A theoretical and experimental approach to the geophone-ground coupling problem based on acoustic reciprocity

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Summary

In order to obtain finer detail in seismics, it is necessary to transmit and to receive signals with a sufficient broad frequency spectrum. This puts restrictions on all the constituent members of the seismic acquisition chain. In land seismics, an important aspect of the deployment of geophones is the coupling of the geophone to the ground. Ideally, we would like the motion of the geophone to be representative for the real motion of the ground. Two phenomena cause the motion of the geophone being different from the motion of the ground without geophone. First, when there is perfect contact between the geophone and the ground, the presence of the geophone will disturb the wavefield and thus will influence the recordings. The second problem may sometimes arise if the geophone is not in good contact with the ground, for instance if the geophone is poorly planted. Both problems depend on the soil conditions. Most existing theoretical models simulate the geophone as a cylinder, located on the earth's surface, and thus neglect the influence of the spike. Tan (1987) noticed that the spike is too important to neglect, and theoretical models neglecting the spike cannot be compared with experiments, in which geophones with spikes are used. In this study, we derive an expression for the ground coupling for a simple model of a cylindrical spike in perfect contact with the surrounding medium. Field experiments, carried out in the Netherlands, partly support the results from the theoretical model, in which the data behaviour is described as a function of the coupling parameters.

Definitions and descriptions

When browsing in the literature about the ground-coupling phenomenon, the first thing that has to be noticed is that there is no clear definition of the problem. There is general agreement that the motion of the planted geophone is not equal to the motion of the ground in absence of the geophone. However, different authors investigate different causes. We divided the phenomenon into two different problems: the Interaction Problem and the Contact Problem.

The Interaction Problem finds its origin in the fact that the geophone itself, as contrasting medium with respect to its surroundings, disturbs the wavefield. The measured wavefield is the sum of the undisturbed field and the diffracted field generated by scattering due to the presence of the geophone.

In the Interaction Problem, we assume perfect contact between the geophone and the ground. Because of the material differences between the soil and the geophone (or spike), the ground displacement is not exactly the same as the geophone displacement. An influence zone can be thought around the geophone. Outside this zone, the presence of the geophone has no effect on the wavefield. The wavefield is the same as the wavefield that would exist if there was no geophone present. But inside the influence zone, the displacement of the ground is different from the displacement in the case the geophone were absent. In order to compare the influence of different parameters on the coupling, we have to define a quantity which qualifies the coupling. The Interaction Coupling is defined as the ratio between the geophone velocity and the ground velocity in absence of the geophone — assuming perfect contact between the ground and the geophone. This is expressed as

$$C_I = \frac{V_{geo,pc}}{V_{gr}}, \quad (1)$$

where

$V_{geo,pc}$ is the velocity of the geophone, assuming perfect contact,
 V_{gr} is the velocity of the ground in absence of the geophone.

In practice, it may occur that there is no perfect contact between the geophone and the ground surrounding the geophone. The geophone may be poorly planted, or the local soil conditions may not allow perfect contact. This is usually to be considered the more serious problem, but will not be considered here for the moment. The Contact Coupling is defined as the ratio between the actual geophone velocity and the geophone velocity assuming perfect contact. This is expressed as

$$C_C = \frac{V_{geo}}{V_{geo,pc}}, \quad (2)$$

where

V_{geo} is the velocity of the ground in presence of the geophone.

From Definitions (1) and (2), it follows that the total coupling — that is the ratio between the velocity of the geophone and the velocity of the ground in absence of the geophone — is expressed as

$$C = \frac{V_{geo}}{V_{gr}} = C_C C_I. \quad (3)$$

Theoretical model for the Interaction Coupling

Since it turns out to be impossible to measure the velocity of the ground — by means of a geophone — without disturbing it, we need a theoretical expression for the Interaction Coupling.

Theoretical formulation

We expect that, at least for geophones with spikes, it is the spike that determines the coupling quality. Therefore, we neglect the geophone case and simulate the geophone by its spike only. The spike is modelled as a cylinder, which is vertically placed immediately below the earth's surface (Figure 1). The cylinder is a perfectly rigid object, and its dimensions are small compared with the wavelengths of the waves we consider. Therefore, we can assume that the velocity at the bottom of the cylinder is equal to the velocity at the top of the cylinder. As a first approximation, we considered an acoustic model, supposing no shear stresses can occur. Our analysis will be carried out in the space-frequency domain.

We consider the geophone as a bounded, contrasting domain located at the boundary of an acoustic half-space. When an incident wavefield is present, the contrasting domain will give rise to a scattered wavefield with velocity component $\hat{v}^{sc}$ in the frequency domain. Following the work of Fokkema and van den Berg (1993), we can derive an integral equation for the scattered particle velocity $\hat{v}^{sc}$ as a function of the total particle velocity $\hat{v}^{tot}$. In particular, the normal component $\hat{v}_3^{sc}$ is given by

$$\hat{v}_3^{sc}(x^R) = \int_{x \in \partial D_{sc}} \left[\hat{G}_3^f(x^R | x) \hat{v}_3^{tot}(x) + \hat{\Gamma}_{3,k}^f(x^R | x) \hat{p}^{tot}(x) \right] n_k dA, \quad (4)$$

integrating along ∂D_{sc} , the surface of this contrasting domain. $\hat{G}_i^f$ and $\hat{\Gamma}_{i,k}^f$ are the Green's functions, describing the relationship between the pressure $\hat{p}$ and the particle velocity $\hat{v}$ respectively, due to a dipole source

Figure 1: Model definition.

located somewhere in the half-space. $\hat{G}_f^i(\mathbf{x}^R | \mathbf{x})$ means that we consider the Green's function $\hat{G}_f^i$ in a point $\mathbf{x}^R$ due to a dipole source in $\mathbf{x}$. Further, $\mathbf{n}$ denotes the unit normal vector perpendicular to the surface and pointing outward.

For relative small dimensions, frequencies of seismic interest and common propagation velocities c , we can write

$$\frac{\omega}{c} |\mathbf{x}| \ll 1, \quad (5)$$

where $|\mathbf{x}|$ is the distance between the middle point of the geophone and some point at the edge of the lower base and ω is the angular frequency.

We neglect all higher-order terms, so no terms including $\omega|\mathbf{x}|/c$ are regarded. We can then derive that the expression for the Interaction Problem becomes:

$$\frac{\hat{v}_3^{tot}}{\hat{v}_3^{inc}} = \frac{1}{2 - \frac{h}{\sqrt{R^2 + h^2}} - \frac{R^2 h}{\sqrt{(R^2 + h^2)^3}} \frac{\rho_{geo}}{\rho_{soil}}}, \quad (6)$$

where

- h is the length of the cylinder,
- R is the radius of the base,
- ρ_{geo} is the density of the geophone,
- ρ_{soil} is the density of the soil.

This term is only the first term in a Taylor expansion, but it shows already some quite significant features. We acknowledge that the frequency-behaviour is not included. For a complete derivation of Equation (6) we refer to the work of Vos (1995).

Theoretical simulations

In all the simulations, we used a spike with a density of 7800 kg/m^3 . In Figure 2, the Interaction Coupling is plotted for a spike with radius of 0.5 cm and a soil density of 2000 kg/m^3 as a function of the spike (cylinder) length h . We see that there is a "resonance-length" for which the spike almost loses contact with the ground. However, this "resonance-length" is rather small, and we can intuitively expect that at this level the gravitational force due to the presence of a geophone case — which is not present in our simulation — will cause the geophone to stay at the earth. It appears that the Interaction Coupling asymptotically reaches a value of 1, which means that the measured quantity is the real ground velocity. In the other figures, the start-value at the x -axis is a few centimeters, so the resonance phenomenon does not appear.

A variation of the soil density (Figure 3) shows that for heavy soils, the unit value is reached earlier in comparison with loose soils. This is

Figure 2: Resonance phenomenon for small spikes. Spike radius $R = 0.005 \text{ m}$. Figure 3: Variation of soil density. Spike radius $R = 0.005 \text{ m}$. Solid line: $\rho_{soil} = 1000 \text{ kg/m}^3$; Long dashes: $\rho_{soil} = 2000 \text{ kg/m}^3$; Short dashes: $\rho_{soil} = 4000 \text{ kg/m}^3$. Figure 4: Variation of spike radius. Density $\rho_{soil} = 2000 \text{ kg/m}^3$. Solid line: $R = 0.02 \text{ m}$; Long dashes: $R = 0.01 \text{ m}$; Short dashes: $R = 0.005 \text{ m}$.

understandable, because when the material parameters of the soil and the spike are getting closer to each other, no contrast will occur. As a consequence, longer spikes have to be used in soils with a lower density in order to obtain the same coupling quality. Also, the difference between shorter and longer spikes will be more explicit in soils with a lower density, since for a given length-range, the curve becomes flatter with higher densities.

A variation of the spike-radius (Figure 4) shows that for thin spikes, i.e. spikes with a small radius, the unit value is reached earlier in comparison with thicker spikes. This means that, when using thicker spikes, one also has to use a longer spike in order to obtain the same coupling quality.

Field experiments

To see whether this model is adequate for determining the Interaction Coupling a few field experiments have been done.

Soil properties

The experiments were done at two locations with totally different soil conditions: consolidated, saturated medium-grained sand at Wassenaar Beach, the Netherlands and compacted clay at Opheusden, the Netherlands. The mean density of the sand is 3050 kg/m^3 and the compressional wave velocity is 200 m/s . The mean density of the clay is 2680 kg/m^3 and the compressional wave velocity is 430 m/s . These densities and velocities were locally measured using soil-mechanics tools.

Field set up

In the experiments, 10 Hz geophones with PE-3 cases were used, with spikes of a different length. The spikes that were used have a length of respectively 50, 25 and 10 cm. Dynamite of 125 grams has been used as source. The recording time is 2000 ms with a sample interval of 1 ms. The geophones were planted on a distance of 150 and 110 meters from the source, respectively in Wassenaar and Opheusden. Geophones were planted in four squares of one m^2 on a cross-line, each square consisting of geophones with the same spike length and having the same planting condition. Near surface variations are assumed to be negligible, both in the sand and in the clay.

Results

From the shot records, the difference in recorded signal for geophones with different spike lengths can be seen immediately. Figures 5a and 6a show the first part of the shot record, for respectively the Wassenaar and Opheusden data, in which the spike length is indicated above the traces. Because the traces of the geophones with the same spike length show good similarity, these traces have been stacked. A good reflection has been selected. In the Wassenaar data this event occurs at 250 ms (indicated by an arrow in Figure 5a) and in the Opheusden data, the reflection at 200 ms has been chosen (indicated by an arrow in Figure 6a). We applied a window of 50 ms over the reflection (including a tapering at the beginning and end) and determined the amplitude spectra of this window. The stacked trace of the window over the reflection for all spike lengths is shown in figure 5b for the Wassenaar data. Figure 5c shows the amplitude spectrum of these windowed traces. Figure 6b and c show the same sequence of figures for the Opheusden data. In general, the differences between recordings of geophones with different spike length are remarkable, both in the time and the frequency domain. Obvious is the decreasing

energy content for increasing spike length, that corresponds with a decreasing of the Interaction Coupling, which is predicted by the model. However, differences in amplitude for the different spikes are dependent on frequency. From the frequency behaviour of the data, we may conclude that the effect of spike length results in a frequency-dependent scaling of the amplitude spectrum. From this, we infer that the difference in coupling introduces apparent dispersion and attenuation, which we cannot explain with the existing model. In the region of 100 to 150 Hz, the difference in amplitude is the most evident. The energy in this frequency region corresponds with the main reflection arrival in the window, that has a period of approximately 10 ms.

The density of the clay in Opheusden is lower than the density of the sand in Wassenaar. Comparing figures 5c and 6c, we see that the amplitude ratios for different spike lengths in the region of 100 to 150 Hz are higher for the Opheusden data, which also is predicted by the model.

Conclusions

One of the goals of our study was to compare field data as measured from experiments with a theoretical model that assumes perfect contact between the geophone spike and the ground. Differences between the theoretical predictions and the experimental data are thus due to the fact that there is no perfect contact between the spike and the ground — what we call the Contact Coupling. Further, the model is only valid for acoustic media. From the experiments, we could see that the main predictions from the model occur in reality (e.g. decreasing energy for increasing spike length). Besides, two important differences are noted:

1. In practice, the coupling turns out to be frequency-dependent,
2. The differences in coupling for different spike-lengths is underestimated by the theoretical model.

Future work will concern the expansion of the theoretical work to elastic models.

Acknowledgments

This work has been sponsored by the EEC under the Thermie programme, contract no. OG/00150/94/DE/UK/NL. Also, one of the authors (JV) has been sponsored by the Erasmus programme to be able to do this work.

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Figure 5: a) Shot record from Wassenaar beach, sand soil; different spike lengths of geophones indicated. b) Window over reflection at 250 ms. From left to right: Spike length: 50 cm, 25 cm, 10 cm, 0 cm. c) Amplitude spectrum of this windowed traces; Solid line: spike length is 50 cm, Long dashes: 25 cm, Short dashes: 10 cm, Dotted: 0 cm.

Figure 6: a) Shot record from Opheusden, clay soil; different spike lengths of geophones indicated. b) Window over reflection at 200 ms. From left to right: Spike length: 50 cm, 25 cm, 10 cm, 0 cm. c) Amplitude spectrum of this windowed traces; Solid line: spike length is 50 cm, Long dashes: 25 cm, Short dashes: 10 cm, Dotted: 0 cm.