Water content monitoring in limestone based on radar velocity analysis (LSBB)

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ABSTRACT

The propagation velocity of ground penetrating radar waves in a karstified limestone is highly controlled by it's water content. We monitor the temporal variations of the EM velocity using multi-offset reflection data on a 50 m long test zone located inside the LSBB tunnel. These data sets allow us to use depth and time velocity analysis. At the moment we are defining the optimal velocity processing in order to perform time lapse acquisations.

INTRODUCTION

The LSBB tunnel (http://lsbb.oca.eu) is located inside a karstified limestone massif. Around the world, such geological formations contain most of the oil reservoirs and numerous aquifers. The tunnel lies approximately 500 m above the permanent water table but transfer of rainfalls across the massif induces prominent variations of water saturation in the vadose zone.

Hydrogeologists perform water sampling at localized places in the tunnel. Non destructive geophysical measurements may give access to continuous spatial investigations. By repeating these measurements during the time, we expect to evidence spatial and temporal variations of water content.

WATER CONTENT VS EM VELOCITY

Within geological formations EM propagation is mainly controlled by two parameters : electrical conductivity σ and dielectric permittivity ε. When the ground is conductive, the wave amplitude attenuation is strong. The propagation velocity v is linked to the EM wave celerity in the void (or air) c by the relation

$$v = \frac{c}{\sqrt{\varepsilon}}$$

Water has a high permittivity (ε=81) whereas the permittivity of a dry limestone is around 7 [1]. Since a karstified limestone is both porous and permeable, the water content will dramatically modify the effective permittivity and hence velocity of EM waves. For instance the empirical Topp formula [2] usually allows to estimate the water content θ:

$$\theta = -5.3\,10^{-2} + 2.92\,10^{-2}\varepsilon - 5.5\,10^{-4}\varepsilon^2 + 4.3\,10^{-6}\varepsilon^3$$

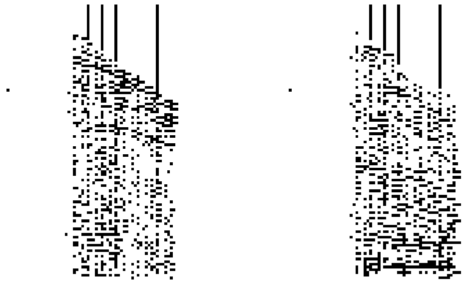
The EM frequency waves used (around 250 MHz) and the propagation velocity encountered (from 6 to 10 cm/ns), lead to a vertical and horizontal resolution around 10 cm. According to the very low conductivity of the Rustrel limestone, the depth of investigation is around 15 meters.

MULTI-OFFSET ACQUISITION

Conventional radar imaging consists to investigate along a line while keeping a constant distance (offset) between transmitting and receiving antennas. This method allows to easily obtain 2D vertical section of the ground measured in propagation time. The result will exhibit the reflections association to permittivity contrasts. Unfortunately single offset data does not give accurate information about the propagation velocity.

Fig. 1: Near offset unmigrated time section.

Fig. 1 exhibits the 1.24 m offset section acquired with shielded 250MHz antennas. Processing includes : time adjustment, DC removal, band-pass filtering and amplitude attenuation compensation. This section displays prominent dipping signals related to the statigraphic layering affected by numerous diffractions.



X=28.4 m. *X=45 m.*

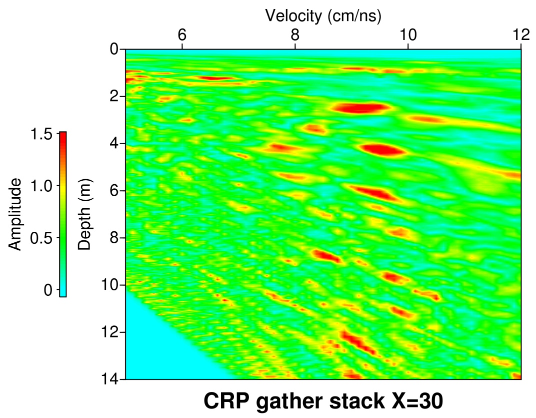
Fig. 2 : Sample common mid-point gathers.

In order to more accurately specify the propagation velocity, one must perform the acquisition with several different offsets (multi-offset acquisition). In that case, each subsurface point will be illuminated by several rays with different raypaths. In that way we introduce a strong dependance between the reflection time and the propagation velocity. Fig. 2 exhibits two sample common mid-point gathers. Offsets range from 1.24 to 8.34 meters by approximate steps of 50 cm. These parameters allow to evidence the relationship between offsets and propagation time.

EM VELOCITY DETERMINATION

With multi-offset data, velocity analysis can be performed by building a velocity model in time or depth domains.

Time domain analysis is the standard method, and allows to easily build time images. It's based on the hypothesis that reflected signal have an hyperbolic shape



which implies a laterally smooth velocity model. The analysis usually involves normal and/or dip moveout processing. The result is a RMS velocity profile in time, which must be converted in actual velocity in depth, using Dix's simplifications [3].

Advanced processing (Pre-stack Depth Migration, PSDM) is based on the determination of a velocity model in depth [4]. It is actually an inversion technique. It allows to use simultaneously reflected and diffracted signals. Basically, migration is the operation that places signal recorded at the (x_1,t) position at its geological (x_2,z) location. This operation is very sensitive to the velocity model. If the velocity model is correct, the migration of each common offset panel will deliver the same depth migrated section.

For each X location, we compute the sum of the depth migrated energies for all the 15 offsets at each depth (ie common reflection point, CRP) and for every velocity between 5 to 12 cm/ns (Fig. 3). On this picture, one can observe maxima of energy around 6 to 8 cm/ns in the first meter and velocities around 8 to 10 cm/ns at greater depth. Simple application of Topp's formula leads to a water content around 25%. This value looks too high but it is expected that time variations of the water content will produce significative relative velocity variations.

TIME LAPSE SURVEYS

First velocity analysis were obtained with a dataset acquired in April 2008. This first acquisition gave good reflected signal but suffered from weaknesses (geometry uncertainty, poor spatial sampling).

A second, satisfactory, data set has been acquired in May 2009. A third acquisition is scheduled for early June 2010 using the same parameters.

CONCLUSION

LSBB is a unique place allowing the study of water content variations in limestone : propagation of EM waves is excellent, prominent reflectors, hydrological monitoring.

PSDM provides a convenient way of measuring EM velocities at the price of multi-offset acquisition.

The 2010 dataset should be easily compared to the 2009 dataset depending on the change of hydrological conditions.

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