Analysis of full-waveform sonic log for face ahead prediction in tunnel excavation

M. Cauduro*, A. Dall'Ara**, A. Geuna*, A. Godio**

*GD-Test S.r.l., Torino

** Department of Georesources and Land, Politecnico di Torino

Introduction

The application of sonic logging for geotechnical characterization of rock mass in civil and mining engineering is continuously increasing. The possibility of estimating directly the elastic properties of rock mass avoiding laboratory tests and analysis makes the technique particularly interesting. The experiments in a horizontal tunnel allow to analyze the reliability of the method during the tunnel excavation and to correlate the results of geophysical logging with the geotechnical parameters of hard rock (quarzyte) and soft rock (gypsum) where the tunnel excavation in a geologically complex Alpine region has been performed.

Full waveform analysis of acoustic well logging is usually performed together with other geophysical or geotechnical logging, such as gamma-ray, conductivity and fluid temperature, induction log or self potential log. These methods are reliable in assessing the main fracturing systems of the rock mass allowing to distinguish between water-bearing or dry fractures.

The main requirements of the geophysical survey is to monitor the rock mass properties and to detect the presence of weak zones potentially related to the failure zones that can be encountered during the tunnel excavation. The choice of the best investigation method can be related to the specific geological condition, to the tunnel length and to the scheduling of the tunnel construction. A systematic organization of monitoring activity can consider horizontal drilling ahead the tunnel face, analysis of drilling parameters, geochemical analysis of groundwater, RQD analysis and laboratory determination of geomechanical parameters. Televiewer inspection and borehole logging are focused to detect the main fractures and their aperture. A non systematic organization of other geophysical investigation considers borehole georadar survey, tunnel seismic prediction methods (TSP).

Theoretical background

Acoustic logging in a broad frequency band (1 kHz up to 30 kHz) permits to estimate the compressional, shear, Stoneley wave velocity and Stoneley wave amplitude. In full waveform acoustic logging the complete acoustic waveform is digitally recorded. The feature of the acoustic signal is affected, among other things, by the mechanical properties of the rock close around the borehole. The compressional and shear velocities can be combined with density data to calculate the elastic dynamic parameters such as the Poisson's ratio, the Young's modulus, the bulk modulus and the shear modulus. The waveform analysis allows one to estimate the permeability in porous rocks (Stoneley wave amplitude and velocity), to detect the fractures and to measure the permeability of the fracture-filling material (Stoneley wave amplitude).

In a borehole excited with a monopole sonic source, different wavefields propagate along the fluid and the rock around the hole: compressional P-wave, converted S-wave and different modes of tube waves (Stoneley wave, pseudo Rayleigh…). The Stoneley waves are pressure waves which propagate both in the fluid filling the borehole and in the rock close around the borehole: the attenuation and wave velocity depends on the elastic properties of the fluid and of the rock mass. Usually the high amplitude of the Stoneley wave can mask the first arrival of the S-wave, typically in soft rock where the velocity of the two wavefields are comparable. The monopole source can be adopted in hard rock to determine both P-wave and S-wave velocity; the data quality also depends on the selection of the transmitter frequency: this must be high enough to excite high amplitude of P-wave. If the frequency is too high unwanted modes of head waves propagate along the borehole and make the received signal much more complicate to be processed and interpreted. In quartzite, where the expected velocity of P-wave is above 4.000 m/s the transmitter frequency could be in the range between 15.000 – 20.000 Hz. In this case, the amplitudes of the shear waves are very high and this allows a good picking of the shear wave arrival times. No shear waves can be recorded in soft formation (where the velocity is less then the acoustic velocity of the borehole fluid) using a conventional monopole source, because there are no critically refracted S-waves. In soft rock, where the shear wave velocity is about as high as the fluid velocity, flexural mode can be excited using dipole source. The flexural mode essentially propagates at the same velocity of the shear waves, therefore only the S-wave velocity can be estimated.

The transmitter frequency plays an important role in the excitation of flexural mode: if the transmitter frequency band contains frequencies higher than the cut-off frequency of the flexural mode, the flexural wave propagates at velocity lower than S-wave. A frequency of 1 kHz should be used for soft rocks and higher frequency can be adopted in hard rock. These frequencies values have been selected and optimized after some preliminary tests.

On the other hand using a monopole source at frequency below the first compressional and shear cut-off frequency, the high amplitude of the received signal are due to the propagation of Stoneley wave. In literature several relationships are available between the Stoneley wave velocity and the compressional wave velocity of the fluid and other elastic properties of rock mass (e.g. White, 1983). Tezuka (1990) suggested to consider the effect of the borehole and tool diameter to compute the Stoneley wave velocity at different frequencies. The analysis of the dispersive behavior of the Stoneley waves can be useful in determining other elastic properties of the rock mass, however this increases the time required for the measurements.

The effect of the hard rock on the Stoneley waves velocity can be negligible due to the low compressibility of the rock mass. In such a case the velocity is mainly affected by the fluid velocity and approximates the compressional velocity of the fluid itself. In characterization of rock mass for the optimization of tunnel works the detection of main fractures is an important task: the interpretation of sonic logging can be improved considering the reflection or diffraction effects due to discontinuities and fractures. Two different phenomena are involved: the conversion of primary P-wave in to diffracted tube way; the diffraction of primary Stoneley wave. These latter provides, for typical effects of diffraction, up-going and down-going wavefields close to the discontinuities.

Acoustic logging tool

The instrumentation adopted is a Mount Sopris Logging Equipment composed by a winch equipped with a precision measuring wheel, a rotary encoder and a 200 m long cable; a data logger contains all circuitry necessary to interface a single conductor tool with the PC and the sonic probe.

The probe is composed, from top to bottom, by a modem, three receivers, an isolator and the single transmitter. The acoustic signal propagates through the borehole fluid to the rock interface where part of the energy is critically refracted along the borehole wall. As a result of wavefront spreading energy, part of the refracted energy is transmitted back into the borehole close to the receivers which pick up the signal, digitize it and send it to the control unit. Using multiple receivers it is possible to calculate acoustic velocities referring to a wave travel-path only through the rock without having to know the fluid velocity or the borehole diameter. The transmitter is driven with a single cycle sinusoid at a frequency between 1 and 30 kHz. The spectrum of this waveform has a bandwidth of approximately the transmitted frequency and is centred on the transmitted frequency.

The importance of using a variable frequency sonic tool is related to the possibility of measuring compressional and shear velocity in both fast and slow formations. Beside this, Stoneley waves velocity can be measured without interference from head waves and normal modes. This is possible with a proper use of the variable frequency tool to yield waveforms that are free from interference from unwanted modes. This system has still to be tested with accuracy and requires strong insulator sections.

An example of acoustic logs during tunnel excavation

The selected case history consists of a base double-tunnel 52,7 km long, across the Alpine massif, for high velocity railway. Four access tunnels (also called geognostic tunnels) are used as survey sectors of the base tunnel and also serve as test sites for identifying the geological and geotechnical conditions that can be encountered in the realization of the main work and for confirming the evaluations on which the tunnel design was based. Moreover, these tunnels are also destined to allow the excavation of the main tunnel in several faces and they will be integrated in the final work for the ventilation, as ways of access and for safety. The first access tunnel will be 4 km long and it is presently being excavated with the use of explosives. A first part of the tunnel (the first 900 m) has a slight ascending slope (1%); the second part (2900 m) is descending with a slope of 12% and the last part presents a slight slope (0,3 %), is 200 m long and reaches the base tunnel (figure 1).

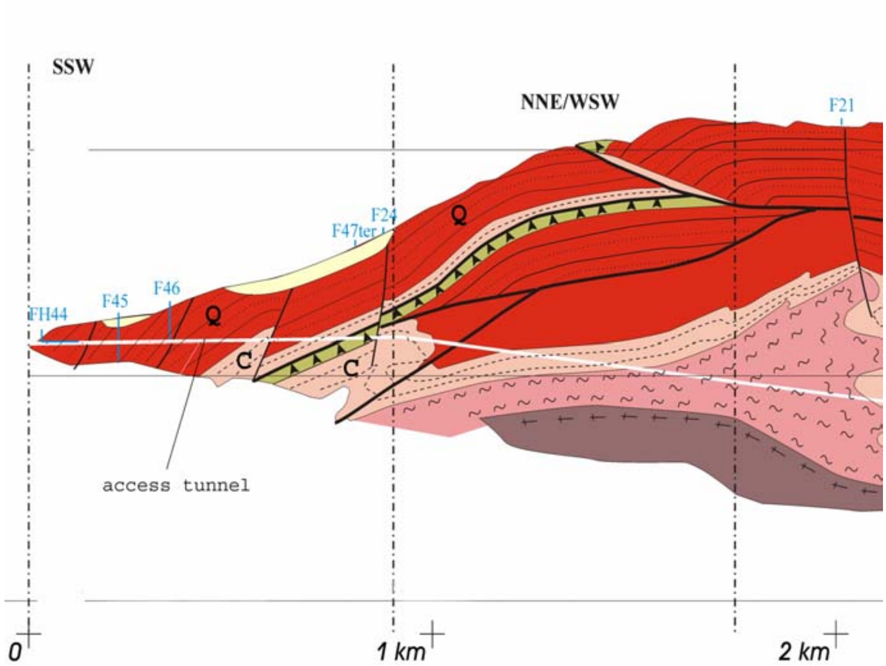

Figure 1. Schematic longitudinal section along the access tunnel axis with all the formations (Q: quartzite C: Carniolas) which will be encountered during the excavation.

From the geological point of view, this access tunnel crosses a sequence of tectonic-stratigraphical units, which are in reciprocal thrust in the west direction and which belong to the Internal Brianzonese Zone. In particular, the first part of the tunnel crosses chiefly quartzite of the Lower Trias (quartzite and mylonitic quartzite). These rocks are in contact at the footwall with mica-schist of the Permo-Triassic and at the hanging wall with Carniolas of the Gypsum Zone (Debelmas et al., 1989). In the deeper part, the access tunnel crosses a Permo-Triassic mica-schist (Debelmas et al., 1989). This study concerns the first part of the access tunnel, which crosses the quartzite of the Lower Trias. Locally, some strongly tectonized zones, constituted by mylonitic rocks of variable nature, have been encountered. Only in the last meters a very important layer of *Carniolas* has been intercepted. Quartzite is generally solid, pure and white colored, sometimes schistose and green-violet colored (mylonitic quartzite) and in more or less fractured zones (Debelmas et al., 1989).

Because of the complex geo-structural feature of the area, distribution of the fractured zones is strongly irregular. The very strongly fractured zones have a 0,1 to 2 m variable thickness whereas the weakly fractured zones (with a spacing between two joints of 5-10 cm) have a 1 to 2 m variable thickness. The joints are often open with smooth, rough and sometimes streaked surfaces. The zone is characterized by high values of trasmissivity (10^{-3} m^2/s) and the flow of the underground waters takes place preferably in the fracture systems and the densely fractured rock mass could be considered as a porous media.

The hydrogeology of this area is strongly characterized by a lot of geological accident as faults and thrust planes, marked by the presence of *carniola*. These rocks are "vacuolated", hard or earth-like, with a yellow-red colored alteration patina. These horizons are characterized by high hydrodynamic parameters and represent the preferential path-way for the underground water flow.

The acoustic well logging requires the need of working with a fluid filled borehole and that the sonic probe is well centralized in the hole (figure 2); horizontal borehole are realized ahead the tunnel face; they have usually diameters of 85-100 mm and length of 40-70 m.

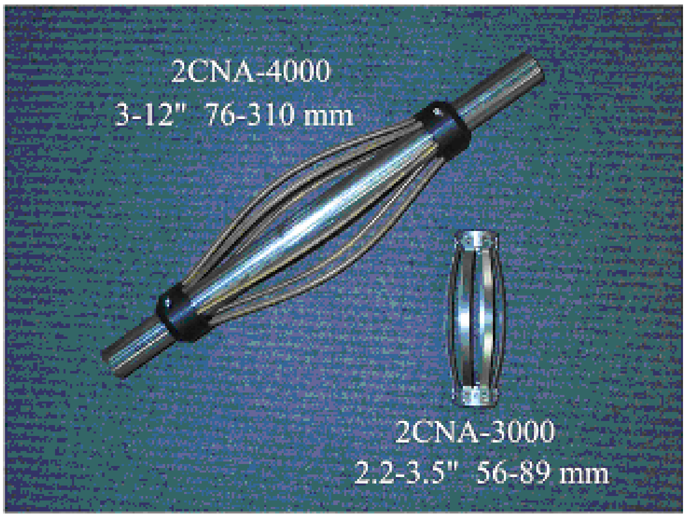

Figure 2. Picture of the centralizers employed.

High pressure air bubbles in the water deteriorated significantly the data quality of the preliminary acquisitions; the detection and the elimination of these bubbles has been performed using a small diameter PVC tube connected with the external of the borehole and inserted with the conductivity-temperature probe before the execution of the acoustic well logging.

The hydrogeology of the area determines a strong groundwater circulation in the fissured system of the hard rock; therefore a big amount of water flowed from the borehole with a rate of 10-20 l/s and a pressure at the hole head that reaches 2 bar. This groundwater circulation (velocity inside the borehole of 7 m/s) guarantee a good filling of the borehole but causes a high level of background seismic noise due to vortex effects at the wall of the hole and at the interface between the sonic-probe and the water; this turbulence strongly affects the quality of the sonic signal. To minimize this effect a closure system located at the borehole head was designed (figure 3); the system permits to control the flow rate of water and obtain a quasi-static flow condition along the borehole. After installing the closure system, a water overpressure is generated for some minutes before reaching a new equilibrium condition.

Figure 3. Picture of the closure system applied at the borehole head to content the water flow.

Results

The acquired waveform is the result of the interference between the multiple modes received. By controlling the transmitted frequency band, the complexity of the received waveform can be dramatically reduced. Normal modes are a result of constructive interference in the wave guide (borehole). The compressional and shear cutoff frequencies depends on the compressional and shear rock velocities and borehole diameter. In hard rock (quartzite), with a borehole diameter of 9 cm and a P-wave velocity of 5000 m/s and S-wave velocity of 2700 m/s, the compressional and shear cutoff frequencies are 22.2 and 25 kHz respectively. This indicates that a transmitter frequency of 20 kHz is a good compromise. The data acquisition confirmed that the best signals for compressional and shear waves are collected using the frequency band between 15 and 20 kHz.

The data processing pointed out that at these frequencies tube waves in hard rock are also present.

The analysis of full waveform acoustic logs points out the passage between Quartzite (Vp = 4000-5000 m/s, γ-ray 30-60 API and low VIA) and Carniolas (Vp = 2500-3000 m/s, γ-ray >80-100 API and high VIA) at the coordinate of 638 m. At the coordinate of 666 m an increase of P and S-wave velocity points out the passage between Carniolas and Quartzite (figure 4-5).

The data acquisition with a transmitter frequency of 2 kHz permitted to estimate tube wave velocity and analyze in detail the presence of diffraction and reflection effects in this wavefield. In fact Stoneley wave can be excited at all frequencies but higher amplitude are evident to low frequencies. Below the lowest normal cutoff frequency the Stoneley wave dominates and their amplitude and velocity can be accurately estimated without interference with other modes. In quartzite, Stoneley velocity is always slightly less than fluid velocity (1.300 m/s).

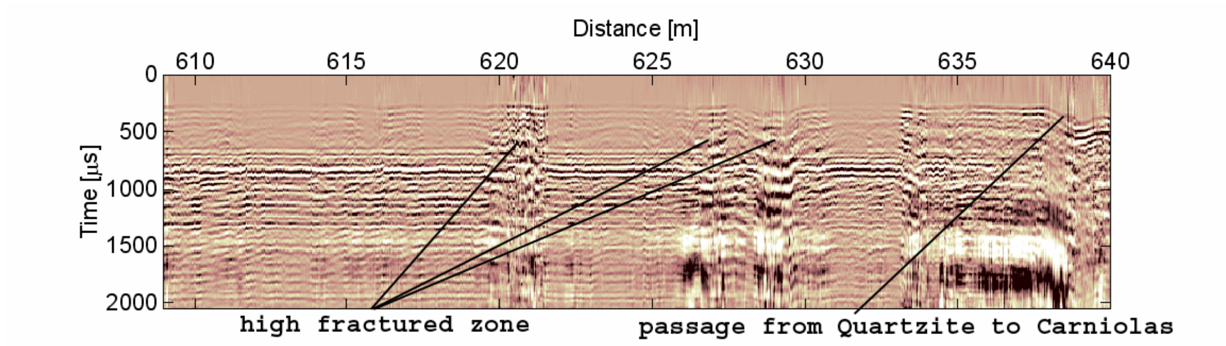

Figure 4. Image of a full-waveform acquired at 20 kHz frequency in hard rock (Quartzite).The passage between Quartzite and Carniolas is at 638 m of distance.

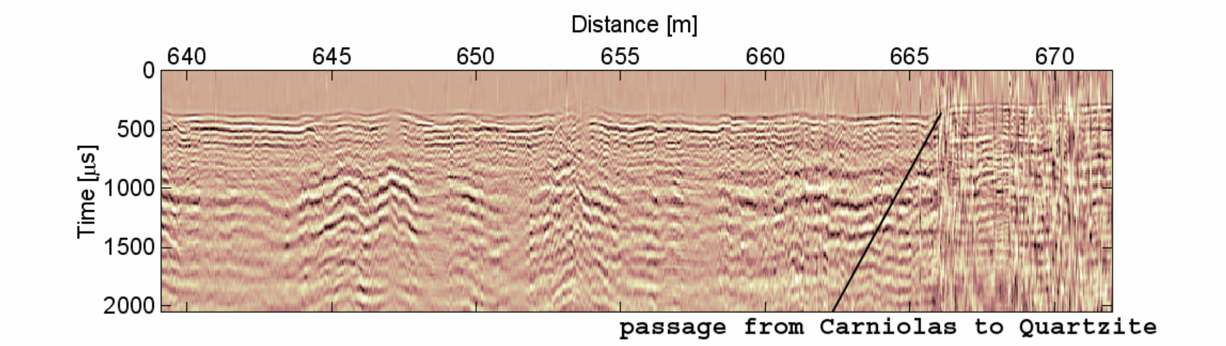

Figure 5: Image of a full-waveform acquired at 20 kHz frequency in soft rock (Carniolas). The passage between Carniolas and fractured Quartzite at 666 m of distance.

In soft rock a high frequency monopole source allows to point out the arrival of P-wave only; the S-wave velocity was determined from P-wave velocity and Stoneley wave velocity according to the relationship proposed by Tezuka (1988).

The figure 6 focus on a strong diffraction phenomena of the Stoneley waves acquired at low frequency: a more detailed interpretation of these effects and the possibility to relate these effects to the presence of fracture in the rock mass is going to be analyzed in details.

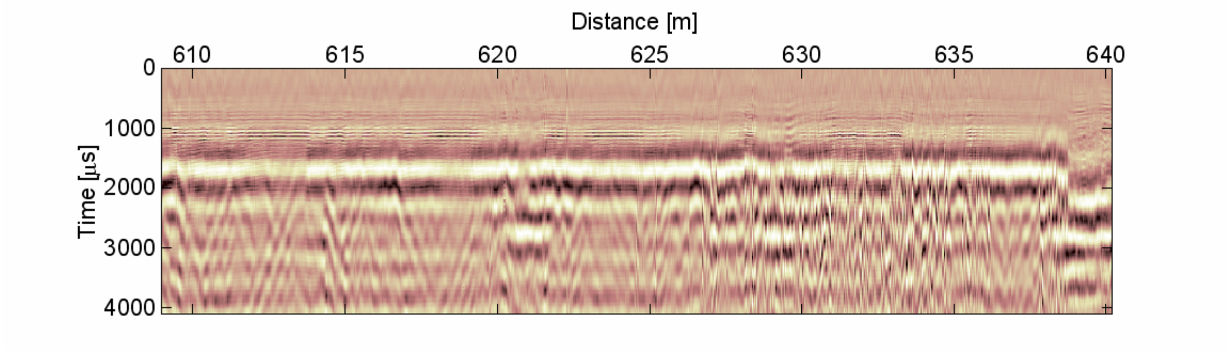

Figure 6: Image of a full-waveform acquired at 2 kHz frequency in hard rock (Quartzite) for the Stoneley wave propagation analysis. In the lower part of the image are visible the diffractions due to the fractures in the rock.

The f-k spectrum of Stoneley waves in quartzite and in soft rocks (figure 7-8) allows to estimate the dispersive behavior of the phase velocity.

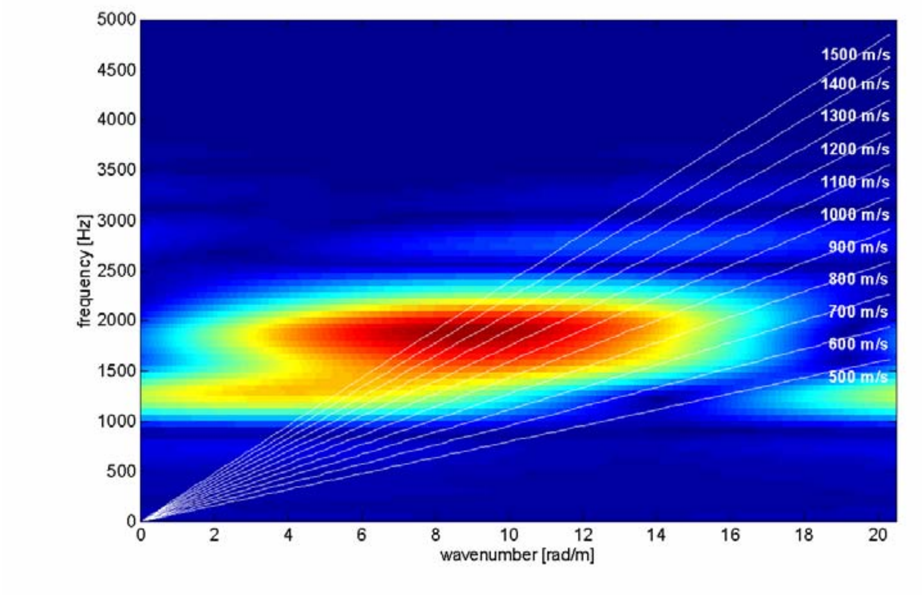

Figure 7. Image of a f-k spectrum of Stoneley wave in quartzite; the peak of energy at nearly 2 kHz frequency has a phase velocity of 1300 m/s.

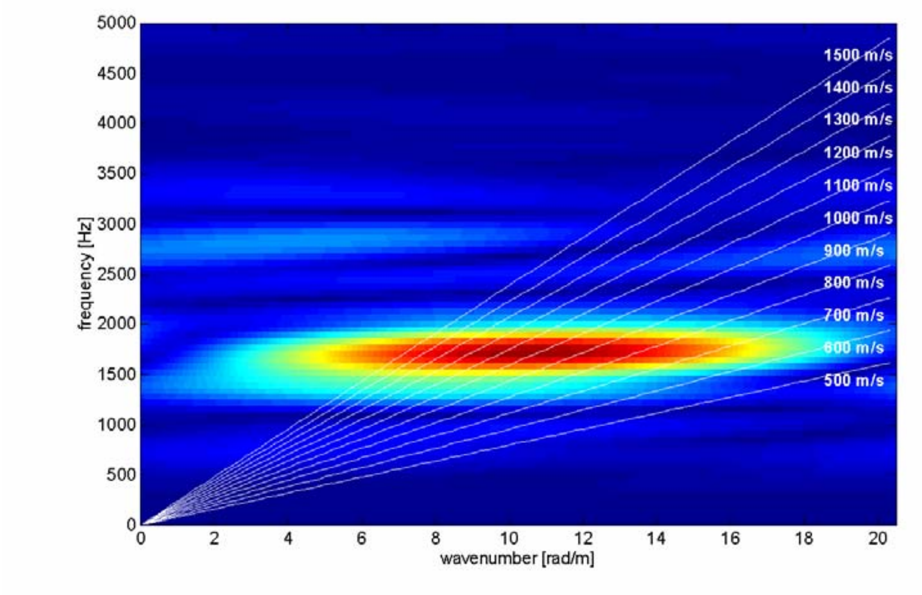

Figure 8. Image of a f-k spectrum of Stoneley wave in Carniolas. The peak of energy at nearly 2 kHz frequency has a phase velocity of less than 1100 m/s.

The energy peaks in the spectra point out the different phase velocity of the two formations.

A statistical analysis of Vp/Vs ratio has been performed on some hundreds of traces acquired during the excavation of the first part of the access tunnel. The selected data permits to evaluate Vp and Vs values of both hard rock and soft rock; therefore the distribution of Vp/Vs ratio shows two different and well separated clusters, as indicated in figure 9.

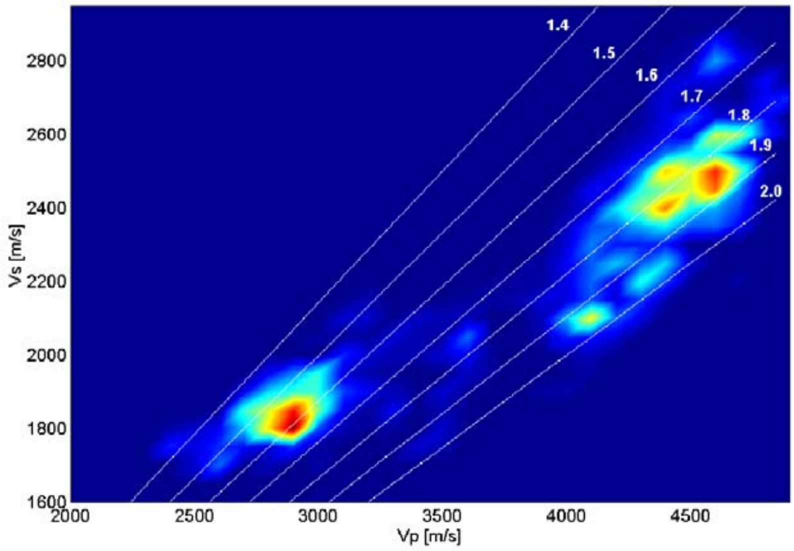

Figure 9. Image of the distribution of the Vp/Vs ratio obtained by the analysis of some hundred traces collected both in hard rock and in soft rock. Two different peaks are distinguishable: the peak at lower values of Vp is related to Carniolas while the peak at higher values of Vp corresponds to Quartzite.

Carniolas are characterized by low Vp/Vs ratio, probably due to the vacuolar nature of this formation; otherwise the Vp/Vs ratio of quartzite show a dispersed cloud, according to the strong heterogeneities of the material: where the elastic properties changes significantly from compact rock zones to high fractured zones.

Conclusion

A systematic borehole sonic logging has been realizing along a tunnel during the excavation activity. The results permit to analyze lithological changes between soft rock and hard rock, to detect weak zones.

The selected examples verify the possibility of obtaining good results in hard rock where P-waves and S-waves can be well recognized by generating an high frequency (20 kHz) source signal.

On the other hand, in soft rock the S-wave velocity can be determined by the Stoneley wave analysis if the P-wave velocity is known.

Vp/Vs ratio is a good indication for lithological changes and for determining the heterogeneities in the quartzite formation.

A more accurate analysis of Vp, Vs and density values should permit the estimation of the elastic moduli at the acquisition frequency and at low deformability. The knowledge of the dynamic elastic moduli should provide an optimization of excavation activity and planning of the reinforcing systems.

At this phase of the project, there are not enough static moduli and uniaxial compressional strength values determined in laboratory for performing a reliable relationship between the results of acoustic log and elastic properties of the material.

Suggested reading

Debelmas, J., Desmons, J., Ellemberger, F., Goffe, B., Fabre, J., Jaillard, E. and Pachoud, A., 1989, Notice esplicative de la feuille Modane à 1/50000, Carte Géologique de la France à 1/50000. Editions du BRGM.

Tezuka, K., Cheng, C.H. and Tang, X. M. 1997, Modeling of low-frequency Stoneley-wave propagation in an irregular borehole: Geophysics, 62, 1047-1058.

Mari, J.L., Delay, J., Gaudiani, P. and Arens, G., 1996, Geological formation characterization by Stoneley waves. European Journ. of Env. and Eng. Geophys., 2, 15-45.

Stevens, J. L. and Day, S. M., 1986, Shear velocity logging in slow formations using the Stoneley wave: Geophysics, 51, 137-147.

Tang X. 2002, Determining formation shear-wave transverse isotropy from borehole Stoneley-wave measurements. Geophysics, 68, 118-126.

Cheng, C.H. and Toksöz, M.N. 1981, Elastic wave propagation in a fluid-filled borehole and synthetic acoustic logs. Geophysics, 46, 1042-1053.