# ANALYSIS OF BOREHOLE RADAR IN CROSS-HOLE MODE

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## 1. Introduction

Subsurface radars operated on the surface and in mines have been widely used since 1970s. Recently borehole radars have also been developed as a useful tool for detecting fractures and permeable zone in rock or detection of boundaries of formations[1]. However, boreholes are normally filled with water or drilling mud and these inhomogeneity make it difficult to apply the techniques developed for the conventional subsurface radars. Directional antennas and improvement of short range resolution are most important subjects on borehole antennas.

Borehole radars are operated, in general, in two different modes, namely single-hole reflection mode and cross-hole transmission mode[2]. The former is used for detection of cracks lying around the borehole and the latter has a potential to measure cracks which are lying between but not intersecting the boreholes. Tomography analysis is also available with the data obtained by cross-hole mode measurements.

The purpose of this paper is to present the theoretical approach to analyze borehole radars in cross-hole mode. Theory is compared with the data obtained in salt deposit. As far as the authors are concerned, theoretical analysis of borehole radars is rare, although many measurements have been carried out.

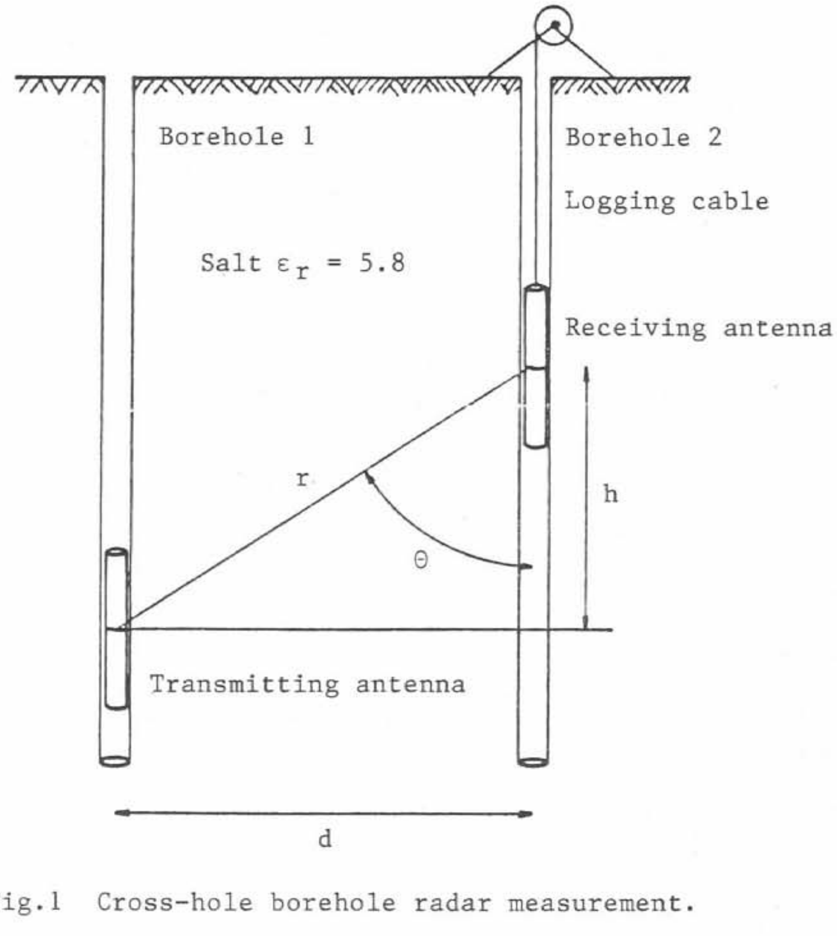

Fig.1 Cross-hole borehole radar measurement.

## 2. Cross-hole borehole radar measurement in salt deposit

The arrangement of a cross-hole measurement of a borehole radar is shown in Fig.1. The transmitting and receiving antennas are cylindrical dipole antennas, with the diameter of 30mm. An avalanche transistor pulse generator feeds DC-pulses of about 5ns in duration and 5kHz in repetition cycle to the transmitting antenna. The battery-powered generator is placed within the transmitting antenna and consequently the antenna is electrically isolated from the other equipments. The signal received by the receiving dipole antenna is transmitted to the surface through a 50-Ohm coaxial cable.

The measurements have been carried out in a salt deposit near Hannover, Federal Republic of Germany. The saline deposit, a diapir structure, belongs to the Zechstein formation (Upper Permian). It extends more than 2km in width, 15km in length and 2.5 km in depth. Rock salt(NaCl) dominates the salt deposit, and several beds of potash salt, anhydrite and pelite of various thicknesses are lying within it. One of the authors has carried out many radar measurements in this site and found that rock salt is almost homogeneous with a conductivity less than $10^{-6}$ S/m and a permittivity of 5.8[3]. On the other hand, most of the interbedded layers have clear electrical contrast to rock salt, and it enables detection of geological boundaries by radar measurements.

Two parallel vertical boreholes of 40mm and 150mm in the diameter are drilled from a horizontal tunnel which lies about 725m deep from the surface. Separation of boreholes is 15.6m and the depth is more than 50m. These boreholes are lying in the midst of this salt deposit. Fig.2 shows the measured time history. After the direct waves, reflections are observed in 0.15 μs, which correspond to the distance of about 10m.

## 3. Analysis of cross-hole pulse transmission

The characteristic of dipole antennas in a borehole is quite different from those in a free space. Among some reports, King et al.[4] gave a simple approximate solution for this problem. Here we use their results to give current distribution on antennas. According to this theory, if the condition given by Eq.(1) is satisfied, transmission-line theory can be directly applied to the antennas with sufficient accuracy.

$$k_m^2/k_b^2 > 2 , \quad k_b b \ll 1 \tag{1}$$

where $k_b$ and $k_m$ are propagation constants in the borehole and the surrounding medium, respectively, and b is the radius of the borehole.

If the separation of antennas is much larger than the wave length, the receiving voltage induced across the loaded resistance $Z_0$ is expressed in the frequency domain as follows.

$$V_r = j \omega \eta \, Z_0/(Z_0+Z_t)(Z_0+Z_r) \, h_r h_t \exp(-jk_m r)/r \, V_0 \tag{2}$$

here $\eta$ is the characteristic impedance of surrounding material, $V_0$ is the exciting voltage, $h_t$ and $h_r$ is the vector effective height functions[5] and $Z_t$, $Z_r$ are input impedances of the transmitting and the receiving antenna, respectively. From a transmission line theory, the vector effective height function of a dipole antenna and the input impedance are given. A Gaussian pulse was used for excitation and is given in the time-domain as;

$$V_0(t) = \exp(t/t_g)^2 . \tag{3}$$

The time history of induced voltage $V_r(t)$ is obtained by Fourier transformation of Eq.(2). We use FFT algorithm for numerical evaluation. Results are compared with measured time histories in Fig.2.

## 4. Discussion

Measured data supports the validity of theoretical results. In the example presented here, the spatial duration of exciting pulse is longer than the dipole length. In such a case, the received signal is a quasi-damping sinusoid and its frequency is dominated by the resonance of transmitting and receiving dipole antennas. In the practical measurements, we use 2 - 0.75m dipole antennas, corresponding to 45-100 MHz resonant frequency in a borehole. On the other hand, it is dominated by the spectrum of the exciting pulse, if the pulse duration is shorter than the dipole length.

It is also evident from these results that the wave form is dependent on the incident angle. When the vertical distance is large, the apparent predominant frequency is lowered and sharp peaks appear. These sharp peaks can not be observed in the measurement, because antennas are not sufficiently thin. Signal deformation is due to phase difference on antennas. Such a deformation was physically explained by one of the authors[6].

## 5. Conclusion

We have derived an formulation for pulse transmission between two dipole antennas set in bore holes. Theoretical results showed good agreement with the measured data obtained in a salt deposit.

These theoretical procedures can be easily applied to the synthetic technique and it enables us to interpret the measured data more accurately. Although here we assumed that the surrounding material is homogeneous, our actual interests is detection of inhomogeneity lying between boreholes and other reflectors. The technique presented here will be applied to more practical problems such as estimation of reflecting material.

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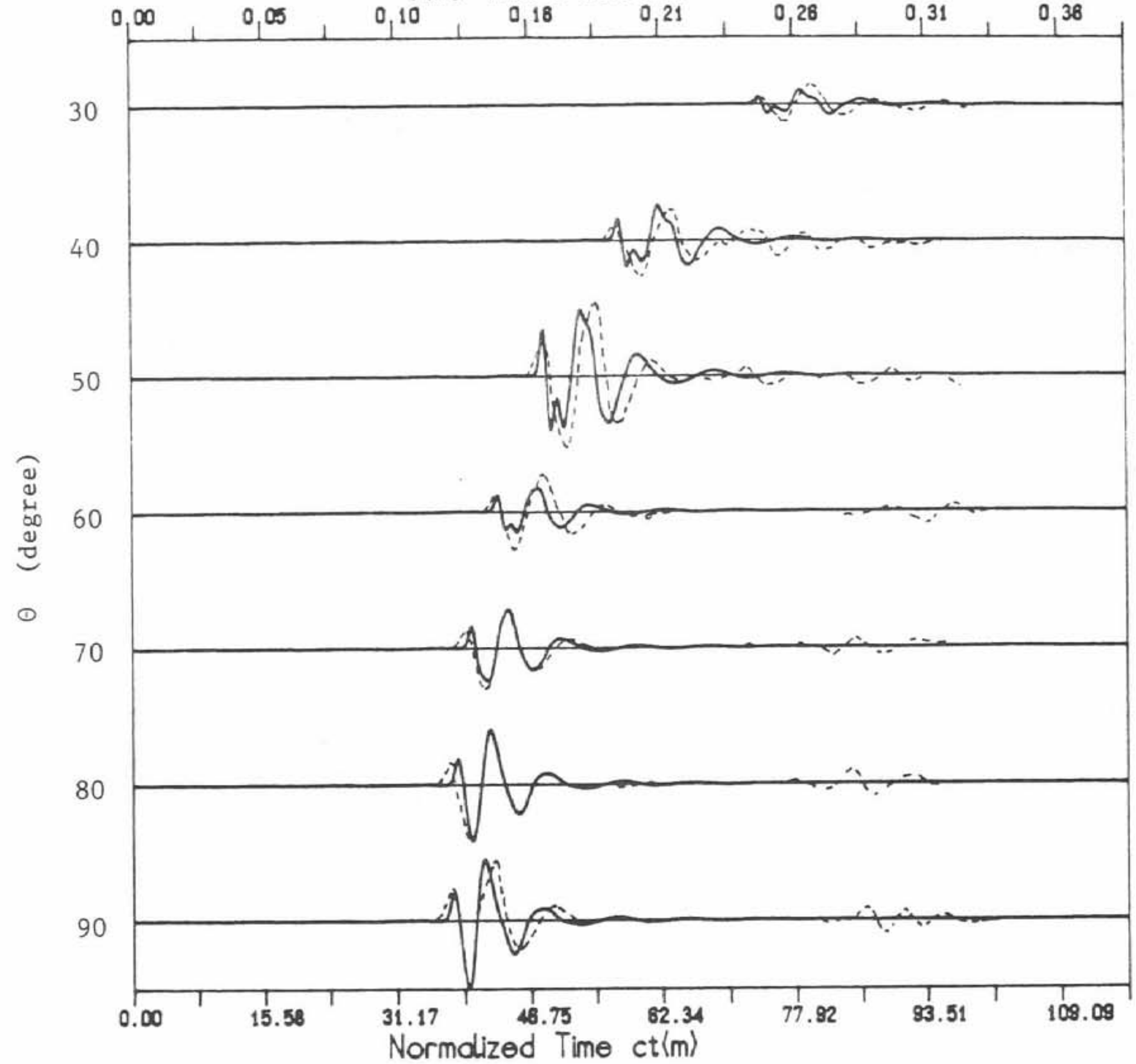

Fig.2 Time history of received signal.

Solid curve is theoretical and dashed curve is measured.
For Θ = 30,40 and 50, signal amplitude is multiplied by 5.

Antenna radius = 0.015m
Dipole length = 1.86m
Pulse duration $t_g$ = 2 ns

Borehole radius Tx = 0.02m
Rx = 0.075m
Borehole separation = 15.6m