^*(r^*, t^*)\, \ddot{w}^*(r^*,t^*) \qquad (2)$$

The modified 3-parameters hysteretic law used here gives the vertical shear strain g versus the vertical adimensional shear stress t*, at any point r of the soil and any time t, by the following expression:

$$\gamma(r,t) = \gamma^*(r^*,t^*) = \frac{\partial w^*(r^*,t^*)}{\partial r^*} = \varepsilon\, \gamma_{hd} + \varepsilon'\, \gamma_m + \frac{\delta}{2}\Delta\gamma\, [1 - h(\alpha\gamma_o,\beta)] \qquad (3)$$

| | | | |
|---|---|---|---|
| For the first loading | $\varepsilon = 1$ | $\varepsilon' = 0$ | $\delta = 0$ |
| For decreasing $\tau^*$ and $\gamma^*$ | $\varepsilon = 0$ | $\varepsilon' = 1$ | $\delta = 1$ |
| For increasing $\tau^*$ and $\gamma^*$ | $\varepsilon = 0$ | $\varepsilon' = 1$ | $\delta = -1$ |

$$\gamma_{hd} = \frac{\tau^*}{1-\alpha\,\tau^*} \qquad \gamma_m = \frac{\tau^*}{1-\alpha\,\tau_o^*}$$

$$\Delta\gamma = \frac{2(\tau^*-\tau_o^*)}{2+\alpha(\tau^*-\tau_o^*)} - \frac{2(\tau^*+\tau_o^*)}{2-\alpha(\tau^*+\tau_o^*)} - \frac{2\tau_o^*}{1-\alpha\,\tau_o^*}$$

$$h(\alpha\gamma_o,\beta) = \beta - \frac{1}{(\alpha\gamma_o + \beta^{-1/2})^2} \qquad (0 \le h(\alpha\gamma_o,\beta) \le 1)$$

a, b = dimensionless parameters

In this law, the Hardin & Drnevich hyperbolic model defined by parameter a is adopted for describing the first loading, where parameter a characterises the mean modulus G of the soil under a maximum strain $g_o(r)$. The extra parameter b is introduced to correct the Masing's overestimation of damping at high shear strains, using the corrective function $h(ag_o,b)$. The values of $h(ag_o,b)$ can vary between 0 (corresponding to Masing's loop dissipation) and 1 (corresponding to a zero dissipation, i.e. to a non-linear elastic behaviour).

### 3.3 Mechanical response simulation

The numerical input is a synthetic displacement at the well wall obtained by filtering the experimental recorded displacement $w_A$ above 50 Hz, higher harmonics being negligible (Figure 2). At infinity, w( ,t) = 0, " t. The output signal, here the acceleration $\ddot{w}$*(r*,t*), is obtained by integrating the constitutive equations (2) and (3) by a finite difference method, with an iteration process at each time step for taking care of the non-linearities. The synthetic acceleration signals are calculated under the following conditions:

$r_0$ = 5.00 E-2 m (well radius)
$r_B$ = 2.50 E-1 m (point B, Figure 1)
$f_o$ = 10 Hz (fundamental frequency)
r = 1.800 E3 kg/$m^3$
$G_o$ = 7.2 E+7 Pa
a = 200, 500, 1000, 1500, 1600, 1800, 2000
b = 0.5; 0.75;1.00 and Masing's case (h=0).

## 4. PARAMETERS IDENTIFICATION BY A TRANSMISSION TEST

The background of the inverse identification problem, by an approach using a classical 2-parameters law at medium strains, can be found in Mabssout [1993]. The identification of the parameters of a 3-parameters law, adapted to very large shear strains, is demonstrated below.

### 4.1 Identification of the linear parameter $G_o$

Parameter $G_o$ can be obtained by the travel time dt of a wave between two points, for instance B and C (Figure 1), in a transmission test at low strain [Mabssout, 1993]. This travel time can be determined by the phase difference between the acceleration signals at these two points. In the present case study, the value obtained for $G_o$ in such conditions is equal to:

$$G_o = \rho(\frac{BC}{\delta t})^2 \approx 7.2 \text{ E+7 Pa} \quad (4)$$

### 4.2 Identification of the dissipation parameters a and b

Using the above value of $G_o$, the inverse process consists in fitting experimental accelerograms with a file of theoretical accelerograms computed for different values of a and b. This comparison can be made either in time space or in frequency space, at different points in the soil. Illustration is given below in the time space, at point B. The difference between the measured acceleration $\ddot{w}_{mes}(t,r_B)$ (Figure 3) and the file of theoretical accelerations $\ddot{w}_{th}(t,r_B, a, b)$ is estimated by the quadratic norm N($r_B$, a, b) defined by :

$$N^2(r_B, \alpha, \beta) = \frac{1}{t_o}\int_0^{t_o} [\ \ddot{w}_{th}(t,r_B, \alpha, \beta) - \ddot{w}_{mes}(t,r_B)]^2\, dt \quad (5)$$

Figure 4 gives the values of N($r_B$, a, b) for a = 200, 500, 1000, 1500, 1600, 1800, 2000 and b = 0.5, 0.75, 1.0. The best estimate of the parameters a and b is obtained for the minimum value of N($r_B$, a, b). Figure 4 shows that a 1600 and b lies between 0.50 and 0.75. Refinements lead to the following best estimate :

$$\alpha \approx 1600 \text{ and } \beta \approx 0.60 \quad (6)$$

A verification of this estimation could be obtained using acceleration recordings at points different from B, for instance at point C (Figure 1).

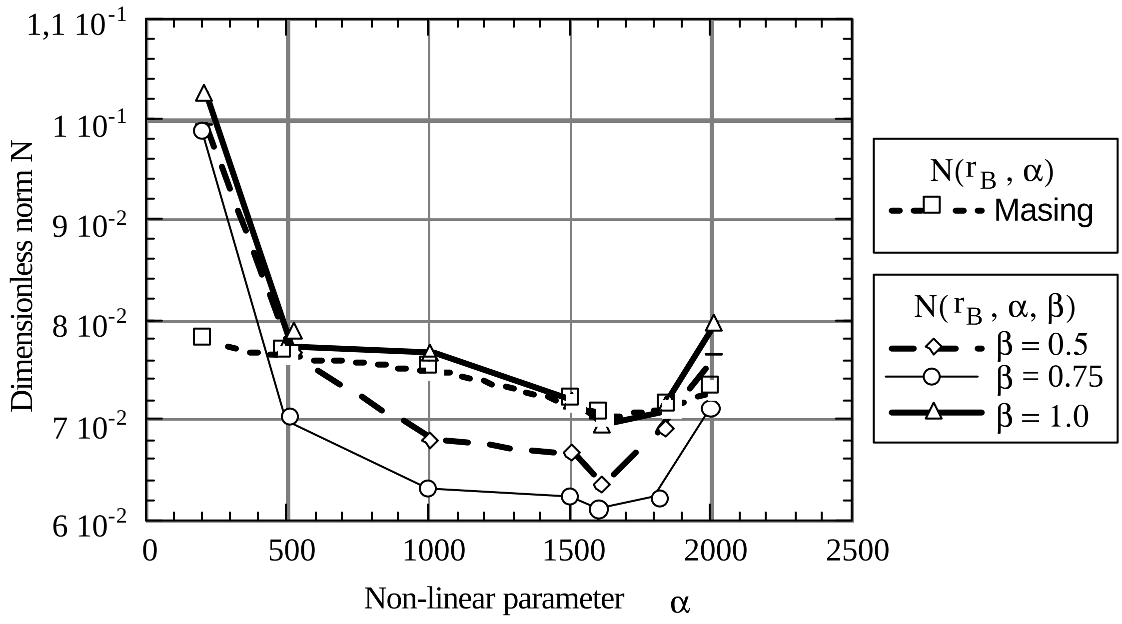



**Figure 4: Dimensionless norms N($r_B$, a, b) and N($r_B$, a) in the Masing's case.**
**( $r_B$ = 2.50 E-1 m ; $G_0$ = 7.2 E+7 Pa ; a variable ; b variable)**

## 5. CONCLUSION

The dynamic behaviour of in situ soils under major earthquakes is possible using the Seismic Harmonic System (S.H.S.) equipment, able to reproduce major earthquake accelerations around a well. Different tests are possible: transmission tests, transfer function tests at the well or thermal tests. The modelling of transmission tests around the well as described here is done using a 3-parameters law which is robust enough for simulating damping at large strains. Its first parameter is the linear modulus $G_0$ at low strain, the second parameter a leads to the modulus G at medium or large strains and the third parameter b makes it possible to extend the classical engineering practice to strains encountered in the most severe earthquakes. It is demonstrated here that the interpretation of transmission tests are able to lead to the identification of the three parameters ($G_0$, a, b) of this behaviour law, up to shear strains equivalent to the most severe earthquakes.

## 6. REFERENCES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