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# Qualitative aspects of seismograph/ocean bottom interaction

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# Qualitative aspects of seismograph/ocean bottom interaction

M. Snoek and R. Herber

**Abstract:** The parameters affecting the coupling of the Ocean Bottom Seismometer to the ground have been studied in a controlled experiment in the large seawater test pit of the Centre Océanologique de Bretagne, France. An outline of the experiment is presented and an attempt is made to understand the processes involved and relate them to a simple physical mechanism. Examples of sensor performance are given and basic ideas for the design of sensors in general and ground interacting elements are presented.

**Keywords:** acoustic propagation ○, bottom interaction ○ coupling ○ interface waves ○ Ocean Bottom Seismometer calibration

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## Preface

Investigation of the influence of the seafloor and sub-seafloor on acoustic propagation requires methods and instruments able to record events generated by the seismo-acoustic wavefield. The acoustic field interacts with the seafloor, is converted partly into seismic energy and is returned back into the waterbody. For shallow-water environments and frequency ranges below the cut-off frequency the bottom propagation path, i.e. the conversion into seismic waves, is the only means of propagation of energy generated in the water body. The converted energy is split up into different seismic wave types, depending on the material parameters and angle of incidence. Among these the interface waves, i.e. seismic waves trapped in the upper sediments, are of special interest to us since they provide information not only on the emitted signal but also on the bottom/subbottom propagation materials. In deploying a sensor unit with preferably three orthogonal seismometers on the seafloor one obtains a powerful tool to investigate the above phenomena, but only if the sensors are well coupled to the ground and there are no resonance phenomena due to the material geometry. This is not always the case: recorded signals are sometimes distorted and in the worst case no signals will be obtained.

To investigate these mechanisms and to understand the coupling parameters, two large experiments have been performed: the Lopez Island Intercomparison Experiment (LIIE) and the Ocean Bottom Seismometer Calibration Test (OBSCAL). In this paper the OBSCAL experiment is explained and qualitative aspects of the coupling complex are discussed. In the past SACLANTCEN has performed seismo-acoustic experiments in various regions with bottom/subbottom materials ranging from very soft sediments to hard rocks, the results ranging from very good to no interface wave propagation. Since even in some regions where good interface wave propagation was predicted unexpected propagation effects were observed, the coupling experiments gain a new importance. An understanding of the coupling complex is essential for particle motion studies as well as for the use of buried seismometers.

## Contents

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## 1. Introduction

Seismic methods in marine environments must be advanced from the mere detection of compressional waves to allow for a dynamic interpretation of the entire seismic wave train. Some success has been achieved in this direction by introducing triaxial geophone-plus-hydrophone sensor units – the Ocean Bottom Seismometer (OBS) – which record events on the seafloor. Since the coupling of seismic sensors to the ground is of paramount importance for the fidelity of the recorded signal, considerable time and effort have been spent in understanding and improving the coupling behaviour on land. With the introduction of OBS this problem has acquired a new dimension, as normally an *a priori* knowledge of the geoacoustical parameters of the actual location on which the sensors will be placed is not available. In most cases one encounters sediments of low rigidity [1]. Compared to the case of a land seismic geophone implanted in the soil or attached rigidly to a foundation measuring the differential motion between the housing following the soil motion and the inertial mass of the sensor, the OBS or external sensor pack together with the elastic seabed constitutes an oscillating system with the OBS/sensor pack itself forming the inertial mass. In contrast to procedures on land, where a considerable effort can be made to secure a good coupling of the seismic sensors to the ground, OBS are usually deployed with little or no control over their placement on the seafloor. Since the coupling of the sensors to the ground cannot in general be influenced directly, the quality of the recorded data might be inferior to that expected. In order to estimate site-specific effects on the recorded data the coupling complex in the marine environment has to be investigated and understood.

In spite of a good deal of useful and relevant information obtained from earlier investigations [2–4] a clear unequivocal theory of the coupling behaviour of the OBS on the seafloor is still missing. As a followup test to the 1978 Lopez Island Intercomparison Experiment (LIIE) [2] a group of OBS-deploying seismologists conducted coupling and calibration experiments (OBSCAL) at the Centre Océanologique de Bretagne, Brest (France) in 1980. Participants came from the following institutions: Centre Océanologique de Bretagne (COB) Brest, Bedford Institute of Oceanography (BIO) Dartmouth, Earthquake Research Institute (ERI) Tokyo, Institute of Oceanographic Sciences (IOS) Wormley and the Institut für Geophysik (IFG) Hamburg. Preliminary results of these experiments have been published [5]. The results of previous experiments indicated that a quick generalization and theory of coupling was not possible and that the horizontal response in particular remained poorly understood.

## 2. Experimental setup

The primary objectives of the OBSCAL experiments were to establish relations between the physical parameters of the coupling ground and the actual sensor-soil interacting unit the coupling area -- also called ground weight, ground anchor or sinker weight - as well as to calibrate the different OBS used in a joint experiment. To determine the parameters describing the coupling of an OBS to the seafloor we conducted a series of tests by varying the excitation source (and thus the excitation signal) as well as the coupling medium. An outline of these tests and plots of all the events in the time and frequency domains were given in a report prepared for the German Science Foundation (DFG) [6]. The basic facilities used in Brest were the large seawater-filled test pit (experiments were performed in 10 to 20 m depth), large concrete test platforms and controlled excitation sources, see Fig. 1. Tests were performed on three different materials: concrete, sand and bentonite. The latter two were supported by large culvert pipes, fitted to the test platforms.

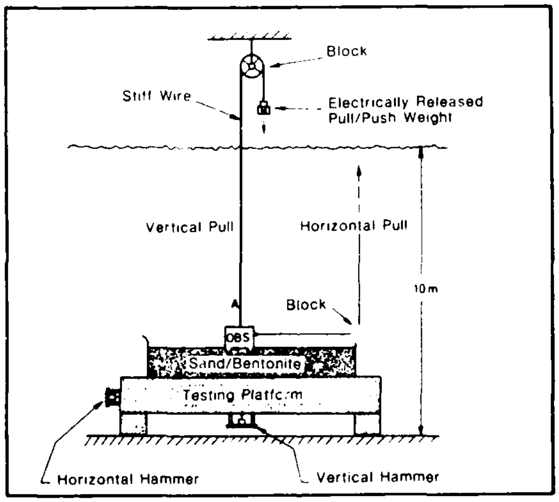

*Fig. 1.* Setup of the OBSCAL experiment, performed in the test pit in Brest. The 3 × 3 m concrete test platforms were located in 10 m depth of seawater with a culvert pipe container filled with bentonite/sand attached to them.

A number of shortcomings of the experiments are evident, e.g. the scale of the testing ground, the test-platform-inherent eigen-oscilllations and the vicinity of the test pit walls. However, since the different site-specific resonance (or corner) frequencies obtained resemble values observed during field work, we believe that the observed phenomena are consistent enough to permit assumptions and allow predictions about the behaviour on different soils. Two excitation sources were used:

- A pneumatic hammer located under the test platform (vertical excitation) and to one side (horizontal excitation), see Fig. 1. The signal generated was variable in frequency content and amplitude; it was controlled by the pressure applied to the hammer (amplitude) and by the material of the hammer heads (frequency). We obtained fairly complex but highly reproducible wavelets, see Fig. 2.
- A modification of the classical weight-lift arrangement, which ensures a step-function excitation, generated by a vertical and horizontal pull/push. The source and quality of this signal is demonstrated in Fig. 3, which shows an accelerometer recording of the event measured at point A on the signal-transmitting stiff wire.

For all the tests, reference geophone systems were installed to enable signal comparison and normalization. The reference geophones were placed under the OBS in the sand and bentonite medium (mobile system), and a pair was rigidly connected to the test platform (fixed system). They consisted of vertical and horizontal SENSOR 4.5 Hz SM6B geophones. For most of the pull/push tests the actual signal applied was monitored by an accelerometer attached to the signal-transmitting wire. All the data were recorded on a central 7-track analog recording unit. The OBS/sensor outputs as well as the references were hardwired to the recording unit. As a calibration source for the tape a continuous 100 Hz sinusoidal reference signal was generated and recorded on one channel. Before digitizing the events a 200 Hz low-pass filter with 24 dB/octave attenuation was applied. The amplitude spectra were calculated by applying an FFT routine to a selected 2048 sample data window, centered around the event. The sample rate was 800 samples/s for four preselected channels.

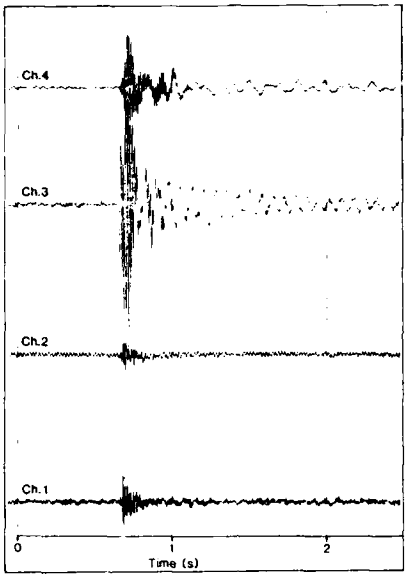

*Fig. 2.* Recording of a vertical hammer blow. From bottom to top: channel 1 – horizontal mobile reference, channel 2 – horizontal fixed reference, channel 3 – OBS vertical geophone, channel 4 – OBS horizontal geophone.

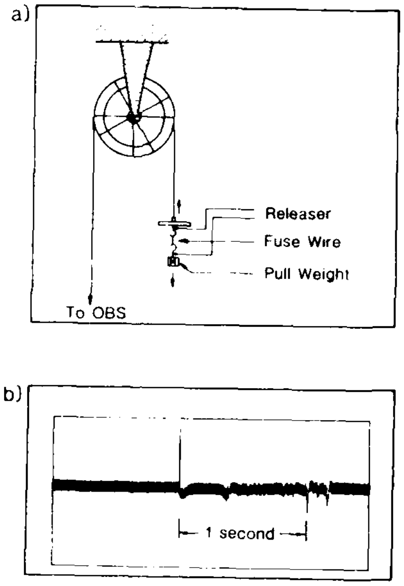

*Fig. 3.* Elements of the transient signal generation mechanism (a) and the accelerometer response to a transient signal (b).

## 3. Observations

For a phenomenological discussion of the results we consider two extremal weight versions of the tested OBS*: the Institute of Oceanographic Sciences (IOS) OBS with a total mass of 80 kg and the Institut für Geophysik (IFG) OBS with about 20 kg (external pack). We confine our discussion to phenomena related to bentonite and sand, i.e. the materials most frequently encountered in the marine environment [1,8,9]. Tests on concrete were unfortunately distorted by pull-induced rocking motions of the OBS due to the nonplane contact areas of the OBS and the ground. As a consequence of this one has to be very careful when designing an OBS/ground-interacting element if work has to be performed in an area likely to encounter a hard seafloor. For some tests, especially when applying a hammer source, rather complex signals were measured. This was not only a result of the source function, but also a result of the geometry of the experimental setup and the fact that the culvert pipes filled with our testing materials (sand/bentonite) rested on a concrete platform with its own vibrational modes. Since we can assume that these secondary experimental effects act equally on all tested OBS, it appears both attractive and permissible to regard them as site-specific parameters and thus we will not discuss them further in this paper. In addition, effects caused by OBS/water and OBS/seabed displacement will be neglected here.

General considerations and our own observations lead to the conclusion that the resonance frequencies and the damping behaviour of the systems determine the performance of an OBS on the seafloor. As we are only presenting a qualitative explanation for the OBS/soil interaction mechanism, a brief description of the mathematical formulation of the problem will suffice. Simplified, the medium will be considered as a homogeneous, isotropic and elastic semi-infinite body. The system investigated will be idealized as a lumped-parameter model. Previous investigations and analysis have shown that the elastic halfspace analog (Fig. 4) is a useful model for explaining the basic features involved in the coupling problem [2-4]. For the model to be valid, the geophones have to be critically damped and rigidly coupled to the housing. Although a single-degree-of-freedom system with viscous damping, represented by a model with mass-spring-dashpot elements is a gross simplification of the actual process involved, it has been shown that it satisfactorily explains the basic physical phenomena observed. The differential equation of motion derived from Newton's second law describes, when completed with an energy-dissipating element, the behaviour of the damped forced vibration of a single-degree-of-freedom system

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* The Centre Océanologique de Bretagne (COB) OBS is considerably heavier with 690 kg, but because of the geometry and size of the coupling area (Fig. 12), system-inherent signal deformation occurs, i.e. the large sinker-weight tripod is triggered to perform eigen-oscillations by the arriving seismic signal and thus exactly masks the event.

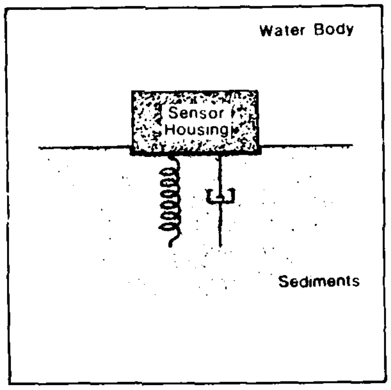

*Fig. 4.* The elastic half-space analog with mass, spring and damping elements idealizing a single degree of freedom system used to explain the coupling as a function of elastic properties of the ground and sensor configuration.

as follows:

$$m\ddot{z} + c\dot{z} + kz = F(t),$$

where $z$ is the linear displacement, $m$ is the effective mass of system, $k$ is the spring constant, $c$ is the damping constant and $F(t)$ is the exciting force.

The excitation force can be written in the form

$$F(t) = F_0 \sin \omega t.$$

Using the abbreviations $\epsilon = k/2m$ and $\omega_0 = \sqrt{c/m}$ we can rewrite the equation as

$$\ddot{z} + 2\epsilon\dot{z} + \omega_0^2 z = F_0 m^{-1} \sin \omega t.$$

Solving this equation one obtains

$$z = e^{-\epsilon t}(C_1 e^{\gamma t} + C_2 e^{-\gamma t}),$$

$$\gamma = \sqrt{\epsilon^2 - \omega_0^2}.$$

Introducing $C_1 = \frac{1}{2}(C + D)$ and $C_2 = \frac{1}{2}(C - D)$, we obtain

$$z = e^{-\epsilon t}(C \cosh \gamma t + D \sinh \gamma t).$$

The term $\sqrt{\epsilon^2 - \omega_0^2}$ essentially controls the characteristics of the oscillation: if the difference is positive (i.e. $g$ is real) one talks of a heavily damped system; if the difference is negative (i.e. $g$ is imaginary) one talks of weak damping.

### 3.1. RESONANCE FREQUENCY

The upper limiting frequency of the linear range of the OBS/seabottom oscillator is determined by the elastic properties of the seafloor (shear and compressional wave velocities and associated elastic constants), the mass of the system and the damping of the system. In performing seismic experiments at sea, the 'worst' conditions for the coupling of an OBS are encountered on very soft sediments, i.e. on materials of very weak stiffness, as in this case the upper limiting frequency $f_c$ would then lie in the range of refraction seismic frequencies. From the push/pull tests performed on these media we can read the peak frequencies obtained for the IFG OBS and the IOS OBS (Fig. 5); these are recorded in Table 1. All OBS placed on bentonite showed critical frequencies in the range $f_c$ =4–8 Hz. For more rigid bottoms the critical frequencies shift to higher values: on sand $f_c$ =20–30 Hz and on concrete $f_c$ =70–80 Hz.

Similar peak frequencies have frequently been observed during actual measurements at sea. We therefore conclude that the peak frequencies are identical to the upper limiting frequencies $f_c$ which determine the system response (Fig. 6). As is evident from the recorded signal (Fig. 5), the IFG OBS is weakly damped on bentonite and critically damped on sand, whereas the IOS OBS is weakly damped on both materials. The spectral analysis of noise recorded on different geomorphological regions shows pronounced spectral peaks, varying with sites. In Fig. 7 we show some spectra to illustrate what we will call geological resonance phenomena, i.e. resonance effects of/in the uppermost sediment layer. Considering the uppermost layer as a mass-dashpot-spring matrix, this layer can be triggered to resonance amplification by the resonance frequency depending on the elastic parameter of the bottom, typically 4–8 Hz on soft sediments and 20–30 Hz on sandy grounds (Fig. 8). Resonance amplification due to the geological structure of the upper layer should be accompanied by resonance absorption observable in the spectra of seismic energy after traversing the medium. An indication of this mechanism can for example be found in air-gun recordings obtained in the LIIE experiment. For both reference systems, the neutral density and the plate-mounted sensor, peaks at about 23 Hz generated by (white) noise are observed (Fig. 9). At the same location there seems to be a 'resonance absorption' at 23–25 Hz for air-gun shots, showing a clear decrease in energy for these frequencies by almost 35 dB for the plate mounted and 30 dB for the neutral density sensor.

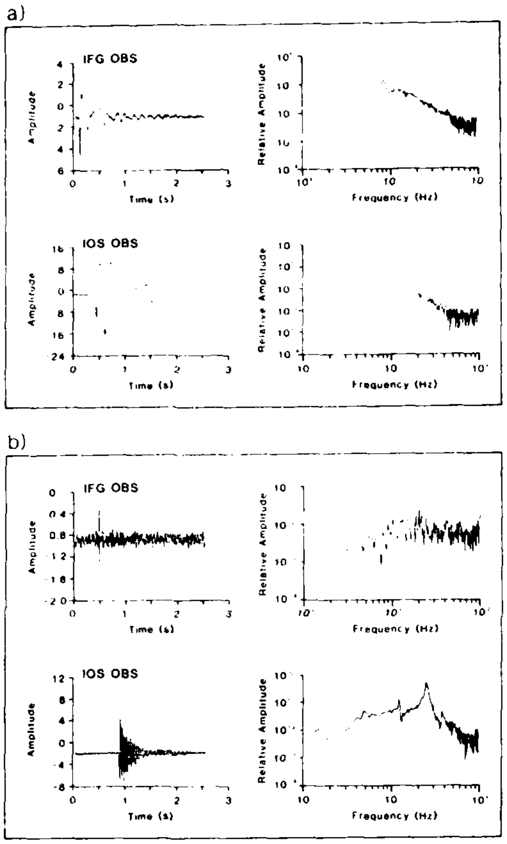

*Fig. 5.* **Examples of transient tests applied to the IOS (Wormley) OBS and to the IFG (Hamburg) OBS on bentonite (a) and on sand (b).**

*Table 1*
**Peak frequencies for test materials**

| OBS | Bentonite | Sand |
|---|---|---|
| IFG | **6 Hz** | **no significant peak** |
| IOS | **4 Hz** | **21 Hz** |

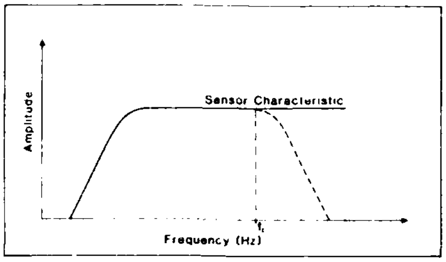

*Fig. 6.* Generalized response characteristics of an OBS with the critical frequency $f_c$ determined by site properties.

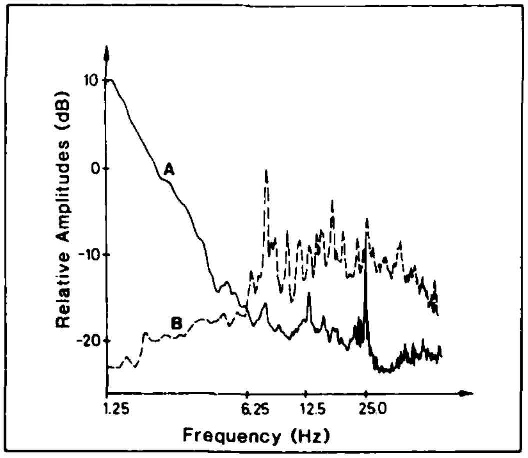

*Fig. 7.* Frequency spectrum of noise from OBS recordings obtained (A) on the West African margin and (B) in the Tyrrhenian Sea.

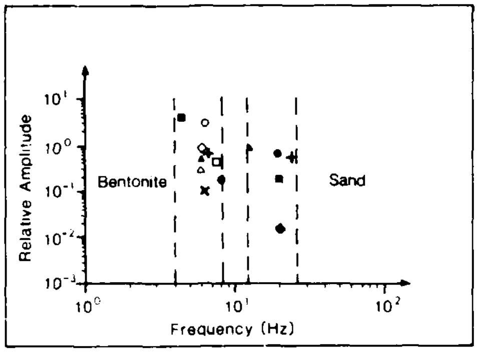

*Fig. 8.* Peak resonance frequencies obtained on the two characteristic soils used in the OBSCAL experiment for all OBS configurations.

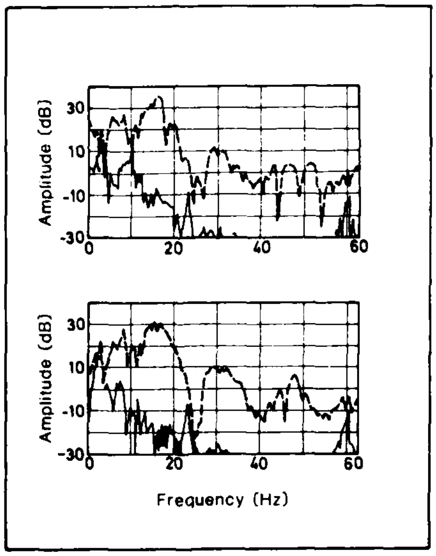

*Fig. 9.* Recording of air-gun shots (AG-182, Lopez Island) in the frequency domain with additional noise spectra plotted under the signal by the neutral density reference sensor (top, and the plate reference (bottom).

### 3.2. DAMPING

By exciting an OBS placed on the seafloor with a step-function input signal, a decaying sinusoidal output signal is generated. The decay ratio of this signal is directly related to the damping of the system. The parameter sensitivity analysis performed as a 'Gedankenexperiment' provides some insight into the processes determining the damping. As variables we have the mass $M$ of the OBS, the coupling area $\mathbf{Ca}$ and the bearing pressure $\mathbf{Bp}$. The variation of the buoyancy is used as a regulative for the bearing pressure. The following OBS cases will be considered:

(i) different mass, same $\mathbf{Ca}$, same $\mathbf{Bp}$;

(ii) same mass, different $\mathbf{Ca}$, same $\mathbf{Bp}$;

(iii) same mass, same $\mathbf{Ca}$, different $\mathbf{Bp}$;

(iv) different configuration of $\mathbf{Ca}$.

*(i) Variation of the mass* The typical response of an OBS to a step function input force can be seen in Fig. 5. In Fig. 10 we present the calculated envelopes of a decaying oscillation as a function of mass. We note that the decay is directly dependent on the mass of the system. This implies that for a weakly damped system with a large mass the output signal can be a monochromatic ringing triggered by the OBS/seafloor specific resonance frequency. This is a phenomenon frequently observed with early OBS data, allowing only a first arrival travel-time analysis.

*(ii) Variation of the ground area* The ground area is the area of the sensor (either the entire OBS when the sensor is inside the housing or the area of the external pack containing only the sensors). Let us consider the response of two instruments with the same mass $M$ but different coupling areas $\mathbf{Ca}_1$ and $\mathbf{Ca}_2$. Let $\mathbf{Ca}_2 = 2\mathbf{Ca}_1$ with $\mathbf{Ca}_1$ defined as a unit area attached to one spring (Fig. 11). The spring tension and thus the bearing pressure reduces to half by doubling the area. Under the assumption of linearity we can attach two springs to the area $\mathbf{Ca}_2$ maintaining the bearing pressure while doubling the mounted mass. A similiar argument shows that the system resonance may be manipulated by using larger ground areas and a smaller mass, resulting in a resonance frequency shift to the higher end of the frequency spectrum. The seismic signal causes a deformation of the surface in the range of only tens of nm at the receiver point. One has to be careful not to overdimension the ground area, since amplitudes generated by eigen-oscillations triggered by the arriving signal or other sources (ambient noise field, currents) larger or of the magnitude of the arriving signal may occur thus masking or distorting the actual signal.

For the OBSCAL comparison test the COB OBS was fitted with a sinker weight tripod with coupling pads of 100 cm length, which showed that these dimensions were beyond the limits mentioned above. It is therefore understandable that very complex signals were recorded in each of the different tests, with rather strong cross-

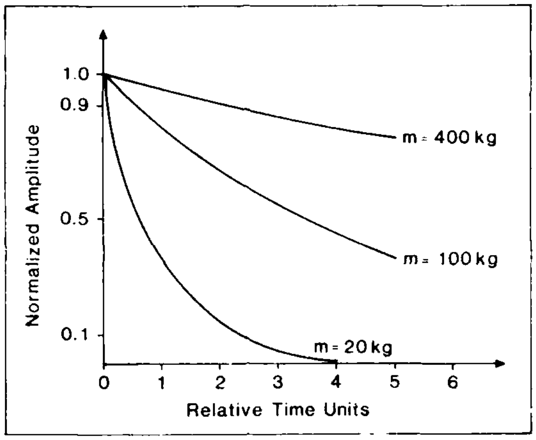

*Fig. 10.* Calculated damping curves (envelope of the oscillation decay) for systems of different mass, but with the same coupling area and bearing pressure.

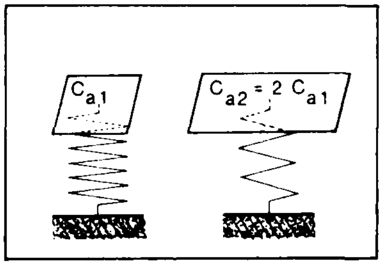

*Fig. 11.* Area-spring model to explain the effects of changes of area on the bearing pressure. Here the doubling of the area reduces the spring tension by half.

coupling effects. To show that signal distortion starts once the critical geometry is reached, we constructed three sinker weight tripods (a,b,c) with identical mass but different coupling areas (Fig. 12). An identical transient signal (vertical pull) was applied and the system output, recorded by geophones fixed to the tripod, was directly plotted on paper. The following results were obtained:

- for (a) the first pulse is well developed and is followed by a wave train of higher frequency signals; there is a certain amount of cross-coupling.
- for (b) we obtain a clear first pulse, with no other subsequent oscillations, and little cross-coupling.
- for (c) a very complex signal is obtained, with considerable cross-coupling.

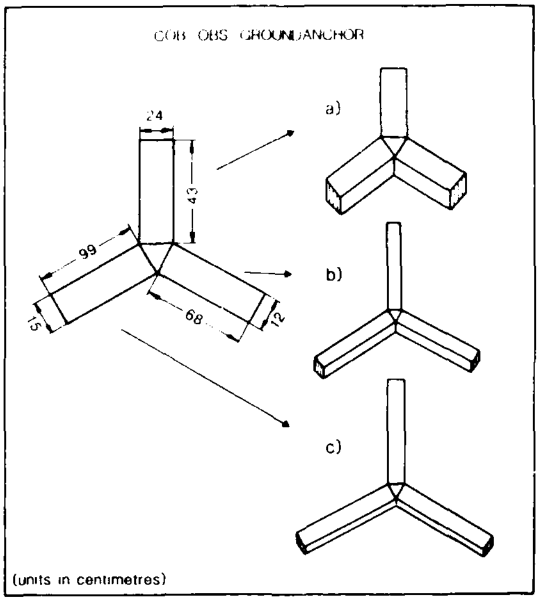

*Fig. 12.* **Ground area modifications of the Centre Océanologique de Bretagne OBS, maintaining the mass of the sinker weight but changing the area.**

*(iii) Change of bearing pressure* We now look at the effects of variable bearing pressure on systems with constant mass and coupling area. This is possible, since we can vary the buoyancy of the OBS accordingly. In our model with the unit area $\mathbf{Ca}_1$, changes in bearing pressure can be produced by varying the tension of the spring, i.e. doubling the spring restoring force (equivalent to doubling the stiffness of

the sediments) implies a doubling of the bearing pressure. The effects of changing the bearing pressure on the response of an OBS can also be simulated by changing the coupling area. Thus, doubling the bearing pressure has the same effects as reducing the area by half, i.e. we can obtain changes in bearing pressure by modifying either the mass or the coupling area (Fig. 13).

BEARING PRESSURE

| Variation of System Mass | | | | | | | Variation of Sediment Stiffness |
|---|---|---|---|---|---|---|---|
| 5 | 10 | 5 | 5/2 | 5/3 | 5/4 | 1 | 5 |
| 4 | 8 | 4 | 2 | 4/3 | 1 | 4/5 | 4 |
| 3 | 6 | 3 | 3/2 | 1 | 3/4 | 3/5 | 3 |
| 2 | 4 | 2 | 1 | 2/3 | 1/2 | 2/5 | 2 |
| 1 | 2 | 1 | 1/2 | 1/3 | 1/4 | 1/5 | 1 |
| 1/2 | 1/4 | 1/2 | 1 | 3/2 | 2 | 5/2 | 1/2 |
| | 1/2 | 1 | 2 | 3 | 4 | 5 | |

Variation of Ground Area

*Fig. 13.* Bearing pressure as a function of mass and ground area.

Critical values for the bearing pressure for systems on very soft sediments are reached when **Bp** exceeds the soil rigidity $\sigma_{\mathrm{break}}$. Applying the empirical formula given by [7] for very soft sediments

$$\sigma = (2 + \pi)C_u,$$

with $C_u$ = shear rigidity, we obtain

$$\sigma_{\mathrm{break}} = 26\ \mathrm{kN\,m^{-2}}$$

with $C_u \sim 5\ \mathrm{kN\,m^{-2}}$.

This means for an OBS landing on the seafloor with a speed of about 1 m/s: we have to design the OBS to a bearing pressure not exceeding $\mathbf{Bp}_{\max} = 10\ \mathrm{kN\,m^{-2}}$ or 0.1 $\mathrm{kg\,cm^{-2}}$. All except two OBS tested in Lopez Island and at the Centre Océanologique de Bretagne have values well below this.

*(iv) Configuration of the ground area* So far we have only considered OBS with a flat coupling area while many other designs are possible and in fact are currently being used. The effective bearing pressure of an OBS is therefore not necessarily a simple function of the shadow area of the coupling element, but the 3-D structure of the ground interacting element must be taken into account (Fig. 14). The assumption that the OBS after deployment rests ideally on the ground is also unrealistic.

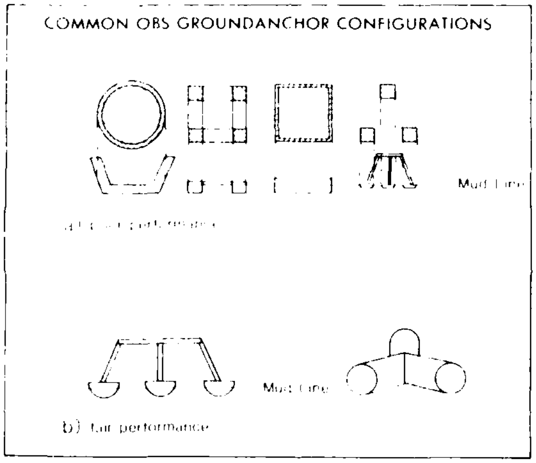

*Fig. 14.* Commonly used OBS ground anchor (area) configurations.

Field work and experiments at the COB have shown that an OBS can easily penetrate the seafloor and come to rest in a tilted position. If one uses ground plates, the sinking process will be dominated by a swinging movement, which might lead on impact with the bottom to the ground area becoming partially embedded in the mud. This may cause coupling as well as recovery problems. It appears that a spherical ground-interacting element should yield the best results, as penetration into the ground, and thus changes in bearing pressure, are automatically adjusted. Since for obvious reasons a sphere is not a practical solution, a low tripod with hemispherical footpads or a construction with cylindrical coupling bars should reveal better results for units combining sensors and recording devices. It is evident however, that the best results will be achieved if the sensor-pack is not integrated. The sensors should have a low profile to avoid current interaction and have a near-spherical structure but with a shape allowing a firm placement on the ground. In the OBSCAL experiment the Hamburg OBS came closest to this ideal, as was confirmed by the good performance on all grounds. Although during our COB experiment we modified only one parameter at a time, the above discussion shows that comparing systems (OBS) as in Lopez Island or in Brest means comparing units with few common coupling parameters, a procedure that is very complex at best.

A comparison of OBS recorded data is only permissible if the following parameters are identical (i.e. mass of the sensor unit, bearing pressure, coupling area, damping behaviour). Calculations of the transfer function of the coupling ground (site-specific filter function) are necessary for understanding and analysing individual OBS data. The comparison of recorded data of different OBS is permissible only if:

- the source function, is identical,
- the geological geometry does not change,
- *in situ* measurements of vertical and horizontal resonances have been performed and they correspond to each other over the profile.

### 3.3. FIDELITY AND SENSITIVITY OF AN OBS SYSTEM

The ultimate aim of recording seismic events with triaxial geophones is to be able to exactly reconstruct the true ground motion, i.e. to display the undisturbed arriving wavefield. Mass has a major effect on the damping of a system. Therefore the mass of a sensor, whether incorporated into the recording unit or placed externally, plays a decisive role in the quality of signal detection. A simulation with the above-mentioned network of mass-spring-dashpot systems (Fig. 15) will help to highlight this problem. If a pulse-shaped signal is fed into and transmitted through this matrix, the result will be a signal with almost the same total energy, but smaller peak amplitude and different frequency content. This recorded signal is directly dependent on the mass of the sensor and is further characterized by a time delay. It has also to be considered that a transducer draws energy from the wavefield due to the inertia effects and returns it with a phase difference. It is therefore necessary to operate an OBS with a density equal or close to the density of the material the sensor is resting on. This will allow the sensor to follow precisely the motion of the material, imaging the true ground motion. Since this cannot be achieved with conventional OBS, we have a strong argument in favour of external-pack sensor units. These can come close to the ideal outlined and represent the 'state of the art' in underwater seismology.

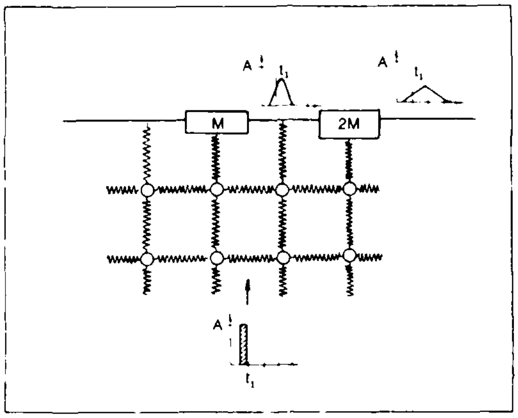

*Fig. 15.* Model of the upper marine sediments as a mass-spring-dashpot matrix showing the effective signal deformation in amplitude and frequency as a function of the sensor mass.

## 4. *Conclusions*

The experiments in Lopez Island (LIIE) and Brest (OBSCAL) have enabled us to outline the basic physics involved in the OBS/seafloor interaction. This was an important step forward in understanding and interpreting seismic data obtained from sensors deployed on the seafloor.

The results convincingly show that seismic measurements are best performed with external sensor-pack instruments since in most other cases the instrument itself distorts and changes the signal one wants to record. An analytical solution to the problems investigated, i.e. to the vertical and horizontal coupling behaviour, is certainly difficult and very complex since many parameters are involved. With the data obtained from the OBSCAL experiment we will try to quantify the processes involved establishing coupling parameters for different materials. We will then extend the coupling theory to include the horizontal components.

The assumption that the system response can be completely described as a linear phenomenon certainly does not hold throughout the entire frequency range investigated. The resonance amplification can obviously lead to nonlinear effects. However, we have so far excluded these specific problems at the resonance frequency from our discussion. A study of resonance and resonance absorption phenomena associated with the OBS/seafloor oscillation system and a physico-mathematical formulation of this complex problem will be the next steps.

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