Determination of Velocity — Depth Distributions by Inversion of Refraction Time — Distance Data: Discussion

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Greenhalgh, King & Emerson (1980) and Greenhalgh & King (1980) have presented significant contributions to the theory and practical interpretation of seismic refraction data. These comments are addressed to the practical interpretation of such data.

At the present time the choice between numerical interpretation methods for refraction data is usually between time-term equations based on an earth model having discrete, constant velocity layers (e.g. Hawkins 1961), velocity-depth functions (Greenhalgh et al. 1980) or, possibly, methods combining both models (e.g. Puzyrev 1960).

On occasions, the seismic data may contain clues as to which model is appropriate, however, analysis of later seismic arrivals is usually required (e.g. Meissner 1975). At present this procedure is fraught with difficulties, particularly in the shallow geological environment.

In practical terms, the choice of interpretation method must therefore be based on:

(a) the appropriateness of the chosen model to the problem for which the seismic survey was undertaken and the known geology (and hydrogeology);

(b) the goodness-of-fit of either curved or straight line segments to first arrival travel-times on the T-X graph; and

(c) the computational convenience of the chosen method.

Decisions regarding (a) although essentially based on experience can be aided by decisions made in (b). Before examining this connection, it is appropriate to refer to a comment by Emerson (1967) '. . . there occurs a dichotomy of the variable velocity layer into velocity layers having no geological significance. Thus the merits, peculiar to the seismic method, could be lost. Velocities may lose significance. Interpreted depths may be inaccurate'. The converse is equally true.

The goodness-of-fit of data to mathematical functions (b) is ultimately dependent on data errors and the significance attached to deviations of travel-time data from theoretical functions. Dampney & Whiteley (1980) recognised this problem and elucidated a method, based on discrete layers and the statistical method of groups, which allows computation of confidence limits for calculated velocities and depths, examines systematic deviations of the data from straight line segments, and permits comparison of velocities calculated from overlapping travel-time data for different shot offsets. A common cause for systematic deviations from fitted straight lines is a velocity increase with depth and this method may be used to indicate such a possibility.

In relation to (c), computational convenience, the example presented by Greenhalgh & King (1980, p. 95) after Shepard (1949) allows a comparison of interpretation methods to be made. It should also be noted that the reference to Shepard (1949) is incorrect. The correct reference is included below.

From the data presented in their fig. 3 Greenhalgh & King (1980, p. 95) fitted a velocity-depth function V(z) of the form $V(z) = 410 + 622\sqrt{z}$, which gave a depth to the deepest refractor (velocity 13 200 ft/s) of 105 ft. Figure 1 (after fig. 3 of Greenhalgh & King) shows an alternative interpretation assuming horizontal layering, a necessary assumption in the absence of reversed travel-time data.

Four straight line segments may be visually fitted to the apparently curved segment of the travel-time graph (Fig. 1). These give seismic velocities of about 1150 ft/s (V_1), 2250 ft/s (V_2), 3500 ft/s (V_3), 4800 ft/s (V_4) and intercept times of 5 ms (T_{12}), 13 ms (T_{23}) and 22 ms (T_{34}) respectively. These layers are underlain by the 13 200 ft/s layer with an intercept time of 54 ms (T_{45}) as calculated by Greenhalgh & King (1980). Using the normal intercept-

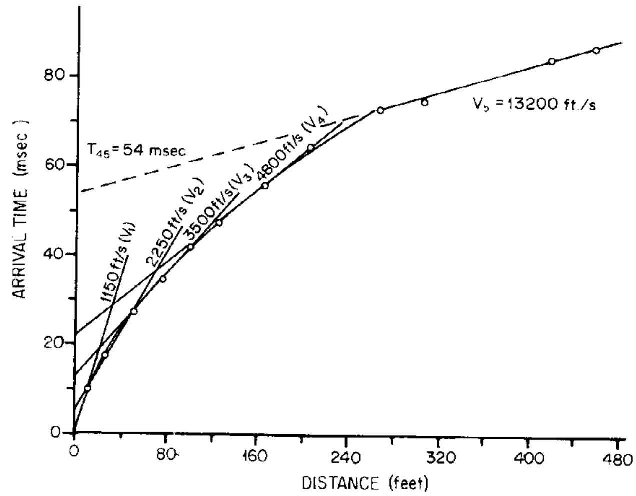

FIGURE 1

Interpretation of seismic data of Greenhalgh and King (1980, p. 95) assuming horizontal layering.

time equations (Hawkins 1961) these data give layer thicknesses of about 3, 11, 20 and 71 ft respectively and a total depth to the 13 200 ft/s layer of 105 ft. This depth is identical to that obtained by Greenhalgh & King based on the fitted velocity function.

If the deepest layer is the object of the refraction survey either interpretation method may be used with about equal convenience. However, the velocities obtained for the intermediate layers may contain information on the nature and condition of the geological materials overlying the deepest refractor. For example, the velocity of the upper V_1 layer (1150 ft/s) is close to the velocity of P-waves in air and probably represents a maximum velocity for dry loose surface material at the site. The velocities obtained for the V_2 and V_3 layers suggest that they represent essentially dry or partially saturated unconsolidated material. The velocity obtained for the V_4 layer (4800 ft/s) is close to the P-wave velocity in water and may represent the water-table, a frequently observed shallow refractor.

Although this interpretation based on discrete layers cannot be confirmed without independent geological data (nor can the interpretation based on the fitted function) it has in this instance, I believe, the potential to yield more detailed subsurface information than an interpretation based on a single smooth velocity-depth function. However, this situation may not always be the case, and there are undoubtedly many problems in which the use of a velocity-depth function is appropriate.

Comments by Derecke Palmer *Geological Survey of New South Wales, G.P.O. Box 5288, Sydney, N.S.W. 2001*

It is pleasing to see the renewed interest in curved raypath methods, as shown by the papers of Greenhalgh, King & Emerson (1980) and Greenhalgh & King (1980). However, I believe there are several important factors which severely limit the usefulness of their methods for routine interpretation.

The first factor concerns the recognition that curved raypath methods are applicable. Despite the fact that both theoretical considerations and statistical studies indicate that layers in which the seismic velocity varies continually with depth are more appropriate, it is rare to see interpretations which do not consist of layers with constant seismic velocities. While the mathematics may intimidate some, I believe the main reason is the difficulty in recognising curvature in the travel-time plots. In those cases where curvature is apparent, the velocity increases with depth are extremely rapid. For example in figs 2 and 3 of Greenhalgh & King (1980), where curvature is obvious, there is at least a four-fold increase in the velocity. For less rapid changes (e.g. less than twice, Palmer 1980, fig. 19) the curvature could easily be overlooked, and a simple linear segment could be fitted (Palmer 1980, p. 47).

The second factor concerns the accuracy of the travel-time data. Hagedoorn (1955) showed that it is possible to fit a variety of velocity functions to a set of data, with an accuracy of better than 6 ms in 2 s (i.e. better than 0.3%). but still produce depths which differ by more than 20%. Clearly greater variations could be expected from data obtained in the field.

The curved raypath problem can be considered to be a special case of the undetected layer problem (Palmer 1980, p. 37). It demonstrates the inherent ambiguity of interpretation of travel-time data, and the instability of extrapolation, on which the standard methods are based. The comments of Whiteley are in fact a variation on this theme.

The only solution, using refraction data alone, is to use the generalised reciprocal method (GRM, see Palmer 1980, pp.46-47) provided of course an XY value can be recovered. The GRM can provide accurate depths without the need to recognise beforehand that a curved raypath problem exists, and without data of unattainable accuracy.

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We thank both Robert J. Whiteley and Derecke Palmer for their comments on our papers in vol. 11 no. 3 of the *Bulletin*, and R. J. W. for correcting the reference to Shepard (1949).

Nowhere in our papers was it advocated that curved raypath methods be used for routine interpretations. Both papers were meant to be a commentary on and a convenient tabulation of useful formulae formerly widely scattered in the literature. The papers are merely a synthesis (with some extensions) of previous work concerned essentially with the 'mechanics' of refraction interpretations involving continuous velocity media. However, the closely related philosophical aspects highlighted by Whiteley and Palmer are clearly deserving of debate.

It is a truism that there is a certain arbitrariness in each of the principal refraction interpretation methods (soon, we would hope to include curved raypath methods!). It is not our intention to present examples, synthetic or real, to demonstrate the (apparent) superiority of *any* of the alternative methods, not only because it is all too easy to produce counter examples. Each of the alternative methods, including curved raypath methods, has particular merits or deficiencies in different situations. In any particular situation, sound scientific method dictates that *the best method is the one which provides the simplest solution which is consistent with the data.* This is merely a statement — or restatement — of the principle of maximum simplicity ('Occam's Razor'); the contentious issues concern the criteria of simplicity, and the definition of data and their accuracy.

The simplest solution might be defined as that solution which can be described by the fewest numbers or parameters (and thus has the least spurious features *not* required by the data). On this basis alone, in the example discussed by Whiteley we prefer the gradient medium interpretation; the intermediate overburden layering can be considered spurious insofar as there is no compelling evidence (e.g. head waves, reflections) for it. Moreover, the derived velocity gradient function can of course be used to calculate any instantaneous velocity required for geological inference; in the example quoted, the two methods detailed differ by 7 ft, or 19%, in the least depth to a velocity of 4800 ft/s. As pointed out by Palmer, any such difference is no more than an expression of the non-uniqueness inherent in the inversion of inaccurate and incomplete data. For this reason, preference for any particular interpretation method is, and is likely to remain, a matter of taste based on a tradeoff between computational convenience and the extent of adherence to the principle of simplicity. In this regard both Palmer (1980) and Dampney & Whiteley (1980) have made valuable contributions to the practical problems of handling real refraction data.

Finally, on a cautionary note, we wish to point out that the GRM method is frequently incapable of providing a solution to the hidden problem, despite Palmer's inference to the contrary. The method requires that an optimum XY value can somehow be recovered from the T-X data. Such recovery is impossible in cases where the refractor(s) underlying the hidden layer are planar and of uniform velocity, since there is no criterion for choosing one XY value over another. The choice of XY value can only be made if the refractor(s) display pronounced irregularity or if some prominent anomaly (e.g. buried channel) occurs along the refraction profile. Clearly, such conditions are not always met in practice.

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