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INFLUENCE OF A NEAR-SURFACE STRUCTURE ON SEISMIC WAVE FIELDS RECORDED AT THE EARTH'S SURFACE

VLASTISLAV ČERVENÝ [1,2] and FERNANDO C.M. DE ANDRADE [2]

[1] *Institute of Geophysics, Charles University, Ke Karlovu 3, 121 16 Praha 2, Czechoslovakia.*
[2] *Instituto de Geociências, Universidade Federal da Bahia, Rua Caetano Moura 123, Federação, 40.210 Salvador, Bahia, Brasil.*

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ABSTRACT

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The hybrid ray-reflectivity method is applied to the numerical modelling of seismic wave fields in laterally varying layered models containing a thin near-surface low-velocity layer. The computations within the laterally varying layered model are performed by the ray method, but the thin near-surface layer is attacked locally by the matrix methods. The thin layer need not be homogeneous, it may include arbitrary inner layering and it may vary slightly laterally. All multiples within the layer are automatically taken into account. Numerical examples of hybrid ray-reflectivity seismograms for two models of the thin near-surface layer are presented. An inverse algorithm to remove the effects of a thin near-surface layer from seismograms recorded at the earth's surface is proposed.

KEY WORDS: seismic waves, ray method, hybrid-ray reflectivity method, near-surface structure, multiple suppression

INTRODUCTION

Seismic wave fields recorded at the earth's surface are greatly influenced by the local structure close to the receiver. Commonly, the structure close to the

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receiver (meters or tens of meters in depth) is rather complex. In a near-surface thin layer, the velocities of propagation of seismic waves are usually very low, considerably lower than the velocities at greater depths. The structure of the near-surface thin layer plays an important role both in the numerical modelling of seismic wave fields and in the inversion of seismic data.

Within the thin near-surface layer, there are very favorable conditions for the generation of strong multiple reflections of a high multiplicity, as the surface of the earth and the bottom interface of the layer are very good reflectors, with strong velocity contrasts.

In the numerical modelling of seismic wave fields by the high-frequency methods (such as the ray method or the method of summation of Gaussian beams), any of the multiple reflections generated within the thin near-surface layer may easily be taken into account. However, if the number of multiples is high, such computations are cumbersome, particularly if the near-surface thin layer consists of several sublayers.

In this contribution, a hybrid ray-reflectivity method proposed by Červený (1989) is modified to perform such computations for models containing thin near-surface layers. The method automatically includes all multiples, including converted multiples. It can, however, be used only for thin near-surface layer, the thickness of which is roughly less than one half of the prevailing wavelength. Attempts have also been made to solve the opposite problem: to remove the effects of a near-surface thin layer from calculated (or observed) seismograms. Such 'clean' seismograms are required in many recent applications, particularly in the inversion of complete seismograms (Born inversion, etc.).

Note that the proposed algorithms can play an important role even in seismology, mainly in seismic microzoning. The near-surface geological structure has a great influence on an earthquake's effects on a given locality.

HYBRID RAY-REFLECTIVITY METHOD

The hybrid ray-reflectivity method has been designed to compute body wave synthetic seismograms in 2-D and 3-D laterally varying layered structures containing thin transition layers. A thin transition layer is not necessarily homogeneous; it may be represented by a stack of roughly parallel sublayers. The velocity, density and absorption contrasts between individual sublayers may be quite arbitrary (in the vertical direction). In the lateral direction, the velocities, densities and absorbing parameters within individual sublayers are also allowed to vary, but only smoothly. The thin transition layers may be smoothly curved. The total thickness of a layer should not greatly exceed one half of the wavelength.

The hybrid ray-reflectivity method combines the ray and matrix calculations. The ray calcalutations are applied in the parts of the model where the rays are not in contact with the thin transition layer. On the contrary, the matrix methods are applied locally at the points of reflection (transmission) on the thin transition layer.

Programs for the calcalution of ray-syntethic seismograms can be modified to yield such hybrid computations. Assume that a single interface of the first order in the model is replaced by a thin transition layer. Then the reflection/transmission coefficient corresponding to the interface should be replaced by the reflection/transmission coefficient at the thin layer, calculated by matrix methods. Such a reflection transmission coefficient at a thin transition layer is, of course, frequency dependent. Thus, the modification consists, in fact, in an application of a frequency filter.

A program package designed for such hybrid computations in general 2-D laterally varying layered structures containing a thin transition layer was written and described in Červený (1989). For the matrix computation of frequency-dependent reflection/transmission coefficients, the routines written by Müller (1985) were used. The package was used to study the properties of PP reflected waves from thin transition layers of different types, see Červený (1989). In Červený and Aranha (1991), the method was applied to the problem of tunneling of the reflected wave field through a high-velocity stack of thin layers situated in the overburden of the reflector. Both these papers present an extensive literature related to these problems. To test the accuracy of the method, the hybrid ray-reflectivity synthetic seismograms were compared with the full reflectivity computations for 1-D models. It was found that the accuracy of the hybrid ray-reflectivity computations was quite sufficient for pratical purposes. The hybrid method is most successful in the case of a near-normal incidence of the wave on the thin layer. With an increasing angle of incidence, the accuracy may decrease.

HYBRID RAY-REFLECTIVITY METHOD FOR A STRUCTURE WITH A THIN NEAR-SURFACE LAYER

In this contribution, the hybrid ray-reflectivity method is modified to include a thin near-surface layer. Above the top boundary of the thin layer, a vacuum is assumed. The modification is as follows: In the ray method, the complex-valued amplitude of the wave incident on the earth's surface should be multiplied by the so-called conversion coefficients to obtain the horizontal and vertical displacement components. If a thin near-surface layer is considered, it is necessary to compute the conversion coefficients corresponding to the wave incident on the bottom of the layer and the receiver situated on the top of the layer at the same lateral position. It is possible to show that such conversion coefficients can be expressed in terms of 'transmission' coefficients through a thin layer, corresponding to the transmitted wave passing formally into the vacuum. Such coefficients can be evaluated simply by matrix methods. In the algorithm, the upper boundary of the earth is replaced by the thin layer, and the standard conversion coefficients are replaced by the relevant conversion coefficients evaluated by matrix methods. In other words, the spectrum of each single event, computed by the ray method at the bottom of the near-surface layer, is multiplied by a scalar filter $F(\mathrm{i},\omega)$ corresponding to the ratio of the local conversion coefficients computed by the two methods,

$$F(\mathrm{i},\omega) = \mathrm{C}(\mathrm{i},\omega) \,/\, \mathrm{C}_0(\mathrm{i}) \tag{1}$$

Here $\mathrm{C}(\mathrm{i},\omega)$ is the conversion coefficient corresponding to the thin near-surface layer, computed by the matrix method, $\mathrm{C}_0(\mathrm{i})$ is the standard conversion coefficient for a free surface, ω is the frequency and i is the angle of incidence. There are four different scalar filters (1); they correspond to incident P- and S-waves and to recorded horizontal and vertical components. The filters, of course, depend on the local structure in the vicinity of the receiver.

REMOVING THE EFFECTS OF THE NEAR-SURFACE LAYER FROM SEISMOGRAMS

The scalar filter (1) can be inverted,

$$F^{-1}(\mathrm{i},\omega) = \mathrm{C}_0(\mathrm{i}) \,/\, \mathrm{C}(\mathrm{i},\omega) \; . \tag{2}$$

The application of (2) to the data calculated (or observed) on the top of the thin near-surface layer removes the effects of the near-surface layer. In greater detail: the filtered wave field corresponds to the receiver situated on the surface of the earth, situated in the place where the bottom of the thin layer was. The filter F^{-1}, of course, includes even the so-called static correction.

Such a scalar filter (2) may be applied to synthetic or to observed seismograms of individual single events. The main problem in the application of the procedure to the observed seismograms consists primarily in a decomposition of the seismogram into single P- and S-events and in an inaccurate knowledge of the local structure and of the angles of incidence of individual events.It would be useful to transform the complete vertical- and horizontal- component seismograms into seismograms corresponding to incident P- and S-waves. After this, it would be possible to apply the inverse filters independently to P- and S-seismograms, considering some average angles of incidence. Both the transformation and inversion filters could, of course, be combined.

EXAMPLES

We will present here two simple examples of the application of the proposed algorithms.

In both examples, we consider a PP reflected wave from a horizontal interface, situated at a depth of 1 km below the surface of the earth. The P-wave velocities above and below the interface are: $\alpha_1 = 3$ km/s and $\alpha_2 = 5$ km/s, respectively. The S-wave velocities β and the densities ϱ are determined from α using the relations: $\beta = \alpha / \sqrt{3}$ and $\varrho = 1.7 + 0.2\,\alpha$. The absorption is not considered. An isotropic point source is situated close to the earth's surface; the interaction of the source with the surface is not taken into account. The source time function is represented by a Gabor signal

$$x(t) = \exp[-(2\pi f_M(t-t_0)/\gamma)^2]\cos[2\pi f_M(t-t_0)+\upsilon], \qquad (3)$$

where $f_M = 30$ Hz, $\gamma = 5$, $\upsilon = 0$, $t_0 = 0.043$ s. Here f_M represents a prevailing frequency, t_0 is a small time shift which is used to shift the time zero to the effective onset of the signal (Fig. 1).

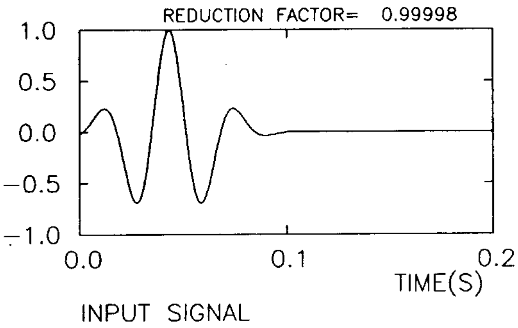

Fig. 1. The source time function used in examples.

The ray synthetic seismograms of the vertical component of the PP reflected wave for receivers situated along the earth's surface at offsets from 0.2 km to 2.5 km (with steps of 0.1 km) are shown in Fig. 2a. The critical distance for a given configuration equals 1.5 km; see the increase of amplitudes and non-zero phase changes immediately behind 1.5 km.

In the first example, we shall modify the global model described above by inserting a thin low-velocity layer of a constant thickness on its surface. We shall also place the receivers on the top of the thin layer. The total thickness of the layer is 20 m. The layer consists of two thin sublayers of 5 m and 15 m thicknesses, with the P-wave velocities of 0.7 km/s and 1.4 km/s, respectively. The S-wave velocities and the densities within the sublayers are determined from the P-velocities using the same relations as in the global model. The absorption inside the sublayers is assumed to be zero.

The synthetic seismograms of the vertical component of the P-wave are shown in Fig. 2b., displaying clear effects of multiple arrivals generated inside the thin layer. The greatest effects can be observed in the critical region. The time shift of the signal due to the thin near-surface layer is also clearly seen in Fig. 2b.

An attempt has been made to apply the inverse filter locally on the seismograms shown in Fig. 2b. The resulting seismograms from which the effects of the thin near-surface layer are removed, are shown in Fig 2c. If we compare the synthetic seismograms shown in Figs. 2a and 2c, we can see that they are practically the same. We can also see that the signals are shifted to a proper time position so that the inverse filter includes the static correction.

In the second example, we shall use the same global model of the structure. We shall, however, use a different thin low-velocity near-surface layer. The layer is homogeneous, with a P-wave velocity of 1.2 km/s, and with the S-wave velocity β and density ϱ determined using the same relations as in the global model. The thickness of the thin layer, however, varies linearly along the profile. It is 40 m at the first receiver and 0 m at the last receiver. The synthetic seismograms of PP reflected waves are shown in Fig. 3a. If we compare Fig. 2a and Fig. 3a, we can observe great changes at small offsets, with expressive multiples. As the offset gets larger, the differences between these seismograms are becoming smaller. We cannot see any difference at the last trace. We can also observe distinct differences in arrival times due to the variation of the thickness of the thin layer.

In addition, a random noise was introduced in the seismograms of Fig.3a, as shown in Fig. 3b. Applying the position-dependent inverse filter to these noisy seismograms, the removal of the effects of the thin near-surface layer is again excellent; compare Figs. 3c and 2a. Even the noise is partially suppressed.

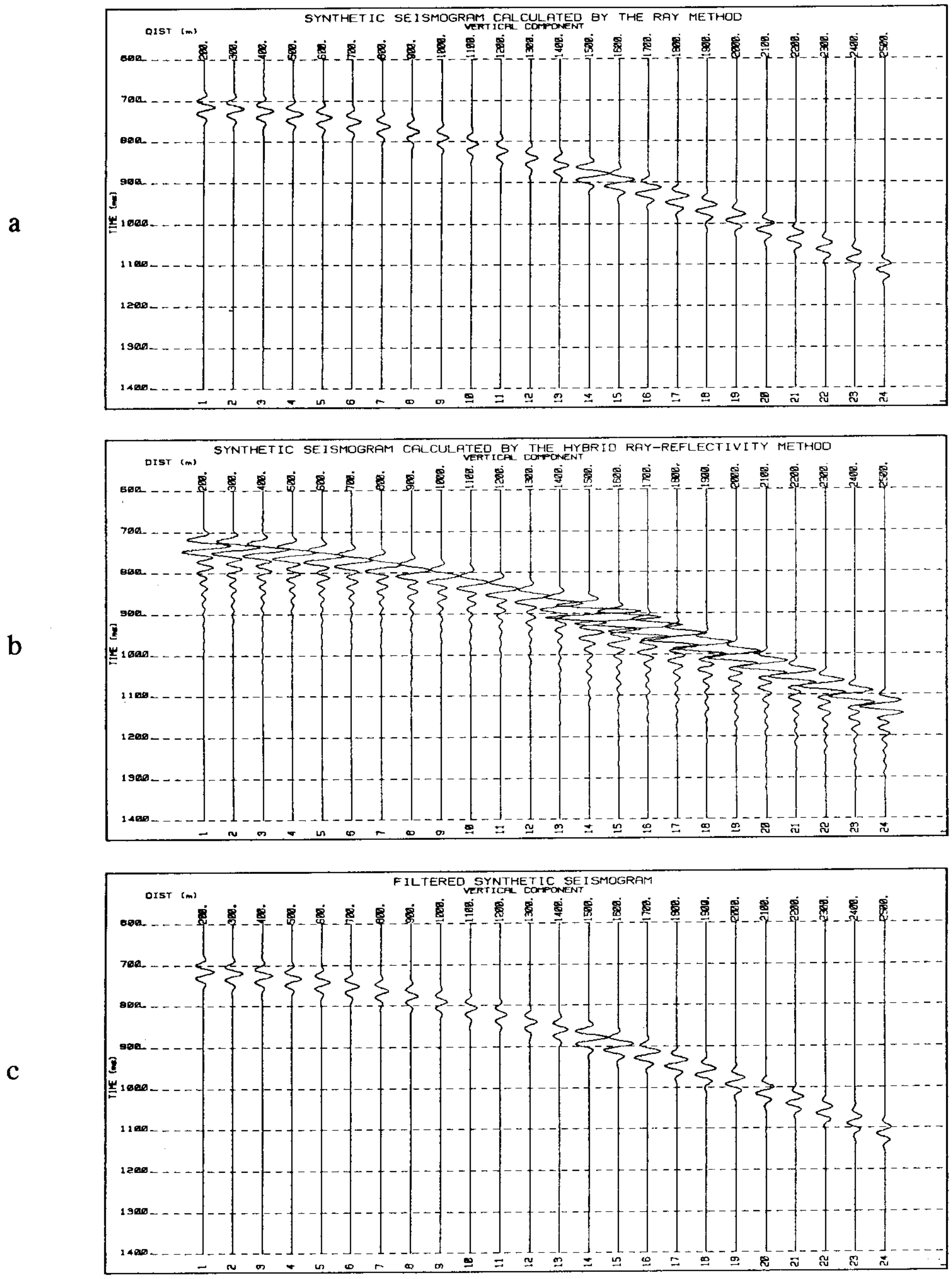

Fig. 2. Synthetic seismograms of a vertical component of a PP reflected wave from a reflector situated at a depth of 1 km. Fig. 2a: No thin low-velocity near-surface layer is considered. Fig. 2b: A thin low-velocity near-surface layer of a constant thickness is considered. Fig. 2c: An inverse filter is applied locally to the seismograms shown in Fig. 2b to remove the effects of the thin layer.

The reason why the removal of the near-surface structure effects in the two synthetic examples presented is so successful consists mainly in the simple form of the seismograms, corresponding to one single event only. Thus, the simple scalar filter (2) can be directly applied. Moreover, the structure and the angles of incidence have been perfectly known. If several different events, e.g., the reflections from different reflectors, arrive at the same detector, the removal of the near-surface effects would be more complicated. For a more detailed discussion and numerical examples of the application of the hybrid ray-reflectivity method and of the removal of the effects of the near-surface layer see Andrade (1991). The examples include the removal of the effects of the near-surface layer from P-reflection seismograms containing reflections from different non-planar reflectors situated in a complex laterally varying structure, the removal with an incorrectly known structure and incorrect angles of incidence, and even the effects of a near-surface layer on incident S-waves. The results are promising.

CONCLUSIONS

A hybrid ray-reflectivity algorithm can be used to compute the seismic wave fields in general 2-D and 3-D laterally varying layered structures containing a thin low-velocity near-surface layer. In an opposite way, the algorithm can be used to remove the effects of a such a thin layer from computed (or observed) seismograms.

Even though the examples presented here consider only a very simple global model, the algorithm and relevant program package can be used to compute synthetic seismograms for very general, 2-D laterally varying layered global models. A slight absorption in the global model is also allowed. Not only P- (as in the examples presented here) but also S- and converted waves propagating in such a model may be taken into account. The structure within the thin layer may also be very complex, with an arbitrary number of sublayers of arbitrary contrasts of velocities, densities and absorption parameters.

As follows from many other computed examples, the influence of a thin low-velocity near-surface layer on S-waves is, as a rule, considerably greater than on P-waves.

Here we have considered only a low-velocity thin layer. The algorithm used can also consider the near-surface high-velocity layers, e.g., permafrost layers. In such a case, the hybrid algorithm will automatically include even certain important non-ray effects, such as the inhomogeneous waves behind the critical angle of incidence on the near-surface layer.

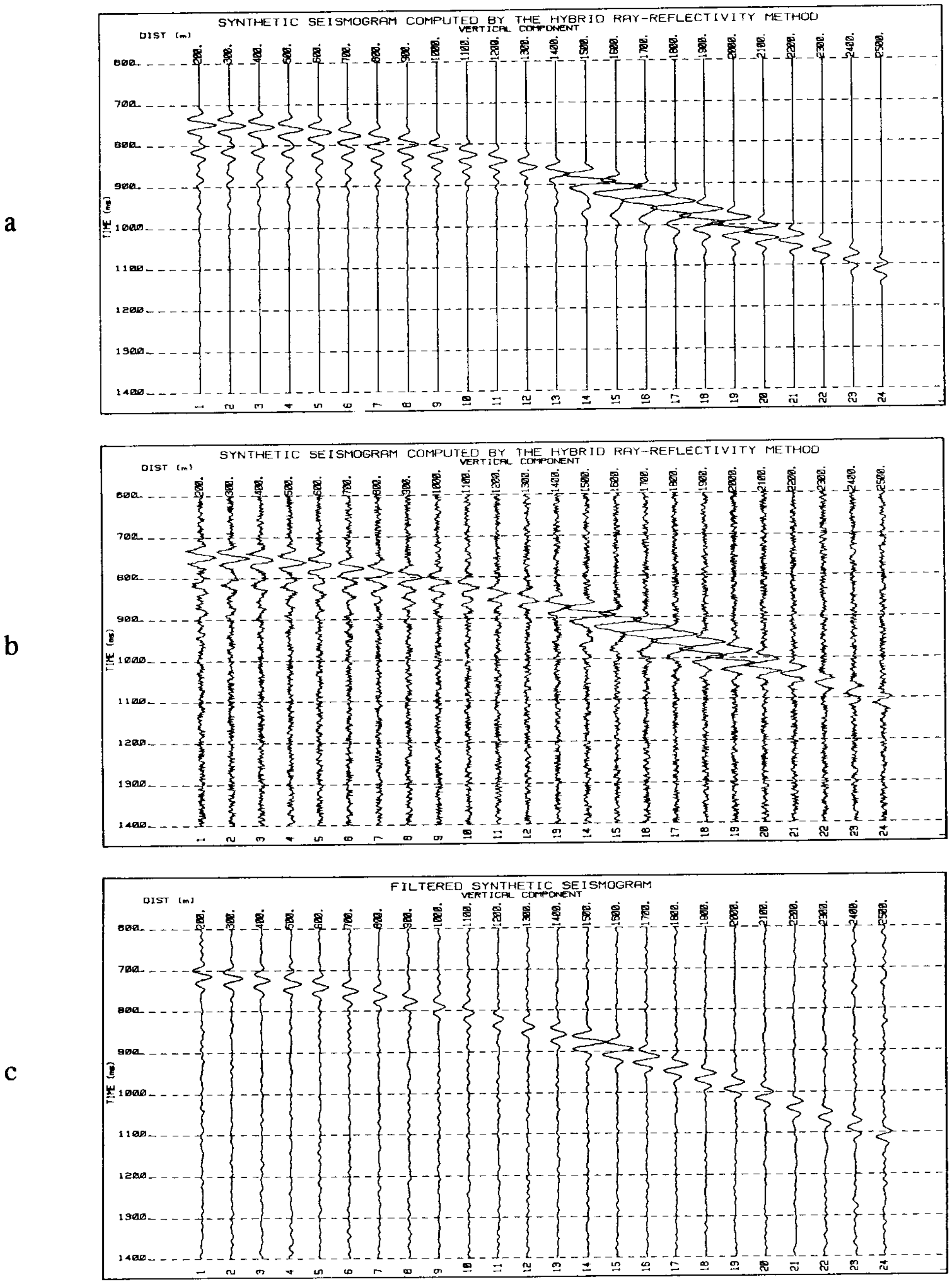

Fig. 3. Synthetic seismograms of a vertical component of a PP reflected wave for the same global model as in Fig. 2. Fig. 3a: A thin low-velocity near-surface layer of a variable thickness is considered. Fig. 3b: Random noise is added to the seismograms shown in Fig. 3a. Fig. 3c: An inverse filter is applied locally to the seismograms shown in Fig. 3b to remove the thin-layer effects.

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