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Three-dimensional Seismic Refraction Travel Time Tomography for Dipping Two Layers

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경사 2층 구조를 위한 3차원 굴절탄성파 주시 토모그래피*

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Abstract : This paper deals with tomographic travel time inversion of three dimensional seismic refraction survey conducted over a dipping interface. The slowness, and thus velocity as its reciprocal, distribution on the subsurface interface is to be determined applying an ART with under-relaxtion parameter. The models chosen are realistic, i.e., most likely to be met in engineering seismics, and the interface includes anomalous zones. It is found that, generally speaking, the inversion could be misleading or meaningless without the correction of the dip of the interface. This is rather surprising when we recall that usual assumption for the interpretation of refraction seismics data is the horizontal attitude of structures within the limit of 15° dip or so. To make the present method tenable for a new means of routine seismics, some practical ways of identifying head wave arrivals are to be devised.

요 약 : 본 논문은 3차원 굴절탄성파 탐사시 얻게 되는 굴절주시를 이용하여 경사진 지층경계면상 속도 분포를 추정하는 방법을 수립코자 수행한 연구를 요약한 것이다. 자료획득은 토모그래피 기법에, 주시역산은 under-relaxation ART 기법에 의거하였다. 모델은 경사 2층 구조이며, 관련된 매개변수는 지반조사시 만나게 되는 지층을 염두에 두고 선정하였다. 하부 지층에는 수직으로 저속도 혹은 고속도 이상대가 존재하며, 따라서 탐사의 주목적은 이러한 이상대를 탐지하는 것이다. 몇 가지 경우에 대하여 역산을 수행한 결과, 경사 지층 경계면의 경우, 경사 보정을 수행치 않으면 역산 결과는 판독이 어렵거나, 판독하더라도 착오를 일으킬 수 있다는 사실을 확인하였다. 종래 심도 추정을 위한 굴절탄성파 탐사에서, 15°이내의 경사지층 경계면을 평균적으로 수평이라고 가정해도 큰 오차가 나지 않는다는 사실을 상기할 때, 앞에 말한 사실은 특이한 일이다.

Keywords : tomography, seismic refraction survey, travel time, three-dimensional

Introduction

Seismic refraction survey method is well known to be one of the oldest, and most frequently utilized geophysical survey methods. And its survey principle is apparently simple though the theoretical basis of head waves is rather complex (Cerveny & Ravindra, 1971). The basic assumptions for seismic refraction survey has been as follows: two-dimensional subsurface structures, survey lines perpendicular to the strike of the structures, source points in line with receiver points, etc. These assumptions are practically valid in many cases of field conditions, and they are therefore not to be discarded. Even in earlier times, however, situations not favorable to satisfy these conditions arose in connection with petroleum exploration and earthquake seismology as well. To delineate salt domes, petroleum geophysicists devised far shooting in which receiver points spread out radially in many directions (Musgrave *et al.*, 1960). Seismologists were interested in determining the crustal structures and come out with the time term method where receiver points are scattered all over a plane (Willmore & Bancroft, 1960: Reiter, 1970). Looking back to these ideas, we realize that their concepts are quite modern and they were indeed faced with three-dimensional problems.

In recent years, three-dimensional seismic reflection survey saw its revival via tomography as a necessity for three-dimensional seismic reflection survey for hydrocarbon resources (Makrides, C. & Dennis, L., 1994: Rühl, T., 1995). These researches dealt with a horizontal interface of two-layered structures.

In this paper is attempted to determine seismic velocity distribution on a dipping interface of two-layered structures by means of three-dimensional seismic refraction to-

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mography. The inversions of travel time data are carried out with an ART algorithm using under-relaxation parameters. The operational environments including model parameters are primarily associated with engineering seismics though the basic ideas and techniques can be put to use to other kind of problems.

Theoretical Background

Travel time field on the surface of measurement

To cope with general situations expected of three-dimensional seismic refraction surveys, it is first needed to investigate the travel time fields on the surface of measurement. The followings are quoted from Cho (1994)'s previous work. In Fig. 1 is shown such travel time field on the surface above two-layered horizontal structures. The travel times marked by t were normalized by the intercept time and are all dimensionless. Naturally the travel time contours are concentric around the source point. The contour marked by C is that of equal cross-over distances inside of which head waves don't exist. A similar picture associated with two-layered dipping structures is shown in Fig. 2. Only those contours at the down dip side are presented and the contour of equal cross-over distance is now ellipse-like, the center of which deviates from the source-point to the down-dip side.

A problem that can really be serious for a three-dimensional field work is that the cross-over distance is not known a priori unless the source is in line with the receiver points. Nevertheless, some ways to overcome this obstacle may be found in the future. The head wave travel time T is a function of the true and apparent dips, δ and δ', the azimuthal angle α of a receiver point with respect to the strike of the subsurface structures, and the angle of emergence β.

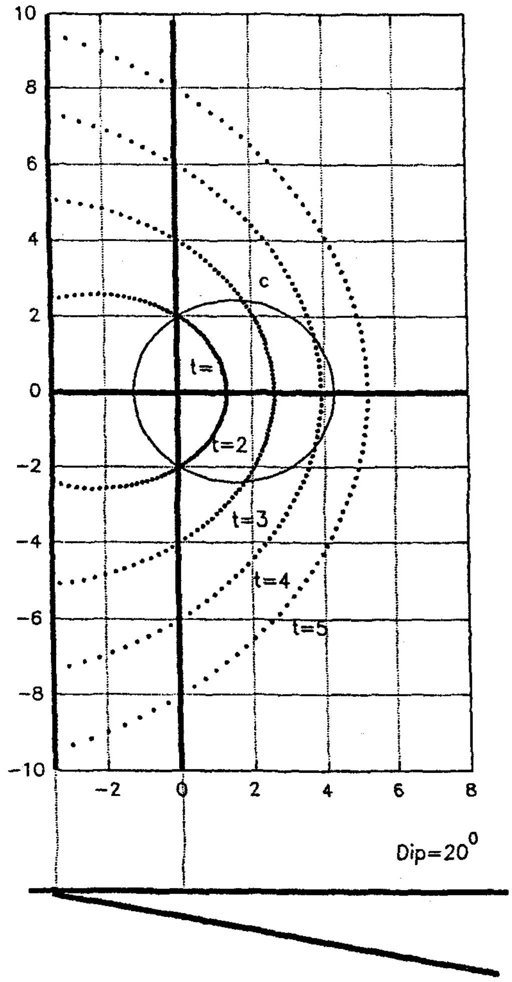

Fig. 2. Refraction time field on the surface (δ=20°).

And the gradient of T is

$$\nabla T = \frac{(\sin\beta,\ \sin\delta\cos\alpha\cos\beta/\cos\delta')}{V_1}$$

where, V_1 is the velocity of the upper layer (Cho, D., 1994). Some use may be made of this equation to discern head waves among various arrivals. For the time being, however, we assume in the present study that the travel times to be used for tomographic inversion are all those of head waves.

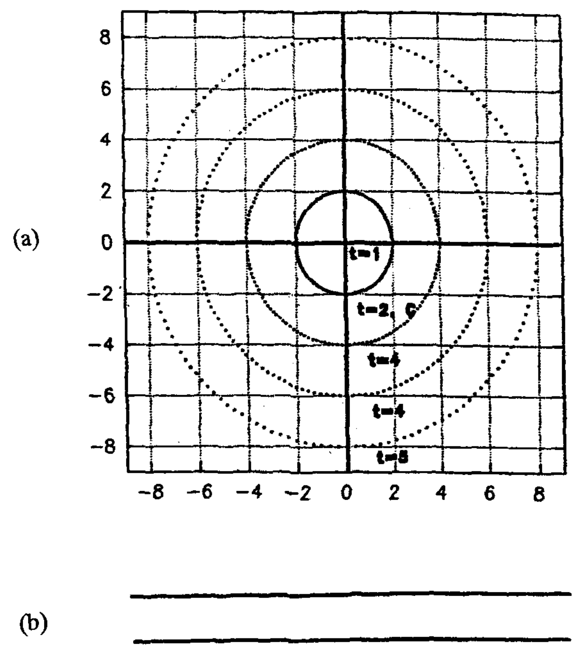

Fig. 1. Refraction time field on the surface (δ=0°).

Tomographic formulation of three-dimensional seismic refraction survey

In Fig. 3 is shown a schematic diagram of three-dimensional seismic refraction survey where S_1 is a source point,

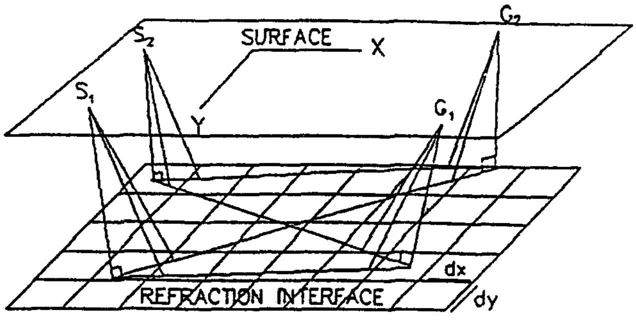

Fig. 3. 3-D seismic refraction tomography.

and G_i a receiver point. As the surface is parallel to interface, the quantity to be determined is the distribution of seismic velocities on the refraction interface which is subdivided into a set of pixels.

The refraction travel time T_i of the *i*-th ray is

$$T_i=\sum_{i=1}^{N} W_{ij}S_j+t_m+t_n,\ i=1,2,\cdots\cdots,M$$

where W_{ij} is the distance the *i*-th ray traversed through the *j*-th pixel, S_j the slowness of the *j*-th pixel, t_m the delay time of the *m*-th source, t_n the delay time of the *n*-th receiver respectively. The slownesses S_j are the unknown quantities and they are determined in the present study using a tomographic inversion with under-relaxation parameter. The formulation has so far follow exactly that of Macrides & Dennis (1994).

The arrangement of sources S_i and the receivers G_j are made along the four sides surrounding the square (Cho, D., and Cho, K., 1997). Of course, all the receivers are located well outside of the cross-over distance as previously mentioned, though its validity is not always guaranteed in practice.

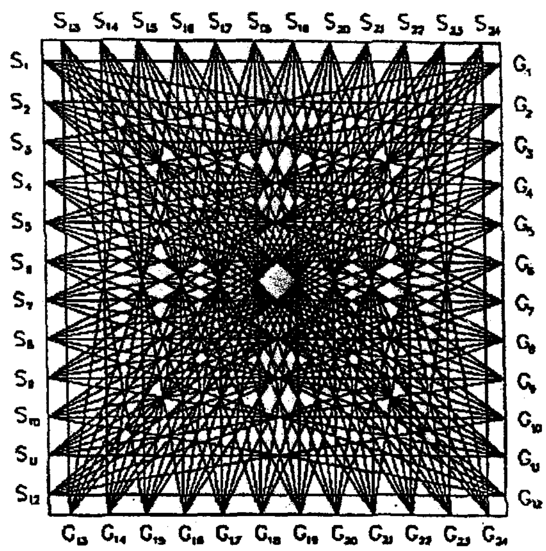

Fig. 4. Straight ray paths assumed on the refractor interface.

First, a tomographic inversion is done under the assumption of a horizontal interface. Next, a dip correction is applied to the inversed data. As for the dip, it must be estimated using in advance the refraction arrivals along two intersecting lines (Helbig, 1981: Sasa *et al.*, 1993: Cho, D., 1994). In the present case the survey lines are mutually perpendicular.

Models and discussions on the inversed data

Models

The models adopted for the present study are two-layered structures: one horizonal structure, two dipping layer cases (Fig. 5). And a vertical structure having anomalous velocity can intrude the underlying medium up to the refraction interface. Thus the anomalous zone is hidden when viewed from the surface.

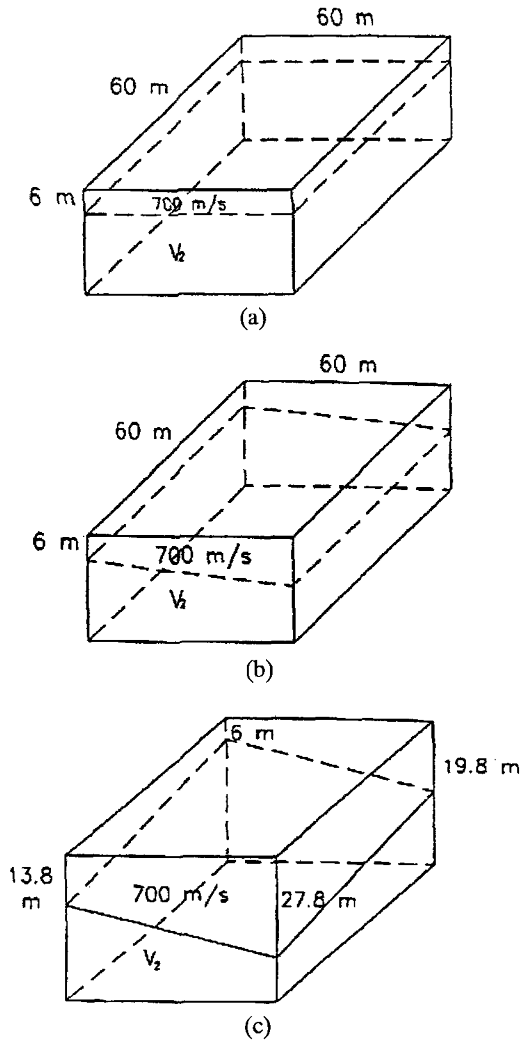

Fig. 5. (a) Horizontal layers, (b) Dipping layers #1, (c) dipping layers #2.

The velocities are 700 m/s in the upper layer, and 1,100 m/s (V_2) in the underlying layer in which an anomalous zone is hidden as mentioned above. The anomalous velocities are varied from 800 m/s, 1,400 m/s up to 1,600 m/s. In Fig. 6 are shown the refraction interfaces intruded by anomalous zones: the numbers in the pixels left of the interface pictures are the slowness, (A) is a case of low velocity zone imbedded in the interface, (B) two low velocity anomalous zones, (C) high velocity anomalous zone. The depth down to the interface is minimum 6 m, and maximum 27.8 m. In this way, the model is made to conform with realistic situations in engineering geophysics.

Discussions

It has been known that the survey mode as represented by Fig. 4 is prefered to other survey modes thinkable (Cho, K., 1997). The favoured arrangement is thus two mutually perpendicular source lines surrounding a corner of the survey area and an identical arrangement of receiver points starting from the other corner diagonal to the former one.

Fig. 7 shows a convergence behaviour of the tomographic iteration associated with the model (A) which is a low velocity anomaly embedded in the underlying medium. After the 90th iteration, the inversed slownesses converge satisfactorily to the given values across the strike of the anomalous zone.

Now let us look at the inversed picture shown in Fig. 8.

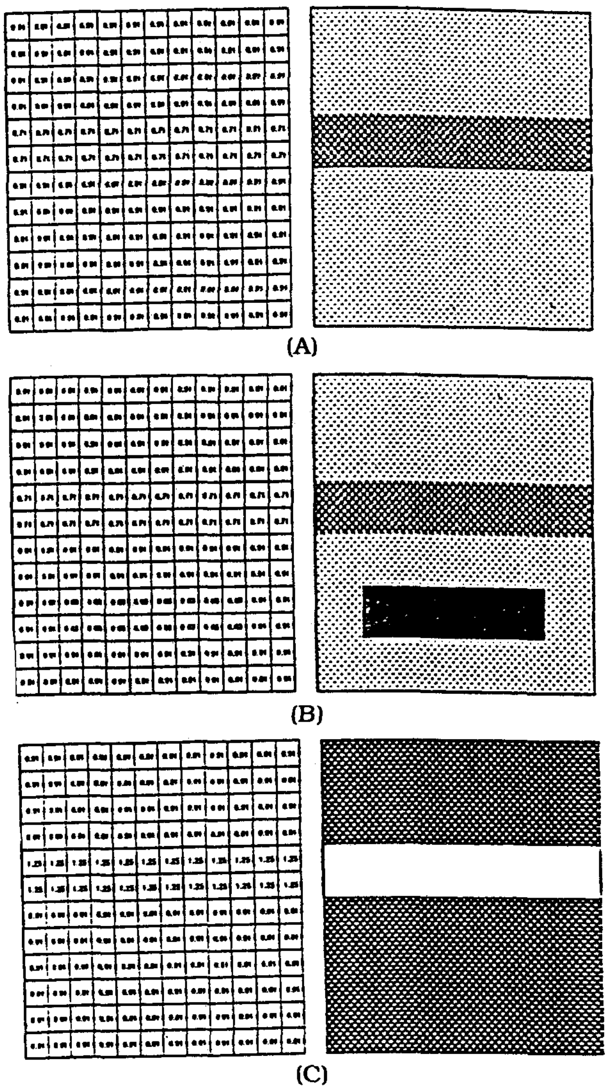

Fig. 6. Slowness at each cell. (A) refraction interface model 1, (B) refraction interface model 2, (C) refraction interface model 3

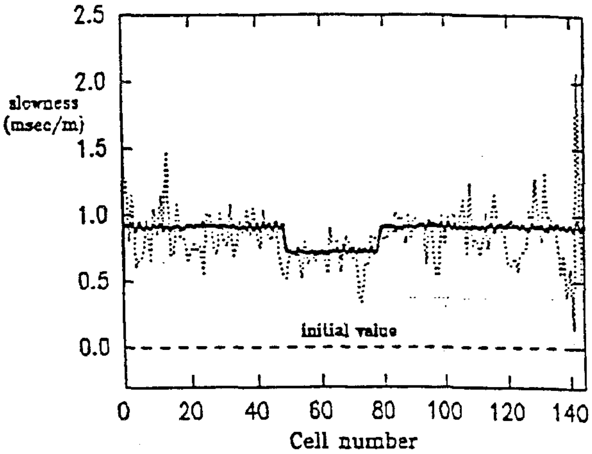

Fig. 7. Convergence behavior of the slowness obtained with iteration (···; 5th iteration, • ; 90th iteration, —; interface model

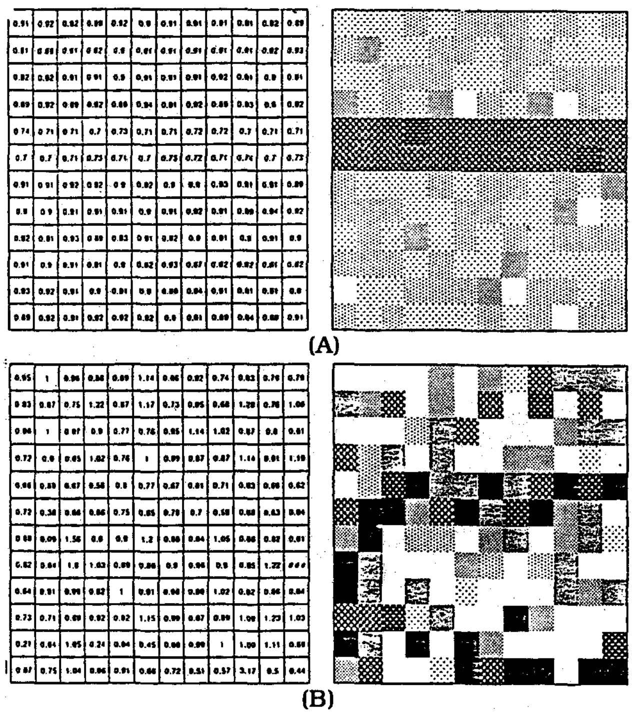

Fig. 8. Reconstructed images for dipping layers model 2, interface model 1 using survey modes D. (A) dipping angle considered (B) dipping angle taken to be zero

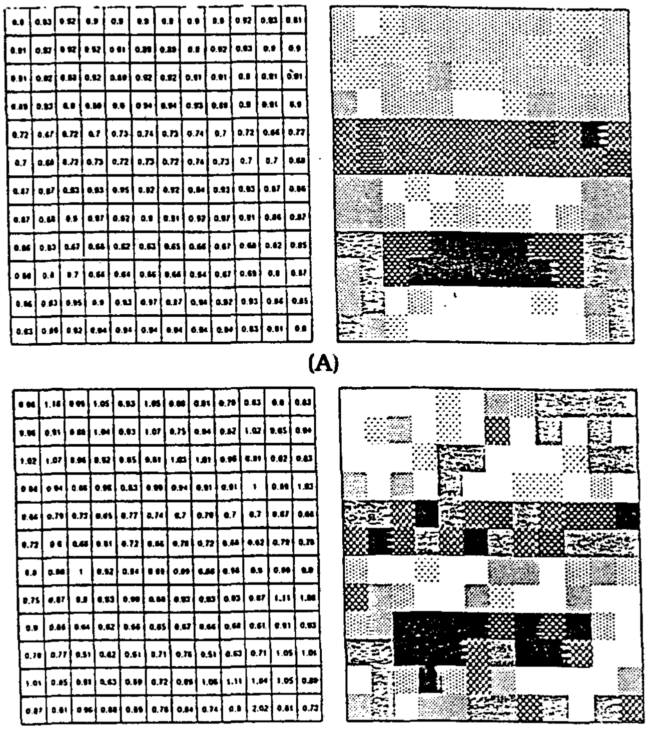

Fig. 9. Reconstructed images for dipping layers model 2, interface model 2 using survey modes D. (A) dipping angle considered (B) dipping angle taken to be zero

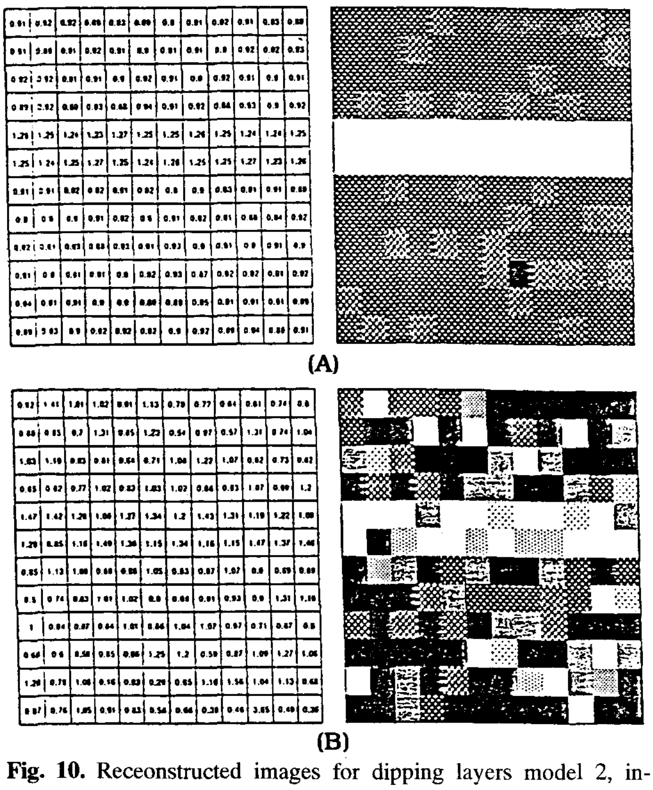

Fig. 10. Receonstructed images for dipping layers model 2, interface model 3 using survey modes D. (A) dipping angle considered (B) dipping angle taken to be zero

The model is the dipping layers model 2 of Fig. 5. Horizontal layers assumed, the inversion is of poor quality and the anomalous zone is hardly discernable. If the dip correction applied, however, the inversion is clearly seen to be very satisfactory.

The same things can be said to the case of dipping layers model 2 having two low velocity anomalous zones, and also to that of dipping layers model 2 of a high velocity anomaly embedded (Fig. 9 and Fig. 10).

Conclusions

As conclusions of the present numerical simulation of three-dimensional seismic refraction tomography using travel times of head waves, we may summarize as follows.

Based on the refraction travel times, three – dimensional seismic refraction survey can be applied to map the velocity distribution on the dipping subsurface interface.

To locate anomalous zones properly, however, the dip correction is indispensible. Without the correction, the inversion could sometimes be quite meaningless or misleading. This is surprising when we recall that the assumption of horizontal structures is well founded within a limit of 15° or so.

And studies has to be undertaken to determine three-dimensional shape, i.e., thickness variation of the interface. In fact, this problem should have preceeded to that of the present study.

Furthermore, practical means of identifying head wave arrivals should be devised. Unless such means is procured, the inversed results will contain inherent defects.

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