Geotechnical information based on well logging in tunnel pre-drilling

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ABSTRACT: During the establishment of the low -and intermediate level radioactive waste management facility in Bátaapáti geophysical well-logging has been carried out in thousands of meters of surface drillings intersecting granite. Based on drilling data a rock mass classification supported by geophysical well-logging has been developed and successfully utilized in drift axis drillings during underground mine workings. This method initially had been frowned upon by the industry later however it was accepted that geotechnical condition of an intersected rock can be predicted with great certainty (in a given geological formation) based on the correlation of the traditional rock mass classification and the chosen geophysical methods (electronic and acoustic). During our research we have completed successful RMR and Q-type rock condition prediction over 100 drillings of a total of 5000+ meters. Based on our results we are convinced that this method is also applicable in other types of rocks such as carbonates, andesite, basalt, sandstone etc. However due to a lack of opportunities this could not be proven so far.

Keywords: well logging; Rock Mass Rating system; acoustical methods; boreholes; core drilling; excavation; granite; resistivity; rock masses; rock mechanics; tunnels

1. Introduction

During the surface geological research in the Bátaapáti low -and intermediate radioactive waste management facility research project essential information on surface geophysics, geology, tectonics and hydrogeology has been provided by geophysical logging. During examination of drillings from the underground workings such as drift axis drilling, geotechnical drilling, hydrogeological drilling and exploratory drilling for chambers emphasis has been put on providing geotechnical information, besides the above. It had already been found during ground surveys that such geotechnical conditions of granite as fracture zones, weathering zone and unique fractures are reflected well in electronic and acoustic methods such as full acoustic waveform and Acoustic Borehole Imager. As such they might be applicable to assisting with drifting, i.e.: in the preliminary determination of spaces between safety installations. We were determined to either include borehole geophysical surveys as a means for rock mass classification traditionally based on core logging or to use it as substitution for the latter during drifting and development of chambers. Although we indeed had been doing quality-based interpretation based on acoustic televiewing and specific resistivity surveys as well as rock mechanical calculations (Young modulus, strength index, etc.) however we have never made indirect classification of rock masses neither did we find any references in literature.

2. Rock mass classification

The main task of geology, hydrogeology, geotechnics and geophysics during underground mine workings is determining strength or geotechnical qualification of a given rock mass in order to choose stoping technology (pre-grouting, spaces between safety installations) and drifting support category objectively in advance. As a result, they would not have to be deduced from inspection of the current headwall. Traditionally predictions are made by examination of the core material from the drift axis pre-drilling. This is done by fracture analysis methods such as RQD, Kiruna, etc. standardized during geotechnical documentation. In practice the documentation occurs as follows: primarily the geotechnical specialist establishes assessment intervals after which they classify these few-meters long sections with the above methods. Then by deducing the results from the above and with other classification parameters such as single-axis compressive strength, water influx spots they make the rock mass classification scheme based on RMR, Q or some other system. Although usually this or similar methods are used everywhere for determining rock classes however there are indeed other methods depending on rock type (limestone, granite, andesite, sandstone, etc.) and best-practice in the industry. It is essential however with any method to have a core presumably as a whole. The core description is widely subjective due to it depending mainly on the experience of the person writing the documentation. It also depends on the designation of the assessment intervals.

Borehole geophysical methods analogous to the 6 geotechnical parameters of the RMR-classification:

- Jointing conditions: specific resistivity and acoustic rock velocity,
- Single-axis compressive strength of rock: shear modulus calculated from acoustic velocity,
- Average distance of joints
- Bedding of joints: stratal dip – Acoustic Borehole Imager
- Fissure filling (average, material quality): natural gamma activity, specific resistivity,
- water influx ratio: flow survey and differential temperature survey.

It is clear, that parameters of the RMR classification can be determined by geophysical methods however this is a long and tedious procedure. We chose a less complex method: we examined which geophysical method has a direct relationship with RMR.

3. Exploration history

Preliminary to drifting years of surface exploration had been carried out, with almost 100 exploration wells, during the establishment of the radioactive waste management facility. In addition to numerous borehole geophysical surveys such as electronic, radioactive, acoustic, ABI etc. drill cores had been examined with geological, hydrogeological and geotechnical methods. Figure 1 shows drilling into a granitoid rock with the most relevant surveys.

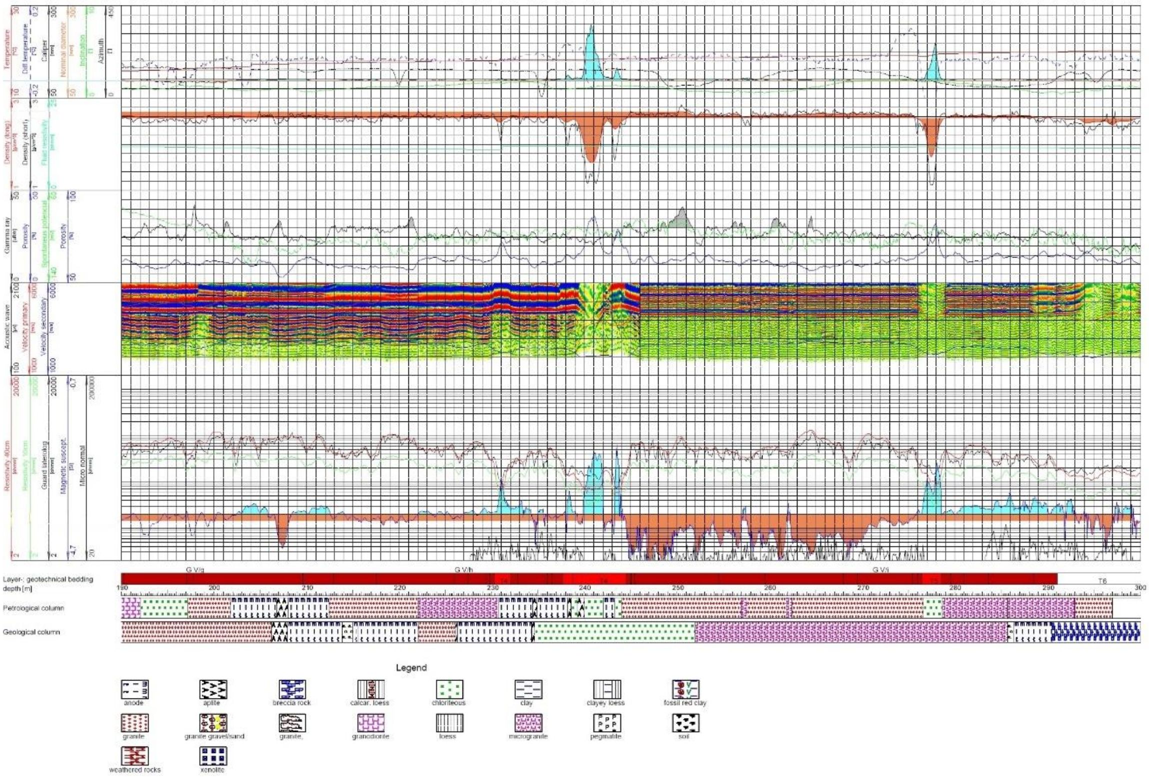

Figure 1. Complex borehole geophysical log of a lowered surface drilling

Weakened fracture zones are characterized by lower resistivity and lower acoustic velocity values. Tectonized zones can be seen on the acoustic image on the middle slip. Notice their faint colours and later arrival times

As a result of geotechnical investigations geotechnical conditions of the intersected rock had been determined by RMR as well as Q methods in 8 deep holes. This was followed by analysing which borehole geophysical methods correspond the most to geotechnical rock conditions and a regression correlation was then determined between geophysical surveys and the results of core inspection (RMR and Q values). As a result of surface exploration, the most appropriate building site had been appointed for the foundation of the underground storage facility and development of the inclined shaft had been initiated. In order to get acquainted with rock conditions exploration core drillings to 100 m had been carried out along the axis of the expected drift. These had to be drilled with a -5 degrees inclination for the purpose of filling them up with liquids necessary for borehole geophysical surveys such as electronic, acoustic, ABI, etc. Then traditional geotechnical investigations (rock mass classification) were completed based on core loggings that provided essential information on planning and construction of the tunnel.

4. Borehole geophysics applied during underground exploration

Due to security reasons all effective methods had been carried out in lowered drillings of surface exploration except the ones using a radioactive source in underground near-horizontal drillings such as density and neutron porosity. The ones used in underground granitoid rocks are the following (with the information they provided in brackets):

- Specific resistivity (geotechnical rock conditions, revealing argilliferous zones)
- Natural gamma (petrology: granite, granodiorite, albite)
- Acoustic (geotechnical rock conditions, rock velocity, geotechnical rock parameters)
- Acoustic Borehole Imager – ABI (diameter to 180 degrees, ovality, drilling direction and dip, joint density, average reflection amplitude, bedding of joints [strike and dip], classification of joints [open, closed, half-open])
- Temperature and differential temperature (water influx spots)

It is clear that applied geophysical methods provide a wide spectrum of information on geological, hydrogeological, tectonic and geotechnical properties of intersected rocks. There are 2 main types of surveys: ones providing information on rock structure and its mechanic properties i.e.: acoustic and specific gravity; and others measuring parameters based on rock material such as natural gamma, magnetic susceptibility and, in some cases, specific gravity.

Figure 2 represents a drilling where only 2 sections could be surveyed as the middle section intersected an argillaceous tectonic zone where casing had to be laid.

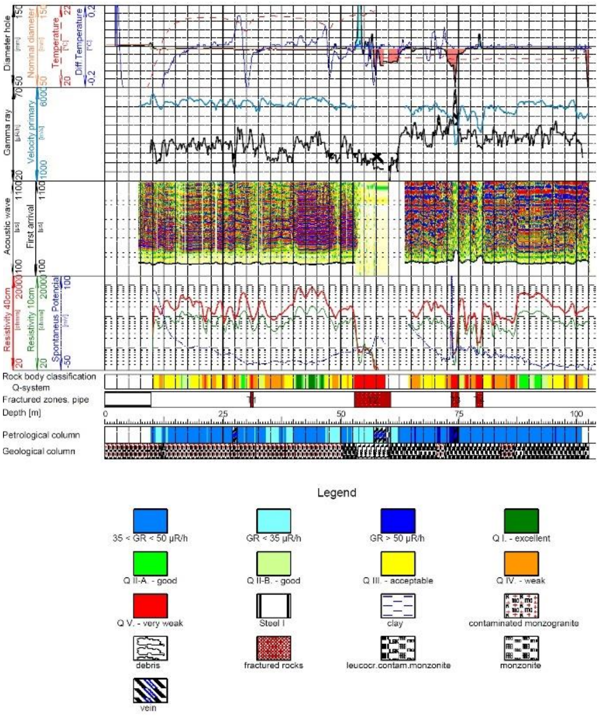

Figure 2. Tectonic zone in a complex survey

This zone was clearly indicated on all geophysical logs: resistivity fell from few thousand ohmmeters, representative of granite, to 20 ohmmeters and acoustic waves were absorbed completely over a 10 m section.

Figure 3 shows an ABI survey section with a significant fracture zone besides numerous small joints. Open joints are represented by red smudges in the 'Travel time' section. A joint density diagram is created from the number of sinus curves positioned on joints while from the reflected amplitude values an average amplitude log is derived. Joint bedding and type (dip, strike, open, closed) were determined by the indicated sinus curves.

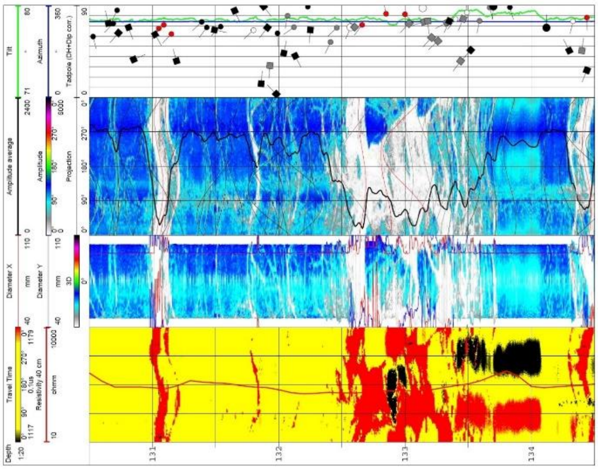

Figure 3. Acoustic Borehole Imager image details

Calculations of rock mechanical parameters are presented on Figure 4. Density survey had not been carried out underground so a regression correlation has been set up between the resistivity and density logs based on surface drillings. A clear correlation was shown in granite so an estimated density log had also become available besides the measured rock velocities (Vp: longitudinal, Vs: transverse) for the calculation of rock mechanical parameters.

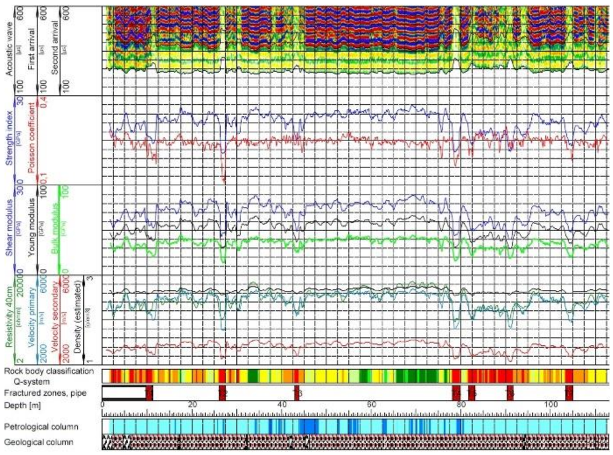

Figure 4. Determination of rock mechanical parameters(Lower slip: calculation base logs. Slips #2-3: calculated parameters. Upper slip: acoustic waveform and indicated arrival times [tp: longitudinal, ts: transverse])

5. Determining correlation between RMR rock mass classification and borehole geophysical logs

The combined RMR string of data derived from the core analysis of the above mentioned 8 surface drillings and such borehole geophysical parameters as resistivity, sonic velocity, joint density and average amplitude were all represented on cross-plots. The regression correlation is best showcased on the specific resistivity-RMR cross-plot. 1000s of survey points were plotted that have quite a wide distribution at first sight.

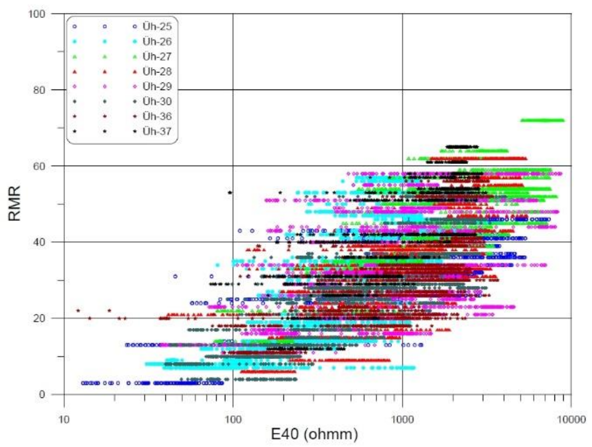

Figure 5. RMR-resistivity cross-plot of 8 drillings

From the difference between RMR ratings derived from few-metre intervals and borehole geophysical logs (with 10 cm sampling intervals) it has been deduced that using an average of each geophysical parameter is much more effective in correlating with RMR intervals so these were represented on a cross-plot. This process is also used during comparison of geo-mechanical lab data and borehole geophysical data arrays. Essentially it is a conversion of geophysical data into a step diagram similar to RMR.

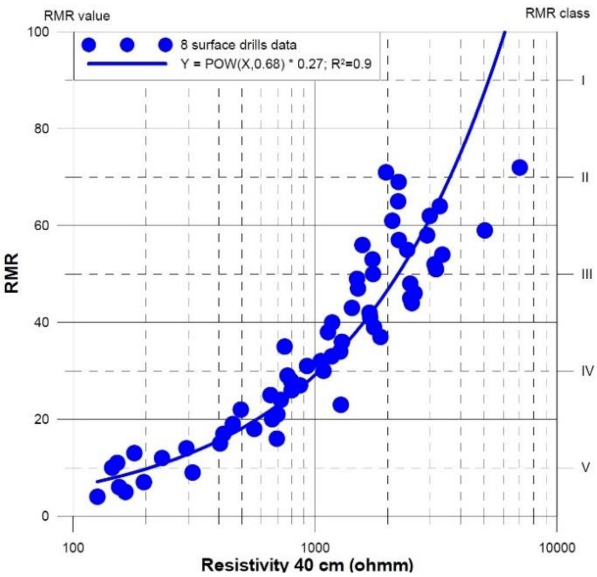

Figure 6. RMR-combined resistivity cross-plot

Another option to reduce the wide distribution of survey points is to average all resistivity values corresponding to identical RMR values with each drilling (as is shown on Figure 6) and extend to all drillings. As a result, there will only be 1 resistivity value for each of the total 100 RMR values. Then resistivity values were averaged to 10 RMR-unit intervals and a power trendline was fit (Figure 7).

Notice how the power trendline describes RMR categories I and V much better than the linear.

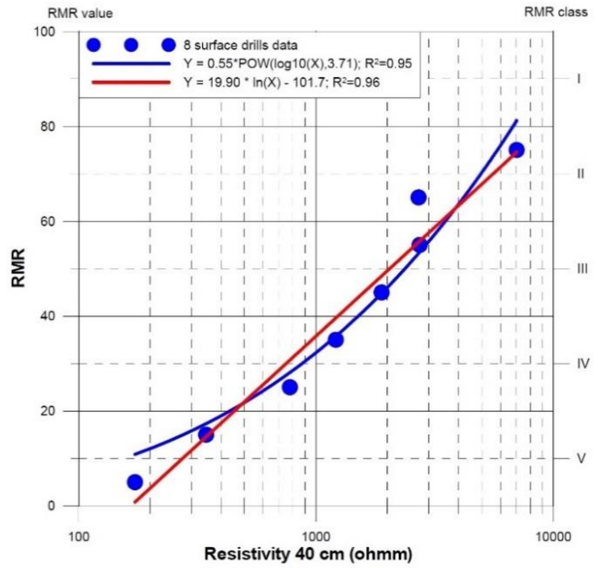

Figure 7. Power trendline fit onto the RMR-E40 cross-plot

The distribution of the final 10 datapoints of the power trendline is considerably better: 95%. Regression correlation is the following:

$$RMR = 0.55[lg(E40)]^{3.71}$$

Similarly regression correlations were determined for longitudinal velocity (Vp), joint density and for the value of log(E40)xVp. Best distribution (98%) was achieved by the last. To make things simpler transposition to the resistivity log was chosen for the RMR and Q-type rock mass classification during underground surveys.

RMR classification derived from borehole geophysics logs is shown on the next two figures. Although the E40 resistivity log has been used the Vp velocity log has also been represented. Notice the correlation between the two despite both being originated from two completely different types of physical parameters. The offsets are originated from the attributes of jointing: velocity primarily depends on joint density in a given volume of rock (basically the average distance of joints from each other) while resistivity depends on joint tortuosity.

Comparison of the RMR values derived from the regression correlation and the one originated from the traditional method by the geotechnical company (RMR core) is represented on Figure 8 and 9.

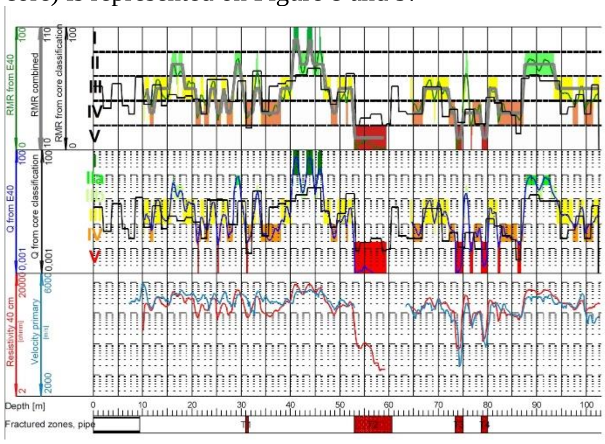

Figure 8. MR classification in underground drilling

On the upper log the automatically determined RMR values and their combination is shown. Combining them is necessary because in practice it is not recommended to change length of advance and timbering method more often than a few meters. Figure 9 clearly shows the small difference between RMR classification derived from geophysics and core logs: in most cases it is only half a class or 1 class at most. The showcased RMR rock condition prediction had been completed in all drift axis drillings in addition to some other exploratory drillings during this project. The core advantage of our method is the immediate interpretation after completion of the drilling survey while the traditional method takes considerably more time with core logging and lab measurements.

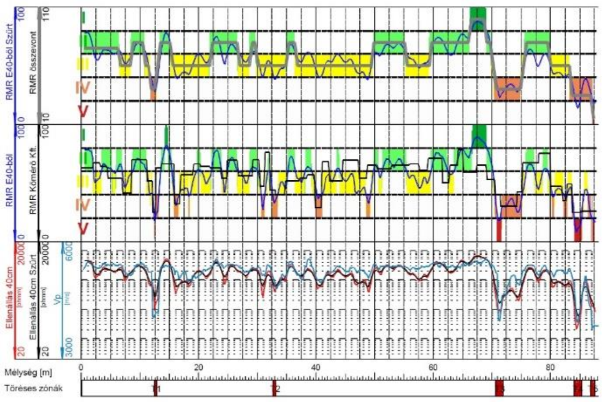

Figure 9. RMR classification in underground drilling

On Figure 10 resistivity curves of 2 drillings initiated from a drift face and the RMR classification derived from it is shown. Notice how well the drillings separated by 2 meters vertically from each other correlate. Both drillings intersected a fractured, clay-weathered zone in significantly bad mechanical condition.

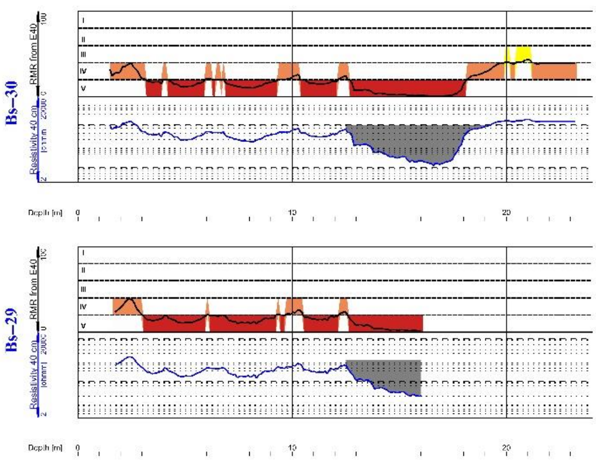

Figure 10. Correlation of two drillings near each other

Later another 2 drillings were initiated from this drift face approximately 2.5 meters away from the previous two (see Figure 11). Only one of the 4 surveys reached bottom hole while the others got stuck due to a collapse in the hole. Besides the thickness of the tectonic zone (5 meters in this case) its bedding, an important preliminary factor in planning the drifting, can also be accurately determined by this correlation.

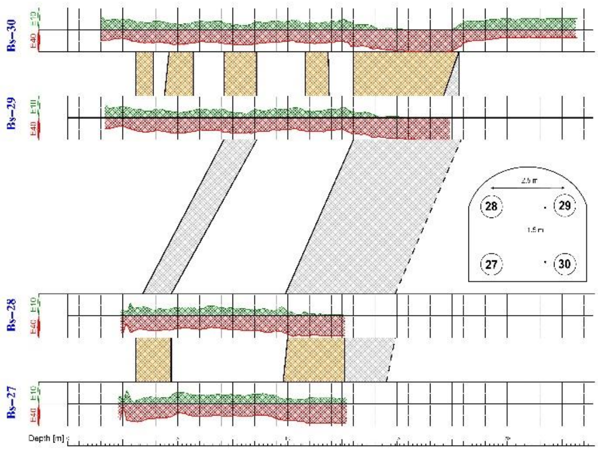

Figure 11. The 4 drillings initiated from the drift face

6. Conclusions and method assessment

Due to the fact that most borehole geophysical methods such as electronic and acoustic indicate geotechnical rock conditions well a good regression correlation can be determined between them and the RMR values of the same section. Since all rock mass classification methods attempt to provide the best description of geotechnical rock conditions, only by different empirical means, it is obvious that similar correlations could also be found with them. Borehole geophysical methods are also derived from the physical/geophysical properties of rocks so they are a fast and cheap means of support for tunnel engineers in planning and development. The method is described as such: values determined by the applied rock mass classification methods should be correlated with values determined by the borehole geophysical logs in some of the initial drillings; regression correlation is determined by this; then rock mass classification can be completed by the borehole geophysical logs.

Continuous borehole geophysical logs assist to a great extent in traditional rock mass classification providing insight into changes in rock condition. They assist in indicating interpretation intervals with great confidence and speed.

This method had only been used in granitoid rocks so far due to a lack of opportunities however it certainly can be used in other rocks such as andesites, carbonates and sandstones. This is due to the structure of rocks that also effects rock survey parameters such as resistivity and velocity similarly in these types of rocks.

This method could be further improved if both the difference between RMR values determined by rock velocity and specific resistivity and the difference between these RMR values and values derived from traditional core logging were examined on a larger scale. Specific gravity values and velocity values are proportional to specific area of the rock and the distance (openness) of joints respectively. As was elaborated earlier RMR values determined as such are quite similar in most cases. Clear differences however also exist in some cases due to different reactions of the two physical methods to rock mechanical conditions. This is primarily the result of cores being examined under atmospheric pressure by default. Same results were to be expected had the cores been put under their original pressure due to core processes being irreversible. It is encouraged to examine what other geotechnical reasons are responsible for these differences and how these could be considered for a more precise method of rock mass classification.

As a summary advantages of our method are listed below:

- a significant number of drillings can be saved
- no gaps in core, no deviations in core depth
- examines 2 magnitudes larger areas and volumes
- sampling density: 10 cm
- objective: no dependence on geo-technician and their level of expertise
- providing immediate results
- no need for expensive and drawn-out lab assessments
- providing clear evaluation intervals
- cheap

Disadvantages of our method:

- providing relative values only (needs a regression correlation for one of the traditional methods)
- by default, water influx spots are not considered but it can be corrected with them
- unknown, brand new process
- experts in core logging consider it as competition

References

[1] Vásárhelyi, B. Basics of applied rock mechanics, Hantken, Budapest, 2016