International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1981 - First International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

29 Apr 1981, 6:30 pm - 9:30 pm

Scale Modelling of Soil Structure Interaction during Earthquakes Using a Programmed Series of Explosions during Centrifugation

A. Zelikson
Laboratoire De Mecanique des Solides, Ecole Polytechnique, Palalseau, France

B. Devaure
Commissariat à l'Energie Atomique, C.E.S.T.A., Le Barp, France

D. Badel
Commissariat à l'Energie Atomique, C.E.S.T.A., Le Barp, France

Proceedings: First International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, April 26 - May 3, 1981, St. Louis, Missouri

Scale Modelling of Soil Structure Interaction during Earthquakes Using a Programmed Series of Explosions during Centrifugation

A. Zelikson
Laboratoire De Mécanique des Solides, Ecole Polytechnique, Palaiseau, France

B. Devaure and D. Badel
Commissariat à l'Energie Atomique, C.E.S.T.A., Le Barp, France

ABSTRACT Scale models of Nuclear Power plants were constructed to study soil structure interaction during Earthquakes. The centrifuge of the C.E.S.T.A. Center near Bordeaux, France, was used to simulate gravity at 100 g (length scale 1 : 100) on a 1000 kg net weight of soil and structure.
The Earthquake was simulated by a surface wave created by a programmed series of small explosions suitably modified so that the free field signals of horizontal and vertical accelerometers had spectra resembling those of real Earthquakes according to similitude laws.
The problem of echoes and suitability of a confined structure was studied without models of structures. In tests including models of structures movements and stresses in the soil and in the structure were measured using transducers of acceleration displacement pressure and deformation. The overall stability was studied.

INTRODUCTION

This paper presents a new method for scale modelling of soil structure interaction during earthquakes the main characteristics of which are :
The soil in situ is utilised in the model.
Stress scale is conserved and gravity is represented by a centrifugal acceleration.
Surface waves propagating along the soil sample are created by a series of programmed explosions suitably modified by filters as to have a chosen spectrum of free field accelerations according to similarity rules.
Quite a number of centrifugal tests of these models have been carried out, the structure represented being an existing nuclear power station, proving the validity of the proposed method besides giving many useful results concerning soil structure interaction. However space in this compact paper does not allow going into details, which are left for oral discussions and for publication elsewhere.
The research work is the result of a concerted action between the Centre d'Etudes Scientifiques et Techniques de l'Aquitaine (S.E.S.T.A.) of the Commissariat à l'Energie Atomique, and of the Laboratoire de Mécanique des Solides (LMS) de l'Ecole Polytechnique, which stemmed from a previous programme on the stability of underground cavities subject to shocks carried out at the C.E.S.T.A. by the LMS (ZELIKSON, 1975, 1977, 1979).
The tests were carried out on the 10 m centrifuge of CESTA by CESTA staff who also carried out the preliminary tests and preparations and built the necessary equipment. The details of this work are described in DEVAURE (1980).
(Remark : Usually results are presented in the transformed "in situ" scale. The index m, designing model, will be added only where confusion is possible. The scale A_m/A is called A^*).

SIMILITUDE

In non linear cases material, stress (σ) and strain (ε) scales have to be conserved, giving $1 = \sigma^* \varepsilon^* = \rho^* (v^*)^2$; $\rho^* = 1 \Rightarrow v^* = 1 \Rightarrow \ell^* = t^*$ $\Rightarrow a^* = (t^*)^{-1}$; $g^* = \ell^{*-1}$ (v material velocity, a accelaration, g gravity, ρ density, t time, ℓ length). The condition $g^* = \ell^{-1}$ is fulfilled by utilizing a centrifugal acceleration.

FREE FIELD INSTALLATIONS

The maximum capacity of the centrifuge (at g = 100) was 1 000 kg, for confining cell, structural model, soil, and for the shock generator. Accordingly, the installation was built of Al. About 50 kg of Al were allocated to the air blast modification chamber which included :
1) an isolating and supporting plate having 10 emplacements for explosive charges of 1-5 g ;
2) accoustical resonating cavities ;
3) mechanical resonating systems of springs and metal plates. The air pressure was applied to the vertical face of the soil through a rubber membrane. The blast chamber is foremost in fig.1 which shows the whole model fixed at the end of the centrifuge's arm.

Figure 1

10 g of explosives are enough to create an earth quake of maximum acceleration of equivalent to 20 m s^{-2} (2 g) in situ.
The confining cell had a length of 1,3 m, a depth of 0,4 m and a width of 0,8 m, tapering at the end towards the blast chamber. This arrangement was sufficient to create a field of acceleration uniform through the width at the main part of the cell, in the middle of which was placed the structural model.
The whole cell including the blast chamber has a mass of 240 kg, leaving about 750 kg for the saturated soil.
Firing was initiated by discharge of capacitors placed on the centrifuge's arm, acting on signals transmitted from programmed clock system.
The soil was Fontainebleau sand, a fine grain reference sand in France of uniform granulometry. It was placed by free dropping from a controlled hight to a density of 1.52 g/cm^3 -a medium compaction-. (An addition of 5-10 % of ground sand filler is currently used to reduce permeability by the length scale, in tests for liquefaction. This however was not done in these series).
Saturation was carried out first by a very small water flow, and then by centrifugation before the test, which makes bubbles 100 times lighter.

STRUCTURAL MODEL

For soil structure interaction the pertinent 3 degrees of freedom of rigid motion were chosen. The rigid Al model had to represent a structure having the following features : base diameter 38.8 m, hight of mass center, G, 22.5 m above the base, mass 52 250 ton, moment of inerty around G of 23,900,000 t m^2. It was chosen to represent a <u>similar</u> structure, reducing lengths by 2/3. The <u>similarity</u> between those structures is : $\sigma^* = \rho^* g^* \ell^*$, $\rho^* g^* = 1$, $\sigma^* = \ell^* = 2/3$
$g^* = 1 \Rightarrow v^* = t^* = \ell^{*1/2} = 0.8$.
The model had the following features :
hight 0,3 m with symmetrically distributed masses, base diameter 0.26 m, mass 15,3 kg, inerty moment 0.315 kg m^2.

TRANSDUCERS

Accelerometers in the soil were Endeveco Picomin, of 0,14 g mass, fixed on 0.7/0.5/0.1 cm, plastic plates acting as antennes and by mobilising a mass of soil many times the mass of the transducer minimizing perturbation. (The cable is very thin). On the structure, larger ones were fixed. Displacement relative to the cell was measured by capacity transducers. Total pressure along the base of the structure was measured by placing straingauges on membranes flush with the base. Total stresses in the soil were measured by units of 3 miniature normal stress transducers fixed on Al prisms 0.7/0.7/0.5 cm.
<u>Pore water pressure</u> :
Miniature transducers were placed within a small volume of sand, inside a rubber poach. They were carefully saturated and tested in the laboratory, then placed in the model's soil. Allowing only the very minimum of flow, they measure static pore pressure normally, and dynamic pore pressure in undrained conditions. They use thus acting as liquefaction indicators.

FEASIBILITY PROBLEMS

1) <u>Echoes</u> :
Reflections from the walls only are considered as perturbations violating the conditions of infinite horizontal dimensions. Echoes were extensively studied "on the ground" in a substitute cell, where the soil's surface was covered by a Latex membrane, and soil rigidified by vacuum. A falling mass, so studied as to give a signal of 1000 m s^{-2} amplitude and 0.4 ms duration, was used to determine the echoes' amplitudes and also to measure the attenuation as a function of the distance from the source DEVAURE [1]). It was found that echoes could safely be neglected in a zone of 0.25 m diameter at the middle of the cell. The suitability of the cell's size was further checked by comparing measured "earthquake" structural model movements to those calculated on the basis of half space theories. The attenuation of free field and of the structure's motions after a single shot gave a further check.

2) <u>Earthquake generated</u> :

Pseudo-velocity acceleration spectra of free field signals were compared according to scaling rules to real earthquakes (Fig. 2). Both single shots and series of shots compare well with actual earthquakes, both in amplitude and in frequency. Another comparison is made by calculating the response of the model to a scaled down real signal and comparing with measured accelerations on the model. The conclusion is that the signal correctly represents real earthquakes.

3) Results of repeated tests are very similar.

4) The signal to noise ratio under water of all the transducers is satisfactory, and the whole gives meaningful and comparable results.

<u>In conclusion</u>, the method is proved.

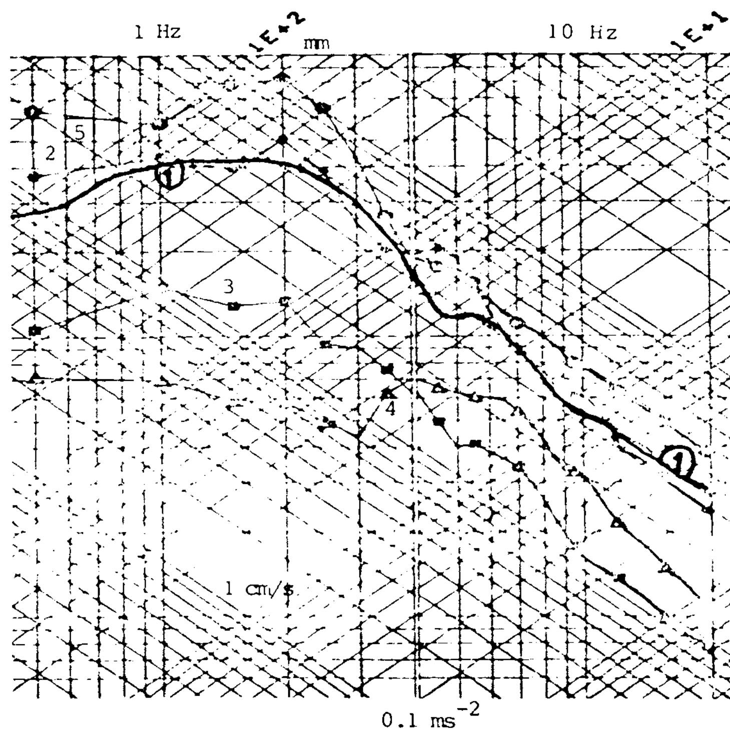


Figure 2 Spectra
1. multi shot 2. El Centro
3. Taft 4. San Francisco 5. Parkfield

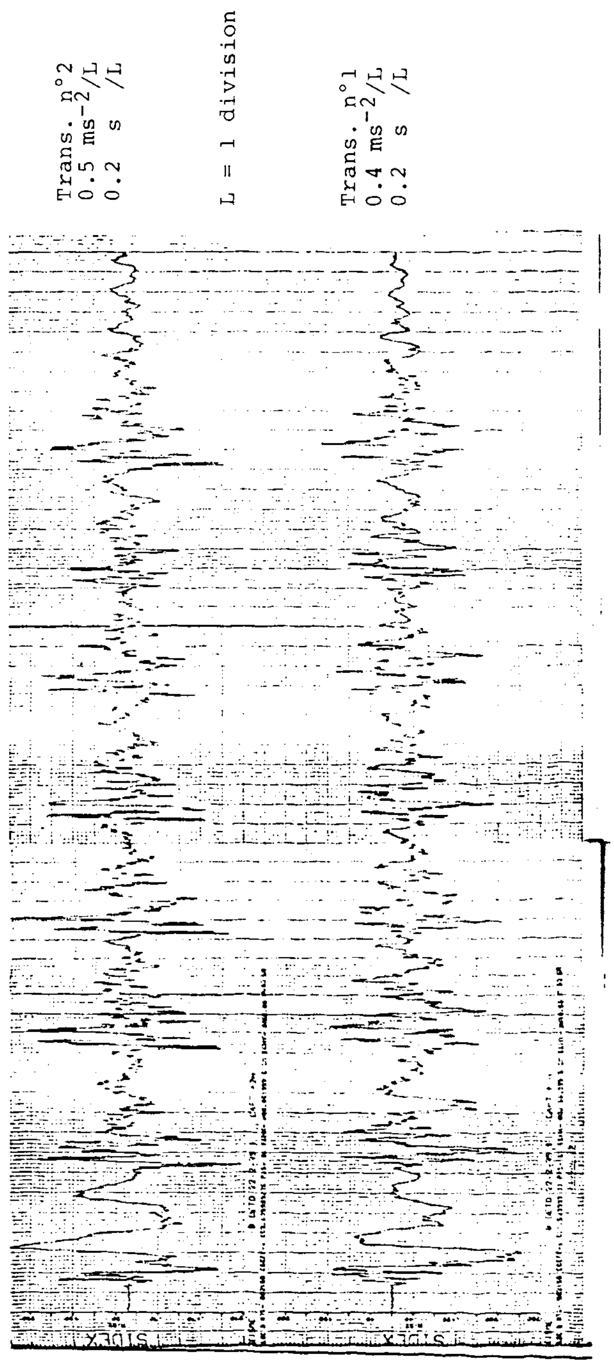


Figure 3: Multi-shot Free Field Acceleration

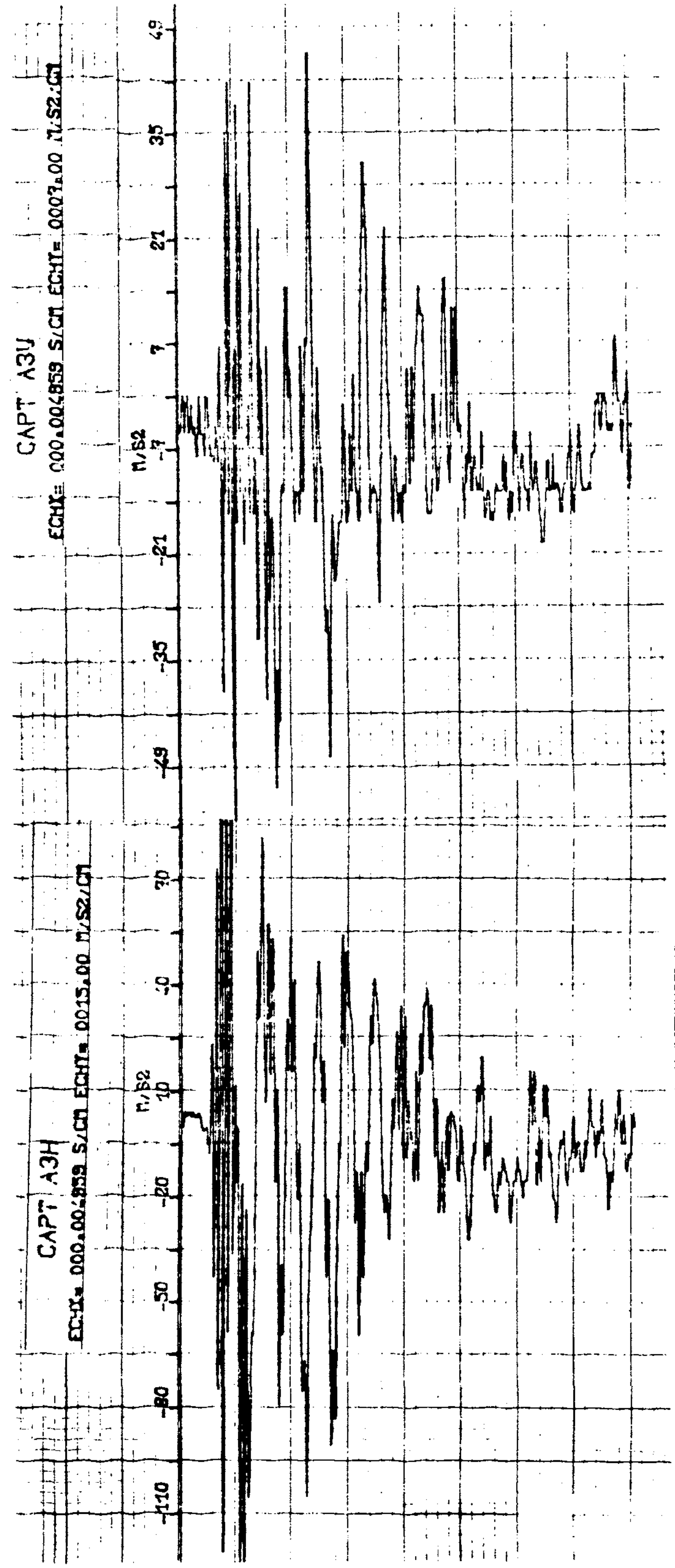


Figure 4 : Free Field Horizontal Acceleration

CALCULATION

Calculation was carried out for the model assuming a rigid motion of vertical and rocking vibrations of a structure based on the soil's surface, and replacing the soil by lumped parameters, calculated by the usual formulae based on a measured wave velocity of 300 m/s. The variables are Z_V, Z_H respectively the vertical and horizontal displacements of the mass center relative to the soil and $Z_\Phi = 0.15\,\Phi$, Φ being the rotation. The forcing term was the vertical and horizontal free field accelerations measured at the future location of the model. The equation is :

$$\begin{bmatrix} \ddot{Z}_V \\ \ddot{Z}_H \\ \ddot{Z}_\Phi \end{bmatrix} = \begin{bmatrix} 2250 & 0 & 0 \\ 0 & 1380 & 1380 \\ 0 & 1500 & 1760 \end{bmatrix} \begin{bmatrix} Z_V \\ Z_H \\ Z_\Phi \end{bmatrix}^{\bullet} + 10^6 \begin{bmatrix} 6.15 & 0 & 0 \\ 0 & 5.5 & 5.5 \\ 0 & 5.96 & 9.35 \end{bmatrix} \begin{bmatrix} Z_V \\ Z_H \\ Z_\Phi \end{bmatrix} = \begin{bmatrix} -\gamma_V \\ -\gamma_H \\ 0 \end{bmatrix}$$

The free field of Fig. 4 was used to calculate the results presented in Fig. 5 and 6. Such calculations are very useful in testing the effect of echoes and in comparing the influence free field signals in the model and in situ.

RESULTS

Some results from a simple shot of high intensity the free field of which is given in fig. 7, are shown in fig. 8,9. It is interesting to note that pore pressures follow the pressures caused by the structure motion .

The amplitude of pore pressure variations shows that liquefaction is possible if not probable. Generally, the soil was compacted by the structure after each shot. The in-situ values are 10-20 cm for the tremor of fig. 7 and ten times smaller in single and multiple shocks of about 1.5 ms^{-2} maximum acceleration.

REFERENCES

[1] DEVAURE B. Thèse présentée à la Faculté de Bordeaux (1980)

[2] HANSEN R.J. (ed.) Seismic Design for Nuclear Power Plants. M.I.T. Press (1970)

[3] MANDEL J. Mécanique des Milieux Continus, Gautier-Villars, Paris, (1966)

[4] ZELIKSON A. Modèles Réduits pour l'Etude de l'Interaction Structures-Sols pendant les Tremblements de Terre - Réunion des Spécialistes OCDE - AEN (Paris, 1975)

[5] ZELIKSON A. Modèles réduits pour l'Etude de l'Interaction Sismique Structures - Sols des Centrales Nucléaires en utilisant les forces centrifuges, Rapport L.M.S. 1977

[6] ZELIKSON A. Artificial Two-Dimensional Sands, Shock Tube, Centrifuge as Experimental Tools in Model Tests of Cavities subject to Explosions. MABS 6, Cahors, France, (1979).

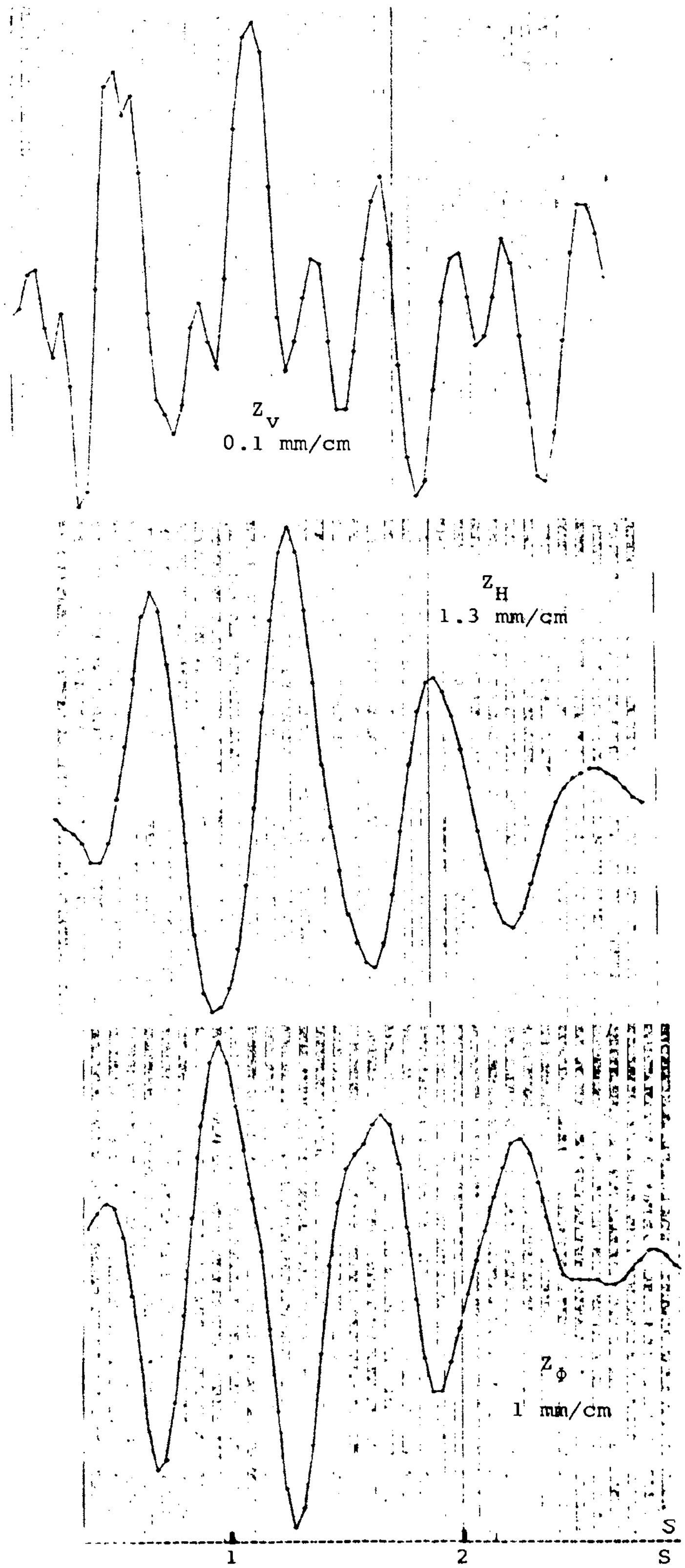


Figure 5 : Calculated Displacements

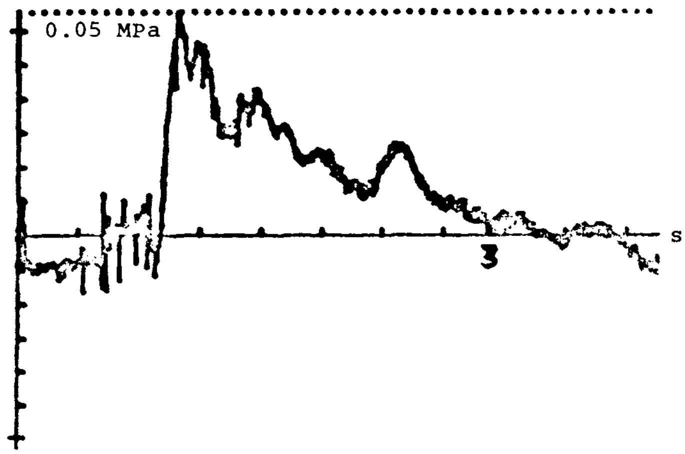


Fig. 10 : Pore Pressure at 8 cm depth on the axis.

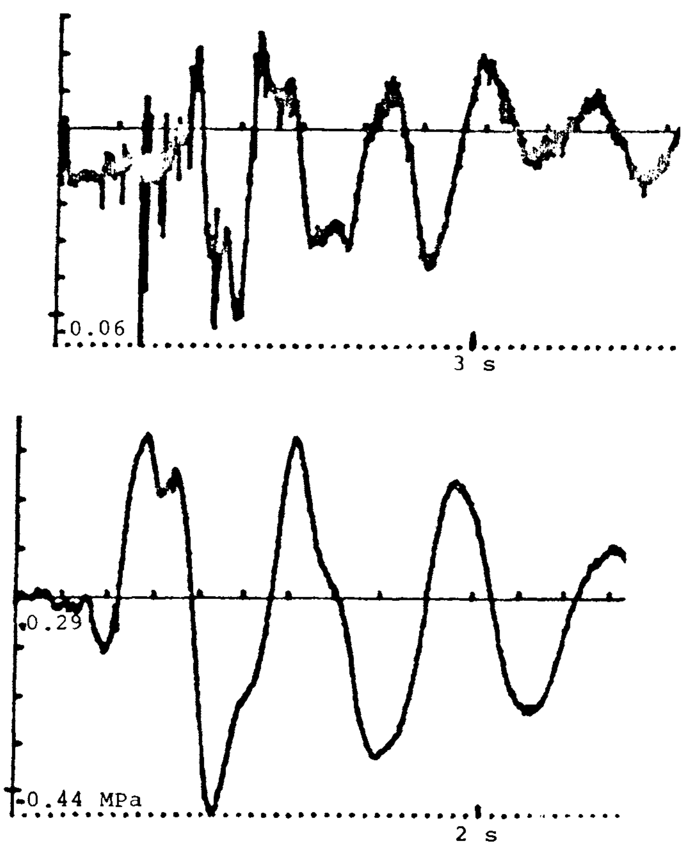


Figure 9 : Pressures at far base's tip
Above : Pore Pressure ; Below : Total pressure on base.

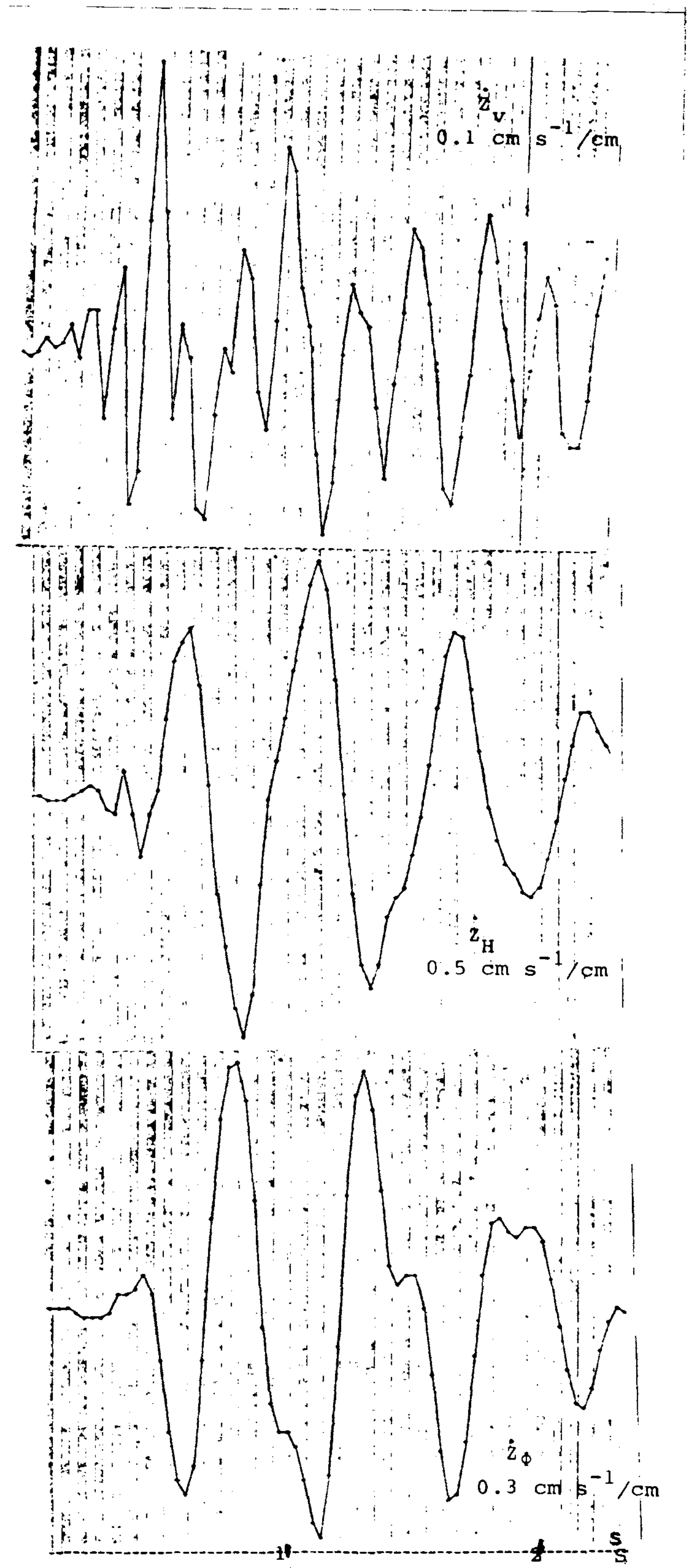
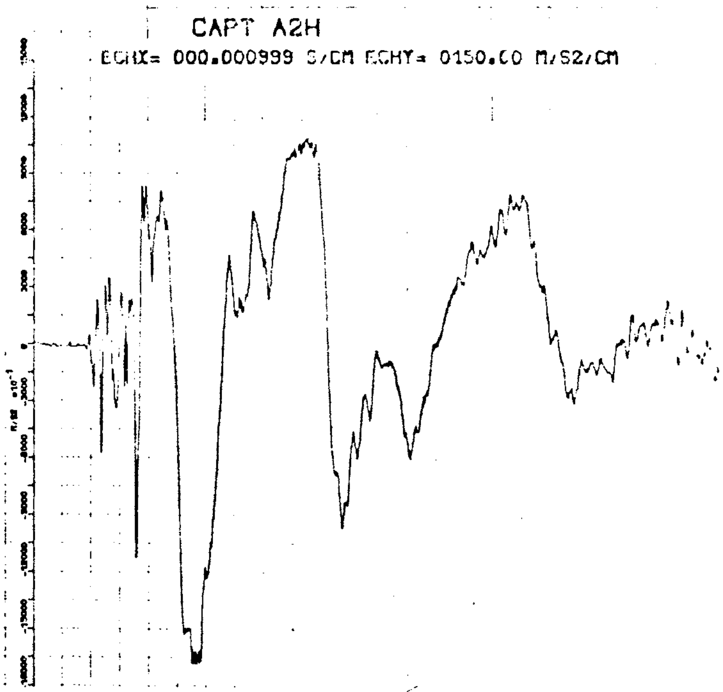


Figure 6 : Calculated Velocities



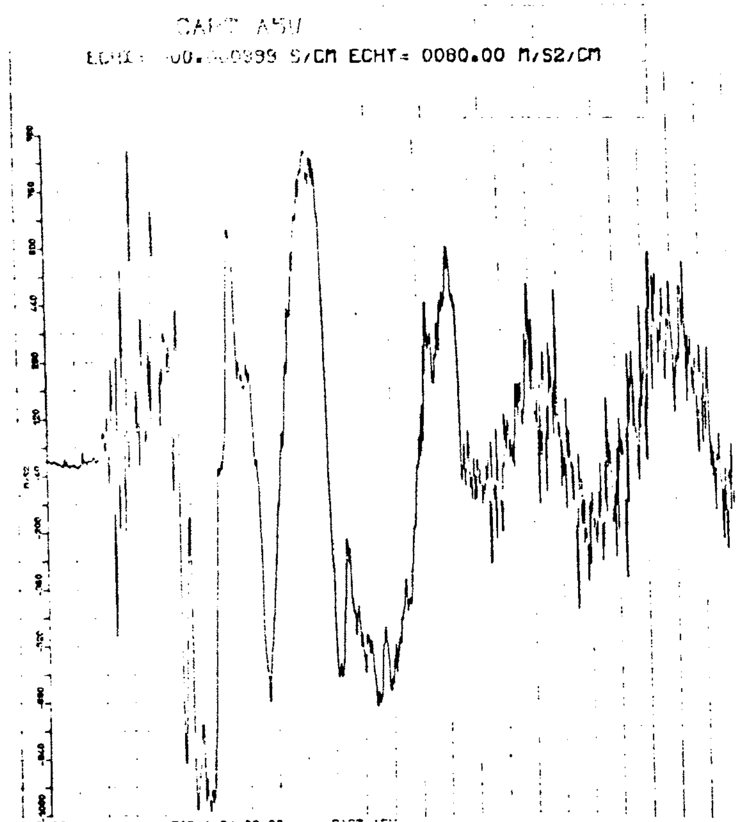


Figure 7 : Free Field (Single Shot)
Left : horizontal ; Right : vertical.

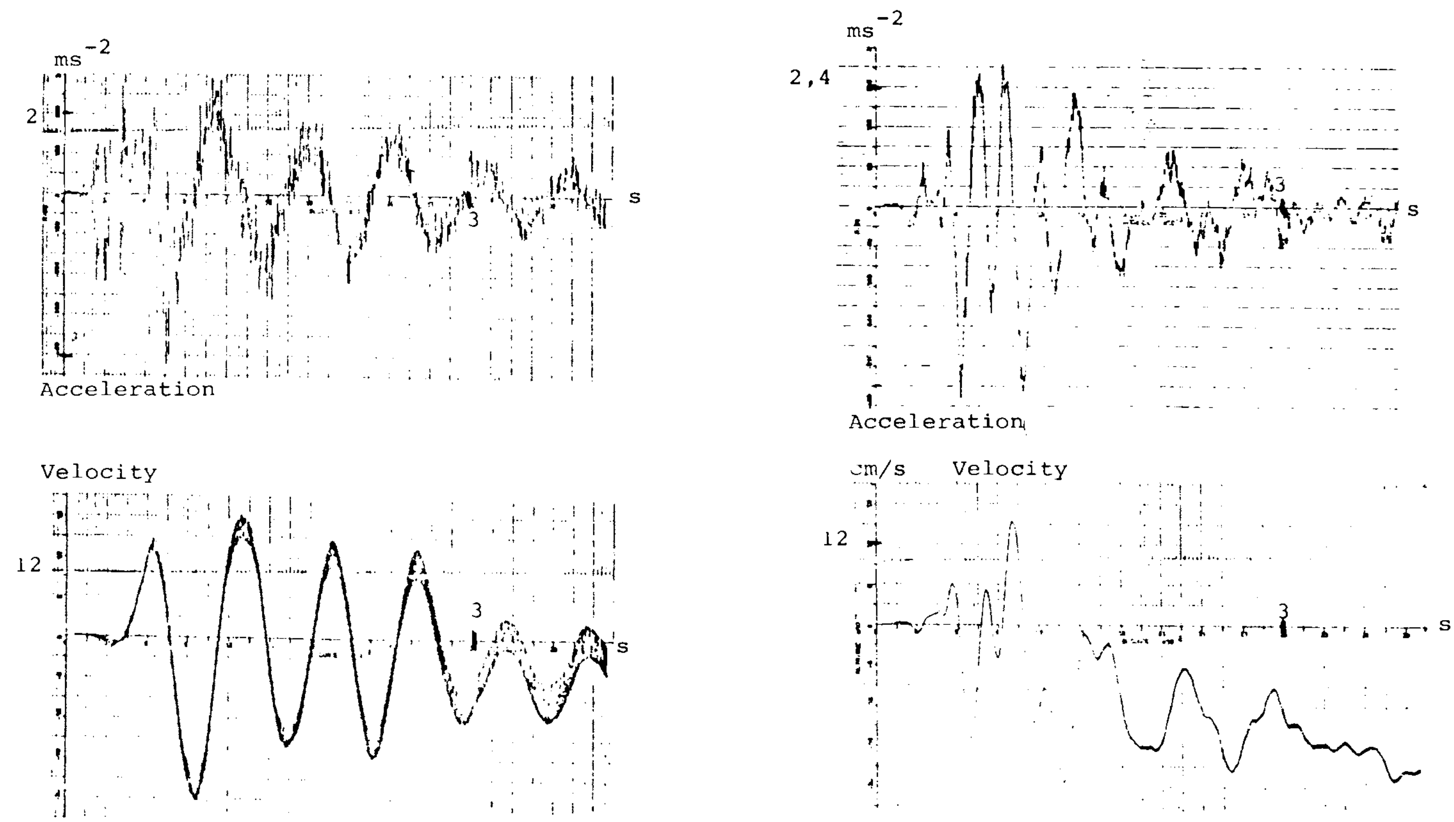


Figure 8 : In situ signals at roof's edge
Left : horizontal ; Right : vertical