GEOPHYSICS, VOL. 65, NO. 6 (NOVEMBER-DECEMBER 2000); P. 1780–1787, 8 FIGS.

The usefulness of geophone ground-coupling experiments to seismic data

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ABSTRACT

Ground-coupling devices measure local conditions around a geophone and are therefore useful for geophone design. For purposes of gathering seismic data, the data from local ground-coupling experiments must be related to seismic data. In particular, the geophysicist wants to know whether a local measurement could help in detecting a ground-coupling problem or in correcting the seismic data for it. Two sets of field experiments have been carried out to investigate these effects. Our experimental data of coupling-measurement devices show that the behavior of well-planted spiked geophones is determined by shear along the spike, while the behavior of poorly planted geophones is determined by its weight. However, when a link is established between the data from a coupling-measurement device to seismic data, it becomes clear that the usefulness of this device for predicting problematic ground-coupling phenomena in seismic data is very limited.

INTRODUCTION

Ground coupling of geophones is still not a well-understood problem. Increased interest in single-sensor technology, three-component technology, four-component ocean-bottom sensors, and high-resolution seismics requires a better understanding of geophone-coupling problems. In this paper, experimental aspects of geophone coupling are investigated further, continuing from reports in the literature. A paper by Krohn (1984) is the most important in this area. The goal of this study was to investigate whether and how local ground-coupling measurements could help in detecting and/or correcting seismic data for ground-coupling problems. To answer these questions, some basic aspects of coupling required careful reinvestigation.

A clear distinction is made in this paper between so-called spike-shear coupling and weight coupling. The former term refers to the assumed way a spiked geophone is coupled to the ground and is important for geophone design. In weight coupling, it is purely the weight of the detecting device that furnishes the coupling between the geophone and the ground. This distinction between the two ways of coupling has become clear after the introduction of a spike in theoretical models by Tan (1987) and by Rademakers et al. (1996). In this paper, the focus will be mainly on the distinction between spike-shear and weight coupling of geophones. This is a common problem that the practicing geophysicist encounters when a geophone is not "well" coupled to the ground.

The paper by Krohn (1984) about experiments on ground coupling clearly describes the different laboratory and field techniques used to determine such coupling. Here, only field techniques are described briefly and used, with a focus on how to relate these measurements to seismic data. Measurements have been carried out in different soils, using two types of coupling-measurement devices. In addition, seismic-shot records were taken at the same locations. These results have been analyzed and conclusions have been drawn about the usefulness of such measurements to seismic data.

CONCEPTS OF GROUND COUPLING

The first issue in ground coupling is to define what geophone ground coupling means. In the past, some confusion has arisen because theoretical models did not explain experimental results about spiked geophones (see, for example, Krohn, 1984). Thus, theoreticians seemed to have a different meaning for ground coupling than that used by the practicing geophysicist. The definition of geophone ground coupling used in theoretical models (see, for example, Tan, 1987) is as follows: Geophone ground coupling is the difference between the velocity measured by the geophone and the velocity of the ground without the geophone. This definition is useful for the design of geophones so that optimal characteristics can be found. However,

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once an optimal geophone design has been obtained, the practicing geophysicist must cope with a geophone that is not deployed appropriately. For example, the geophone is not coupled "well" to its surroundings. In this situation, the above definition is not appropriate and should be revised as follows: Bad geophone coupling is the difference between the velocity as measured by the badly planted geophone and the velocity as measured by the well-planted geophone.

The theoretical implications of "well-coupled" and "not well-coupled" geophones become clearer when different theoretical models are considered. Until the publication of Tan's note (1987), ground coupling was modeled theoretically by a cylinder resting on a half-space (Lamer, 1970; Hoover and O'Brien, 1980). Although this model is in contradiction to what has been used for decades in the seismic industry, namely spiked geophones, it has been used to describe geophone ground coupling. Krohn (1984) already has mentioned that the spike should be taken into account in the modeling, but Tan (1987) was the first to carry this out. However, Tan (1987) did not quantify the ground-coupling phenomenon, which was undertaken by Rademakers et al. (1996). In this latter model, where the spike is modeled as a cylinder, the final expression contains two integrals resulting from the bottom and side of a cylinder, respectively. The dominant contribution is from the side. More details can be found in Rademakers (1996). Physically, we learn from this model that when the geophone is "well" coupled, the term with the shear force along the spike is dominant. However, when the force along the spike is removed, the model no longer holds and the models from Lamer (1970) and Hoover and O'Brien (1980) should be used. In particular, it is the weight that is dominant, hence the name weight coupling.

A difference in the response resulting from different models is caused by the ground coupling showing amplitudes larger than one around the resonance frequency in previously reported models (Lamer, 1970; Hoover and O'Brien, 1980), but in the model by Rademakers et al. (1996), the ground coupling always has an amplitude less than one. It is hypothesized that the model of a cylinder resting on a half-space is useful for weight coupling when the spike of the geophone no longer provides coupling and is a device that uses its mass to couple to the ground.

In practice, the problem is associated strongly with the two types of coupling. Spike-shear coupling generally is well behaved for spiked geophones, but weight coupling generally is not well behaved. Practical examples of both these "states" will be given later in this paper. Weight coupling generally is not well behaved because the contact area between the geophone (or another sensor) and the ground is rough. Often, the only way to improve the coupling is to increase the mass of the geophone so that the contact with the ground becomes better (stronger coupling, more regular contact area). In practice, geophones are kept lightweight because of weight limits imposed on transporting thousands of geophones. The requirement for light weight and a good coupling condition for weight coupling work against each other. We investigated whether it is possible to detect experimentally whether geophones are spike-shear or weight coupled or, in practical terms, well or not well coupled. When a "badly coupled" (that is, weight-coupled) geophone is detected, the ideal situation would be to change this weight-coupled geophone to one that is spike-shear coupled. This question also is addressed in this paper.

FIELD TECHNIQUES FOR MEASURING GROUND COUPLING

Different techniques for measuring ground coupling were described extensively by Krohn (1984). She described laboratory (shake-table) and field tests and compared the two methods. As she found out, which is also our experience, shake-table tests show some extra scattering effects resulting from interference of the soil with the box and other box effects. Consequently, it was decided to carry out only field tests. In our experiments, three methods were deployed, in which one of the methods was used only to validate another of the three methods, as described below.

The first is a standard method available in some seismographs. In our case, this is a Bison Spectra, which works as follows: A signal is generated in the seismograph and sent into the geophone; the response from the geophone then is recorded.

The second method used a setup similar to that originally deployed by Washburn and Wiley (1941), namely, one geophone bolted on top of another geophone. In our setup, a cylinder was constructed between the two geophones, with the mass of the cylinder equal to the mass of a geophone. The upper geophone is used as an actuator, and the response from the lower geophone is measured. This method was used only to validate the response of the third method.

The third method used was a slight modification of the method described by Hoover and O'Brien (1980). A small weight was dropped from a fixed height, and the seismograph was triggered simultaneously with the release of the weight. Special care was taken to ensure that the geophone was not excited outside its linear range. To be sure of the coupling response, the second method (double-geophone configuration) was deployed under the same conditions in the field as the weight-drop method. Therefore, the responses from these two methods should be identical.

EXPERIMENTS

The aims of the experiments were twofold:

1) The first set of tests (experiment 1) was carried out to make an inventory of the information one obtains from the separate measurements, such as coupling conditions (such as a geophone on its side), or to see whether a geophone was well coupled to the ground. The separate measurements were performed multiple times to build up a statistical basis for computing the mean and variance. From different measurements, it became clear what could and could not be detected.
2) The second set of tests (experiment 2) was carried out to investigate the usefulness of ground-coupling measurements in relation to data obtained from seismic shots. First, the aim was to see whether the same behavior could be observed in the measurements of the coupling devices and in the shot data. If this was the case, then the aim was to see whether the shot data could be corrected for this behavior by using the responses from the coupling-measurement devices.

EXPERIMENT 1: LOCAL GROUND-COUPLING MEASUREMENTS

As mentioned above, these tests were undertaken to see what could and could not be measured by local ground-coupling measurements by using the techniques described earlier. Let us first concentrate on the signal generated by the seismograph and sent directly into the (receiving) geophone. An example of this is given in Figure 1. On the four left traces, the response is measured from well-planted geophones. Note that the dominant effect in the response is the resonance frequency of the geophone, which is a 10-Hz geophone in this case. The next four traces in Figure 1 show the response of badly planted geophones. Bad planting resulted from picking up a well-planted geophone and letting it drop in the same hole. Care was taken to create a hole which nearly vertical (within 5%). Comparing these traces to the responses of the well-planted geophones, no differences could be observed. Determining the average responses and errors from 20 measurements, we find that the average response of the badly planted geophone falls within the error bars of the well-planted geophones. Consequently, such a system cannot be used for detecting badly planted geophones.

This method can be used to determine whether a geophone is planted at all. In the last four traces in Figure 1, the responses are given from four geophones lying on their side. Note that the responses are significantly different from those of a planted geophone. Such a measurement system thus can be used for automatic detection by choosing some appropriate attribute(s).

When the responses of the planted geophones are compared with those from geophones on their side, a small peak could be seen in the time responses of the planted geophones at approximately 25 ms. This is caused by an artifact of the geophone, and separate analysis showed that the different planting of the geophone did not affect this peak.

To detect and/or correct for well- or badly planted geophones, the other two methods described in the section "Field techniques for measuring ground coupling" must be used. We will describe a series of tests performed on two soils, namely pure sand, wetted, and pure clay, with some grass on top. The experiments were repeated 20 times to build up statistical confidence. These tests were undertaken only with a small mass (22.8 g), dropped on the geophone.

In Figure 2, a subset of four responses out of 20 is given for one geophone being planted well into sandy soil (beach sand), and also for four responses of badly planted geophones. Some striking differences can be observed: The energy content (sum of squared amplitudes) of the badly planted geophone is consistently higher than that of the well-planted geophones; for the 20 responses, the ratio of the average energies is 2.0. In addition, the responses of the badly planted geophones contain more low-frequency energy. The average for the (statistical) first moments of the amplitude spectra was 270 Hz for the well-planted geophone and 163 Hz for the badly planted geophones. This analysis also has been undertaken on 20 responses obtained from the geophones in the clay. Four of these are given in Figure 3. The ratio of the average energies is 1.9. The average of the (statistical) first moments of the amplitude spectra

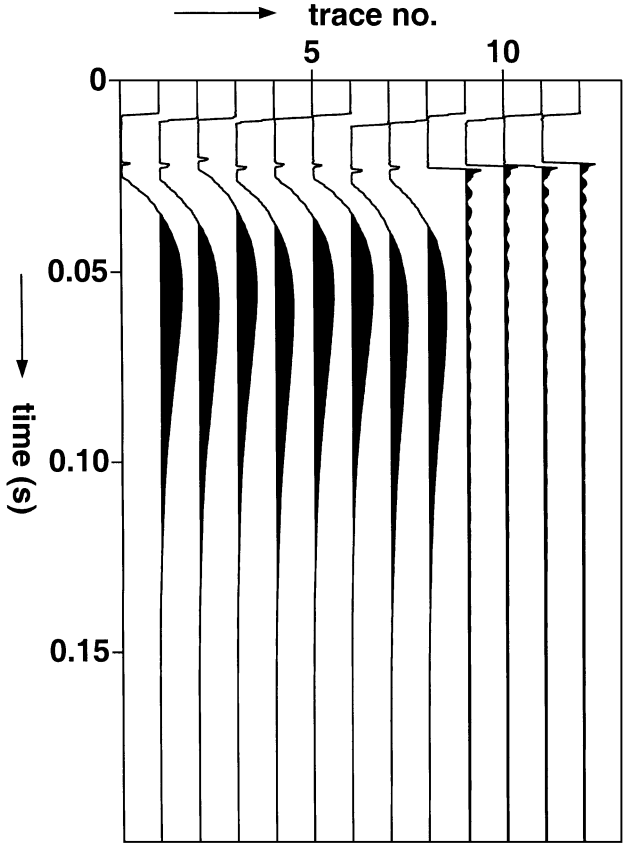

FIG. 1. Geophone response to a signal from a Bison seismograph. Traces 1–4, well planted; traces 5–8, badly planted; traces 9–12, geophones lying on their side (not planted).

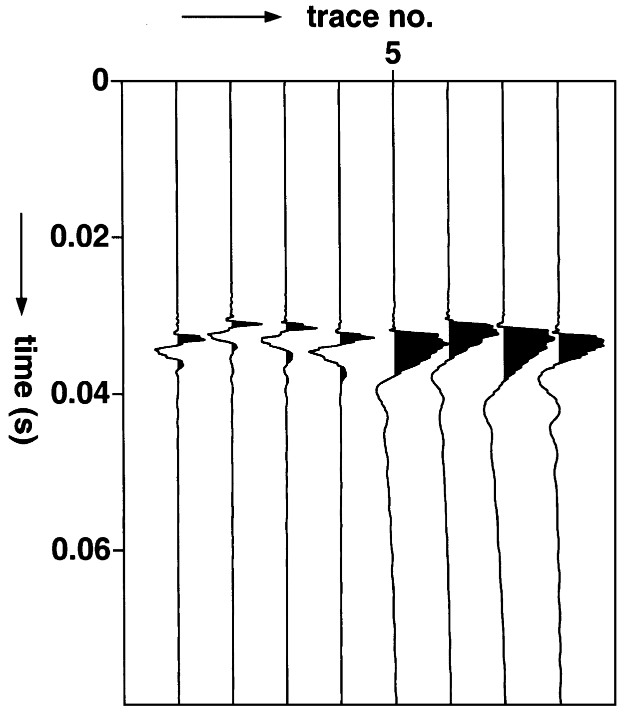

FIG. 2. Geophone response to a signal from a small weight drop for geophones in sand. Traces 1–4, well planted; traces 5–8, badly planted.

is now 243 Hz for the well-planted geophones and 151 Hz for those that were planted badly. These measurements are consistent with the measurements of, for example, Krohn (1984) and Faber et al. (1994). However, from our experimental results, we can claim something that these authors did not; that is, only two "states" can be discerned. To support this with some statistical confidence, the standard deviation has been determined. The relative standard deviation (one standard deviation divided by the average) from the well-coupled geophones in the sand is 8% and for clay is 4%. For the badly planted phones, the deviation is 16% for sand and 6% for clay. The higher values of the standard deviation are well known from experiments by others. Geophones coupled by their weight need to be made heavier because the contact area on many types of surfaces is a serious problem. Another solution is to bury the phones (Krohn, 1984). Because the amplitude spectra of the well- and badly planted geophones have their own average and standard deviation, we can state with statistical confidence that there are only two distinct "states." The literature seems to imply that the coupling could vary continuously, but this was not the case in our measurements.

Combining these observations with the concepts obtained from modeling the spike as a cylinder in the ground (Rademakers et al., 1996), we conclude that well-planted geophones are of the spike-shear coupled type, and badly planted geophones are the weight-coupled type. It should be noted here that this observation could be used for making devices that can determine the coupling locally without using a coupling-measurement device. Specifically, a force should be applied that would be slightly larger than that necessary to compensate for the *weight* of the geophone. Then, if the geophone is not lifted, it is spike-shear coupled and thus well coupled. However, if the geophone is lifted, it is weight coupled and thus badly coupled.

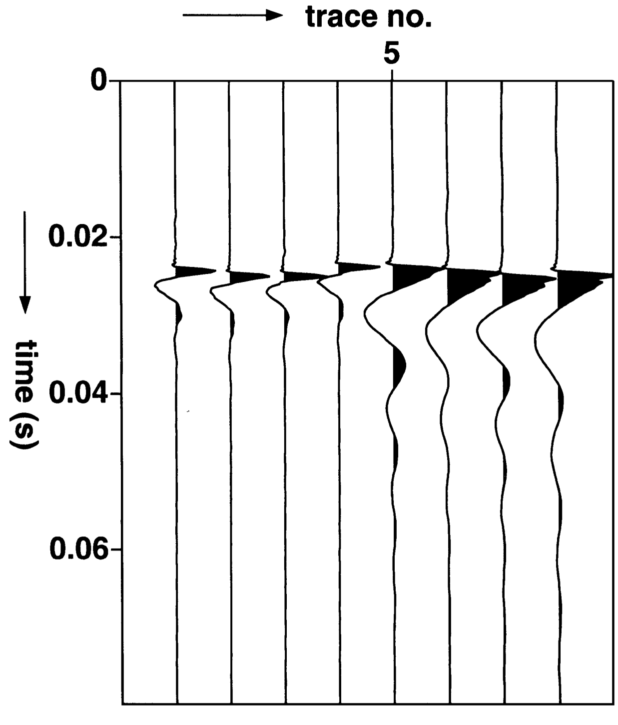

FIG. 3. Geophone response to a signal from a small weight drop for geophones in clay. Traces 1–4, well planted; traces 5–8, badly planted.

Another comparison was performed for the validation of a new model by Rademakers et al. (1996). Specifically, this was the impedance contrast between the soil and the geophone. Tan (1987) showed theoretically that the density of the spike should match the density of the soil to obtain the best coupling. However, in the model by Rademakers et al. (1996), the effect of spike density was not dominant. Consequently, two spikes with different densities (stainless steel and aluminum) were deployed in clay and sand. For each situation, the geophone was planted well coupled 20 times so that a statistical base could be gathered. Four from each of these 20 are shown in Figure 4. The first eight are the geophones in clay, where the first four are with the steel spike and the second four are with the aluminum spike. Although the weights are different, the responses are not different statistically. The same conclusion can be drawn from the responses in the sand. Statistically, there is no difference. However, when we compare the responses from the clay with those from the sand, we do see a significant difference. The (normalized) energies, with their standard deviation in parentheses, are: 4.45 (±0.47), 4.30 (±0.30), 3.26 (±0.25), and 3.51 (±0.19). This effect also can be seen often in vertical seismic profiles (VSPs) where the geophone passes through many rocks with different characteristics. In conclusion, the effects of soil variation can be determined with local devices, but the effect is determined by the characteristics of the soil itself rather than the difference in characteristic between the soil and the spike. This confirms the model by Rademakers et al. (1996).

EXPERIMENT 2: LOCAL GROUND-COUPLING MEASUREMENTS IN RELATION TO SEISMIC-SHOT DATA

In this set of experiments, the usefulness of local techniques is investigated with respect to their use for seismic-shot data. As observed in the first set of experiments, there is a significant

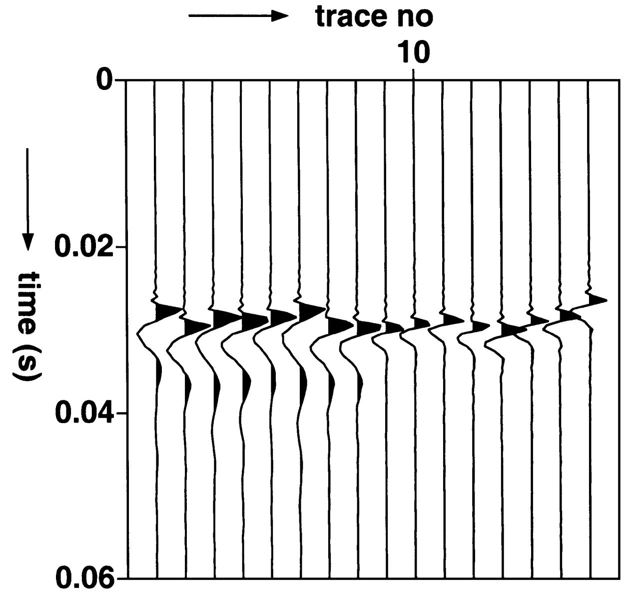

FIG. 4. Geophone response to a signal from a small weight drop for geophones in clay and sand, with steel and aluminum spikes. Traces 1–4, steel in clay; traces 5–8, aluminum in clay; traces 9–12, steel in sand; traces 13–16, aluminum in sand.

difference between well- and badly planted geophones in responses from local techniques (see Figures 2 and 3). In these experiments, the local techniques are combined with seismic-shot data to see whether the differences, as seen in the local measurements, also can be seen in the global (seismic-shot) measurements. To that end, many experiments have been carried out on types of soils, with four typical soils having been chosen: peaty soil, sandy soil, gravel, and hard rock. The set discussed here is only a subset of a larger data set, and the examples shown are typical.

For each soil type, a set of experiments consisted of a shot from a small charge located 50 m from a group of single geophones. The geophones were perpendicular to the shot-geophone direction so that phase differences would be minimal. Two of the geophones had the weight-drop device on top, with one well planted and one badly planted. Other geophones have been used to build up some confidence in the results of the observations. When the data from one shot is analyzed, the variations seen in the seismic data should then be caused by:

1) The difference in local soil conditions (geology). This variation is hard to quantify, but a qualitative conclusion can be obtained by looking at the variation of the responses of the well-planted geophones from the same seismic shot.
2) The difference in geophone-coupling conditions. This variation could be determined partly from a comparison with the other well-planted geophones. It should be realized that coupling could be a 3-D effect. For bad planting, the data consisted only of the geophone with a weight-drop device on top, so that no variation could be determined in this case.
3) Differences in geophones. This variation was tested in the laboratory and did not make any significant contribution to the total variation.

Let us look at the first set of data obtained from peaty soil. This soil was located next to a marsh area near Hannover, Germany, where measurements were taken in a dried-out portion of the marsh. The different responses are given in Figure 5. On the left side of the figure, two seismic traces are shown from the seismic-shot data, where the left one is the well-planted geophone and the one on the right is the badly planted geophone. One can see the difference in the response resulting from the bad planting: The first arrival is reverberatory. On the above right of the figure, the amplitude spectra of these two traces are given. A difference can be seen between the data at about 100 Hz. Also shown in this panel is the relative standard deviation in the amplitude, determined from 14 well-planted geophones. On the bottom right of the figure, the amplitudes of the weight-drop responses from these two particular geophones are given. These responses should give the difference seen in the shot data. In these weight-drop responses, a clear maximum (resonance) can be seen at about 75 Hz. In addition, it can be seen that the amplitude of the weight-drop response for the badly planted geophone has amplitude that is higher than the amplitude for the well-planted geophone. However, there are also some differences to be seen between the spectra of the weight drop and the seismic shot. First, the difference between the two weight-drop responses is larger than the difference between the responses to the seismic shot. Moreover, the weight-drop response for the well-planted geophone still has a maximum at the same frequency as the response of the badly planted geophone. This may suggest that the resonance

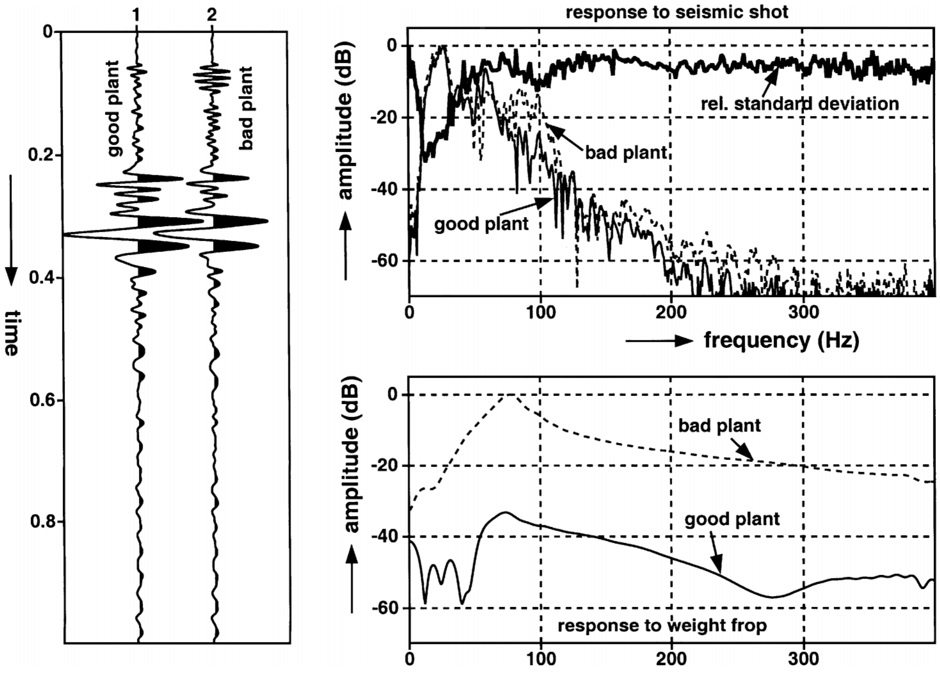

FIG. 5. Response to a seismic shot and small weight drop for geophones in peaty soil. Left panel: time traces from seismic shot, well planted (trace 1) and badly planted (trace 2). Upper right panel: amplitude spectra of traces shown on the left: relative standard deviation (solid thick line), well planted (solid thin line), badly planted (dotted line). Lower right panel: amplitude spectra of responses to weight drop: well planted (solid line), badly planted (dotted line).

is purely a soil-related resonance rather than a resonance related to the coupling condition. In general, it is obvious from Figure 5 that if we could deconvolve the seismic data of the bad planting by using the weight-drop data, the result would be incorrect.

The next set of measurements was carried out on sandy soil, specifically, sand from the beach of Wassenaar, Netherlands, which was partly wet and fairly compact sand. Again, the different data are plotted next to each other and shown in Figure 6. The left trace is again from the well-planted geophone, and the right is from the badly planted geophone. In this case, there are some minor differences to be seen in the time traces. This is also the case for the amplitude spectra. Examining the responses of these geophones to the weight drop, it can be observed that there is no clear maximum (resonance); the responses are flat. If the maximum is viewed as a resonance, the badly planted geophone has a slight resonance at about 170 Hz. In the seismic-shot data, a difference also can be seen around these frequencies, although it is not very significant. Again, it is clear that in this case, if the weight-drop data are used for correcting the data for bad coupling, the results will not be correct.

The third set of measurements was carried out in a gravel deposit near Hannover, Germany. In this area, it was not easy to plant the geophones well. The data from this area are shown in Figure 7. The time traces show only minor differences. However, the amplitude spectra show some clearer differences. What is striking in this example is that the amplitude of the well-planted geophone is higher than the amplitude of the badly planted geophone. This is probably caused by the gravel, because it was difficult to establish spike-shear coupling. The responses from the weight drop show a resonance at about 130 Hz and at frequencies where the seismic data show the most marked differences. The weight drop indicates that maximum/resonance occurs at approximately the correct range of frequencies. In addition, the responses of the well-planted geophone have higher amplitudes than geophones that were planted badly. Again, if we use the weight-drop data to correct the seismic data for its plant, the result will be incorrect.

The last set of measurements took place in a limestone mine near Hannover. The rock outcropped at the surface, and measurements were made by planting the geophones in the cracks of the limestone. The results are shown in Figure 8. In the seismic-shot data, a slight difference can be seen between the responses of the well-coupled and badly coupled geophones. In the amplitude spectra of the seismic data, the most marked difference can be seen at about 200 Hz. The amplitude spectra of the weight drop show a maximum (resonance) at about 200 Hz for the well-planted geophone and about 120 Hz for the badly planted geophone. Therefore, the weight-drop device predicts a decrease in the resonance frequency for bad planting, a higher amplitude at the maximum (resonance), but it does not quantitatively predict the difference in behavior of the seismic data for good and bad planting. A possible explanation here could be that the geophones are "rocking" sideways because the geophone was planted with only the tip of the spike into the rock. Because the weight-drop device excites the geophone only vertically, it does not measure this sideways movement.

DISCUSSION

One can query why there is no quantitative relation between the responses of the coupling-measurement device and the shot data. The reasons could be:

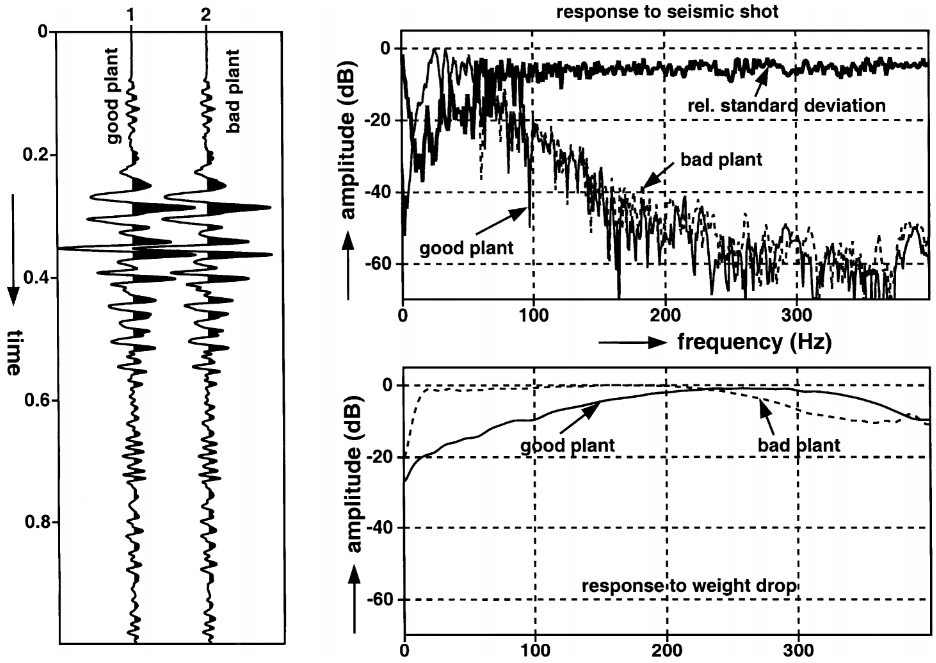

FIG. 6. Response to seismic shot and small weight drop for geophones in sandy soil. Left panel: time traces from seismic shot, well planted (trace 1) and badly planted (trace 2). Upper right panel: amplitude spectra of traces shown on left: relative standard deviation (solid thick line), well planted (solid thin line), badly planted (dotted line). Lower right panel: amplitude spectra of responses to weight drop: well planted (solid line), badly planted (dotted line).

1) Coupling-measurement devices measure coupling conditions *and* local soil characteristics. It is not possible to discriminate between the two. The term *coupling-measurement device* may be confusing.
2) three-dimensional movement. The coupling-measurement device excites the geophone only in one direction, but the wave motion from the seismic shot is 3-D. Clearly, this is a restriction of the coupling-measurement device. A typical problem of nonvertical movement is the rocking (sideways) movement of the geophone. This occurs when spiked geophones are planted in hard rock. For unconsolidated soils, Krohn (1984) partly solved the rocking problem by recommending that the geophones be buried. However, 3-D movement will remain. It may be worthwhile to design geophones with lower cross-sensitivity at the cost of performance in the vertical direction.
3) Although theoretically there is a relation between reflection and transmission, it is often difficult to obtain transmission data from reflection data. Washburn and Wiley (1941) gave a formula that would accomplish this for the weight-drop device, but it turned out not to be very useful when applied to seismic-shot data. It may be better to *measure* the transmission of the local geophone-coupling conditions rather than to determine it from reflection measurements.

CONCLUSIONS

Local ground-coupling-measurement devices, such as a small weight-drop device, measure directly the most important characteristics of ground coupling. In particular, they show the amount of energy transferred, the maxima (resonances), and the shifts in maxima (resonances). From the measurements discussed in this paper, it has become clear what can and cannot be detected. In addition, it was shown by using the weight-drop device that well-coupled geophones are the so-called spike-shear-coupled geophones, while badly coupled spiked geophones are the weight-coupled type. One cannot speak of a continuous variation of coupling conditions, but mainly, two "states" can be discerned: spike-shear or weight coupled.

However, when relating the coupling responses to seismic data, it has become clear that the responses of the coupling-measurement devices can be used only qualitatively. When it was used quantitatively, the following problems arose:

1) The maxima (resonances) in the amplitude spectra of the coupling-measurement device often do not coincide with the maximum difference seen in the seismic data.
2) A maximum in the response of the coupling-measurement device does not mean it is a resonance of the coupling condition. It also may be a feature that is purely a characteristic of the topsoil.
3) The differences observed in the responses of the coupling-measurement device do not explain quantitatively the differences seen in the seismic data.

In general, one can say that coupling-measurement devices are very suitable for small "field-laboratory" tests, as undertaken in experiment 1 of this paper. We can learn from such experiments, for example, that there are two distinct states for good and bad coupling. However, quantitative use of such devices for seismic data, such as correcting for bad coupling conditions, is very limited.

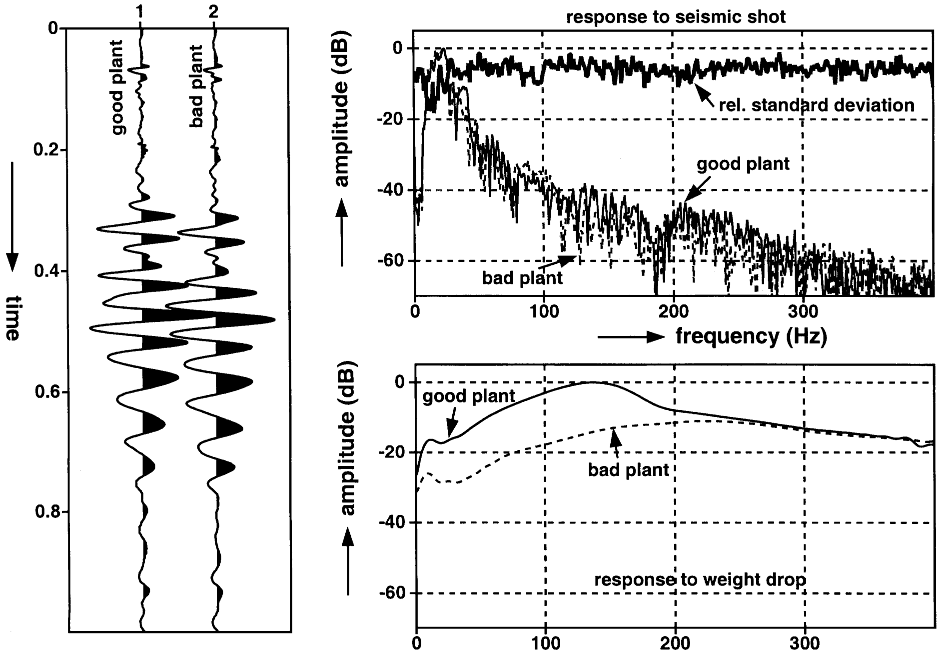

FIG. 7. Response to seismic shot and small weight drop for geophones in gravel. Left panel: time traces from seismic shot, well planted (trace 1) and badly planted (trace 2). Upper right panel has amplitude spectra of traces shown on the left: relative standard deviation (solid thick line), well planted (solid thin line), and badly planted (dotted line). Lower right panel has amplitude spectra of responses to weight drop: well planted (solid line), badly planted (dotted line).

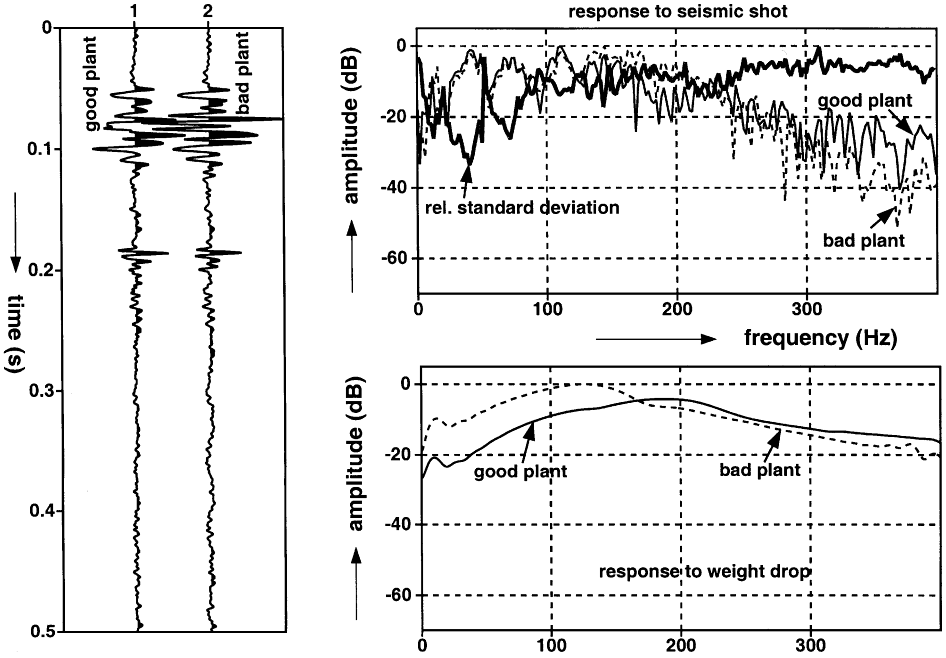

FIG. 8. Response to seismic shot and small weight drop for geophones in limestone. Left panel: time traces from seismic shot, well planted (trace 1) and badly planted (trace 2). Upper right panel has amplitude spectra of traces shown on the left: relative standard deviation (solid thick line), well planted (solid thin line), and badly planted (dotted line). Lower right panel has amplitude spectra of responses to weight drop: well planted (solid line), badly planted (dotted line).

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