THE DELINEATION OF NARROW LOW VELOCITY ZONES WITH THE SEISMIC REFRACTION METHOD

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The Lateral Resolution of Structure and Seismic Velocity

There has been an historical trend of seismic reflection methods gradually replacing seismic refraction techniques. In petroleum exploration this occurred in the late 1920's–early 1930's. In deep crustal studies, the success of continental reflection profiling programs is now well established. Even the domination by refraction techniques of the shallow environment, such as for geotechnical investigations, groundwater and alluvial mineral exploration, and for weathering corrections for reflection surveys, is currently under challenge. Recent experimental reflection surveys for very shallow targets (Hunter *et al.* 1984, 1986) have been quite successful and it is probably only a matter of time before such surveys become common place.

Is there a future then for exploration refraction seismology?

The perceptions most geophysicists have of the technique give little cause for optimism. Statements such as 'it is likely that within five years shallow reflection surveys will replace refraction surveys as the most common seismic tool for engineering and groundwater studies' (Dobecki and Romig, 1985, p. 2626) are probably representative of widely held views.

This paper challenges those views.

Exploration refraction seismology has a major strength which provides significant advantages over reflection methods, irrespective of the data quality of the latter, and which is particularly important in geotechnical applications. It is the ability to resolve lateral variations in depth to, and seismic velocity in, a refractor. Of these two aspects, the measurement of seismic velocity is possibly the most important, because it is probably the most commonly used geophysically derived parameter for assessing rock strength for foundations, rippability, excavatability, etc. In particular, narrow low velocity zones in the refractor are especially significant because they indicate areas of low rock strength as well as high porosity and permeability. The delineation of these zones, especially for waste disposal projects, is essential.

Velocity Analysis with Reflection Methods

Although it is possible to compute seismic velocities, dips and depths from data with a common shot (Dobrin, 1976, pp. 202–204; pp. 207–210), it is more usual to arrange the data into common mid point gathers. This avoids the effects of dip and their explicit measurement (Taner and Koehler, 1969). This computed normal moveout (NMO) velocity is in fact the velocity divided by the cosine of the dip angle (Cressman, 1968; Levin, 1971). Generally this NMO velocity is taken as the RMS velocity.

This approach works well, except when there are large velocity contrasts, and departures from plane layers (Blackburn, 1980). Structure on the lower interface presents few problems because the focusing effect on the common mid point gather requires only a very short interval to be plane. However, irregularities on the upper interface of a layer with a marked velocity contrast are not easily accommodated, because the moveout is a function of both offset (i.e. NMO) *and* structure on the interface. In extreme cases, the moveout can in fact *decrease* with increasing offset, and the computed NMO velocities can bear little resemblance to the RMS velocities (see for example Kleyn, 1983, pp. 71–72). This situation occurs in the determination of bedrock velocities for geotechnical applications, when the bedrock surface is irregular and when there is a strong velocity contrast between the overburden and the bedrock.

Velocity Analysis with Refraction Methods

In many ways, the techniques for refraction velocity analysis have close parallels with those for reflection methods. Although it is possible to compute seismic velocities, dips and depths from reversed travel time data with the classical approach of the intercept time method (Ewing *et al.* 1939; Dobrin, 1976, p. 303–305), it is more usual to use the harmonic mean of the updip and downdip apparent velocities (Heiland, 1963, p. 523; Palmer, 1986). The explicit determination of dip is avoided, and the computed velocity is the true velocity divided by the cosine of the dip angle. An important advantage of the harmonic mean approach is that it is extended from computations at each shot point, to computations at each detector through the conventional reciprocal method (Hagiwara and Omote, 1939; Hawkins, 1961).

However, the conventional reciprocal method produces fictitious seismic velocities when there is an irregular refractor surface (Palmer, 1981; Sjorgren, 1979). Under these conditions it is necessary to use a velocity analysis technique which employs the principle of migration such as with wavefront methods (Rockwell, 1967), Hales' method (Hales, 1958; Sjogren, 1979), and the generalised reciprocal method (GRM) (Palmer, 1980, 1981, 1986). Although these methods produce identical results under the ideal conditions of complete detection and definition of all layers above the target refractor, this is not the case when there are undetected layers, variable velocity media, etc.

Under these conditions, the migration process is inaccurate, and the resulting velocities are inaccurate. With the GRM, a range of migration distances is used, and the optimum value is taken as that which results in the simplest model with the most detail. This criterion, which has been described as 'minimum perturbation' is not unknown in exploration geophysics. For example, the velocity scan method for measuring NMO velocities (Dobrin, 1976, pp. 233–235), and the Nettleton method for determining densities (Dobrin, 1976, pp. 413–414) both employ a minimum perturbation approach.

Narrow Low Velocity Zones

When there are narrow low velocity zones in the refractor, this minimum perturbation approach is essential. Even in the absence of undetected layers, the appropriate migration distance for the definition of lateral velocity variations is not a simple function of overburden and approximate bedrock velocities (Sjogren, 1984; Palmer, 1986).

The benefits of variable migration have been demonstrated with targets which are reasonably deep in relation to the detector spacing (Palmer, 1980, pp. 59–81). However, it is still generally considered that migration is not necessary for very shallow refractors. The data and processed data in the accompanying figures dispute such a proposition. Even though the refractor is only about 10 m deep, the use of a 3 m detector interval, as well as the GRM velocity analysis technique, has resulted in precise definition of a narrow low velocity zone. The zone corresponds with a fault mapped in a coal mine below, and with a topographic depression.

Conclusions

Narrow low velocity zones are most effectively delineated with the seismic refraction method using a refractor velocity analysis technique employing migration. Such targets are not easily defined with reflection methods.

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THREE DIMENSIONAL REFRACTION METHODS

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The Requirements

Most methods for interpreting seismic refraction data assume that the seismic traverse is oriented in the direction of any lateral changes in depth or seismic velocity. This assumption treats the subsurface as two dimensional and greatly reduces the complexity of interpretation.

However, there are often situations where two dimensional methods are not applicable. The line orientation may be inappropriate because of insufficient regional geological control, or because of access constraints. If the seismic profile is not orthogonal to the contacts between lateral variations in refractor velocity, then refraction in the horizontal plane occurs, and the measured seismic velocities are higher than the true seismic velocities (see Sjogren, 1984, p. 168).

Alternatively, the target may in fact be three dimensional. This applies to seismic velocity as well as geometry. In particular, seismic velocity anisotropy, caused by foliation, jointing, etc. (Bamford and Nunn, 1979; Crampin *et al.* 1980) is common, and its measurement in the horizontal plane would be of considerable geological value.

Possibly the earliest three dimensional refraction method was fan shooting (Nettleton, 1940, p. 277; Dix, 1956, p. 31; McGee and Palmer, 1967, p. 5–8). A modern development is tomographic imaging (Mason, 1981; Worthington *et al.* 1983). Limitations of this approach are that it assumes an isotropic rock mass and that it ignores refraction effects, and so velocity inhomogeneities less than about 15% are not fully accommodated.

Three dimensional refraction methods offer the opportunity to overcome the limitations of treating the subsurface geometry as two dimensional. However it is also probably necessary to resolve any ambiguities between velocity inhomogeneities and horizontal anisotropy.

Wavefront Reconstruction in the Refractor

One approach which accommodates irregular geometries, velocity inhomogeneities of any magnitude, and anisotropy, is reconstruction of the horizontally propagating wavefronts in the refractor (Palmer, 1986). The following are the major features of the method.