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The use of surface wave inversion and seismic reflection methods for engineering applications

L'utilisation des méthodes d'inversion d'ondes de surface et de réflexion sismique en géologie de l'ingénieur

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ABSTRACT: The recent development of digital recording equipment allows to use the whole seismograms in place of first arrival times for sub-surface exploration. We present applications of high-resolution seismic reflection method and surface-wave inversion to engineering geology. The seismic reflection method, widely used in oil exploration, can be applied to map shallow interfaces. On the other hand, the surface-waves inversion method, initially developed in seismology, is a technique for determining shear wave velocities as a function of depth. The method, based upon the analysis of wave dispersion, can be applied to seismograms recorded during refraction tests. We performed seismic surveys including refraction and reflection tests as well as surface wave inversions in two test sites. The results of the different seismic methods are compared and show a good agreement.

RESUME: Le developpement des systèmes d'acquisition numérique permet d'utiliser des informations jusqu'à présent négligées sur les sismogrammes. Nous présentons des applications à la caractérisation des sols de 2 techniques utilisant le signal complet en place de simples pointés d'arrivées: la sismique réflexion et l'inversion des ondes de surface. La sismique réflexion classiquement utilisée pour l'exploration pétrolière peut être transposée pour étudier des réflecteurs superficiels. L'analyse des caractéristiques de dispersion des ondes de Rayleigh permet de déterminer la loi de distribution de la vitesse des ondes de cisaillement avec la profondeur à partir d'enregistrements qui sont essentiellement ceux de la sismique réfraction usuelle en ondes P.

Nous présentons des résultats de prospections sismiques en 2 sites où différentes techniques ont été mises en oeuvre. Les résultats obtenus sont en bon accord.

1 INTRODUCTION

Seismic refraction and cross-hole experiments *are examples of non* destructive techniques to investigate the dynamic characteristics of soils. These methods only use arrival times of specific phases, mostly the first arrival. Nevertheless, the signals are often recorded with numerical devices that allow to store a much larger amount of information. The seismic reflection technique is an attempt to use coherent arrivals of reflected waves at a series of receivers. *This technique is widely* used for hydrocarbon exploration in sediments.

For civil engineering purposes, the shear wave velocity is very often required. For its determination, standard methods can be used with specific seismic sources and receivers. The analysis of surface waves (ground roll) is a technique that does not require to set up experiments different from those of classical P wave refraction. The dispersion curves of Rayleigh waves (velocities as a function of frequency) are primarily sensitive to the shear wave velocity and therefore can be inverted in order to find S wave velocity distribution with depth. This technique can be used only when the soil structure is nearly flat.

2 THE SEISMIC REFLECTION METHOD

The seismic reflection method is based on the analysis of reflected waves generated at boundaries of geological layers characterized by different seismic impedances (product of the mass density and the wave velocity).

In practice, it is difficult to isolate reflected waves from ground roll by band-pass filtering. To identify the reflections, an optimum window on the time-distance graph must be selected from preliminary tests (Hunter,1984).

On this basis, the shot-to-receiver offset is chosen. In order to enhance the reflection signal, each shot is recorded by a string of 12 close high-frequency geophones. Special care must be taken in the choice of the geophone interval to avoid spatial aliasing (Steeples,1988).

The whole device is then moved of the geophone spacing to a new position. The advantage of this method is that 6 signals come from the same reflection point (common depth point) and are added after processing.

The standard processing sequence, very similar to that used in oil exploration (except the migration step), is as follows :

- Static correction (delays caused by topography and variations of the surficial cover)
- Noise and first arrivals mute
- Gather of the same common depth point data
- Velocity analysis and normal move out
- Band-pass filter
- Stack for each common depth point.

3 SURFACE WAVE INVERSION

When refraction seismic surveys are carried out on land, surface waves are generally predominant in the signal. The Rayleigh wave, that is observed on the vertical and radial components, consists of perturbations propagating in the shallow layers. Its penetration depth increases with period. This property will be used, through an inversion scheme, to retrieve the shear wave distribution with depth from the variation of Rayleigh group and phase velocities with period. The group velocity is the actual velocity of the energy transfer while the phase velocity is the apparent velocity of a given harmonic component. The group velocity can be derived directly from the phase velocity (see for example Waters, 1985). At high frequency, because of interferences between waves trapped in the upper layers, different modes of Rayleigh waves can exist, similar to the harmonics of a resonant system.

In Figure 1 an example is given of theoretical dispersion curves for the Rayleigh wave fundamental mode in a medium consisting of a single layer over a half space. The phase velocity varies from a value near the shear velocity of the surficial layer at short periods to a higher

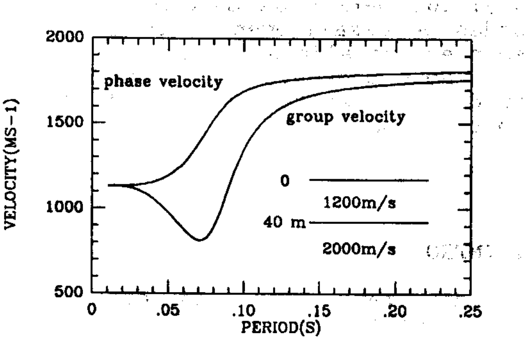

Fig.1 Rayleigh waves theoritical dispersion curves for a simple one layer model. Depth and shear wave velocities are depicted in the diagram. Densities are 2.0 and 2.4 A Poisson ratio of 0.3 is assumed.

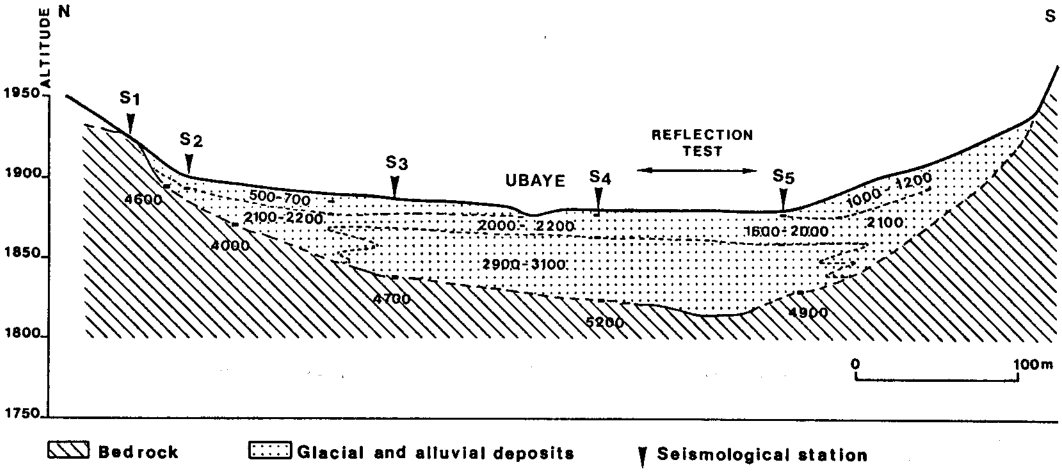

Fig.2 Approximate geological structure of the Ubaye valley inferred from geophysical prospecting. The values indicate the range of wave velocities in m/s.

value near the velocity of the half space at large periods. This clearly illustrates the physical variation of penetration depth with the surface wave period. The dispersion characteristics can be related analytically with the shear wave velocity distribution, and consequently a inversion scheme can be built to infer the distribution of S velocity from the dispersion curves (Dziewonski and Hales,1972).

4 FIELD TESTS IN THE UBAYE VALLEY

A geophysical survey was conducted in the Ubaye valley (France) in order to determine the geometry and the dynamic characteristics (P and S wave velocities) of the deposits.

The valley, located in the Alps, is 500 to 600 meters wide. The shallow geological formations, composed of alluvium and moraine, are overlying Mesozoic limestone. At the edges of the valley, these deposits are overlaid by alluvial fans.

The geophysical investigation has included 16 refraction profiles of 24 to 360 meters long and one reflection test . Surface wave inversions were usually performed on seismograms recorded during refraction tests. Figure 2 shows the geological structure with P wave velocities inferred from this geophysical prospecting.

One seismic reflection profile was carried out in the flat part of the valley (see Figure 2) in order to map the top of the bedrock. The data were collected using a gun as a source and twelve 50 Hz geophones. From walkaway tests, an offset of 50 m and a geophone interval of 2

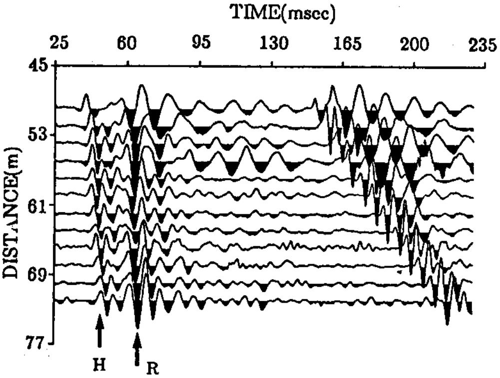

Fig.3 Typical field seismograms of a reflection profile. Head waves and reflection from the bedrock are marked with "H" and "R" respectively.

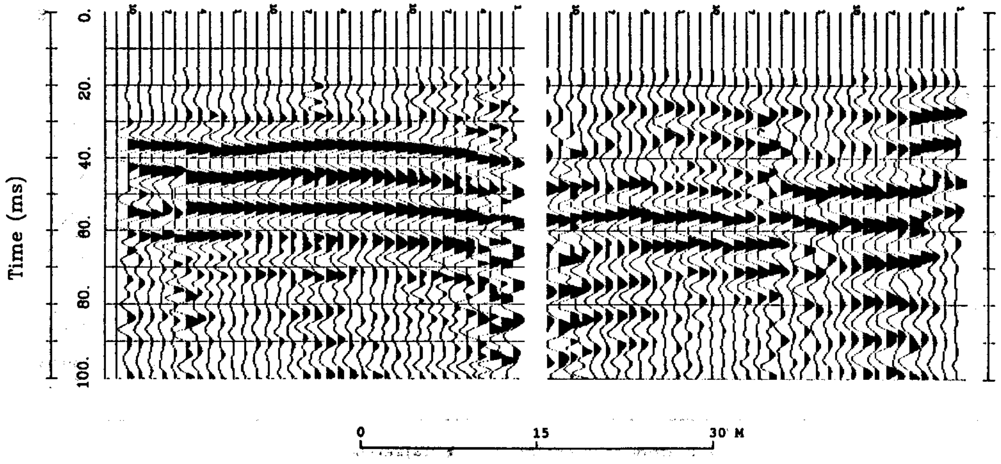

Fig.4 Final seismic section.

meters were chosen. An analog low-cut filter of 100 Hz was used to reduce the effects of ground-roll . Figure 3 shows a typical field seismogram with head waves, a reflection from the bedrock at about 60 ms, air-ground coupled waves and ground roll. All the data were processed using Geoflex, the shallow reflection data processing software of EG&G Geometrics. No static corrections were applied to the traces because of the flatness of the topography and of the near-surface layers. Normal move out corrections were performed using velocity values deduced from short refraction tests.

The final seismic section is presented in Figure 4. The bedrock reflector appears at about 55 ms. It is the only regular event present on all the section. The events between 20 to 45 ms are refractions that could have been muted before stacking. The interesting feature is that refractions can appear as coherent events and , as pointed out by Steeples(1984), it is sometimes difficult to separate shallow reflections from refractions.

The bedrock interface topography inferred from the time section is presented in Figure 2. The comparison with the refraction results is fairly good. Both tests indicate that the bedrock depth is ranging from 55 to 60 meters in the flat part of the valley.

For seismic risk analysis, the prominent parameter of near-surface geological formations is the S wave velocity. Some refraction tests were performed using horizontal geophones and a sledge hammer striking a loaded plank as a source. The energy obtained is however too low to reach a great depth penetration.

The processing of surface waves generated by a explosion allows to obtain S wave velocity profiles. Figure 5 shows field seismograms

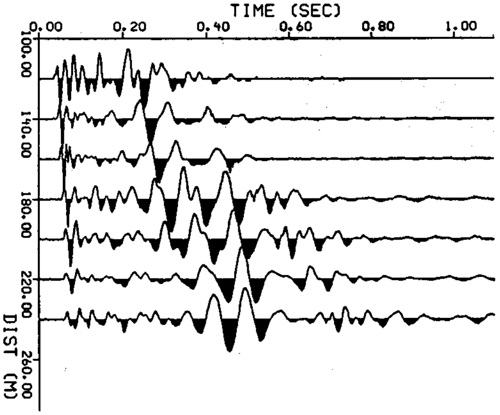

Fig.5 Field seismograms used for the surface wave inversion

recorded between 120 m to 240 m from the source by vertical 4.5 Hz geophones. The Rayleigh waves clearly dominate the signal.

Both phase and group velocity dispersion curves are computed using the software developed by Herrmann (1987). The experimental curves , presented in Figure 6, were inverted assuming an initial 18 layers model. The theoretical dispersion curves deduced from the inversion are plotted on Figure 6. The final model is shown in Figure 7 and is compared with the refraction data at the same site. A low velocity layer appears at about 20 meters depth. The results are consistent with the refraction data. Because of the relatively narrow frequency bandwidth of the source, we are unable to compute the long period part of the dispersion curve (over 0.15 sec. as shown in Figure 6). This indicates that the method lacks of precision at depth in this case. Therefore the velocity and the depth of the bedrock are poorly determined. The ability to generate energy in a wide frequency range is a major limitation of the method . Another constraint is the assumption of a plane layered model.

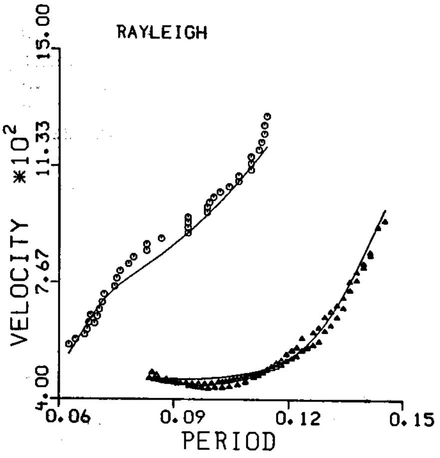

Fig.6 Triangles and circles denote group and phase velocity measurements respectively. Solid lines represent theoretical dispersion curves computed from the final model .

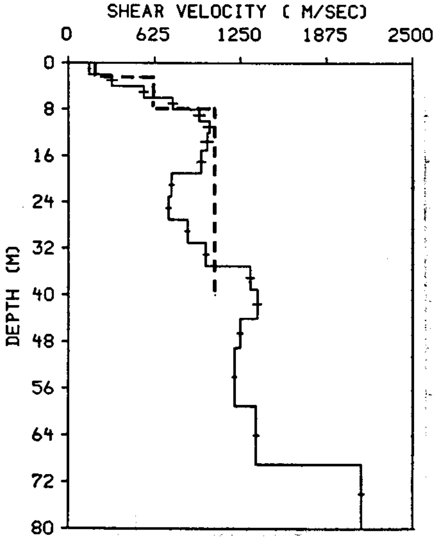

Fig.7 Shear wave velocity model deduced from the inversion of the experimental data shown in Fig.6 (solid line) and results obtained from S wave refraction tests (dashed line).

5 EXPERIMENT IN THE SART TILMAN SITE

Another example of the use of surface waves is given in the case

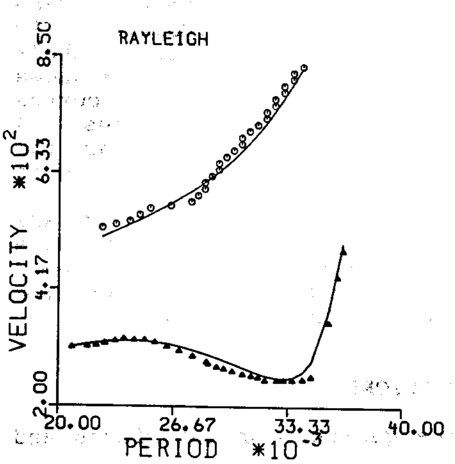

Fig.8 Dispersion curves . Same as Fig.6 for the Sart Tilman site.

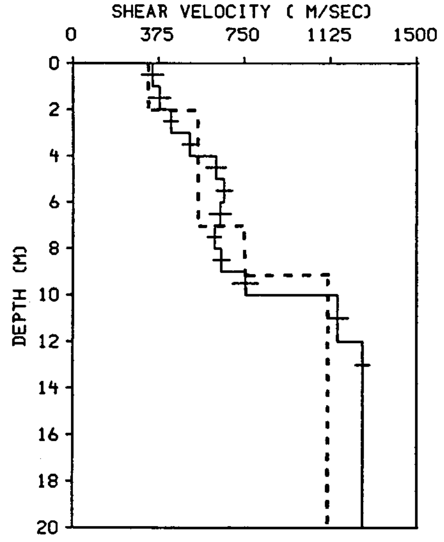

Fig.9 Shear wave velocity model obtained from the inversion process of the experimental curves of Fig.8 (solid line) compared with results of down hole measurements (dashed line).

of a shallow bedrock. Field seismograms were recorded at close distance (10-20 m) on the Sart Tilman site (Belgium). The Emsian bedrock, composed of folded layers of schists and sandstones, is overlain by a 6 meters thick weathered layer and a thin terrace level (2 m). The Vs profile to 20 meters depth is known from downhole and refraction tests. Figure 8 shows the experimental dispersion curves for group and phase velocities. A 12 layer model was used for the inversion. The resulting profile is presented in Figure 9 while the corresponding dispersion curves are drawn on Figure 8. The S wave velocity values are in good agreement with those determined from the other geophysical tests.

6 CONCLUSIONS

The fine geometry of interfaces and the S wave velocity profile are poorly retrieved from standard refraction experiments. These informations can be best inferred from two modern techniques, namely (1) the high resolution reflection method, and (2) the inversion of surface wave dispersion curves. These two techniques can be applied in engineering geology for shallow exploration. Although the data processing is heavier than with the refraction method, it can be performed on work stations and PCs.

Field experiments were conducted in two sites in order to test the capability of the methods. Reflection profiles allowed to map a 60 m deep interface. The resolution of the method is strongly dependent on the spectral characteristics of the signals recorded in the field. The spectral content of the source radiation and the response of geophones must cover a frequency range as high as possible.

The analysis of surface waves leads to the S wave velocity distribution at depth using an experimental set up very similar to the one of P wave refraction technique. The method does not require boreholes and allows to detect intermediate low velocity layers. The results obtained with this technique are in a good agreement with data inferred from other investigations. Practically, the penetration depth is limited by the amount of energy emitted by the source at low frequency.

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