# APPLICATION OF GROUND PENETRATING RADAR IN A MINING ENVIRONMENT

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# ABSTRACT

The possibilities and limitations of the ground penetrating radar in quarries and mines are illustrated, using several examples. First, the radar was tested in limestone quarries and in a salt mine to detect karsts (in limestone) and fractures (in both media). In the limestone quarry, the medium velocity could be estimated using a common-mid-plot acquisition. Second, an inversion method based on the frequency content of the radar reflection was developed to characterise the fracture properties (filling material and opening). It was first tested on experiments using limestone blocks with controlled fracture properties. The radar signal analysis showed that both the opening and the filling material could be estimated, if the openings are not too small compared to the wavelength. The inversion method was then applied to in-situ data registered in a salt mine to estimate the opening of open fractures present in the roof of the drifts. Boreholes were available to compare the estimated opening with the real opening. Most of the results were satisfactory, although some poor results were also obtained. It can be explained by geological factors or it can also be due to the method itself.

#### INTRODUCTION

The radar method is based on the propagation and reflection of high frequency electromagnetic waves (20MHz-2GHz). The technique is widely described in Daniels (1996). The radar method provides images of non-conductive media at shallow depths. The reflections are due to a contrast in the dielectric properties. The radar pulse has a large bandwidth to achieve a high resolution. The penetration, which can reach several tens of meters in resistive environments, decreases when the used frequency increases. The quality of the profiles is well improved by using processing techniques like filtering, automatic gain control, background removal and migration.

The principle of the method used at the surface is presented in Figure 1. A transmitter antenna and a receiver antenna are moved along a profile with constant transmitter-to-receiver offset. A planar reflector will give a planar event on the radar profile. Heterogeneities (e.g. a hole) with smaller dimensions than the wavelength result in a hyperbolic event on the radar profile. The method can also be used in reflection from a borehole or in transmission between two boreholes. In the first case, the analysis provides an image of the discontinuities around the borehole. In the second case, the analysis provides a map of the velocities and attenuation between the two boreholes. The velocity of the electromagnetic waves can be estimated by permittivity analysis of samples in laboratory. Insitu the medium velocity can be estimated by a common-midpoint (cmp) acquisition, whereby the distance between the transmitter and the receiver increases with regular steps during the acquisition. Discontinuities parallel to the surface will result in a hyperbolic event on the cmp plot. The shape of the hyperbolic events is related to the propagation medium velocity. Flat hyperbolas correspond to media with higher velocity. For a same velocity, deeper events are also more flat. Using those considerations, it is possible to estimate the mean

propagation velocity with a satisfying accuracy. With the knowledge of the velocity, the time scale can be converted in a depth scale. The electromagnetic waves are attenuated by the medium. For very conductive media, the method becomes non-effective (e.g. in clay, loam).



Figure 1. Principle of the radar method.

# **APPLICATIONS**

The radar method is effective to detect discontinuities (fractures, bedding planes, lithologic contacts,...) in resistive media such as limestone, granite, salt,... (Dubois, 1995; Halleux, *et al.*, 2000). The penetration and the resolution obtained depend on the used frequency.

In a first test, radar data were collected in limestone to detect and locate open fractures (Grégoire and Halleux, 2002b). The 100MHz radar antennas were used to insure a good penetration. The profile is presented in Figure 2. A penetration of about 20m could be obtained. A first fractured area was located between 5m and 10m from the surface. The individual fractures within this zone could not be differentiated due to the resolution. A reflection corresponding to an isolated fracture appeared at about 350ns on the radar profile corresponding to a depth of about 17.5m.



Figure 2. Radar profile carried out in limestone. The frequency used is 100MHz.

The velocity of the electromagnetic waves in the limestone (100m/ls) was established using common-mid-point measurements (Figure 3). On Figure 3, the first event corresponds to the direct wave propagating from the transmitter to the receiver without penetration in the investigated medium. Two groups of hyperbolas can be observed on the cmp plot. The first group corresponds to reflectors in limestone. The second group corresponds to obstacles at the surface. The hyperbolas are flat due to a higher propagation velocity in air. The shape of the first family of hyperbolas is used to determine the velocity of the electromagnetic waves in limestone (in this guarry 95-100 m/₀s).



Figure 3. Common-mid-point plot in limestone (100MHz).

Another example shows the ability of GPR to detect and locate karstic areas in a working limestone quarry of ornamental stone. The stone is locally called 'Petit Granit'. The 'Petit Granit' is a compact encrinidic limestone from the Tournaisian serie. The operator in the limestone quarry was interested in the detection of possible karsts prior to the excavation (Grégoire and Halleux, 2002a; Grégoire and

Halleux, 2002b). Such analysis allows to estimate the volume of good limestone which can be extracted. Several areas in the quarry were investigated. The frequency which is chosen for the measurements depends on the location in the quarry.

The first investigated area was characterised by the presence of a thin clay layer at 4m depth. The penetration below this layer was not possible. The 500MHz antennas were used because they insure a penetration of 4m and to improve the resolution in the investigated area. The first profile (Figure 4) was registered in an area where the limestone was good. The radar profile was compared to the different limestone banks present in the quarry. These banks are characterised by different limestone quality (Figure 4 at right) and are separated by very thin bedding planes. The horizontal events on the radar profile correspond to these bedding planes. Although these reflectors are very thin (order of size of millimetres), they were detected by the radar. The event located at 50ns does not correspond to a real event in the ground. It is a multiple of the reflection at 25ns.



Figure 4. 500MHz radar profile carried out in limestone (left). Comparison with the stratigraphy of 'Petit Granit' (right) and various banks present in the quarry.

The second radar profile (Figure 5) is carried out in the same quarry but in a different area where karsts are present. The reflections are due to contrast in permittivity between the limestone and the altered areas. The shapes of the reflection are due to the irregular interfaces of the discontinuities. From the radar profile, it can be deduced that the karstic areas are filled with a conductive filling material (mixing of clay and sand). Indeed, the signal is very attenuated below the reflections. This signal attenuation can also be observed on the discontinuity of the reflection corresponding to the clay layer.

Radar profiles were carried out in two perpendicular directions in order to get a good coverage of the investigated area. After processing and analysing of the profiles, the location of the karsts was mapped in 2D with information about the extension over depth. The analysis of a radar profile allows the determination of extension of a karstic area with depth but not a decrease of the size of the karstic area. This interpretation could be verified after extraction. It was quite satisfactory, except for an overestimation of the karstic areas.

Another example of the use of the radar technique is situated in a salt mine. The radar is efficient in salt to image the fractures or geological discontinuities (Halleux, *et al.*, 2000).

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Two years ago, a trial was conducted in the Werra mine of K+S KALI GmbH to use the ground penetrating radar as a possible method to detect fractures in the roof of the drifts. These fractures sometimes occur in horizontal bedded salt up to approximately 3 m above the roof because of stress relief due to mining. When fractures are detected, the roof has to be scaled mechanically or anchors have to be installed to prevent blocks falling. The early detection of these fractures is therefore very important. A car is equipped with a control unit (4 channels) and a hydraulic arm to lift a maximum of 4 antennas near the roof of a drift. Two 900 MHz Gssi antennas are installed. A working distance of 0.5 to 1m from the roof gives a satisfactory signal quality. The survey speed is about 15km/h so that an extensive survey can be realised in a relatively short time period.



Figure 5. 500MHz radar profile carried out in limestone.

Figure 6 shows an example of radar profile registered in the salt mine. A penetration of 2 or 3m is obtained in salt. The first reflection corresponds to the reflection of the roof of the drift. The reflections which are indicated by an arrow correspond to fractures present in the salt.



Figure 6. Radar profile carried out in a salt mine at 1GHz. The antenna is not located against the roof of the drift.

These examples have shown that the radar method was effective to detect and locate discontinuities like fractures, bedding planes, or karsts in limestone and salt. Nevertheless, the analysis of the profile does not give information on the fracture properties (opening and filling material).

#### ESTIMATION OF FRACTURE OPENING

In order to characterise the fractures, a more detailed analysis of the radar signal is required.

# Theory

The reflection coefficient at the interface of two semi-infinite media (1) and (2) is defined in function of the wavenumber k:

$$R_{12} = \frac{k_1 - k_2}{k_1 + k_2} \tag{1}$$

where  $k_1$ ,  $k_2$  are the wavenumbers related to medium (1) and medium (2).

The wavenumber k is related to the electric and dielectric properties of the medium by:

$$k = \omega \sqrt{\varepsilon_e \mu} \tag{2}$$

where 1 the magnetic permeability

The effective permittivity is frequency dependent. The signal radar being broadband, it is important to take into account this frequency dependence. The Jonscher model with 3 parameters is used to characterise the frequency dependence of the effective permittivity (Jonscher, 1977). It means that 3 parameters are required to describe the dielectric behaviour of a filling material. Due to the frequency dependence of the effective permittivity, the reflection coefficient is also frequency dependent.

A thin layer is characterised by a thickness smaller than the vertical resolution. It is not possible to differentiate the reflections on both interfaces. The reflection coefficient due to a thin layer (<1/2) corresponds to the sum of the reflections on each interface. This is illustrated on Figure 7 (Hollender and Tillard, 1998).

$$r_{12} = \frac{R_{12} + R_{21}.e^{-i\varphi}}{I + R_{12}.R_{21}.e^{-i\varphi}}$$
(3)

1





Figure 7. Reflection coefficient due to a thin layer.

The reflection coefficient is represented on Figure 8 and on Figure 9 respectively for a fracture filled with dry sand (perfect dielectric material, relative permittivity equal to 2.5) and filled with clay (conductive material, relative permittivity equal to 55). The wavelength in clay is smaller than the wavelength in sand (at 1GHz, the wavelengths in sand and clay are respectively equal to 0.19m and 0.04m). The different curves correspond to several openings (1mm, 10mm, 50mm and 100mm). In the case of dry sand as filling material, the shape of the reflection coefficient is linear as a function of the frequency for fracture openings of 1mm and 10mm. The reflection coefficient presents extremes for larger openings. In the case of a fracture filled with clay, only the curve related to a fracture of 1mm is linear in function of the frequency. The curves corresponding to larger openings are smoothed due to the high conductivity of the clay.

The figures show clearly that the reflection coefficient in the frequency domain is very sensitive to the fracture properties (opening and filling material characterised by the permittivity).



Figure 8. Reflection coefficient in the frequency domain due to a thin layer filled with dry sand.



Figure 9. Reflection coefficient in the frequency domain due to a thin layer filled with clay.

It was proposed to study the radar reflections on fractures in the frequency domain in order to characterise the fractures (Grégoire, 2001a; Grégoire, 2001b).

#### Application of the inversion method to real data

Experiments were carried out to simulate fractures with controlled properties between two limestone blocks. Fractures with various openings and various filling materials were simulated. These measurements aimed to test the theoretical formulation of the reflection coefficient. From this analysis, an inversion method was developed to be applied to the radar reflection to estimate the fracture opening and the filling material (effective permittivity characterised by the 3 Jonscher parameters).

To test the inversion method on in-situ data, complementary testing measurements were carried out in the Werra mine of K+S KALI GmbH. The inversion method was applied to the radar reflections to estimate the opening of fractures present in the roof of the drifts (Grégoire and Halleux, 2002a). These measurements aimed also to see the influence of the acquisition speed and to evaluate the effect of the antenna-roof distance on the data quality.

Static (antenna fixed at one position) and dynamic data (moving antenna) were collected at two sites of the mine. Two radar systems were used (a 900MHz Gssi antenna and a 1GHz Ramac antenna). Fifteen boreholes were available on the two sites to compare the estimated fracture openings with the measured fracture openings. The fracture openings vary from 1mm up to 90mm. Complex fracture systems, characterised by fractures located very close to each other, could be observed in several boreholes. The minimal distance to separate the fractures is the vertical resolution (62mm in salt at 1GHz).

A dynamic profile is represented in Figure 6. The location of the boreholes is indicated. The first energetic reflection corresponds to the reflection on the roof. The other reflections correspond to fractures. It can be observed on the profile that the reflection amplitude can vary very fast with the distance. The penetration in salt is about 3m.

The inversion method is applied to the radar measurements to determine the opening of the first individual fracture in the roof. As reference signal, the reflection on the roof is chosen. This signal has a high signal-to-noise ratio and is quite stable, except in areas with irregularities in the roof. The dielectric parameters of the salt being known ( $\square$  = 5.85,  $\square$  = 0.5 mS/m), the corrections related to the propagation in air and salt can be applied to the signal. When the first fracture is very thin and not detectable, the second fracture is analysed.

The results of the inversion method are presented in Figure 10. Most of the results are satisfactory although poor results are also obtained. It can be explained by the fast spatial variation of the fractures (the position of the profiles was not accurately defined), the irregularity of the fracture, the complex fracture systems composed of several fractures or the quality of the reference signal. It can also be due to the method itself for opening ranges where the reflectivity is less sensitive to opening variations (Grégoire, 2001a). The reliability of the

results should be improved using a statistical analysis. Although the method is not perfect, the knowledge of the fracture is improved.

### CONCLUSION

The possibilities and limitations of the radar technique in quarries and mines are illustrated, using several examples. The method is efficient in media such as limestone and salt to detect fractures, bedding planes or altered areas. Geological discontinuities can also be imaged. The penetration depends on the used frequency and is particular to each site.

The frequency content of the radar reflection was analysed and compared to a reference signal to characterise the fracture properties. An inversion method was developed and first tested on laboratory experiments with controlled fracture properties.



Figure 10. Results of the inversion method applied to the radar data collected in the Werra mine.

Both the opening and the filling material can not be estimated if the openings are too small compared to the wavelength. The ratio depends on the used frequency and on the filling material.

The inversion method was applied to in-situ data registered in a salt mine to estimate the opening of open fractures present in the roof of the drifts. Most of the results are satisfactory although poor results are also obtained. It can be explained by geological factors or it can also be due to the method itself. The reliability of the results should be improved using a statistical analysis.

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