Masking Effects of Subsurface Layers on Shallow Reflecting Horizons

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Abstract

Reflection seismic measurements of shallow underground structures are complicated by subsurface low-velocity layers (e.g., sediments above the water-table level), and usage of the surface sources. As a rule the weight-drop surface source generates P and S waves with a complicated radiation pattern, and the ground roll is also very strong. Moreover, the high P-wave velocity contrast at the water table gives rise to intensive head waves, whose arrival times may be close to those of the primary reflections from the investigated horizons. Conventional processing methods to eliminate head waves and ground roll, like muting and/or f-k filtration do not help enough, and the underground discontinuities may not be properly imaged. For example, step-like structures are imaged as flat. Problems like these are discussed by means of numerical experiments in which the synthetic data are inverted into the CDP stacked time sections by professional software. Two numerical methods, the ray and finite-difference, are used whose comparison and combination throw some light on to the mentioned processing problem.

Key words: modelling, finite-difference method, ray method, CDP stacked sections

Introduction

Reflection measurements require sophisticated data acquisition systems designed accordingly to particular prospection targets. Our targets are step-like layers at shallow depths. This may be the case of lignite deposits, where detection of the steps (due to tectonic faults) is essential for preventing technical problems arising from unexpected meeting of the faults during excavation work. Equally well, step-like underground structures are important in earthquake engineering and seismic microzonation, where variations in the layer thickness yield variations in the ground-motion resonance frequencies, and the transitional zones between the shallow and deep layers may create dangerous differential ground motions.

Standard practice is that synthetic seismic wavefields are mainly used in the interpretation of reflection measurements. This work shows that modelling is highly useful also prior to the data acquisition, allowing to check whether the target (e.g. the step-like layer) can be revealed or not.

First, we perform numerical experiments with the so-called loaded reflector (a method similar to the so-called “exploding reflector method”). We find no problems in seeing the layer step even at relatively low frequencies. Second, we calculate a set of surface sources along a profile, and simulate the CDP stacked time sections. In that case the layer step is no longer seen in the topmost event of the time section. We analyse reasons for the failure, and find the free surface and subsurface low velocity layer to be responsible for such a “masking effect”. Finally, we show a possible way how to suppress the masking effects, at least in the framework of synthetic modelling. The finite-difference (FD) and ray methods are combined

in this study. They serve different purposes: the former to calculate the complete elastic wavefield and the latter to interpret it. An important by-product will be a caution that a similar feasibility study performed solely by the ray method would not reveal the interpretation problems.

Method

Consider the model of a step-like shallow coal seam (Fig. 1). The medium just above and below the seam is the same. However, there is a water-table level at a depth of 10 m; hence the top layer below earth's surface is a low-velocity layer (LVL) for P waves. According to the available preliminary geological and geophysical data, the model roughly represents a part of a lignite basin at the Domenico site in Central Greece (A. Tselentis, pers. comm.). We model the 2D reflection measurements along the 500m long profile: 126 receivers with 4m separation. The complete elastic (P-SV) wavefield at the free surface is calculated by the FD method. The 2nd-order accurate PS2 scheme of Zahradník and Priolo (1995) is employed on a regular square grid, with gridstep size of 0.5 m. Only the vertical component is presented below.

Loaded reflector

We apply vertical body forces simultaneously on the top of the seam with a 0.5 m step. The time variation of the forces is a Gabor wavelet, dominant frequency of 50 Hz. The response is recorded at the earth's surface at the 126 receivers. The result (Fig. 2) clearly shows that the step-like seam is imaged well, correctly exhibiting the 10 ms shift of the reflections, although the frequency used is relatively low. This experiment is similar to the so-called exploding reflector. As shown by Carcione et al. (1994), his FD exploding-reflector experiment provided results similar to the CDP stack simulation. Below we show that in our model the relation between the loaded-reflector result (Fig. 2) and CDP stack result (Fig. 5) is more complicated.

CDP stacked sections

Although we are aware of the fact that real measurements prefer a many-fold setup, only few sources are considered here. We do this because the elastic full-wave calculations are time consuming, and, with noise-free data, the many-fold system is not necessary. We assume 7 surface sources at the profile locations x=100, 150, ..., 400m (see Fig. 1). To approximate the weight-drop, each source consists of a single applied vertical force, Gabor wavelet of dominant frequency 50 Hz. As an example, the FD synthetics for the source at x=100 m are shown in Fig. 3. This is the wavefield after automatic gain control is applied to allow us to see details both outside and inside the ground-roll fans. In Fig. 4 the synthetics are accompanied by the ray-calculated travel times (subroutine packages MODEL and CRT, Červený, Klimeš & Pšenčík, 1988).

The next step is standard processing of the synthetic data (the 7 individual sources), using WinSeis software. It includes the suppression of the ground roll by f-k filtering, CDP gathering, velocity analysis, NMO correction and CDP stack. The result in Fig. 5 shows no step-like shape of the primary reflections. Let us mention that similar negative results were obtained in many other processing modes (varying all the parameters). The same occurred when processing by ProMAX software, done by two independent experts who did not know the "true" structural model.

To understand why the processing does not reveal the step-like structure we return to Figures 3 and 4. We find that the inability to see the step is due to the fact that the primary P-wave reflections superimpose (within the 20 ms pulse duration) with the other phases. It is

the superposition with P and S-wave reflections inside the LVL layer in small offsets, and the superposition with the head waves corresponding to the LVL bottom in larger offsets. Although higher frequency would help in distinguishing the P-reflections, we keep 50 Hz and discuss how to suppress the masking effects.

Removing masking effect

The intention here is to show that the subsurface LVL effects can be removed, and the step-like seam can be seen, even in the case of the previously considered low frequency of 50 Hz. Therefore, we calculate two models: that one discussed above (including both the LVL layer and the step-like coal seam), and the model consisting of the same sources, and LVL, but the LVL underlain by a homogeneous halfspace without the coal seam. Then we subtract seismograms obtained from the two models, hence obtaining the so-called differential wavefield. Processing the differential field yields the stacked CDP section shown in Fig. 6, in which the desired step (10 milliseconds) is imaged quite well. Removing the LVL effects from real measurements by computational "subtraction" of the masking waves would require a good knowledge of the subsurface layers, including their lateral variations, and a good knowledge of the source wavelet.

There is, however, an even simpler way how to overcome the masking in the medium with seam and LVL layer, i.e. the CDP stacking of converted phases in later recording times. These problems, however, go beyond the scope of this paper, whose objective was mainly to demonstrate and explain the masking.

Conclusions

Using surface sources may create problems due to masking effects of the free surface and the subsurface LVL layer upon the P-wave reflections from shallow horizons. This is not only due to the well-known ground-roll effects, but also due to reflections inside LVL and head waves from LVL. Standard processing methods do not suppress these masking waves enough and the resulting time sections might be misinterpreted.

The FD calculation with a loaded ("exploded") reflection horizon is useful to check whether the wavelength is short enough to image the underground step-like structure, but the method gives no indication of the LVL masking effects. Modelling the CDP stacked time section is needed to reveal the problems.

Even with low predominant frequency the step-like coal seam can be imaged if the LVL effects are removed from measurements by auxiliary calculations. Full wave method (FD) is needed, because the ray method does not completely describe the masking waves.

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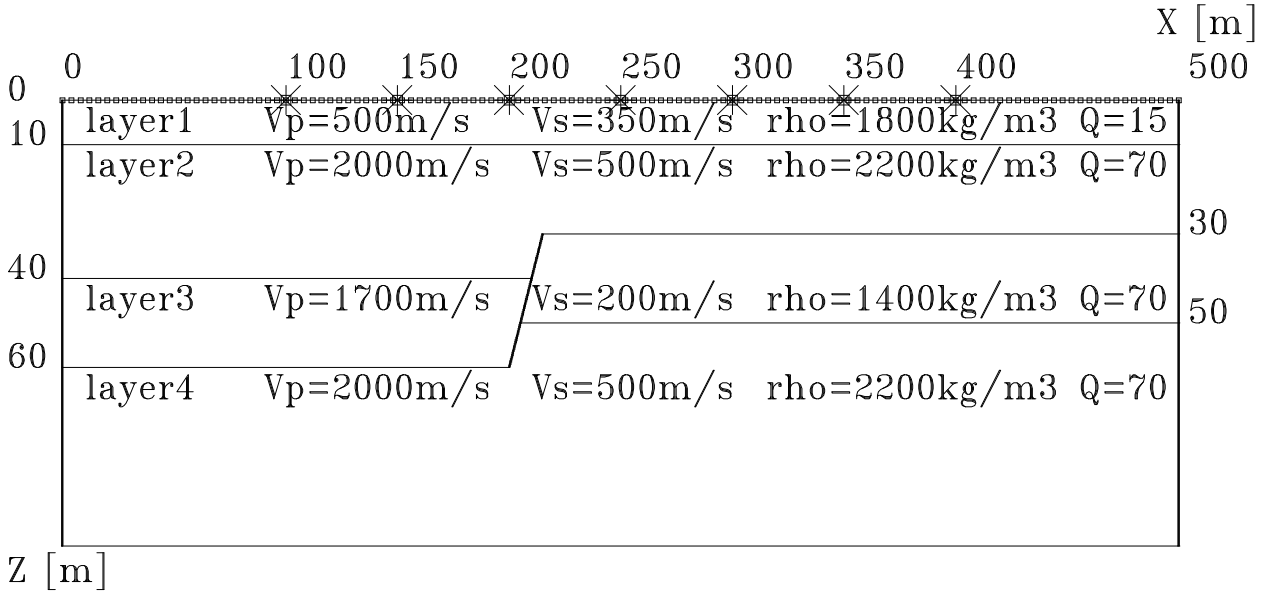

Fig. 1. Parameters of the model “COAL”. Asterisks at the top of the model denote sources and circles denote receivers.

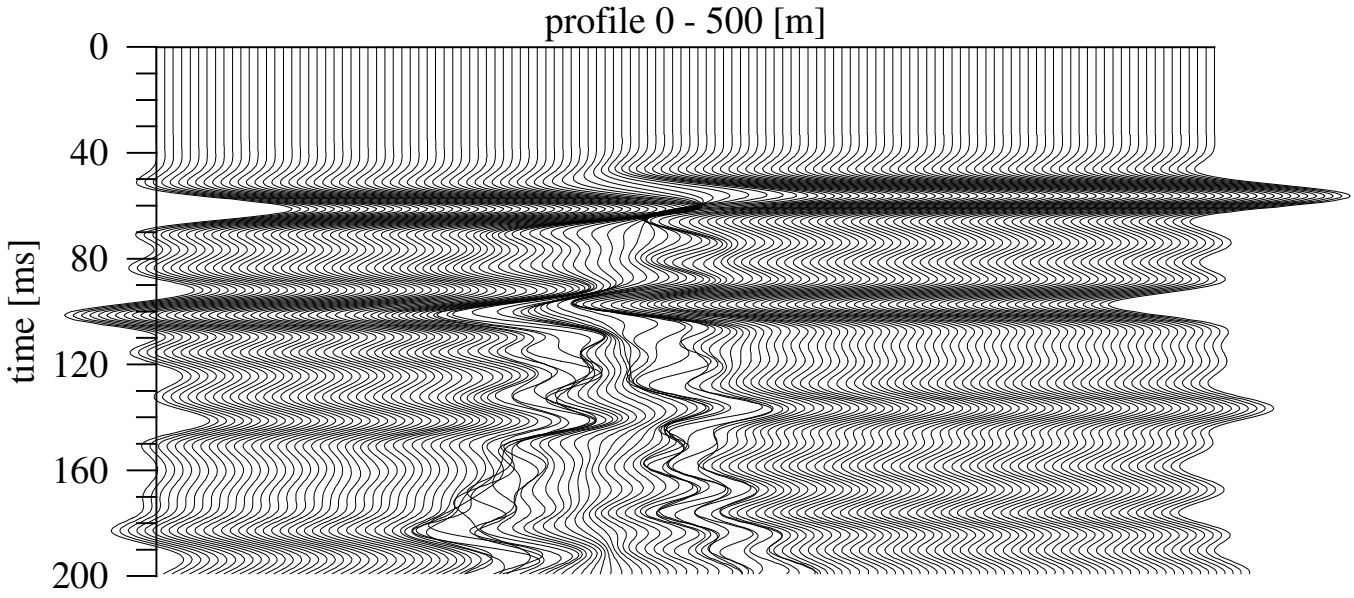

Fig. 2. Response of the model “COAL” excited by loaded-reflector method.

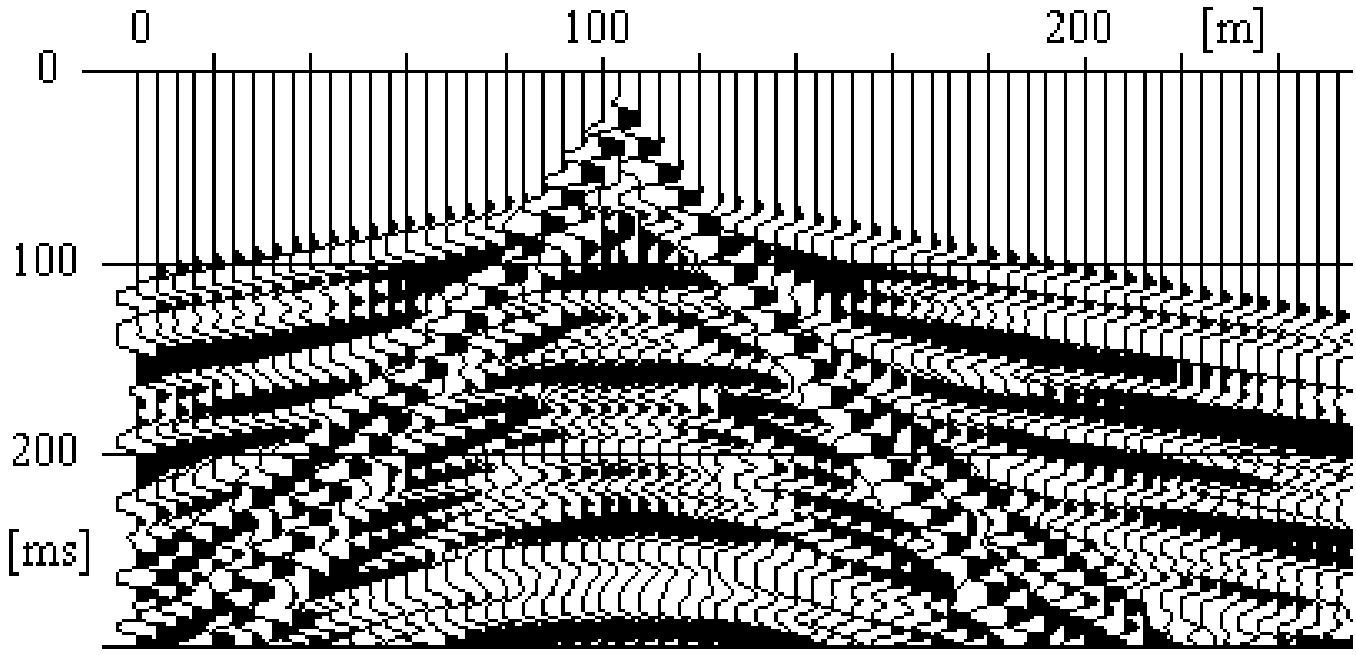

Fig. 3. Single-shot (x=100 m) response of the model “COAL”, vertical component.

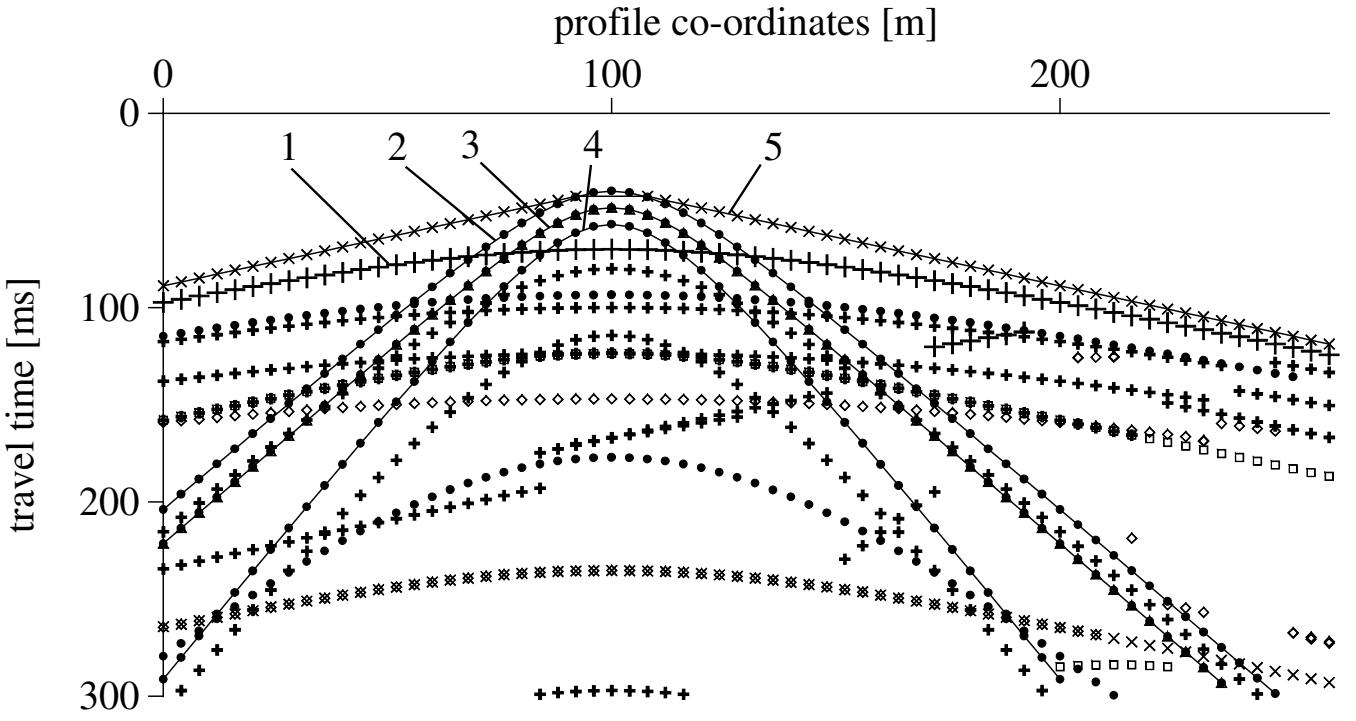

Fig. 4. Travel times of some P, S and converted phases for the source at x=100m: 1 - primary P reflection from the top of the coal seam, 2, 3, and 4 - P, PS or SP, and S reflection from the bottom of the LVL layer, 5 - P head wave from the bottom of the LVL layer. The detailed classification of the other phases, unimportant for this text, is given in Bucha (1996).

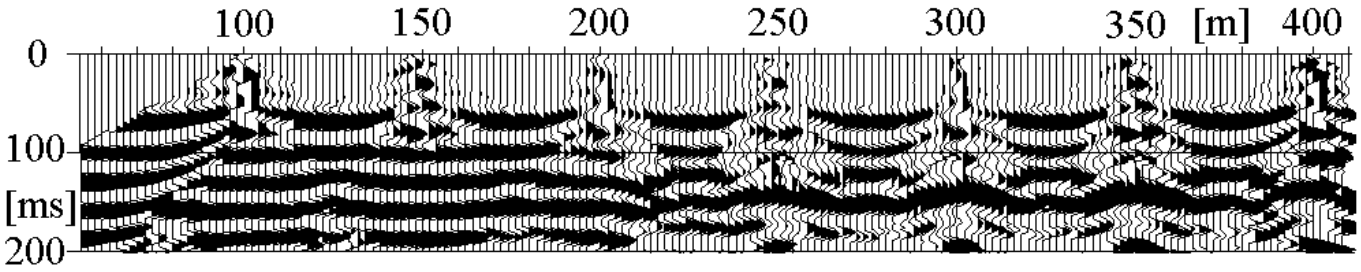

Fig. 5. CDP stacked section of the model “COAL” with masking effect.

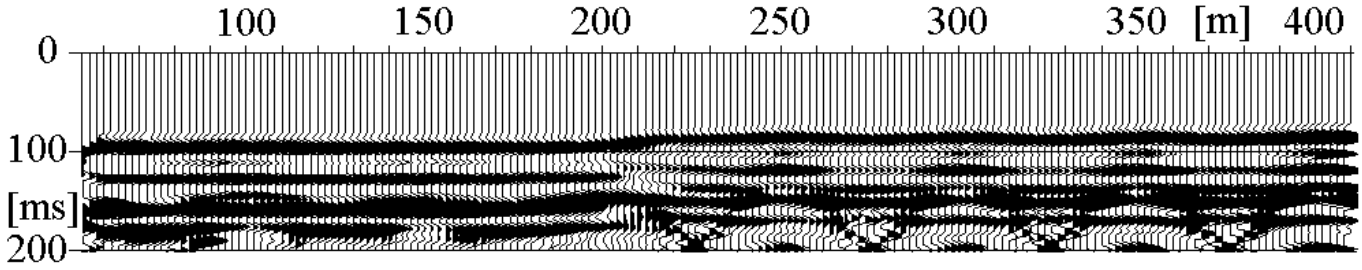

Fig. 6. CDP stacked section of the model “COAL” with masking effect removed.