EXCAVATION DAMAGE ZONE (EDZ) INVESTIGATION BY GROUND PENETRATING RADAR IN GRANITE

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INTRODUCTION

As a part of the underground research of intermediate and low level radioactive waste disposal site in Bátaapáti geophysical measurements were carried out 2-3 weeks after the excavation (base measurement) and one year later (repeated measurement) for determination of extension of the EDZ evolved in the granite.
The measurements of borehole radar have given very good, while the measurements on the wall (radar, acoustic and tomography) have given good results. GPR has proven itself to be the most usable method obtaining valuable information about the rock.
Several typical differences can be observed on the sections of the two (base and repeated) measurements. These are appearing and strengthening of new reflections and diffractions. New processing and visualizing techniques were developed for examination of amplitude and phase changes of different wave types on the borehole radar sections. The physical changes of the surroundings of tunnels can be mapped by these results. These changes can be explained only by realignment of stress and enlargement of classical EDZ.

DEFINITION OF EDZ

The reason of EDZ evaluation is the mechanical change in the vicinity of the tunnels during and after the excavation because the changes of stresses caused by the workings or directly by the blasting (SAIANG 2008). The cracks induced by blasts start from the wall while fractures caused by the stress-changes locate farther (Fig. 1).
The effect is decreasing with increasing distance from the shafts. Much of the changes are performed within a limited time, about 2.5 months (SUZUKI ET AL. 2004). Stress change can be expressed in 2-3 m around a tunnel with diameter of 5 m. These values are typical in homogeneous materials only — the zone can grow in cracked rocks. The dimensions of EDZ are very anisotropic, downward are generally larger (TSANG ET AL. 2005).

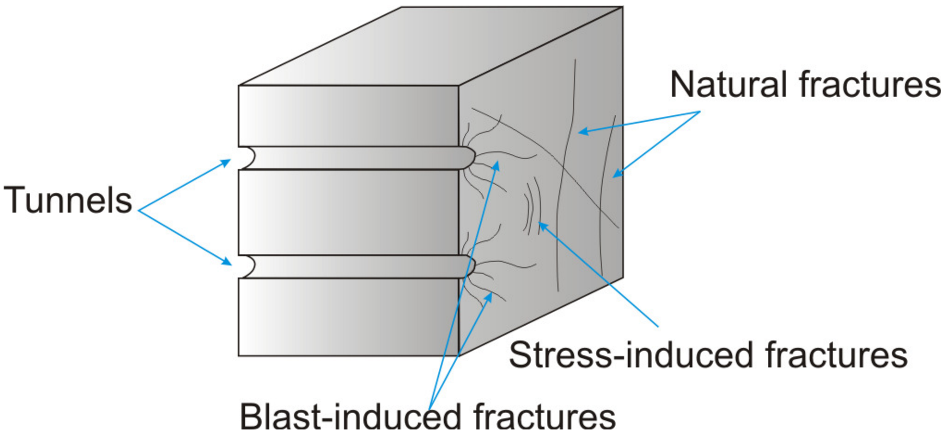

Fig. 1 Surroundings of the tunnel

STRATEGY OF MEASUREMENTS

Examination of EDZ is not an easy task because we have to search for in homogeneities in naturally inhomogeneous material (by definition 'rock — inhomogeneous anisotropic discontinuous material', EGERER 1977). The measurements were planned to examine of the near (< 2 m) and the far (2–10 m) zone up to the depth of drillings based on the information about the thickness of EDZ. As a rule of thumb greater depths can be examined only with less resolution.

The measurements of borehole radar have given very good while the measurements on the wall (radar, and geoelectric tomography) have given good results. On the other hand there was a strict constraint for the applicability of acoustic methods. The causes of it were that the larger cracks and the boundary between the shotcrete and the rock are obstacles for propagation of high frequency mechanical waves, so there were no suitable results between some transmitter/receiver pairs. The electrical measurements on the wall map the changing of the water content usefully.

The GPR method has proven itself to be the most usable obtaining valuable information about the rock; therefore that one is described in details hereafter.

GPR MEASUREMENTS ON THE WALL

The signal emitted by transmitter of the GPR instrument hit the receiver on different direct and reflected ways. The wave reflects from interfaces. The registered signal is digitized and stored in the memory of the computer. We get a GPR radar section by repeating this process by constant step in a direction. The parameters of the wave propagation (travel time, amplitude) — according to the Maxwell theory — are governed by the dielectric constant and the conductivity of the medium

The measurements were planned for two frequencies (225 MHz and 1 GHz) — which mean two different penetration depths. Between the two measurements the thickness of shotcrete becomes thicker, and on the wall pipes, cables, boxes were mounted causing significant alteration of radar records.

During the measurements the antennas were mounted on a working machine (Fig. 2.). Seven 50 m long horizontal lines nearly equally spaced on the perimeter of tunnel have been measured. Distinct differences could have been observed on the repeated measurements such as strong new reflections almost on the whole length of the sections, intensifying and widening of diffractions as a result of the existing cracks. Apart from these changes new surface elements evolved on later sections which can be following about down to 1 m thickness

Fig. 2. GPR measurements in the tunnel

Two sections can be seen on Fig. 3. as an example for typical changes between the two measurements. The first strong signal front after the horizontal direct wave is the reflection coming from the wall. After comparing one can recognize that on the second stage measurement a strong reflection emerges on the whole length of the section. The intensifying and widening of diffractions (for example at 34.5 m and between 38-41 m) refer to the increasing of the originally existing cracks. New surface elements evolved on later sections which can be following about down to 1 m thickness. The changes in the Western Inclined Shaft are shown on the Fig. 4. on each direction and axonometric representation.

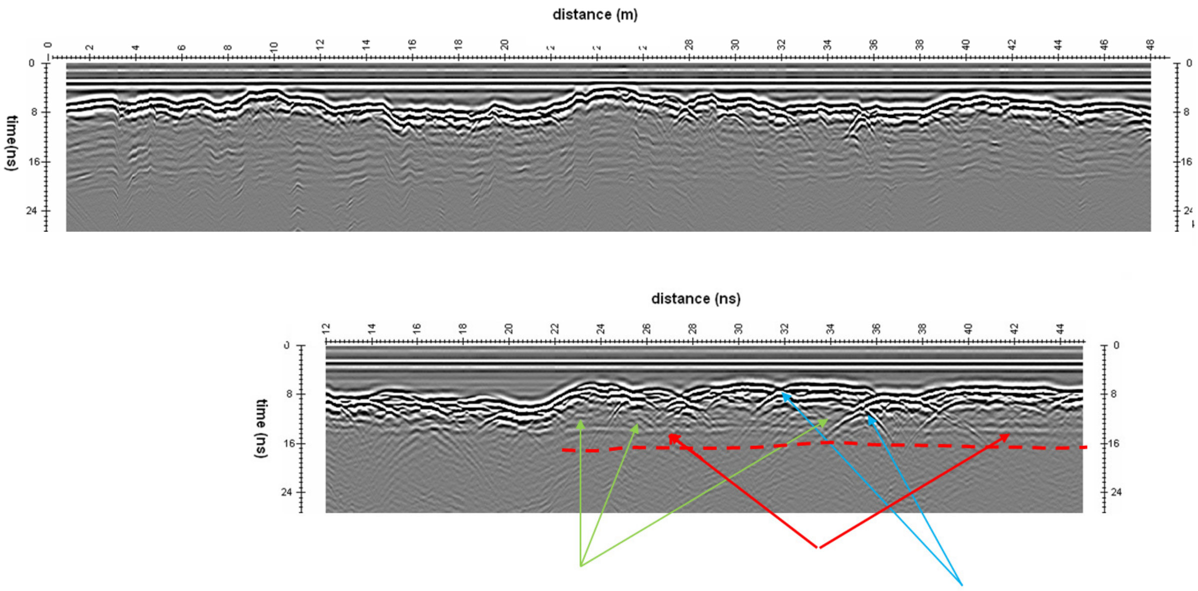

Fig. 3. Processed radar sections

Top Western Inclined Shaft, base measurement, height 3 m, direction east 45º;

Bottom the same line, repeated measurement (the shortening of measurement line is the result of the objects mounted on the tunnel wall)

Red—new continuous reflection, green—intensifying of diffractions, green—new surface element

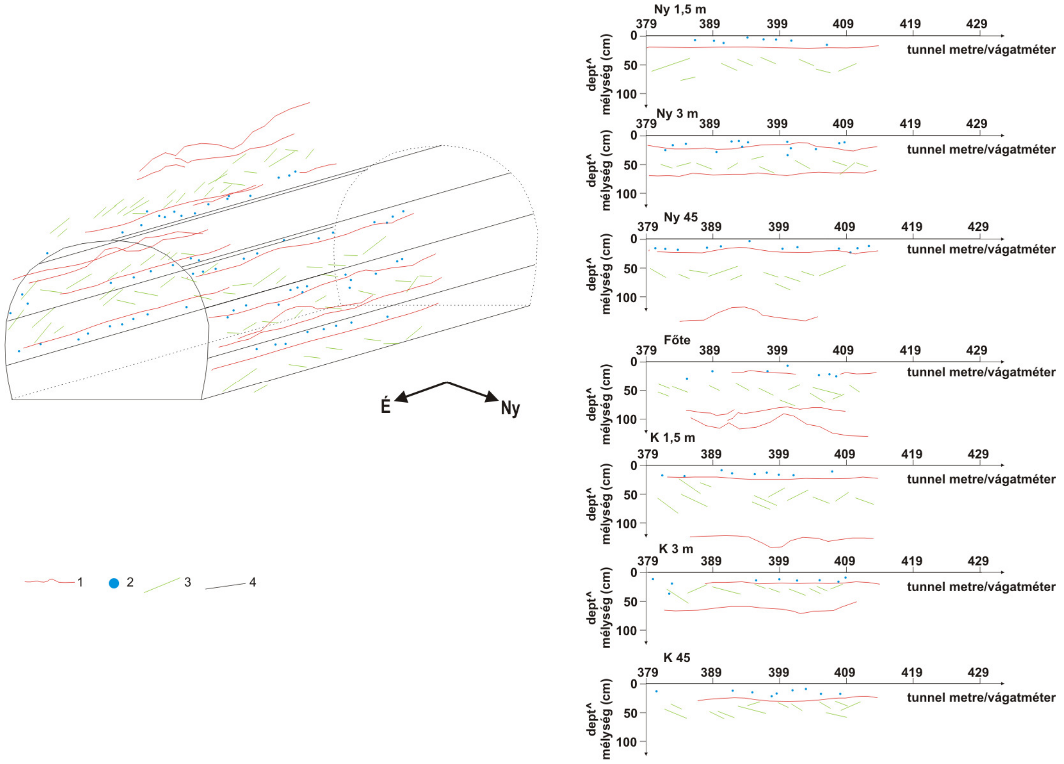

Fig. 4. Characteristic radar reflections on the wall of the Western Incline and their positions in space
1—new continuous reflection, 2—diffraction, 3—reflection element, 4—mean plane f the tunnel wall

The sections measured in the Eastern and Western Inline Shafts are significantly different (Fig. 5.). The Western Inclined Shaft can be separated into three zones as going outwards from the wall. The first 20-30 cm thick zone is appeared almost on each of slices characterized by numerous diffractions. The next zone is 50–70 cm thick with short reflecting elements. Overlapping this second zone up to 150 cm there is a space characterized by long (1–10 m) reflections but because of the limitations of the penetration depth of the method can not be define the border of it. The Eastern Inclined Shaft has more diverse image — its zone structure is not as clear as the western one, the categories overlap each other in space.

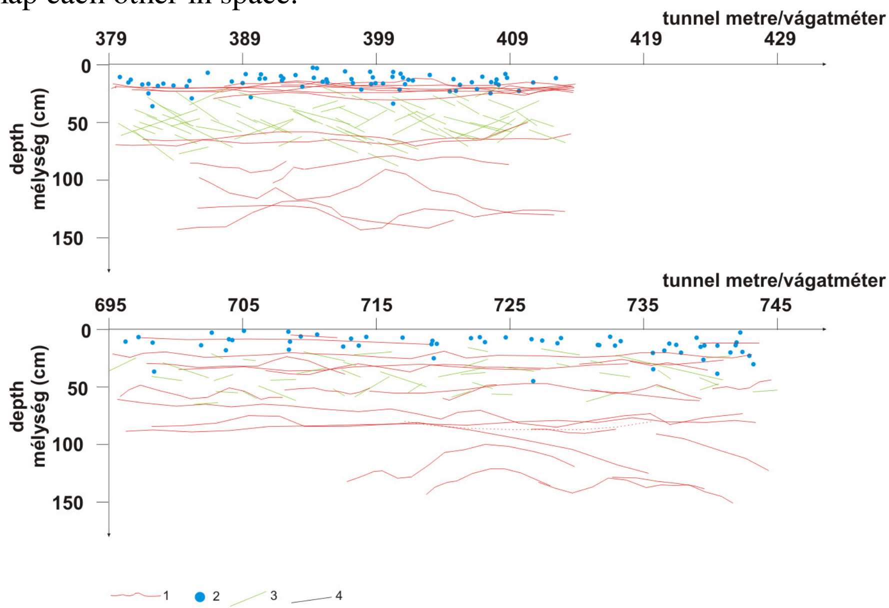

Fig. 5. Radar reflections measured on the walls of shafts — overlapping illustration
Top= Western Incline, bottom=Eastern Incline 1—new continuous reflection, 2—diffraction, 3—reflection element

BOREHOLE MEASUREMENTS

The principles are similar in case of on-wall and borehole GPR measurements, the main difference is the in-probe settlement of the transmitter and receiver antennas with fix offset of the latter one. Different type of waves can be observed on a registration (Fig 6.):

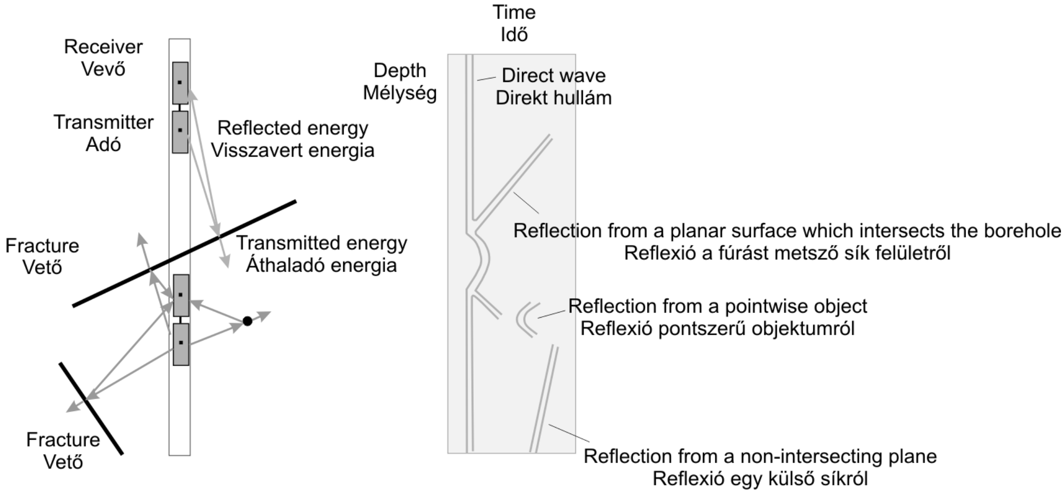

Fig. 6. Principle of borehole radar and its wave types

- Direct wave front spreading across the filling media (air or water) of the borehole
- Direct wave spreading across the neighbor rock
- Reflected wave from interfaces (fractures)
- Diffracted waves

Direct waves spread directly from the transmitter to the receiver, traveling the shortest distance. Direct ground (or rock) waves carry information about the structure, as direct air (or water) waves can be consider as noise. Diffractions arise from a point wise object (i.e. the dimensions of the object are much more less, then the dominant wavelength).

Borehole measurements were carried out at all member of the borehole sets Bf–[11–18] and Bf–[21–28] at the 417.5 m of the Western Inclined Shaft and 717.5 m Eastern Inclined Shaft respectively with the same parameters on two temporal phases one year amongst them to compare the changes, with two opposite direction at each borehole. The layout of the boreholes can be seen on Fig. 7., a typical GPR section on Fig. 8.

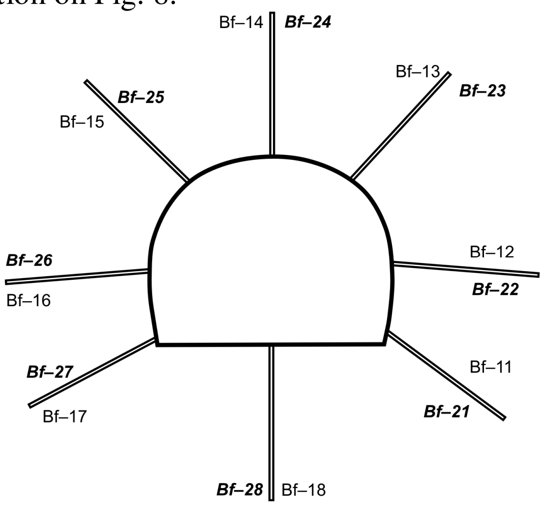

Fig. 7. Locations of EDZ boreholes on the tunnels

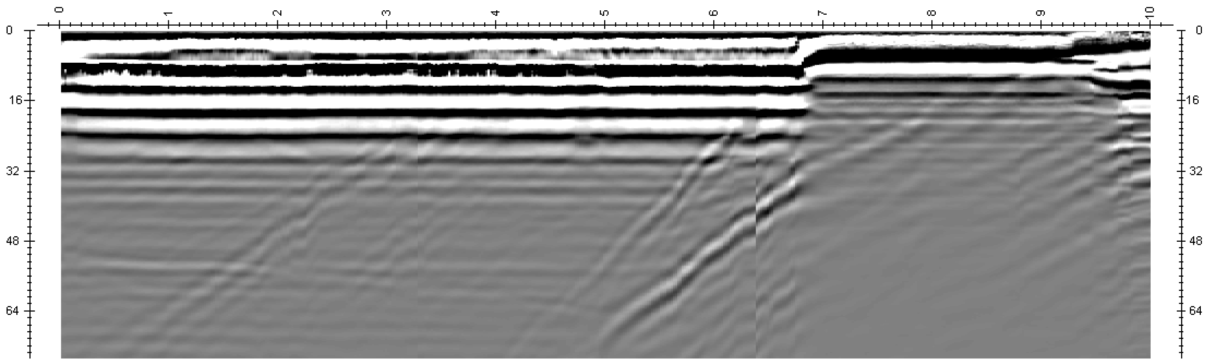

Fig. 8. Raw GPR section of borehole Bf-11

Analysis of direct wave amplitudes

Purposeful processing was applied to emphasize the noticeable temporal changes of the sections. As a first stage the direct wave amplitude were analyzed. The amplitude of the direct ground (rock) wave is determined by the attenuation i.e. the electric resistivity of the medium, so the amplitude changes can be consider as a transformation of the resistivity distribution. As a first step of processing a time window was applied to separate the direct air/water and ground waves on row records. The ratio was calculated by the average of the separated amplitudes of the measured directions to characterize unambiguously the surrounding of the borehole, and it was used for interpretation. The amplitude ratios of borehole Bf–11 are shown on Fig 9.

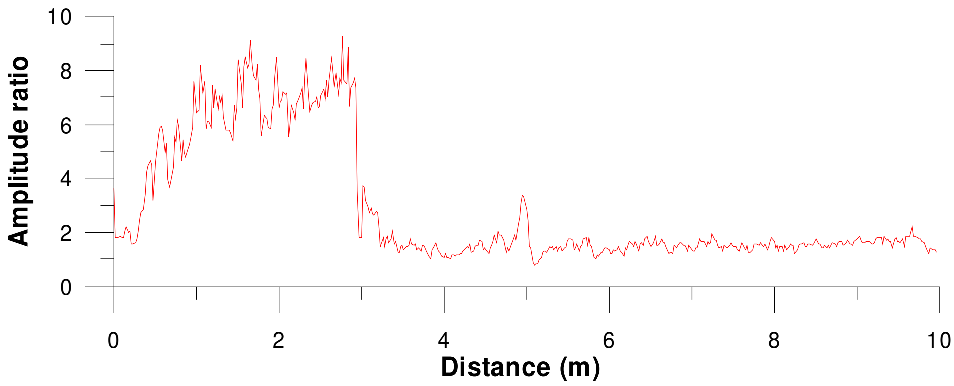

Fig. 9. Direct wave amplitude ratio of the base and repeated sections (A_{base}/A_{rep}) of borehole Bf–11

The changing of the ratios can be originated from the changing of the electric resistivity (i.e. the water content) of the rock and/or increasing of number of cracks. At the latter case the reflections from the interfaces of the cracks between the transmitter and receiver can't be identified because of the resolution limit, but we can recognize the energy decreases caused by them. The more micro cracks mean the more attenuation of the radar wave. As the electric resistivity of the rock near the wall has increased (this effect was proven by the time laps geoelectric tomography measurement) the only possible cause of the amplitude decreasing is the increasing of the interfaces.

The amplitude ratios were illustrated graphically, and fitted them to the borehole geometry. As an example the amplitude ratios calculated from the results of the borehole set measured in the Western Inclined Shaft are shown in Fig 10. The EDZ extension is shown a little bit arbitrarily by blue dashed lines. The dimensions of the extension are between 2.5–5 m, and these are extended to downward direction.

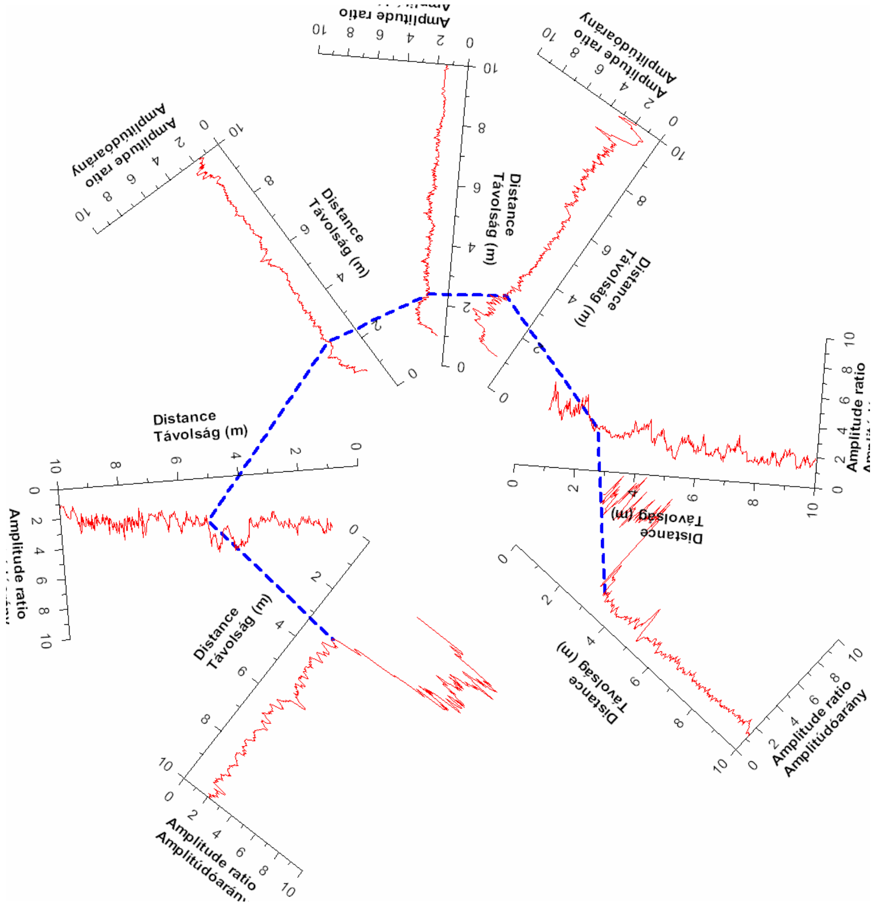

Fig. 10. EDZ at the Western Incline assigned by the direct wave amplitude ratio

Analysis of Reflections

The study of reflections was made on the processed sections. The processing was restricted to the removal of the direct waves to prevent of arise any filter noise. Reflections can also be visible on the raw sections (for example on Fig. 8. on 4.3 and 7.1 m distance), but on the processed ones their quantity exceeds the expected (Fig. 11.).

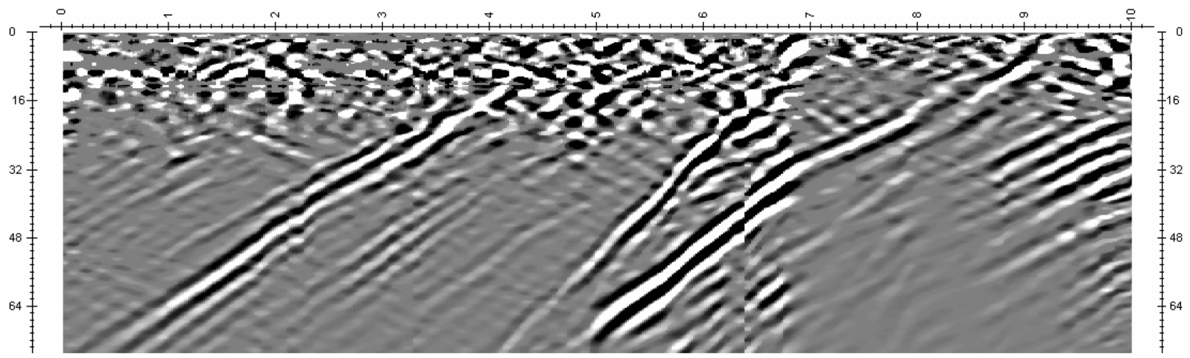

Fig. 11. Processed GPR section of borehole Bf-11

The reflections originate from inhomogeneities characterized by larger than 3 cm dimensions taking into account the resolution of the method. Because of the large number of reflections we simplify the sections applying image processing procedure.

As a first step we composed the contour of wave-fronts. After that it's necessary to reduce the pair-like appearing of contours because the up- and downward zero crosses are also assigned by the former step. This operation is analogous to the „skeletonizing" adjusted to the characteristics of GPR sections. The resulted skeletons of the second measurement can be fitted to the first one making them easier to compare (Fig. 12.). The process can cause loss of some weak reflections, but the advantage of comparability overcomes this drawback.

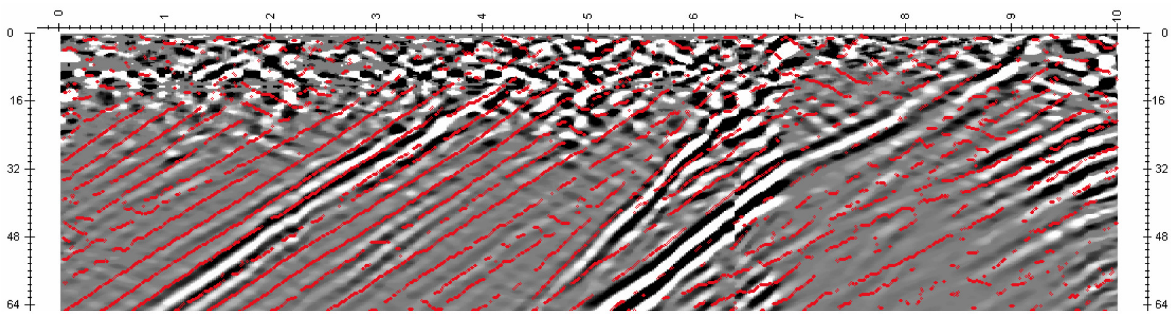

Fig. 12. Processed GPR section of borehole Bf-11 (base measurement) covered by the "skeleton" of the repeated one (red lines)

A new parameter, the relative reflection density of a 10 cm distance step can be derived from the "skeletonized" sections. The values of the relative reflection density show the ratio of pixels constituting reflections to all of them within a distance (i.e. depth) section. At any depth this value is also a function of the apparent direction of the reflections beside the reflection density, so the maximal value was taken into consideration. Generally the reflections were rather dip (the apparent "inclination angles" determined by the time section dimensions are between 30-40º), therefore the reflection density section reach beyond the top and bottom of the borehole. The whole point is that the relative reflection density increase with the increasing length and number of reflections cut the borehole. The parameters of borehole Bf–18 are shown on Fig 13, of all boreholes around the Eastern Incline on Fig. 14.

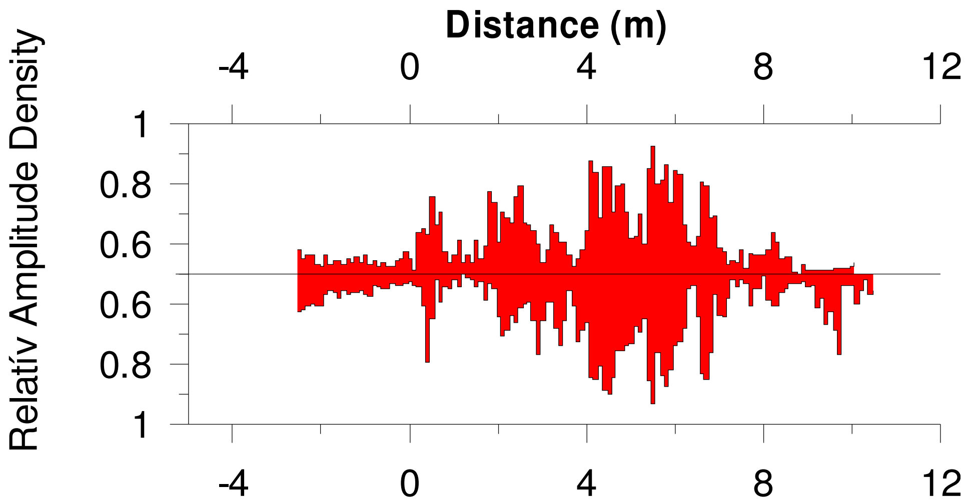

Fig. 13 Histogram of relative reflection densities of borehole Bf–11 (up and down directions)

Generally a relatively close zone around the tunnel with 2-3 m thickness can be seen on the sections as long as the densities decrease as a trend from the maximum value of the top of the borehole. This behavior is in accordance with the expectations of characteristics of EDZ as the influences of mechanical changes decrease moving away from the tunnel.

The tracing of the boundary is real ambiguous near the top of the shaft, because of the low value of the parameter near the starting (open) point. However there are some intervals with much higher reflection ratio values at deeper parts of some boreholes assigned with green lines in the figure. There are two possible explanations for these phenomena: the time lapse between the excavation and the measurement was enough to complete most of the mechanical processes of the rock or the effect of these processes is weaker than the existing inhomogeneity around the tunnel. As a technical conclusion we can say, that it would be essential to perform the GPR measurement as soon as possible after the excavation.

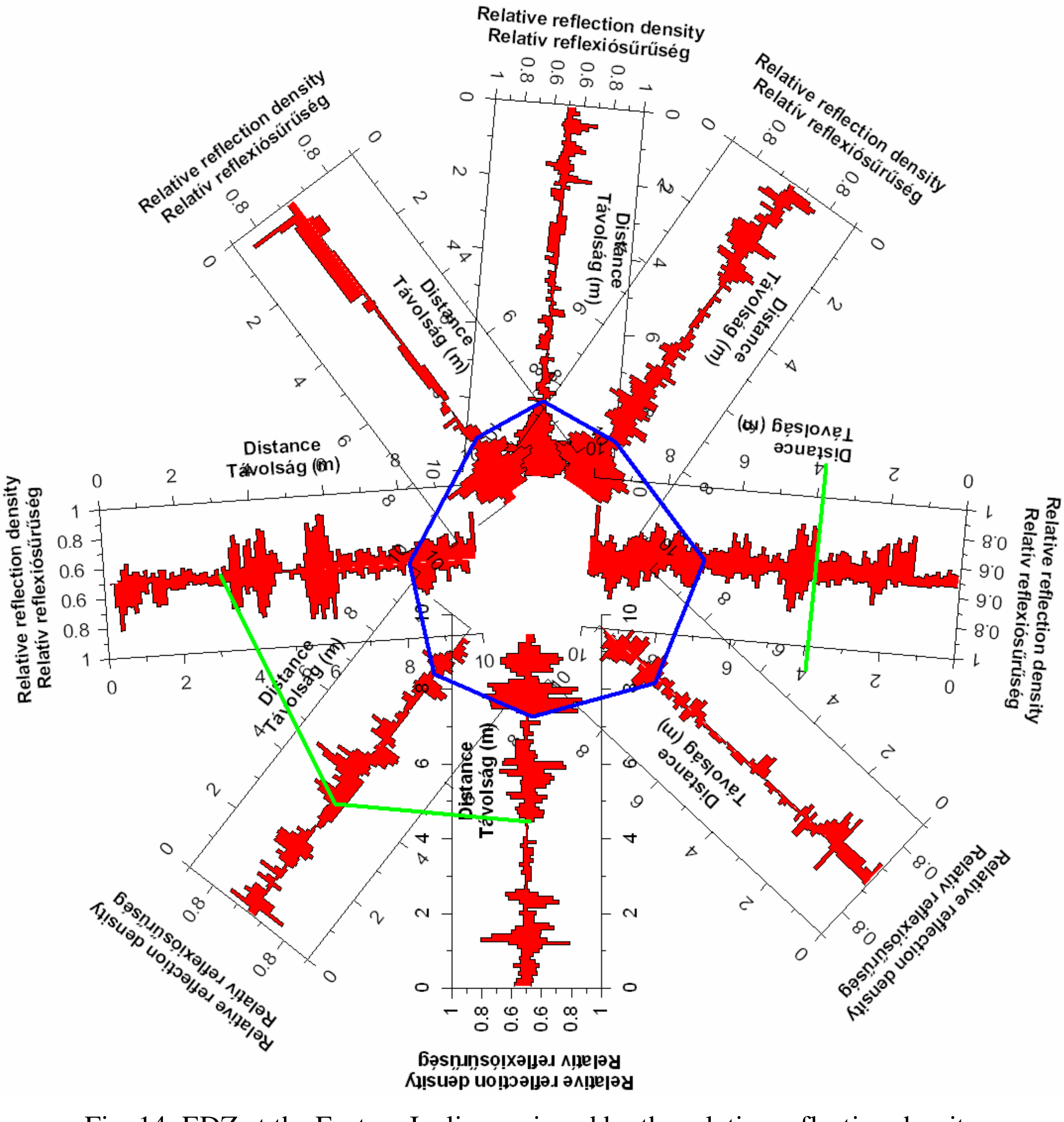

Fig. 14. EDZ at the Eastern Incline assigned by the relative reflection density

The processed section pairs were analyzed individually, too and the conclusion is contrary with the expectations — the reflections of the repeated measurements often become weaker or downright disappear. The most interesting changes of the reflection image at the Western Inclined Shaft are shown on Fig. 15. The different phenomena are assigned with different colors. The phrase “: equalization of velocity” on the legend mean velocity increase in practice. The only place when velocity decrease can be detected is the roof. The phrases “gain” and “decay” mean significant changes, the “new reflection” mean even more amplitude change.

The furthermost important change in each borehole was considered as the boundary of EDZ. In case of borehole Bf–11 this boundary coincided with its depth, so the EDZ can reach its penetration, but it was the only borehole with such feature.

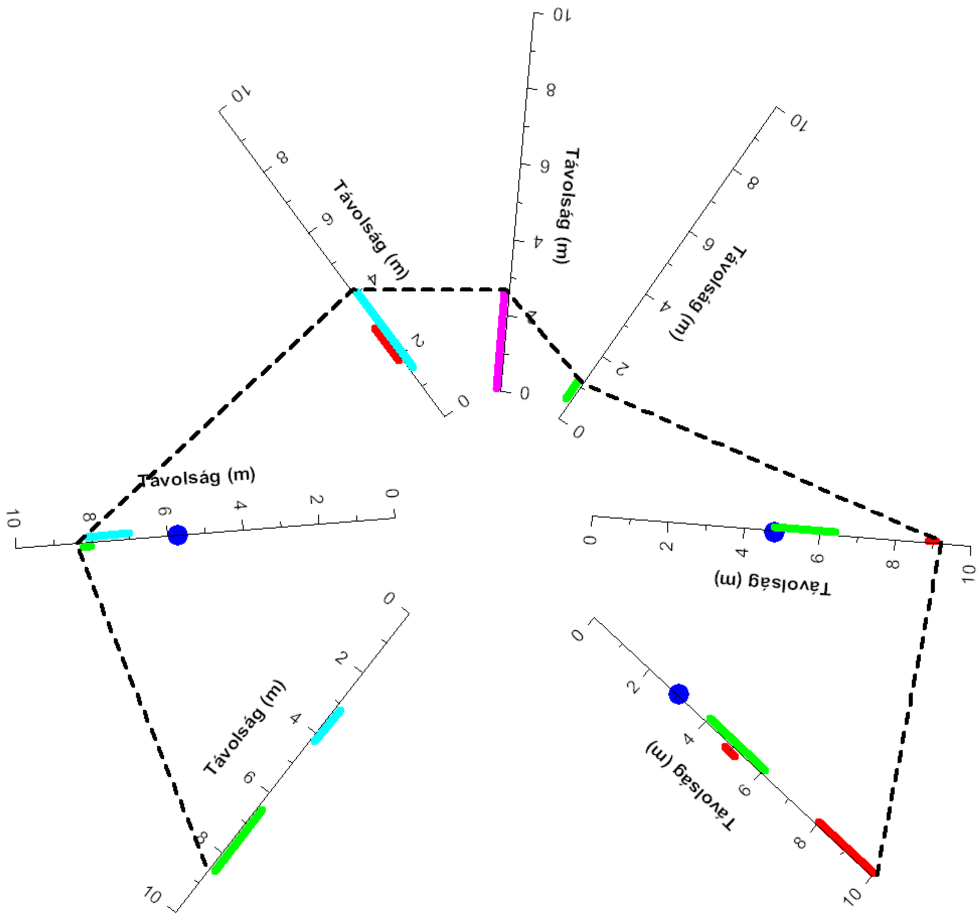

Fig. 15 EDZ at the Western Inclined Shaft assigned by borehole reflections

Blue: equalization of velocity, green: reflection gain, red: new reflection, violet: velocity decrease, light blue: reflection decay, dashed black line: the furthermost changes

CONCLUSIONS

The results can be distilled by different principles from the radar measurements are summarized on Fig. 16. and 17. An inner well separated zone is outlined by dark blue colour by the tendentiously decreasing part of relative density of reflections on each borehole set. The thickness of it is 1-2.5 m, and it can continue on the wall measurements, too. This phenomenon shows little vertical asymmetry and can be identified as the classical EDZ. On the figure the maxima of relative reflection density (broken green lines) cannot be connected to the changes in the shaft – they probably show the natural inhomogeneities of the crystalline rocks.

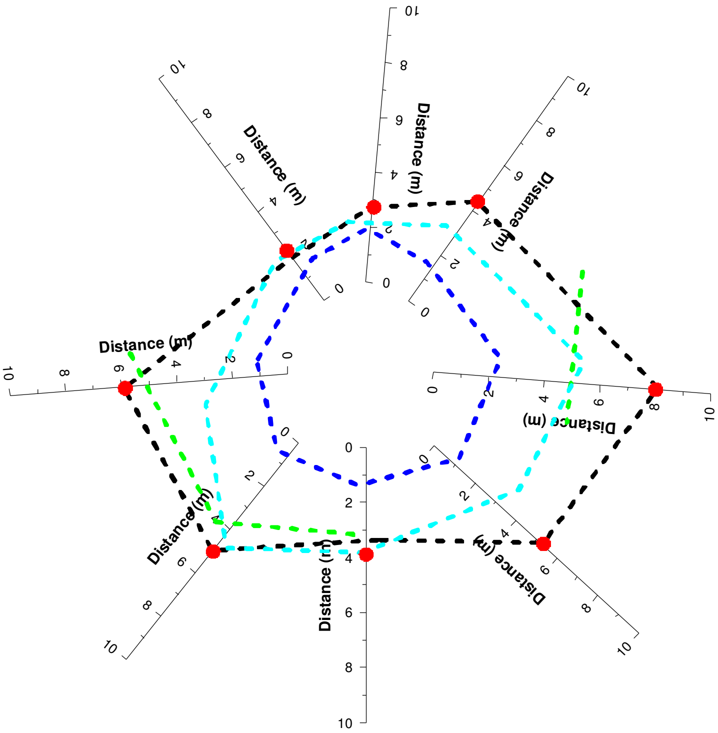

Fig. 15. EDZ at the Easter Incline assigned by GPR measurements

Red spots = the furthermost GPR signal which can be in connection with EDZ, dark blue = border line by the relative reflection densities light blue = border line by the direct wave amplitude ratios, black = border line by the changes of reflection image, green = the maxima of the relative reflection densities

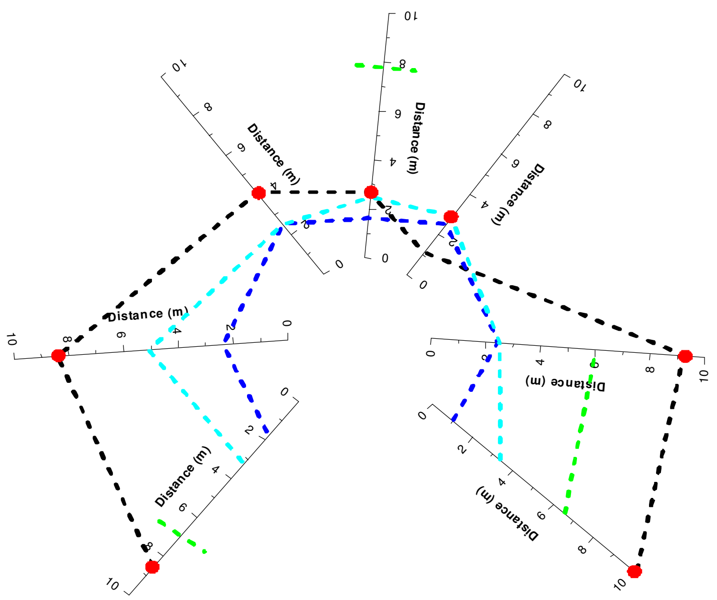

Fig. 16. EDZ at the Western Incline assigned by GPR measurements

Red spots = the furthermost GPR signal which can be in connection with EDZ, dark blue = border line by the relative reflection densities light blue = border line by the direct wave amplitude ratios, black = border line by the changes of reflection image, green = the maxima of the relative reflection densities

There is an outer zone which is drawn by the furthermost place of the appearance/disappearance or at least the change of character of borehole radar reflections. The borehole Bf-13 is exception because the furthermost alterations on its sections are the changes of amplitude of direct waves. The borders of this zone are between 2.5-10 m showing essentially larger asymmetry both on vertical and horizontal axes. The width of this zone is significantly larger below as above. The changes in this stripe are unambiguous — a sort of displacement have happened closing and/or opening cracks between the two measurement campaigns. These changes can be explained only by realignment of stress and enlargement of classical EDZ.

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