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EVALUATION OF GEOPHONE GROUND COUPLING USING GEOPHONE/HYDROPHONE COMPARISON

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Ground coupling defines the transfer function from ground motion to geophone motion. Ground coupling can be described using a variety of models, which must all be adequately parametrized before being used on data. The ocean bottom seismometers and ocean bottom cables are the devices confronted to ground coupling problems. Besides the velocity measurements made via geophones, the mentioned two types of devices allow pressure measurements due to presence of hydrophones. In this paper, we introduce a method that searches iteratively for the velocity boundary conditions which, when applied to a finite element model, allow the simulation results to fit with pressure data measured by the hydrophones. The iterative process is supported by a genetic algorithm. The obtained velocity values provide the evaluation of ground coupling of the geophones.

KEY WORDS: geophone, ground coupling, hydrophone, velocity boundary conditions, acoustic pressure, iterative process, genetic algorithm

Ступiнь зчеплення з грунтом визначає передавальну функцiю, яка пов'язує змiщення грунту iз змiщеннями сейсмоприймача (геофони). Зчеплення з грунтом може бути описане з використанням рiзних моделей, якi повиннi бути належним чином параметризованi перш, нiж використовувати їх з даними вимiрювань. Океанськi доннi сейсмометри й океанськi доннi кабелi є пристроями, для яких гостро стоїть проблема оцiнки зчеплення з грунтом. Окрiм вимiрювань швидкостi, якi проводяться за допомогою сейсмоприймачiв, зазначенi два типи пристроїв дозволяють вимiрювати тиск завдяки наявностi гiдрофонiв. У цiй статтi запропоновано метод iтерацiйного пошуку граничних умов для швидкостей, якi, будучи застосованими в скiнченно-елементної моделi, дозволяють узгодити результати моделювання з даними про тиск, вимiряний за допомогою гiдрофонiв. Iтерацiйний процес реалiзовано у виглядi генетичного алгоритму. Отриманi значення швидкостi забезпечують оцiнку зчеплення сейсмоприймачiв iз грунтом.

КЛЮЧОВI СЛОВА: сейсмоприймач, зчеплення з грунтом, гiдрофон, граничнi умови для швидкостей, акустичний тиск, iтерацiйний процес, генетичний алгоритм

Степень сцепления с грунтом определяет передаточную функцию, связывающую смещения грунта со смещениями сейсмоприемника (геофона). Сцепление с грунтом может быть описано с использованием различных моделей, которые должны быть надлежащим образом параметризованы прежде, чем использовать их с данными измерений. Океанские донные сейсмометры и океанские донные кабели являются устройствами, для которых остро стоит проблема оценки сцепления с грунтом. Помимо измерений скорости, проводимых с помощью сейсмоприемников, указанные два типа устройств позволяют измерять давление благодаря наличию гидрофонов. В этой статье предложен метод итерационного поиска граничных условий для скоростей, которые, будучи примененными в конечно-элементной модели, позволяют согласовать результаты моделирования с данными о давлении, измеренном с помощью гидрофонов. Итерационный процесс реализован в виде генетического алгоритма. Полученные значения скорости обеспечивают оценку сцепления сейсмоприемников с грунтом.

КЛЮЧЕВЫЕ СЛОВА: сейсмоприемник, сцепление с грунтом, гидрофон, граничные условия для скоростей, акустическое давление, итерационный процесс, генетический алгоритм

INTRODUCTION

Seismic and seismology need accurate measurement of soil motion. Geophones and hydrophones are designed to produce a linear response to velocity or to pressure in accordance to the ground motion.

In practice, the transfer function of the geophone is never perfectly linear. Firstly, because of the geophone itself which response depends on its resonance frequency. Secondly, because of the so-called geophone ground coupling term that describes the transfer function from ground motion to the output voltage of the geophone. Ground-coupling affects seismic exploration and monitoring. Papers [1,2] and others have shown that the effect of geophone coupling may play a prominent role even for frequencies below 100 Hz.

The two main causes responsible for ground coupling include the disturbances in the wave-field influencing ground motions due to the presence of the device and disturbances resulting from contact conditions between the device and the ground, also referred to as weight coupling.

A very general definition is used for ground coupling:

$$C(w) = \frac{V_{\text{geophone}}(w)}{V_{\text{ground}}(w)} . \qquad (1)$$

Different models of ground coupling have been developed. Some resolve the equation of motion by modeling the geophone and the ground as a spring and mass system like in [3]. Other resolve a weak form equation of motion as in [4]. These models explain ground coupling mechanism but depend on tests to be used on exploration data, which is usually the only available information.

In marine acquisition, geophones are mainly used in Ocean Bottom Seismometers and Ocean bottom cables. These devices often comprise three geophones and one hydrophone. Our method compares hydrophone and geophone data to estimate the amplitude spectra of vertical and horizontal coupling coefficients.

We will start our discussions with the assumptions required by our method. We will then explain its principles, describe the finite element model and the iterative process on which it rests, and we will conclude this paper with results obtained on synthetic data.

1. HYPOTHESIS

Geophone ground coupling has various dependencies to seabed parameters as buried depth, contact surface, seabed density and type, etc. Measuring those parameters is often complicated and expensive. To avoid these issues, we have developed a method that relies on hydrophone and geophone data comparisons.

To make this comparison possible, we first assume that the device's transfer function can be neglected and that hydrophones, due to their two opposite ceramics that attenuate acceleration, are not affected by ground coupling.

We also assume that seabed can be modeled by an elastic solid with a perfect fluid interface, and we consider that seismic waves are plane waves. These assumptions are often used in seismic like in [5]. In these conditions, vertical stress and pressure are opposite at fluid/solid interfaces and the velocity and the pressure have the same time dependency in e^{iwt}.

2. GENERAL APPROACH

In "perfect" coupling conditions, when ground velocity is equal to geophone velocity, the OBS should behave as a volume of sediment. If we model this "perfectly" coupled OBS and apply geophone data as velocity boundary conditions, simulation pressure should be equal to hydrophone measurements. Otherwise, coupling is involved.

By modifying iteratively geophone data using weighting on selected frequency bands, we can produce new boundary conditions and significantly reduce differences between the simulated pressure and the hydrophone data.

Comparison between these modified geophone data and geophone measurements allows us to evaluate ground coupling.

3. THE FINITE-ELEMENT MODEL

The finite element method has been used for years within the industry and has been described extensively. For a good review of this method, the reader is referred to the work of [6]. This section focuses on describing our modeling choices.

OBS measures its own motion which is supposed to be similar to ground motion. In optimal conditions, the OBS should behave like a volume of sediment ; a volume whose size can be considered negligible compared to the wave length of the measured signal, to acknowledge the measure as a point.

The OBS is therefore modeled as an elastic solid moving at ground motion velocity with its upper surface behaving as fluid/solid interface. Our model uses velocity as boundary conditions with pressure calculated from its upper surface.

The finite element method requires discretization in both space and time as well as the characterization of the material behavior:

- To reduce computational time, the OBS is represented as a cube formed of 32 linear tetrahedrons. Time discretization rests on a backward Euler method which discrete time using consideration on the future step

  $$\Delta t = t_{n+1} - t_n, \qquad (2)$$

  where Δt is the time step that must be sufficiently small to assume the system response approximatively constant during $[t_n, t_{n+1}]$. This method gives an approximation $f(x(t)$ at each time step using its value at the interval endpoint $f(x_{n+1})$:

$$x_{n+1} = x_n + \Delta t f(x_{n+1}). \qquad (3)$$

- As an elastic and homogeneous solid, the mechanical behavior of the OBS is described as follows:

$$\sigma = 2\mu\varepsilon + \lambda\,\mathrm{tr}(\varepsilon)\,\boldsymbol{I}, \quad \varepsilon = \frac{\nabla v(x) + \nabla^T v(x)}{2}. \qquad (4)$$

- Our model uses a weak form based on a displacement formulation:

$$u(x,t) \in S \qquad \forall v(x) \in \Omega$$

$$\int\limits_{\Omega} \rho \ddot{u}(x,t) v(x) d\Omega + \int\limits_{\Omega} \sigma\varepsilon^* d\Omega = \\ = \int\limits_{\partial\Omega_f} f(x,t) v(x) dS. \qquad (5)$$

We then apply boundary conditions to our model:

- On the vertical and the inferior boundaries of the model, we apply a velocity which, in our method, either is the velocity measured by the geophone, or is a modification of this velocity.
- As a fluid/solid interface, the upper surface $\partial\Omega_{\mathrm{upp}}$ assumes no shear:

$$\sigma_{xz} = \sigma_{yz} = 0. \qquad (6)$$

These choices allow the construction of a linear system that we solve using the Newton method.

The simulation pressure can then be obtained at the upper surface by relating the vertical stress and the pressure at a fluid/solid interface using:

$$P = -\sigma_{zz}. \qquad (7)$$

4. VELOCITY BOUNDARY CONDITIONS

As a test, a first simulation is done using geophone data for the velocity boundary conditions.

We evaluate the results using a method of the least squares (MLS):

$$C(a_j p_j, P) = \frac{\left(\sum\limits_{i=0}^{n} \left(\sum\limits_{j=0}^{N} a_j p_j(i) \right) P(i) \right)^2}{\sum\limits_{i=0}^{n} \left(\sum\limits_{j=0}^{N} a_j p_j(i) \right)^2 \sum\limits_{i=0}^{n} P^2(i)}. \qquad (8)$$

Values of $C(a_j p_j, P)$ closest to 1 indicate close approximations to hydrophone data.

As pressure results usually diverge from the hydrophone, we search for new velocities to apply to the model.

Modification of boundary conditions

According to our hypothesis, with perfect coupling, the calculated pressure should fit the hydrophone data. When it doesn't, coupling is involved. We must then find better velocity boundary conditions to obtain a new pressure that assumes better resemblance.

Coupling has often been described as a resonance phenomena lightly influenced by phasing [1]. We decide not to modify the phasing to operate on the geophone amplitude spectra only. This operation divides each geophone signal in 10 frequency bands using a forward and backward discrete Fourier transform:

$$S(x) = \sum_{n=0}^{N-1} s(n) e^{-2\pi k n/N} \quad \text{for} \quad 0 \le k < N, \qquad (9)$$

where $S(x)$ is the geophone signal in the frequency domain and $s(n)$ in the time domain.

Frequencies out of the band of interest are discarded and the selected 10 frequency bands are weighted. An inverse Fourier transform brings the signal back in the time domain:

$$s(n) = \frac{1}{N} \sum_{n=0}^{N-1} \sum_{i=1}^{10} a_i S_i(k) e^{2\pi k n/N} \qquad (10)$$

with $a_i = 0$ for $if < k < (i-1)f$; f is the size of the frequency band and a_i is the weighted coefficient of the i-th frequency band.

Three new velocities are then created (one per geophone) and are used as new boundary conditions for a new simulation.

We now need to find the right coefficients for the simulated pressure to be close enough to the pressure measured by the hydrophone.

Weighting coefficients

Searching randomly for a solution would mostly be inefficient and even searching over a space of finite possibilities would rather be impossible due to the time needed to cover a space containing a sufficient amount of possibilities to provide a suitable solution.

We therefore select an iterative process based on a genetic algorithm [7]. Genetic algorithm have strong convergence properties and are often used to select a

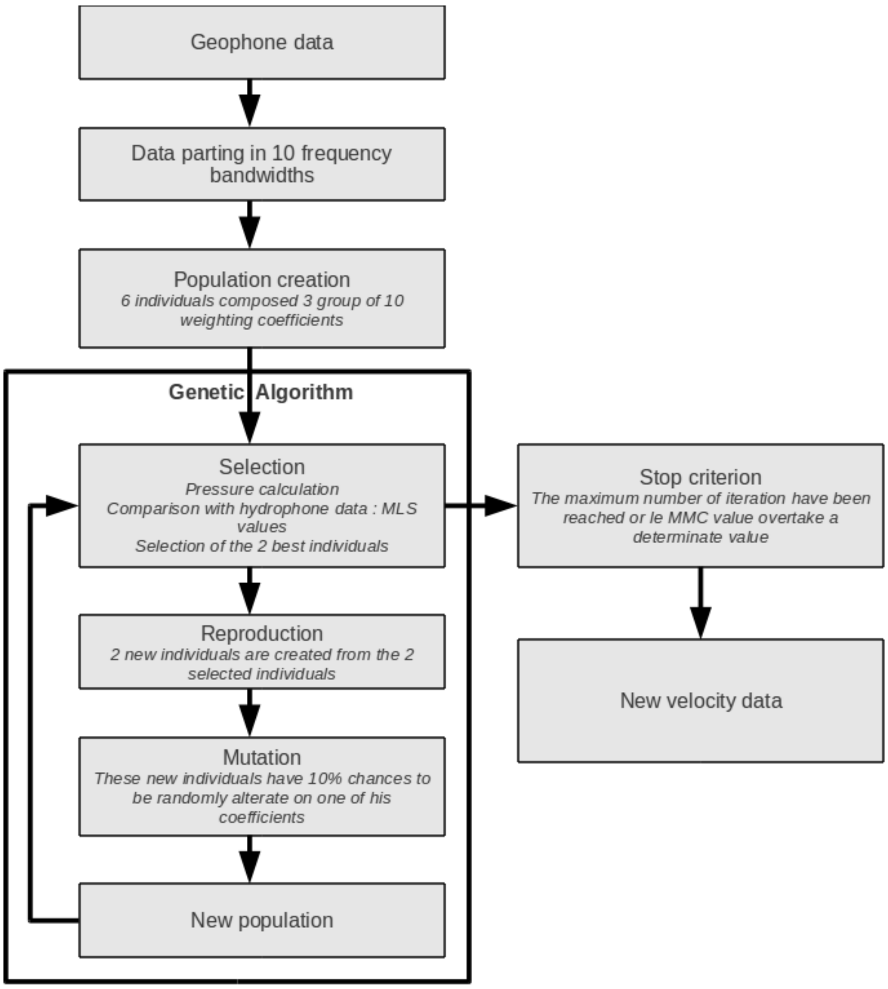

Fig. 1. Outline of our method

solution in important value sets. Genetic algorithms copy natural selection which can be summarized in four steps:

- *creation of a population*: we create six individuals, each containing 30 weighting coefficients and three geophone datasets divided in 10 frequency bands.
- *selection*: a simulation pressure is calculated for each individual and compared to the hydrophone signal using MLS. Two individuals are then chosen randomly with a greater probability for individuals with MLS values closest to 1 to be selected.
- *reproduction*: two new individuals are created from the two selected individuals sharing half of the weighting coefficients of each parents.
- *mutation*: each new individual has a 10 % chance to undergo random modification for one of his coefficients.

New individuals replace the two worst individuals in the population. The process is then repeated with the new population and ends when the desired MLS or an iteration number is reached.

Our method is summarized in fig. 1.

5. GEOPHONE GROUND COUPLING

Once the new velocities are found, ground coupling coefficients $C(t)$ can be calculated using:

$$C(w) = \frac{V_{\text{geophone}}(w)}{V_{\text{modified}}(w)}. \tag{11}$$

6. NUMERICAL RESULTS

We present here the results from four different datasets. These datasets are synthetic data obtained using a software developed in SEATECH that calculates the amplitude and the propagation time of different reflections of a wave propagating in a stratified media. This software does not take into account multiple reflections.

With this software we have produced a unique dataset of 2.5 s duration, on which we have applied 4 different coupling coefficients. These coupling coefficients are calculated using the G. G. Drijkoningen model [4].

Coupling coefficients are calculated for a cylinder of 3 cm radius, 60 cm length, an OBS density of 4700 kg/m^3 and a soil density of 1700 kg/m^3. The signal created lasts 2.5 s and is sampled at 250 Hz. It has been shown that horizontal and vertical coupling often differ. Even if G. G. Drijkoningen's theory is only made for vertical motion, we also apply that coupling on horizontal components. Our purpose is to show the capacity of our approach to recover coupling coefficients.

Dataset 1 has a low coupling contribution over its horizontal component (obtained using G. G. Drijkoningen's elastic model with $v_p=800$ m/s and $v_s=400$ m/s) and a strong one applied to the vertical component (with $v_p=200$ m/s and $v_s=100$ m/s).

Dataset 2 is similar to dataset 1 except that the same low coupling contribution is applied to the vertical component and the strong contribution to the horizontal one.

On dataset 3, the cylinder has the same coupling on both components ($v_p=200$ m/s and $v_s=100$ m/s).

Dataset 4 is obtained using strong coupling contributions on both components (with horizontal coupling coefficient obtained for $v_p=200$ m/s and $v_s=100$ m/s, and vertical coupling coefficient obtained for $\rho=2200$ kg/m^3, $v_p=800$ m/s and $v_s=80$ m/s).

After applying our method on these datasets, we study frequencies in the 50 to 150 Hz domain.

Fig. 2 displays the amplitude spectra of the coupling coefficient applied to the dataset and those recovered using our method. Results show erratic variations all over the studied frequencies. On low coupling contributions, differentiating between artefacts and coupling effects becomes challenging. Genetic algorithms are not determinist and using them on a short 2.5 s signal and a simple run of our method certainly explains most of these artefacts. Still, our method seems to enhance strong coupling contributions (cf. fig. 2, *b*, *c*, *e*, *f*, *g* and *h*).

7. DISCUSSIONS

Our method suffers from two main limitations:

- the first is the link to the variations that may be introduced in the results and can complicate the interpretation of the coupling contribution. A better accuracy could be obtained by working on a longer signal and multiplying simulations with various configurations (changing the number of coefficients, the size of the frequency bands) to combine results and find a trend.

- the second limitation is the computational time. The finite element method is computationally intensive even with our simple model. With a 1.4 GHz core and 4 Gb RAM, it takes close to 48 hours to produce the results displayed in fig. 2. Improving the calculation time should also improve the method accuracy allowing the method to search in a bigger space of solution. This could be done by parallelizing the code and using analytical or empirical calculation instead of the finite element model. We have already made some trials that divide the computational time by 60, but further tests are still required.

CONCLUSIONS

In this paper, we have presented a new method which evaluates geophone ground coupling by comparing geophone and hydrophone data. The method searches the velocity boundary conditions of a finite element model required to produce simulation results close to the pressure measured by the hydrophone. The calculated velocities allow the estimation of the geophone ground coupling. Current results produce artefacts that could conclude to misinterpretation and the calculation time is too important to apply this method to a huge amount of data. However different solutions are to be tested to solve those problems and results on strongly coupled datasets are encouraging for both horizontal and vertical components. As this method does not need any preliminary test, it can then be applied to historical measurements, at first to test the method and, if the tests confirm its relevance, to estimate OBS ground coupling.

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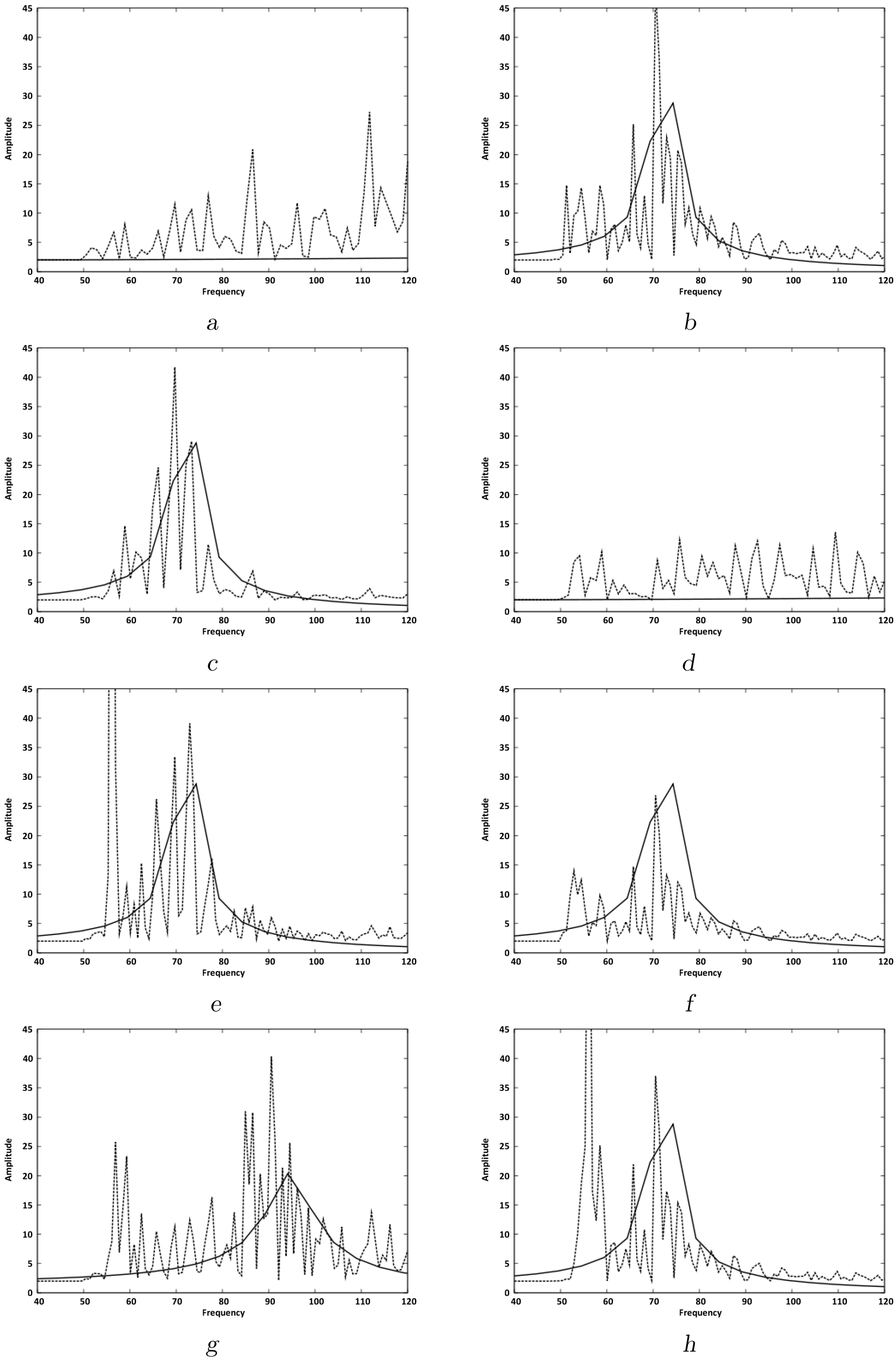

Fig. 2. Comparison between the amplitude spectrum of the coupling coefficients applied to different datasets and those found using our method. Left figures concern amplitude of horizontal components, right figures of vertical components. Amplitude spectrum of couplings coefficients applied to components are represented by solid lines, dash point lines are amplitude spectrum of coupling coefficients obtained using our method:

a, *b* – coefficients from dataset 1, *c*, *d* – coefficients from dataset 2,
e, *f* – coefficients from dataset 3, *g*, *h* – coefficients from dataset 4

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NOMENCLATURE

C	– geophone ground coupling coefficients;
u, v, $\ddot{u}$	– displacement, velocity, acceleration;
$\dot{V}_{\text{geophone}}$	– Velocity measured by geophone;
$\dot{V}_{\text{ground}}$	– Velocity of the ground;
V_{p_i}	– P-wave velocity in the media i;
V_{s_i}	– S-wave velocity in the media i;
w	– frequency;
σ	– stress;
μ, λ	– Lamé coefficients;
ρ	– density;
ρ_w	– water density;
ε	– strain;
P	– pressure.