Pseudo Three Dimensional Refraction Method for Rock Bed Detection

Jong-Ha Lee¹⁾, Yoshinori Sanada¹⁾, Toshifumi Matsuoka¹⁾ and Yuzuru Ashida¹⁾

1) Dept. of Earth Resources Engineering, Kyoto University, Kyoto, 606-8501, Japan.

Abstract: Refraction tomography nowadays has developed to unveil 3 dimensional structures of subsurface. Delineation of a rock bed which usually happens to be one of the main purpose of a survey in most engineering sites, however, is not easy because inversions usually produce images of gradual change of the material properties. From the survey designed for 3 dimensional refraction data acquisition, we can get the contours of first arrivals of a shot on the surface by applying an interpolation such as kriging. Re-sampling first arrivals from these contours, we get reciprocal traveltimes between two shots respectively. Then, we applied the generalized reciprocal method (Palmer, 1982) using these data finally to get a pseudo 3 dimensional subsurface structure.

Introduction

Geophysical techniques using refraction waves have been much developed from the early days of geophysical prospecting history to present. The majority of these techniques had been those which manipulate the time-distance curves to delineate the underground layers until geo-tomographic techniques were introduced in recent years (Cox, 1999). Much part of data from 2D or 3D refraction surveys, nowadays, is dealt with the tomographic techniques to get either 2D sections or 3D volumes. The tomographic techniques like traveltimes tomography and waveform inversion, however, usually gives us resulting images that are rather smoothed throughout some inversion stages. Even though we could distinguish some anomaly from background from these images, it would be difficult to point out rather exact depth of a rock bed which most of the civil engineers supposedly want to know.

For 3D refraction data, we usually plot contours for each source after picking first arrival only to check the consistency of first arrivals picked. Letting those first arrivals be contoured well, we can get first arrivals of any points on the surface. In practical 3 D survey, location of sources is along each inline and is not usually overlapped with receivers and the number of channel available for any direction is limited. Re-sampling from the contour would enable us to get additional traveltimes data between the receivers on a line. And, also, we can apply some conventional methods using reciprocal traveltimes for any direction between the source pair. This process is illustrated in Fig. 1.

To grid traveltimes on the surface, we used Kriging that is a well-known geo-statistical method to predict values from spartial samples. On the next chapter, we describe the method and show the applicability to estimate traveltimes on the surface. Generalized reciprocal method (Palmer, 1982) is implemented for estimation of depth and velocity of refractor as it is easily programmable and produces rather stable solution. To test the algorithm, we made a 3D

Fig. 1 An example showing the core process of this algorithm; (a) Forward traveltime contour kriged out of source A data; (b) Reverse traveltime contour kriged out of source B data. We imagine receivers between A and B. (c) The depths of the second layer beneath receivers are estimated by GRM.

synthetic model that consists of 2 layers where the bottom layer has topographic complexity including faults throughout the structure and showed some results from it. Finally, we applied this algorithm to field data.

Kriging first arrival data

Kriging is a well-known statistic method for gridding out of spatially sampled data and has widely applied to geostatistic problems (Wackernagel, 2003). Though it is an arguable point whether we can use interpolated first arrivals for interpretation, we premise that the first arrival of an unknown point can be estimated by using kriging interpolation. Kriging estimates the value of the unknown point E by calculating the weighted sum of known points $P_k = (x_k, y_k, z_k), k = 1, \dots, K$:

$$E = \sum_{k=1}^K w_k z_k, \quad \sum_{k=1}^K w_k = 1 \quad (1)$$

where w_k is the weighting for the k th known point. The appropriate selection of the weighting becomes the core of kriging algorithm. The variogram V of the known points are constructed to calculate the weights:

$$V = \begin{bmatrix} D_{11} & \cdots & D_{1K} \\ \cdots & \cdots & \cdots \\ D_{K1} & \cdots & D_{KK} \end{bmatrix} \quad (2)$$

where D_{ij} represents the distance between two known points P_i, P_j . We can estimate the value

Fig. 2 An example showing (a) the result of kriging interpolation of first arrival from the source at O(0,0). The symbols on figures indicate the receiver positions where first arrivals are sampled. (b) Exact solution of first arrivals on the synthetic model calculated by forward modeling. The synthetic model is shown in Fig.3 (b). (c) Difference between (a) and (b).

of the unknown point by calculating $E = w_k P = (d_k V^{-1}) P$ where d_k is the distance vector of the distance from the unknown point to each known point.

We used tk3d routine in GSLIB for kriging. The estimation is conducted with ordinary kriging considering no nugget effect, searching for at least 10 to at most 20 samples around 300m around an unknown point. Fig. 2 (a) shows an example of kriging interpolation carried out in the study. Comparing the exact solution of the first arrival shown in Fig. 2(b), though the complicated changes between the receiver lines was not clearly interpolated, difference between two images in Fig. 2(c) shows less than 5 msec error in interpolation.

Generalized Reciprocal Method(GRM)

When we have a reciprocal traveltime we can find out the depth and velocity of the layers by using GRM (Palmer, 1982). Although there exist lots of techniques using the reciprocal traveltime-distance curves (Cox, 1999), we selected GRM because it produces rather stable solutions and it is rather easily programmable. The algorithm supposes that we know the velocity of the first layer and find the depth and velocity of the second layer. It estimates the optimum XY value, which is twice the refractor offset distance by selecting XY value which make the smoothest velocity analysis function t_v , defined as

$$t_v = \frac{1}{2}(t_{AY} - t_{BX} + t_{AB}) \quad (3)$$

where t_{AY} is the traveltime from source A to receiver Y, t_{BX} is the traveltime from source B to receiver X, and t_{AB} is the reciprocal time from source A to source B. From the slope of t_v , we

estimate the apparent refractor velocity v_1 . Then we can get the generalized time-depth t_G defined as

$$t_G = \frac{1}{2} \left(t_{AY} + t_{BX} - \left(t_{AB} + \frac{XY}{v_1} \right) \right) \quad (4)$$

and finally the depth of the second layer at each geophone location from

$$z_G = t_G \left(v_0 v_1 / \left((v_1)^2 - (v_0)^2 \right)^{1/2} \right). \quad (5)$$

Application to Synthetic Data

To verify the approach, we made a two-layered 3D model shown in Fig. 3 (b). Note that the wireframe shows the shape of the second layer. We selected an extremely complex model with ups and downs and the fault throughout the structure of $400\text{m} \times 400\text{m}$ on purpose. In Fig. 3 (b), the depth of the second layer is exaggerated the depth changes between -5m to -35m . The velocity of the first layer is set to 1500m/s and that of the second layer to 4000m/s . The sources and receivers are located on the surface where depth is zero. Fig. 3 (a) shows the configuration of the surveys where sources and receivers are described with the stars and triangles respectively. Kriging is performed with the data from the 369 receivers distributed on each line with 10m offset. We used the sources around the model to get appropriate reciprocal data between the source-source pair. We calculated first arrivals on each receiver by forward modeling with eikonal solver. An example of the contours was previously shown in Fig. 2 (a).

For every source-source pair, we resampled reciprocal first arrivals on imaginary receiver points. The offset of receivers between a source-source pair is set to 5m regardless of the total number of receivers for convenience. When the estimation sometimes fails to get reasonable velocity of the refractor, we gave up the estimation. Although the GRM kernel estimates the depths and the apparent refractor velocities, this changes little bit for every source-source pair. So, we took the average of the apparent refractor velocities, 4080m/s in this case and carried out the estimation one more time. After the approximation of the depth, we carried out kriging with all

Fig. 3 (a) The configuration of 3D survey is shown. The location of sources and receivers is illustrated by star and triangular symbols on the figure. (b) The wireframe showing the shape of the second layer of which the depth changes from -5m to -35m . The velocities of the first and second layers are set to 1500m/s , 4000m/s respectively. (c) The estimated second layer of which the velocity is estimated 4080m/s .

the depth acquired to delineate the second layer. Fig. 3 (c) shows the depth of the refractor estimated with this algorithm. The velocity of the first layer is assumed to be 1500m/s and that of the second layer 4080m/s. We can see the depth and the shape of the second layer are estimated very well.

Interpretation of Field Data

We applied this algorithm to the field data from a 3D refraction survey. The configuration of the survey is illustrated in Fig. 4 (a) with stars and triangular symbols indicating sources and receivers. In $102.5\text{m} \times 30\text{m}$ area, we have 24 sources and 84 receivers with 20m and 5m spacing respectively. The first arrival on each receiver was manually picked by the interpretator with care. We added the zeros on the source location to enhance the accuracy. Imaginary receivers where the depth was estimated are illustrated in Fig. 4 (b). We neglected source pairs that are too close each other. Fig.4 (c) illustrates the shape of the second layer assuming the velocity of the first layer is 300m/s, which is estimated from the data near the sources. By averaging the apparent refractor velocity we estimated the velocity of the second layer to be 2089m/s. We showed the contour of the depth of the second layer estimated. We can observe the changes of the second layer.

Discussion and Conclusion

We developed pseudo-3D refraction method to delineate the depth and velocity of rock bed. Yet the algorithm continues to inherit in itself the weakness of GRM or the conventional 2D

Fig. 4 (a) The configuration of the 3D survey where sources and receivers are illustrated by star and triangular symbols. (b) Imaginary receivers where the depth were estimated are illustrated by symbols. (c) The shape of the second layer assuming the velocity of the first layer be 300m/s. The velocity of the second layer is estimated to 2089m/s. (d) The depth of the second layer is contoured.

algorithm as so we assumed. We need a careful consideration to determine the depth of the first layer as it affects the depth of the second layer in equation (5). We need more consideration on interpolation methods of the first arrivals. Careful 3D survey designing also can be considered. As we have seen from example in Fig.2, dense receivers on 2D lines wouldn't detect faults running in in-line direction. As far as we can assume that the underground consist of two layers, this algorithm could be applied to get the depth of the depth and velocity of rock bed.

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