

DISTRIBUTION OF SEISMIC VELOCITIES AROUND UNDERGROUND DRIFTS

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INTRODUCTION

Excavation of underground openings generally causes damage to the rock in the vicinity of the opening. The level of damage depends, among other factors, on the method of excavation, the rock properties, the stress field, the geometry of the opening and time. The damage changes the properties of the rock. For repository performance, changes in the hydraulic properties close to the walls of underground openings are of major interest. Increased permeability in a damaged zone may cause problems for the efficiency of plugs and sealing systems if the geometry and the properties of such zone is not known in advance. Thus it is very important to find suitable methods to determine the damage, and especially the hydraulic properties, by in-situ measurements. Because of the fact that damage is very closely related to the walls, measurements with high spatial resolution are necessary to describe the degree and spatial distribution of damage.

It is well known that seismic velocities of rock change significantly with progressive failure. The velocity decrease is mainly due to increasing micro-cracking and should therefore be related to the hydraulic properties. Measurements of the elastic properties of rock can effectively be performed by seismic methods. Seismic methods are well known to characterise and discriminate rocks. The methods usually used to analyse geological features in the range of meters (soil mechanics) to several kilometres (geophysical prospecting) can also be applied in the cm-range. This requires the use of higher frequencies (some 10kHz), smaller probes and recording systems with high sampling rates ($>1\text{MHz}$ sampling rate). Thus probes and recording system are similar to ultrasonic measurement equipment. The data processing and analysis is as known from seismic measurements.

In this paper results of downhole measurements, interval velocity measurements and refraction seismics will be presented. The measurements have been carried out in the Grimsel rock laboratory (Swiss) and in the ASSE salt mine (Germany).

DOWNHOLE MEASUREMENTS

Downhole measurement is a well established technique in engineering practice to measure low amplitude soil dynamic properties. Only one borehole is needed to get the velocity as a function of depth. The average traveltimes are measured between a source on the surface and the receiver at depth in the borehole. The method has many advantages: Low cost source at the surface, detection of low velocity layers possible, easy and accurate determination of source to receiver distances, fast measurements. The disadvantages are: the signal to noise ratio decreases with depth, the ray path increases with depth and so the frequency content of the signal decreases.

The boreholes used have total depths of 3 or 5m and are 86mm in diameter. A mechanical hammer was used as source at the surface and a piezoelectric accelerometer was the receiver that was moved along the borehole. The signals were in the frequency range of 1 to 15 kHz.

Figure 1 shows the seismograms obtained in a horizontal borehole in granite at Grimsel. From such sections the first arrivals of P- and S-waves are picked and average velocities are calculated (Fig.: 2, squares). Finally the velocities can be derived as a function of depth (Fig. 2, triangles). The calculation of the true velocities from average velocities requires a smoothed average velocity vs. depth function (solid line). The smoothing process reduces the influence of measuring errors but also can reduce the visibility of local details. However, the velocity reduction close to the wall of the drift can clearly be seen. A comparison of P-(circles) and S-(squares) wave velocity distributions (Fig. 3) demonstrates that the effect is well documented in both records. The v_p/v_s -ratio however decreases within the low velocity zone what indicates that S-waves obviously are less affected than P-waves, possibly because of their different direction of partial motion.

Figure 4 shows the results of measurements in boreholes drilled in various directions from a drift in rock salt as indicated in the small insert. The velocity reduction is more pronounced in the vertical and 45° upward boreholes. The extensions of the low velocity zone are about 1m and 0.7m respectively. In the borehole oriented 45° down, no reduction in velocity was determined. The horizontal and the vertical downward holes show intermediate velocity changes up to 0.7m depth. This example demonstrates that the zone of velocity reduction is not uniformly distributed around the underground drift. In the presented case the velocity is most pronounced in the roof of the drift. The distribution is not the same for similar geometry of the underground opening but obviously depends on additional parameters.

The effect of local inhomogeneities, for example open cracks, on downhole measurements can be seen in Figure 5. The results were obtained in a horizontal hole at the Grimsel test site. At a depth between 0.245 m and 0.265 m a sudden change in traveltimes and frequency content of the signal is observed. The average velocities show a clear breakdown at this depth (Fig.: 6, squares) and velocities as a function of depth (Fig.: 6, triangles) demonstrate the presence of a local discontinuity, identified as an open crack. Thus the method allows to discriminate open and closed cracks in situ, which is often not easy to be determined from cores. However the quality of the signal is strongly reduced in the „shadow“ of an open crack.

As a variation of the downhole measurements a source can be used inside the borehole. This technique can overcome problems due to insufficient signal-noise ratios if a highly absorbing layer or large open cracks are close to the surface.

INTERVAL VELOCITY MEASUREMENTS

Measurements of the interval velocity are also performed along single boreholes. The seismic velocities are measured across a small borehole interval, typically about 10 cm long (Fig. 7). This technique requires a source and two receivers in the borehole. With the BGR mini-sonic probe a pneumatic hammer is used as source and the receivers are piezoelectric accelerometers.

The signals are in the frequency range of 10 to 40 kHz (10kHz high pass filter applied) and the sampling rate of the recording system is 10 MHz (Time resolution 10^{-7} s). The advantage of this method is, that the length of the ray path is independent from the measuring depth.

Thus the signal to noise ratio and the frequency content of the signals neither depend on the depth nor on absorbing discontinuities outside the 10cm measuring interval. In addition no „smoothing“ is required to obtain true velocities.

Results of measurements at Grimsel are shown in Figure 8. The shear wave velocities are plotted against the depth for four boreholes at one measuring section. The velocity decrease at the wall of the drift is obvious in all traces. The maximum decrease (to about 1500 m/s) is observed in the hole 45° upward. The extension of the zone of reduced velocity is about 0.45m. The other locations show low velocities of about 2000 m/s at the wall and a smaller extension of the zone of reduced velocity. In the borehole 45° downward the velocity of the intact rock is already reached at a depth of about 0.25 m. Thus the distribution of the damaged zone is similar to the distribution stated above for rock salt.

Figure 9 gives the results of interval velocity measurements in the same borehole in which downhole measurements were performed shown in figures 5 and 6. The interval velocity measurements give a clear indication of the open crack and at greater depth a more detailed velocity distribution than the downhole measurements. The crack appears to be larger than in the downhole measurements. The extremely low velocity indicating the crack is obtained as long as the crack is within the measuring interval. Thus the width of this low velocity zone corresponds to the measuring interval of 10 cm. Of course the crack position can be derived better by further analysis.

REFRACTION SEISMIC MEASUREMENTS

Refraction seismic measurements can be performed without boreholes just from the wall of the underground opening. This technique is based on the fact that seismic waves are refracted along a curved path back to the surface if the velocity increases with depth. The maximum depth of the ray path depends on the distance between source and receiver. The measurement of traveltimes at different source receiver distances reveals a traveltime versus distance function. From this function the velocity distribution with depth can be derived. The method is well established in seismic prospecting and geotechnical engineering. The great advantage of the method is that no boreholes are necessary. The disadvantages are a lower resolution than borehole measurements and difficulties to detect low velocity layers.

Refraction seismic measurements were performed in the ASSE salt mine along the wall of a drift. The source to receiver distances varied from 0.1 m to 4.8 m in steps of 0.1 m or 0.2 m. First, from the velocity distribution obtained with downhole measurements (Fig.: 10, left) a theoretical traveltime versus distance function was calculated (Fig.: 10, right, solid line). For better visibility the reduced traveltimes are plotted on the vertical axis. To get the reduced traveltimes the traveltimes for a characteristic velocity (in this case 2500 m/s) are subtracted from the actual travel times. This procedure increases the visibility of velocity deviations. From figure 10 it is obvious that the measurements (crosses) do not fit the theoretical function. Thus a new velocity distribution was determined from the results of the refraction seismic measurements (Fig.:11). The new velocity distribution shows a higher velocity close to the wall, a smaller zone of reduced velocity and a lower velocity in the intact rock salt at greater depth. This can be explained if the velocity distribution is not isotropic. The rays measured in downhole measurements are more or less oriented parallel to the borehole (in this case perpendicular to the wall). The direction of the raypath used in refraction seismic measurements varies with depth and has components perpendicular as well as parallel to the

wall of the drift. Thus close to the wall of the drift the velocities parallel to the drift seem to be less influenced by the damaged zone as the ones perpendicular to the drift. A reason for this could be a preferential orientation of micro-cracks parallel to the free surface.

CONCLUSIONS

It could be demonstrated that downhole measurements and direct measurements of interval velocities provide a reliable estimate of the EDZ with respect to its extent and amount of velocity reduction. A similar distribution of the EDZ which is not uniform around the drift could be found for granite and salt rock.

Refraction measurement is a promising method for exploring the EDZ without the necessity of existing boreholes. The inversion of seismic refraction traveltimes leads to a less pronounced velocity reduction for waves propagating parallel to the wall of the drift. The anisotropic velocity distribution may be caused by the preferential orientation of micro cracks parallel to the surface.

Further research is still necessary to evaluate the influences of stress distribution, saturation and degree of rock damage on seismic velocities.

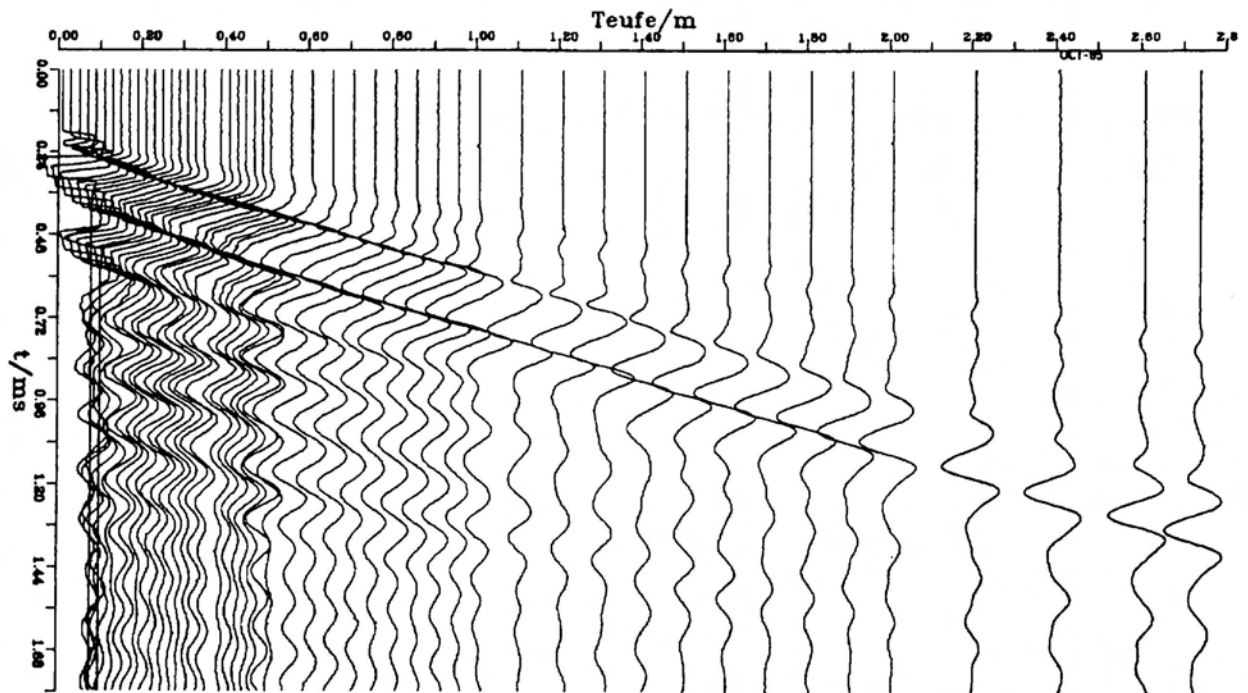


Figure 1

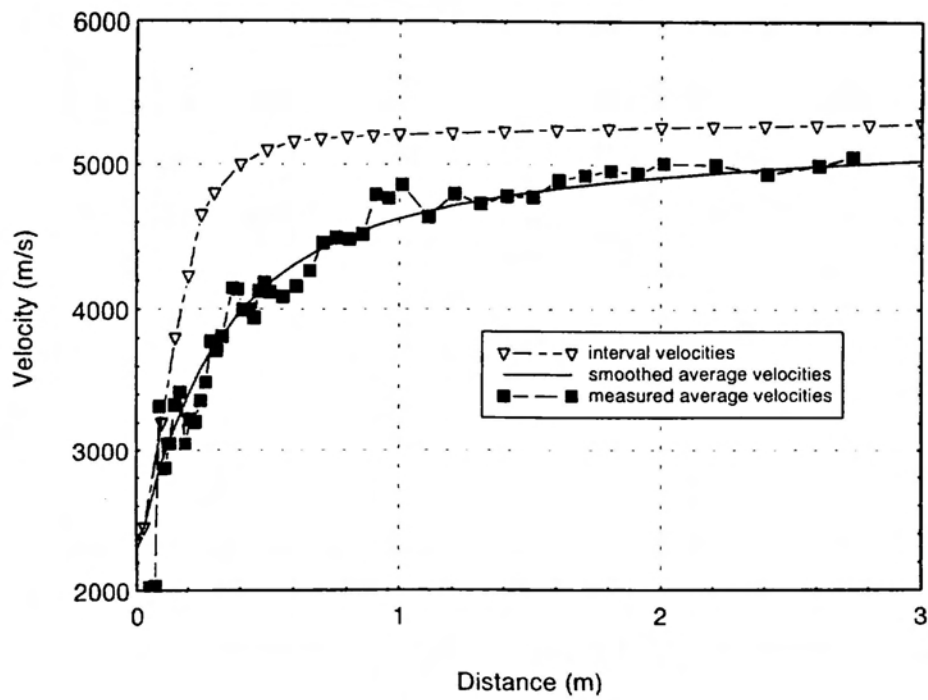


Figure 2

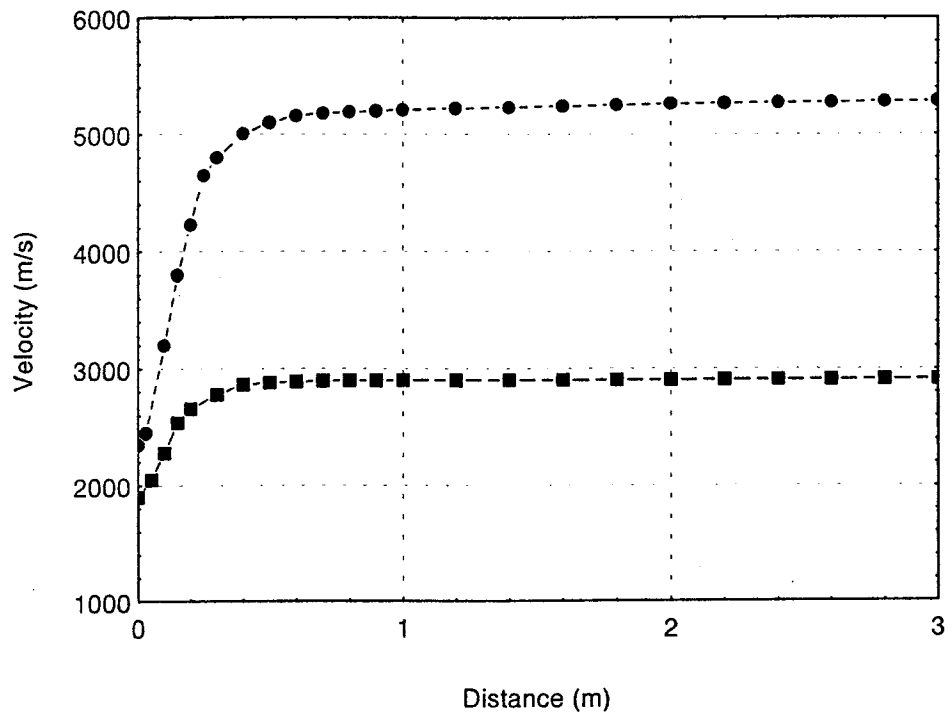


Figure 3

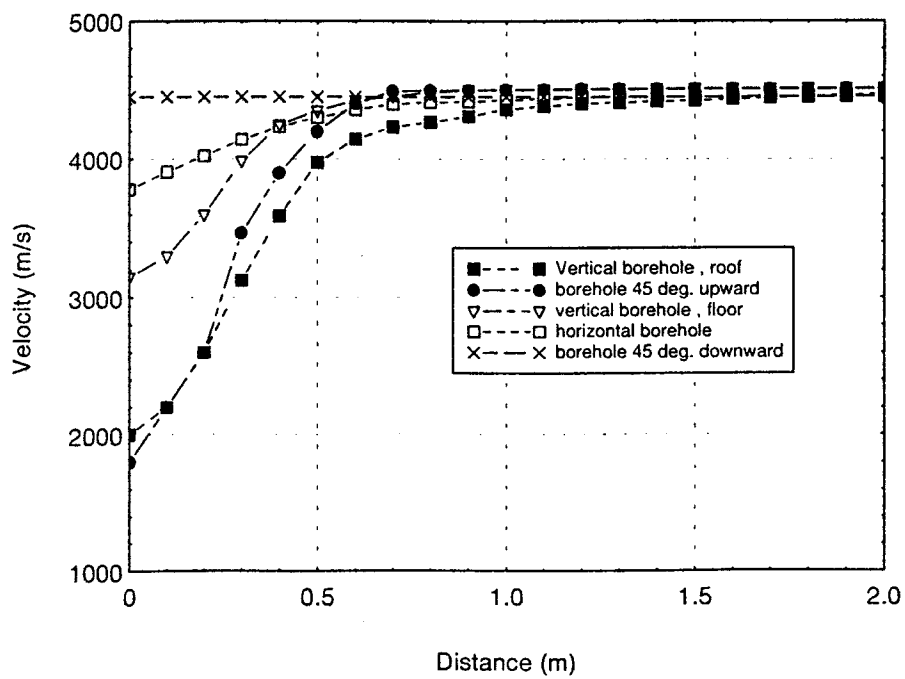


Figure 4

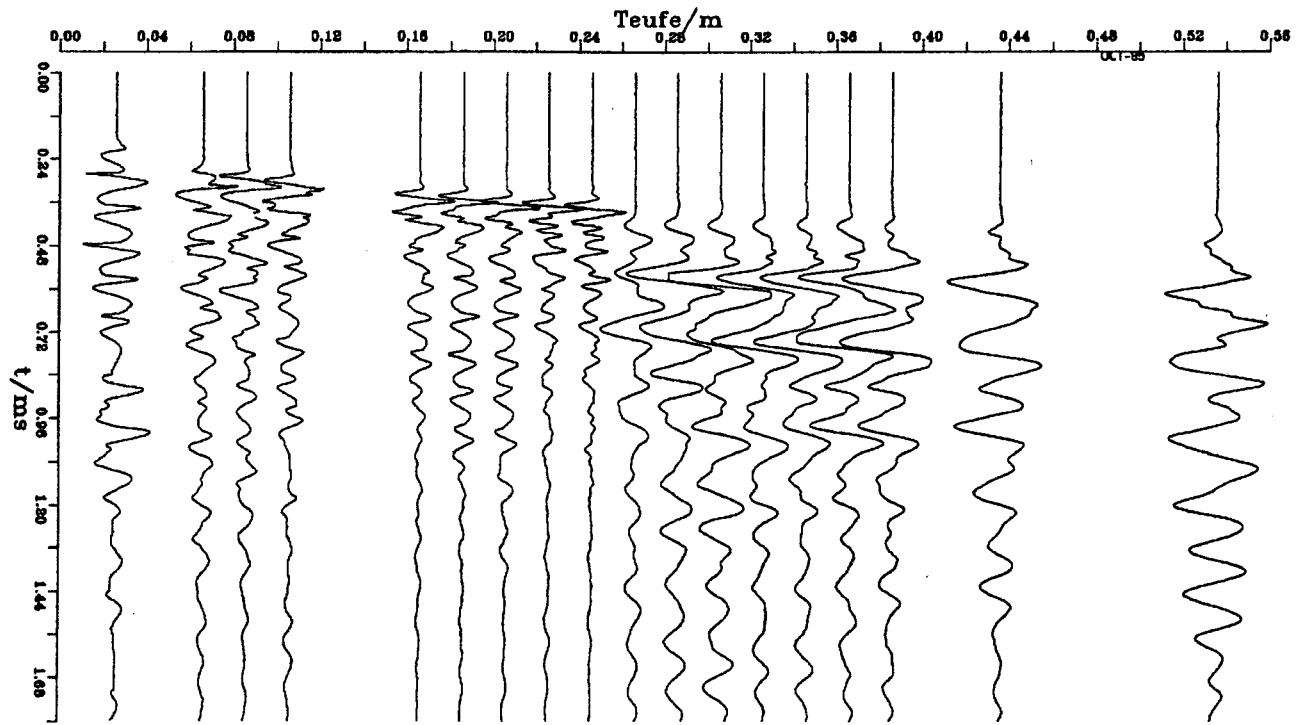


Figure 5

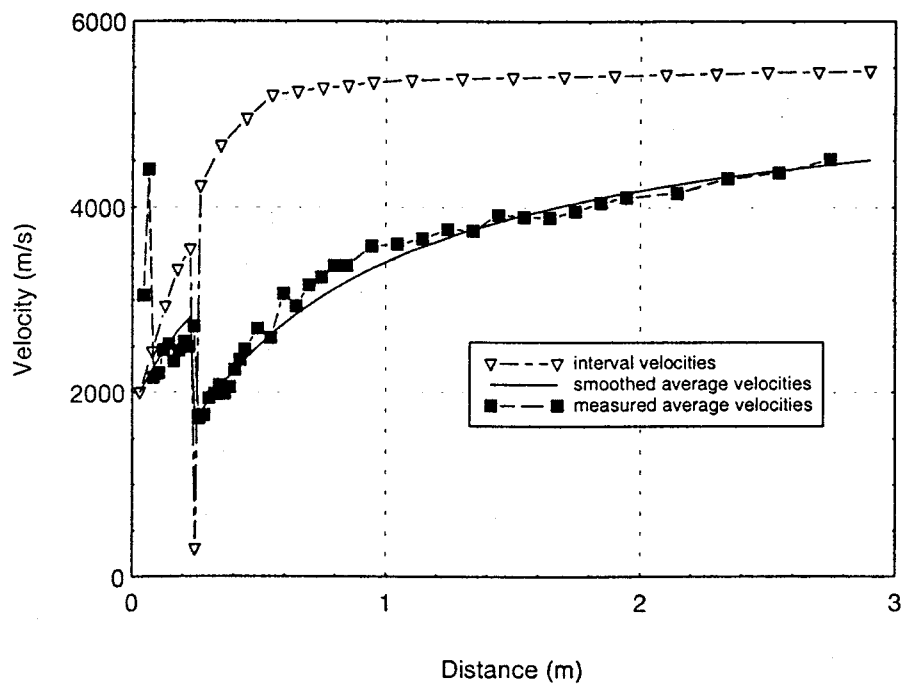


Figure 6

Mini-Sonic Probe

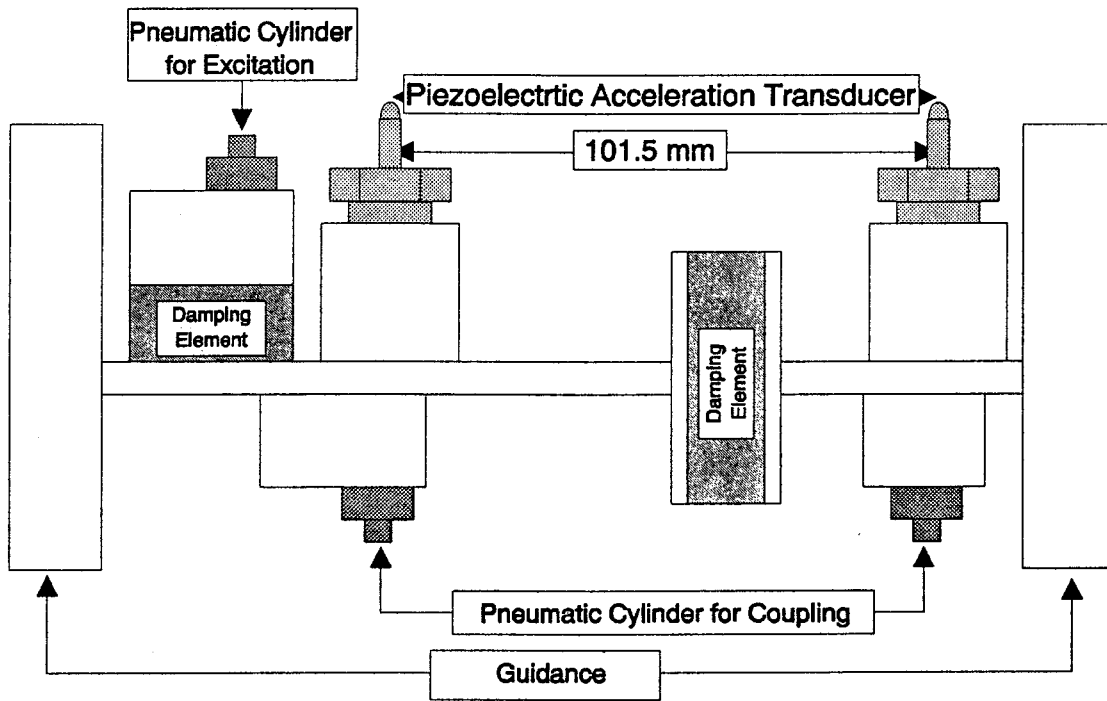


Figure 7

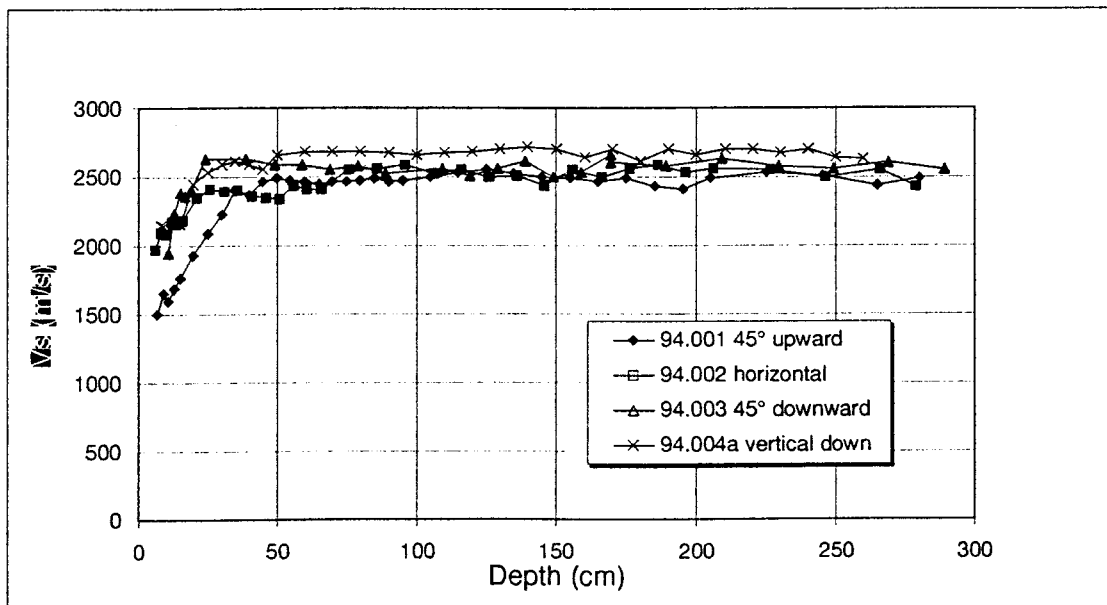


Figure 8

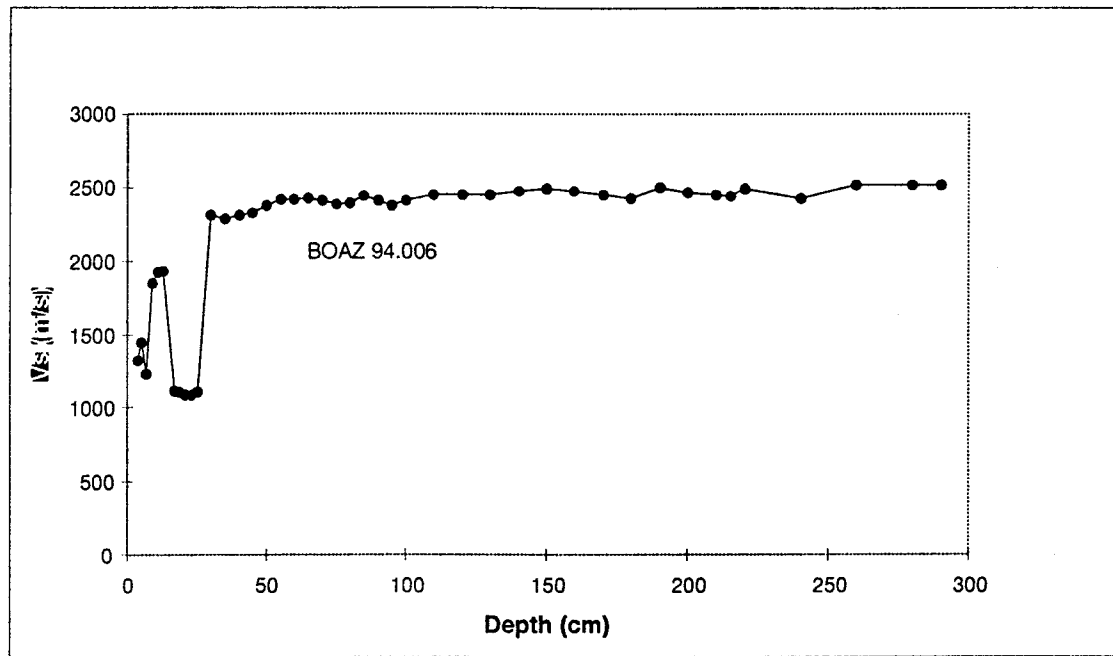


Figure 9

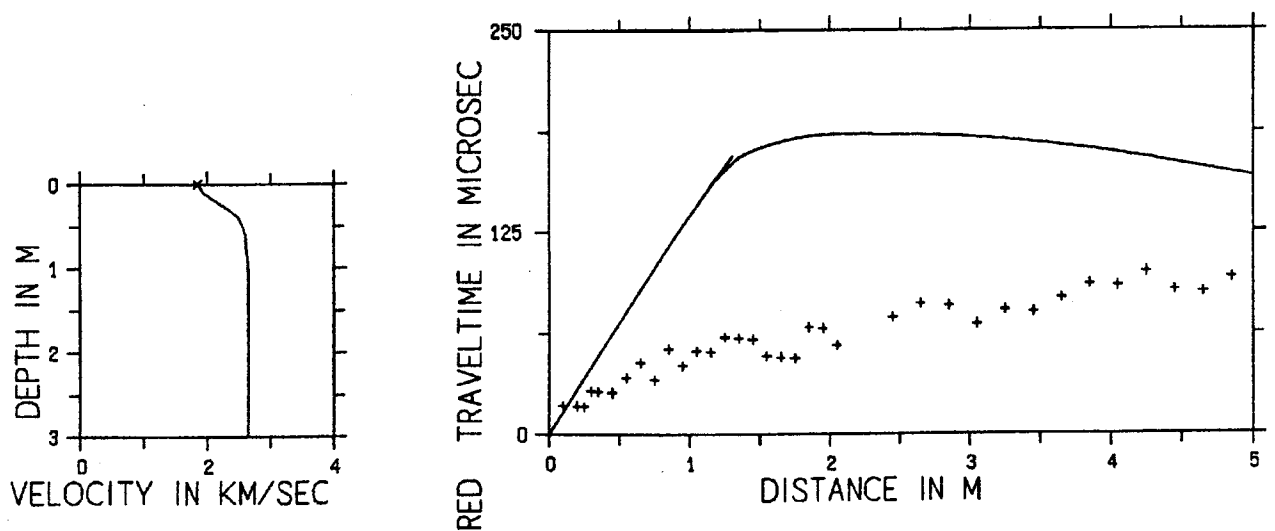


Figure 10

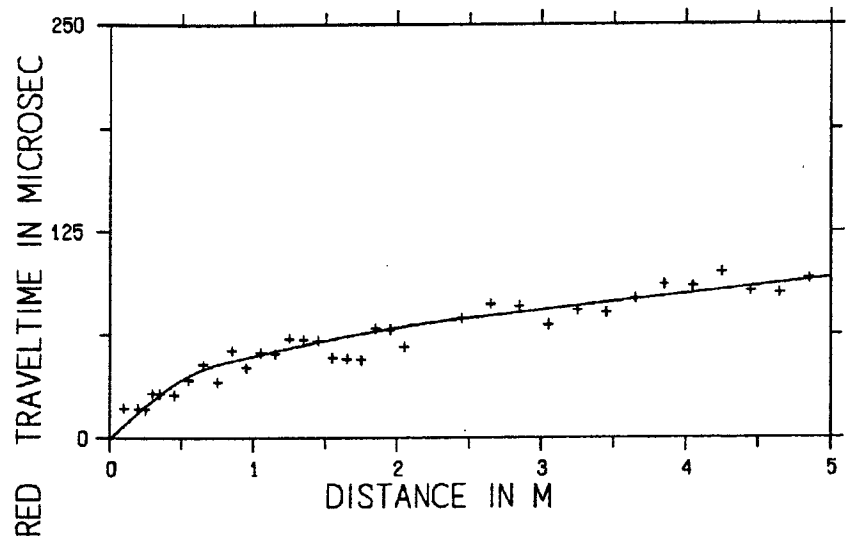
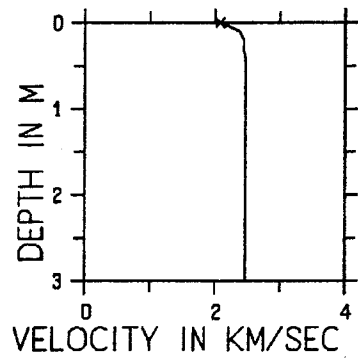


Figure 11