Keywords: cross-hole methods, down-hole methods, fracture zones, granite, Hungary, Southeastern Transdanubia, tomography, velocity analysis, vertical seismic profiles

To explore the inner structure of the granite body, high-resolution cross-hole and down-hole seismic surveys were carried out. On the tomographic sections the zones of different seismic velocities, i.e. the major structural features can be easily distinguished. The fractured zones were detected with high resolution in the vicinity of boreholes by using VSP.

1. Introduction

In the Üveghuta site explored for low- and intermediate-level radioactive waste disposal, Eötvös Loránd Geophysical Institute of Hungary (ELGI) carried out a seismic survey to determine the structural state based on existing boreholes.

By the application of geophysical well logging — though with high precision and reliability — only the immediate borehole environment can be imaged. The resolution of a seismic survey from the surface is significantly limited by the thick sedimentary cover of the granite.

In international practice to map structural, hydrological and geomechanical features for radioactive waste disposal one of the most important method is seismic tomography. VSP surveys are more applicable for the detection and mapping of linear structural elements such as fractured zones.

A location map of the current study is given in Figure 1. Both methods will be presented and finally a summary will be given.

2. Seismic tomography

In the published literature covering non-hydrocarbon topics, a significant part of the papers relating to tomography presents projects dealing with radioactive waste disposal (Blüming and Satelli 1988, Wong et al. 1987, Sekl and Pratt 1996, Dyer et al. 1996). Tomography is referred to an image reconstruction technique based on calculating a series of line integrals of some image sensitive parameters through an observation space. In seismic surveys a close relationship exists between the reciprocal of the velocity (slowness) and the propagation time along travel paths. By an endless number of shot and receiver points located at
Despite using this high-energy source, in combination with recording devices successfully used in other projects, i.e., a Geosource type receiver sonde clamped to the wall at a distance of about 200 m, no usable data was obtained. Finally a home-made array consisting of several hydrophones connected in parallel was used, and by using computerised ESS-03-24 type engineering data acquisition equipment, signals with good signal/noise ratio were obtained with a dominant frequency of 350–450 Hz (Figure 2).

During the measurements the initially planned data acquisition system could not be entirely implemented. To attain a better ray coverage we tried to observe source signals on the surface as well, but due to the filtering effect of the thick and loose surface layer the signals become attenuated below the detectable level. During measurements between Boreholes Üh-3 and Üh-2 the source was collocated in one borehole, and the receiver in the second. Later the devices changed position so we managed to receive an identical data set with receivers of 3 m spacing in both boreholes. Here a total of 158 three-channel registrations were obtained. As the condition of Borehole Üh-2 seemed to get better all the time, when working between Boreholes Üh-4 and Üh-2 the source remained in Borehole Üh-2, while the receiver sonde was moved in Borehole Üh-4. On the emitter side the spacing was 10 m and on the receiver side 3 m, so 287 three-channel registrations were made. In Borehole Üh-2 the receiver could be moved from the borehole mouth down to 304 m, and the emitter down to 240 m while in Borehole Üh-3 the receiver was able to move down to 292 m and the emitter moved down to 180 m depth. During the second survey between Boreholes Üh-4 and Üh-2, Borehole Üh-4 proved to be passable from the borehole mouth only down to 205 m in spite of the efforts made by the drillers. Borehole Üh-2 was usable down to 300 m depth.

2.2. Data processing

Using the source-receiver geometry and propagation times as input, the tomographic reconstruction of the wave field was done by the curved path algorithm SIRT (Simultaneous Iterative Reconstruction Technique). This algorithm modifies the initial wave field by several iterative steps on the basis of measured and calculated differences of propagation times.

To determine exact source-receiver geometry the distance alternations of borehole pairs was determined from the borehole inclination log. Initial velocity distribution was built up in the usual way using apparent velocities calculated from horizontal ray paths (supposing wave propagation along linear ray paths) and from the down-hole survey data.

Seismic wave propagation was modelled by the so-called “expanding time field” algorithm (Vidale 1988) where propagation times are given at the geophone points by the values of the time field calculated for a given shot point, and the curved ray paths were traced back from the
geophones to the shot point along the highest negative gradient of the time field.

The elementary cells of the reconstructed velocity field were of 5×5 m dimension, while grid constant of the time field was one third of this value. Calculations were performed up to 10 iteration steps for each data set.

As shown by histograms of apparent velocities calculated from the horizontal ray paths (distance between source-receiver/propagation time), significant differences can be encountered in the time values of the measurements displaying the structural features of the velocity field.

Due to limited source-receiver geometry the resolution of the output sections in certain directions will be weaker. Precision and reliability may arbitrarily be increased but because of the finite wavelengths the resolution can not be increased (Williamson 1991). The limit of resolution independently from the length of the ray path within the same range is one half to one quarter of a wavelength. In the present case the wavelength is 5 m on the portion sufficiently covered by ray paths. At the lower part of the wave field only nearly parallel rays are included in the coverage so the resolution limit is direction-dependent, and consequently it is indeterminable.

2.3. Results

To retain the whole information content the output sections (Figures 3, a, b) are determined in a grid system (5×5 m) in accordance with the physical resolution. This grid dimension provided a sufficient ray coverage on the greatest part of the area (ray coverage = number of ray paths crossing one another assigned by grid points). Both sections are discussed below.

2.3.1. Measurements between Boreholes Üh-3 and Üh-2

The velocity histogram of the tomogram is relatively homogeneous, and velocity differences are small (Figure 3, a). The velocity field basically can be divided into two different parts. In the surroundings of Borehole Üh-3 velocities are characteristically lower when compared to the environment of Borehole Üh-2. A higher velocity domain can be observed at a distance of 60–150 m, and at a level of 120–170 m, separated by a lower velocity zone from a higher velocity space domain observed in Borehole Üh-2. Similar but oppositely dipping velocity anomalies become apparent at increasing depth.

In the velocity section the domains of extended and different velocity boundaries are well defined and subdivided by lower velocity zones. Due to resolution limits small-range inhomogeneities (0.8–5 m thick) cannot be directly detected by the tomography therefore we suppose that larger portions of these zones are equally fractured and that their combined effect may appear in the velocity sections as well.

As for geological information relating to rock material between the two boreholes, no considerable difference is described. Velocity differences can be attributed to deviations owing to fractures and/or stress state. This argumentation can be supported by the RQD (Rock Quality Designation, Deere 1963) values presented in Figure 4 but mostly by similarities to the smoothed RQD values (owing to the poor resolution of tomography). In the literature (Dubinsky 1979), and from our own experiences in mines (Kormendi et al. 1986) the stress increase may cause a velocity increase of 10%.

Attention should be called again to the fact that in the lower part of the tomogram the horizontal resolution is
weaker therefore the velocity decrease encountered at a depth of 20–30 m in Borehole Úh–3 and its continuation towards the second borehole is not necessarily a closely related phenomenon. Nevertheless it is apparent in both boreholes.

2.3.2. Measurements between Boreholes Úh–4 and Úh–2

Compared to the previous study in this plane (Figure 3, b), the velocity histogram is broader. In the tomogram it seems obvious that velocity values in the vicinity of Borehole Úh–2 are higher. In Borehole Úh–4 at a depth between 80 and 130 m a low-velocity zone is present, confined to the borehole surroundings.

In this section the highest velocity zone encountered so far in both studies (>5800 m/s) is seen, bordered by a velocity decrease near to Borehole Úh–2 while intersecting Borehole Úh–4 at about a depth of 60 m. Unfortunately this occurrence is only present in the lowest part of the examined domain, therefore its exact delimitation is impossible. The white coloured area has been bypassed by ray paths executing the last iteration step. It is worth noting that the velocity boundary which starts from Borehole Úh–2 at a depth of about 180 m ends at the depth of 110 m near to Borehole Úh–4 in an already mentioned low-velocity zone.

At formerly mentioned structures the smaller velocity changes encountered in the higher velocity domain die way and break off.

When building up velocity structures, we noted that in the velocity field of Boreholes Úh–3 and Úh–4 an essentially close similarity can be recognised. In both boreholes there is an approximately 20 m thick zone with a somewhat lower velocity than 4000 m/s which is present also in the well-log sections. Heights above sea level are 22–24 m in Borehole Úh–3 and 98–116 m in Borehole Úh–4. The analysis of their connection may be the subject of a later study.

3. Down-hole seismic surveys

As it has been mentioned in the introduction, the high-frequency attenuation effect of the superficial thick and loose sedimentary layer significantly limited the implementation of seismic surveys to map the fractured and potential aquifer zones, very important factors from the viewpoint of the site. For the detection of these relatively thin and possibly inclined surfaces we applied a high-frequency VSP (Vertical Seismic Profiling) measurement by a multi-source and multi-receiver system.
VSP is a variant of the seismic reflection survey and similarly examines reflected waves originating from surfaces characterised by the change of their acoustic impedances (seismic wave velocity multiplied by the density, PRONAY et al. 1998, 1999). Unlike the conventional seismic reflection surveys, sensors are collocated in a borehole and the excitation occurs at the same source location. The scanning of the examined domain is performed by moving sensors through given steps. In this case the source was collocated in a relatively deep borehole below the weathered layer. An attraction of this is that the ray paths on the emitter and on the receiver side do not pass through the near-surface weathered layer and as a result cross-hole data does not suffer significant losses in the higher-frequency content of the spectrum. By the application of more sources at different locations the imaging may be further improved.

In what follows first the measurement, then the data processing and the interactive modelling technique required for the interpretation, and finally the results are reviewed.

3.1. Measurement

The survey was carried out in several steps. In fact it was planned for the examination of a particular tectonic zone, and the parameters (shot point separation and azimuth) were optimised for this work (Uh-2 and Rp-1, Figure 1). Later this geometry was completed by a new source point (Rp-2) and by the VSP measurement carried out in Borehole Uh-3. The plane of the VSP study is approximately identical to the plane of the cross-hole tomography performed in Boreholes Uh-2 and Uh-4.

In a borehole drilled for this special purpose, elastic waves were generated at a depth of 65 m with the simultaneous explosion of 5 caps. A Geosource T42-3D sonde clamped to the wall served as receiver. ESS-03-24 digital seismic equipment was used for data acquisition. The main parameters of the survey can be seen in Table 1.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Source location</th>
<th>Receiver location</th>
<th>No. of registrations (pc)</th>
<th>Depth interval (m)</th>
<th>Sensor spacing (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rp-1</td>
<td>Uh-2</td>
<td>60</td>
<td>104-370</td>
<td>5.00</td>
</tr>
<tr>
<td>2</td>
<td>Rp-2</td>
<td>Uh-2</td>
<td>41</td>
<td>170-370</td>
<td>5.00</td>
</tr>
<tr>
<td>3</td>
<td>Rp-3</td>
<td>Uh-23</td>
<td>42</td>
<td>85-300</td>
<td>5.25</td>
</tr>
</tbody>
</table>

Similar to tomography, the dominant frequencies were about 400 Hz. As for the effect of the weathered layer it is characteristic that the geophone on the surface at the borehole mouth registered signals of 40 Hz.

The reflection coefficients (incident and reflected amplitude quotient relating to a given interface) were calculated on the basis of acoustic velocity and density data determined from geophysical well-log in the axis of Borehole Uh-2 (Figure 5). The maximal value is about 0.08. Apart from other losses the observed reflection amplitude is equal at most to its 8% value.

3.2. Data processing

Data processing consists of two steps: pre-processing and the processing s.s. The aim of the pre-processing is the improvement of the signal/noise ratio. Except for reflection signals, all other signals were considered as noises.

To compensate for the turning of the receiver sonde a routine-like first step ("rotation") is used in the VSP data processing to enhance signals from the plane of the measurement. By the application of the transformed seismograms the rotation process was performed also in the vertical plane by the use of horizontal and vertical components facing the shot point. Then a rotated seismogram was chosen which optimally represented the given reflection. One reflection may appear on several differently rotated seismograms because the arrival angle of the reflected waves significantly changes on the channels representing different depths if the reflecting interface is inclined.

The second step of the processing sequence is the separation of downward (direct) and upward (reflected) propagating waves (HARDAGE 1992, LEE 1984). This is achieved by f-k filters which provide the separation of waves accord-
ing to their apparent velocities. Filtering should be done very carefully so as not to loose useful signals because in the VSP studies reflections from steeply dipping reflectors and apparent velocities of the first arrivals in the routine VSP work may show up with nearly equal velocities, in contrast to the case of a horizontal-reflector velocity. In Figure 6 arrivals from an interface of 300 m depth are shown for different dips. Half wavelengths are indicated by line segments on the first arrivals and on the reflection arrivals coming from an interface of $+60^\circ$ dip. It is clearly seen that on indicated segments these two wave types are not or hardly separable.

In the third step the frequency filtering was accomplished for both wave types.

The processing s.s. before the implementation of the common midpoint stacking, consisted of the prestack depth migration with a modified time field method (Vidale 1988, Wiggins and Levander 1984, Pronay et al. 1998), for the case of the upward propagating waves.

This procedure can image any kind of dips and can transform seismograms from the time domain to depth domain. All the pre-processed seismograms served as input for the migration.

Smooth curvatures (Figure 7), particularly at locations of small amplitudes, are due to the process itself because the migration is only able to image surfaces optimally in the case of a multi-fold coverage. This is why only high-amplitude portions were considered in the interpretation.

With the exception of classic VSP data processing a "manual" interpretation was also implemented by a simple ray path modelling program (Pronay et al. 1996, 1998). Out of differently rotated and pre-processed seismograms the best were chosen (after $f$-$k$ domain frequency filtering) to represent the examined reflection. While changing the depth and dip of the supposed reflector, a best fit was sought to match time values of the given arrivals. In the course of these surveys an effort was also made to identify or follow already defined occurrences with data of other studies having different geometry (different shot hole and different borehole locations). Dozens of reflections were analysed. An interactive modelling technique enabled us to examine the accuracy of defining reflecting planes (depth and dip). On the basis of statistical examinations seven basic reflections were identified. Figure 8 shows imaged reflection segments rotated into the plane of the surveys. Reliability was computed from the length of the imaged section divided by the product of the depth and the angle.
determination error. This value was weighted by the number of independent surveys. The calculated reliability factor was divided into four categories (Table 2).

Before the analysis of the results it seems useful to examine the imaging domain of the VSP, and particularly in the case of dipping reflectors, which of them could be detectable in the near vicinity of the borehole.

Imaged location in space depends on the source-receiver geometry (spatial location of source and receiver), and on the depth and dip attributes of the reflector. Figure 9 shows imaged domains calculated for the case of reflecting planes of different dips in 100-400 m depth range, and taking into consideration the real measurement geometry. In accordance with our results a reflector with a given dip can be observed only within this range. Imaging depends in the first place on borehole location and on reflector dip, barely on the source location. Therefore the spatial location which can be examined can be only slightly influenced by the choice of source location. To facilitate the determination of fault plane azimuths a multi-source and/or multi-well geometry is suggested. If fault plane segments determined by modelling approximately coincide with one another, or in the migration process signals stack correctly, then as a good approximation the reflector plane is perpendicular to the plane defined by the two boreholes.

### 3.4. Results

Two different kinds of processing — interactive modelling and migration — were performed to confirm and check one another, because the interpretation was extremely difficult due to the complicated geological structure. It was to...
be expected that migration would give a picture close to reality, while the modelling supported different imaging and statistical studies, although its output has given a very simplified picture.

As a result of the three measurements structures nearly perpendicular to the plane of the surveys were imaged in space at the same location, and the migration facilitated a good stacking of the signals. Irregular reflections originate from outside the survey plane. By our calculations the survey plane fits borehole to the angle domain of ±15°, where results coming from different surveys could be expected to be in good agreement.

Due to steep dips and restricted geometry conditions (existing boreholes) several reflections observed in Borehole Üh–23 were imaged south of Borehole Üh–2 (Figure 7 and 8). Reflections A and C appear in the migrated section showing a steeper dip compared to the result of the modelling. Reflection B practically is the same by both processing. D1 and D2 reflectors are very close to one another and in accordance with the result of the interactive modelling they intersect each other. In the migrated section an interface of similar depth and dip can be seen at an almost identical depth, but by this method they cannot be separated unambiguously. In the migrated section reflections F and E do not show up as interpretable surfaces. Reflector C could be followed in either interpretation as far as the borehole location, therefore its depth is an extrapolated value. Compared to other reflections this is a relatively powerful one and cannot be tied to the change of the reflection coefficient in the borehole. Maybe it is broken close to the borehole. Reflections A and B can be tied unambiguously to the change of the reflection coefficient, but deeper reflections suffered interferences disturbing the depth picture of the section.

In the migration depth sections and in the interactive modelling, reflectors were approximated by planes and it can be recognised that in a northward direction the dip of certain reflections are gently decreasing.

The results of velocity tomography which is rather applicable for the separation of spatial blocks, and VSP results imaging reflection interfaces, can be compared within the common depth domain of the plane defined by Boreholes Üh–2 and Üh–4. While reflectors B and C in the vicinity of their “intersection point” can be tied to velocity changes, reflector A is not detectable in the velocity section (elements D1 and D2 are encountered deeper).

4. Summary

The resultant section processed by the curved ray SIRT algorithm of cross-hole velocity tomography between Boreholes Üh–3, Üh–2 and Üh–4, Üh–2 provides a reliable picture on the velocity relationships of longitudinal waves within the limit of resolution.

Different velocity domains are clearly separated and the macro range structural directions are clearly indicated. Low-velocity zones suggest higher fracturing in the block (low RQD) and suggest material or strain stress changes.

In our opinion a successful study was made by the VSP measurements to image the geological structure in the surroundings of Boreholes Üh–2 and Üh–23, despite all kinds of physical restrictions.

Reliable reflection arrivals were obtained because of the given source-receiver geometry, but not necessarily from the optimal direction.

Owing to the diversity of dips and azimuths, the study of each separated structure needs measurements with optimised parameters (Moos 1984). In changeable geological conditions it is always problematic that three-dimensional structures are attempted to be mapped by two- or even one-dimensional studies. Similar complicated situations have not yet been presented in the literature. In spite of all the problems we encountered, the target geological structure was successfully mapped by the method.

References


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