DETERMINATION OF WAVE ATTENUATION IN ROCK SALT IN THE FREQUENCY RANGE 1 - 100 kHz USING LOCATED ACOUSTIC EMISSION EVENTS

GERD MANTHEI, JÜRGEN EISENBLÄTTER and THOMAS SPIES*
Gesellschaft für Materialprüfung und Geophysik, Dieselstraße 9, D-61231 Bad Nauheim, Germany. *Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, D-30655 Hannover, Germany.

Abstract

Rock salt is a candidate material for construction of a telescope detecting ultrahigh-energy neutrinos by acoustic emission measurements. These ultrahigh-energy neutrinos are generated, for instance, by the collision of galaxies or supernova explosions. Interaction of these ultrahigh-energy neutrinos with matter is extremely seldom. Therefore, the telescopes have to have dimensions of kilometers in all directions and should be placed in the ocean, or in the polar ice, or in salt domes. The economical feasibility of an acoustic neutrino detector strongly depends on the spacing between the acoustic sensors. In this paper we will report on our experience of acoustic wave propagation and wave attenuation in rock salt in the frequency range of 1 to 100 kHz and some conclusions with respect to the usefulness of rock salt as a neutrino detector. The experience bases on long-term acoustic emission measurements in a salt mine.

Keywords: Acoustic emission, microcracking, rock salt, wave attenuation, neutrino detector

Introduction

Before we are going to present results of our acoustic emission (AE) measurements in salt rock, a brief introduction on neutrino detection is given. Neutrinos are particles which are emitted from most violent astrophysical sources like exploding stars (see http://icecube.wisc.edu). They are interacting extremely seldom with matter. The feeble interaction of neutrinos with matter makes them ideal astronomical messengers. Neutrinos can travel across the universe without hindrance and interference. However, this same attribute makes cosmic neutrinos difficult to detect. Most of the trillions of neutrinos that stream through a human body or a square meter of the Earth’s surface every second do not leave any trace. But, on rare occasions, a passing neutrino crashes into a proton or neutron. This collision produces a particle called muon. The muon travels in the same direction as the parent neutrino hundreds of meters or even kilometres through a detector material like ice, water or salt rock. Muons from high-energy neutrinos (energy range between $10^{11}$ and $10^{16}$ eV) radiate blue light, which is the so-called Cherenkov radiation. In transparent ice or clear water this light can be detected by optical sensors like photomultiplier tubes. A neutrino telescope must be huge, transparent, dark, and below the earth surface to shield cosmic rays. Therefore, deep oceans or the 3000-m-thick Antarctic ice cap are used as a neutrino telescope. The so-called IceCube is the first kilometer-scale neutrino observatory, which is now under construction [1]. About 4800 photomultipliers will be installed 1500 m below the ice surface in a 1 km x 1 km x 1 km volume.

Ultrahigh-energy neutrinos (energy of $>10^{17}$ eV) have great cosmological significance and may reveal new physics beyond the standard models. Because of decreasing neutrino flux with
increasing energy an observatory far larger than one cubic kilometer will be required. An estimation shows that no more than one ultrahigh-energy neutrino per year can be detected with IceCube (see http://icecube.wisc.edu). For a few years, salt domes have been under consideration to detect the interactions of ultra-high energy neutrinos with rock salt. Salt domes are widely distributed and have a suitable size of typical dimensions 3 x 4 x 5 km. The disadvantage of salt relative to ice is due to the rapid decrease of Cherenkov light intensity. Ice is far more transparent than salt to light.

Besides the Cherenkov radiation, a part of the energy is converted into acoustic energy. The basis for the AE of ultrahigh-energy neutrinos is a thermo-acoustic effect, which was first proposed by Askariyan [2] and Learned [3]. Their model is based on the fact that in a condensed medium the energy of an electromagnetic cascade resulting from the neutrino interaction is concentrated in a roughly cylindrical volume of length \( L \approx 5 \) m and diameter \( d \approx 5 \) cm in a liquid or solid (see Fig. 1, left-hand side).

![Thermo-acoustic model](image)

**Fig. 1** Thermo-acoustic model of electromagnetic cascade resulting from the neutrino interaction (left-hand side) and radiation pattern of P wave with this model (right-hand side) [4].

Due to the rapid thermal expansion of the material in the cylindrical volume, compressional waves or so-called P waves are produced. The amplitude of the P wave is determined by the cascade energy, the thermal expansion coefficient, and the wave velocity in the medium. The maximal amplitude is in a direction orthogonal (incidence angle \( \theta = 90^\circ \)) to the axis of the cylinder (right-hand side of Fig. 1). In axial direction (\( \theta = 0^\circ \)) of the cylindrical volume only small signal amplitudes will be emitted. The expected frequency of the P wave is in the range between 10 to 60 kHz and lies exactly in the frequency range in which we are detecting microcracking in salt mines. Besides the primary effect of thermal expansion a secondary source of acoustic emission may be microcracking in the heated volume induced by the generated transient deviatoric stress field.

The idea of many researchers in this field is to investigate the feasibility of detecting high-energy neutrino interactions in underground rock salt domes using a network of many AE sensors. To determine the spacing between the sensors, attenuation of acoustic waves plays a major role for the use of salt domes as a neutrino detector. Price [5] calculated attenuation coefficients for grain diameters from 0.2 to 2 cm for rock salt as a function of frequency in a range from 1 to 100 kHz. He concluded that in pure and undisturbed rock salt, the scattering at grain boundaries is the limiting factor of the detection length and that absorption plays a minor role and can be
neglected. He compared the result of his calculations with ultrasonic measurements at 58 to 64 kHz in the Huckle Salt Mine, Texas [6] and with our AE measurements in the repository in Morsleben, Germany [7].

The present authors have already reported several times about AE measurements in rock salt at earlier conferences [8-11]. Their earlier contributions showed field studies from the central and southern sections of the underground repository of Morsleben in a salt mine in northern Germany. Originally, the central section of the repository was monitored by a network of 24 AE sensors since 1995. This network was recently enlarged to 48 channels and covers now a rock volume of about 250 m x 200 m x 120 m. The signals are recorded in the frequency range from 1 to 100 kHz. The sensors are distributed at three excavation levels installed in 3 to 20 m deep boreholes. The average depth of the monitored volume is about 400 m. Mining in this area continued until the 1960's, but most of the rooms in the rock salt were mined 60 to 70 years ago. The aim of these AE measurements is to investigate the micro- and macrocracking processes, which are important for the evaluation of the stability of cavities and the hydraulic integrity of the rock, which is of special interest in the case of an underground disposal of hazardous waste in salt rock.

To estimate the attenuation of ultrasonic signals during their propagation through the rock salt, we describe a method, which is successfully applied for many years during long-term AE measurements in salt mines. This method uses the maximum amplitudes of the signals and the location of the events to calculate an event magnitude analogous to the magnitude in seismology and the damping coefficient of AE signals in rock salt.

In general, the deformation of large rock salt formations occurs for the most part without the formation of macrocracking. Microcracking occurs, however, near cavities and at rock boundaries. The cavities are mined mostly in rock salt, which has a high tendency to creep. It is not always possible to avoid excavating cavities near anhydrite layers. The brittle anhydrite is much more rigid and has a higher strength than rock salt. The redistribution of stresses around cavities leads to deviatoric stresses near rock boundaries. If these stresses exceed a certain level, microcracks form.

For this study, we investigated wave attenuation in rock salt under high deviatoric stress conditions accompanied by high AE activity. For this purpose, AE events, which have been located in a time period of 9 months (November 15, 2004 to August 23, 2005), were considered in our analysis. Half a year before, in this mine segment, one cavity was backfilled. This mine segment showed persistent high AE activity because of stress redistribution and high humidity [11]. Previously, there was almost no activity before backfilling in this segment.

Location of AE Events

To determine the attenuation of acoustic waves the length of the travel paths from the AE source to the sensors and, therefore, source location is of upmost importance. During long-term AE measurements in salt mines, a huge number of events (up to 350 located events per hour) can be detected. Fast data-acquisition systems and in-situ location are essential to process all data. Therefore, in-situ location is a standard procedure during data acquisition [12]. The locations of AE events are determined by inversion of the travel times of P waves and S waves, which are extracted from the signals (see for example Fig. 2, where very clear P- and S-wave onsets are discernible at each channel).
Fig. 2 Signals of a located AE event from the Asse salt mine, detected using 8 borehole sensors in rock salt [12]. This test site contains no larger cavities that could hinder wave propagation.

This is done in different steps. After pre-processing of the signals by filtering and smoothing operations, in a first step the P-wave onsets are automatically picked using high-quality signals only, i.e. signals with high signal-to-noise ratio. From these P-wave onsets a first estimation of the source coordinates is made using an iterative least-squares procedure. If the residual error is larger than 0.8 m, the onsets with the largest residues are stepwise eliminated and a new solution is calculated until the residual error drops below the 0.8-m limit.

In order to be able to locate sources outside of the sensor network, we also consider the S-wave onsets. Therefore, we automatically pick the S-wave onsets in a time interval around the S-wave onsets expected due to the result of the location using P-wave onsets only. In the second step of source location, we use the found S-wave onsets together with the remained P-wave onsets. P-wave and S-wave onsets with large residues are again eliminated until the residual error falls below 0.8 m. Locations are considered valid only if at least ten onsets (P wave or S wave) have remained. A by-product of such location procedure is that typical working noise without clearly discernible onsets and, therefore, wrong arrival times are eliminated due to large travel time residuals.

In spite of the complex geometric situation with AE sensors in the vicinity of closely spaced excavations and resultant masking of direct wave propagation paths, we obtain a location accuracy of about one meter in distance up to 50 m around the sensor network, using the described procedure.

Figure 2 shows the signals of a located event in salt rock. In this case, an array of eight AE transducers was used for source location. The onsets of the first signal peaks were automatically determined ("Tr") in addition to the residual error, the agreement between calculated onsets of the P wave ("L") and the S wave ("T") with the observed onsets assesses the quality of location. In this example, the event is located within the sensor network in an undisturbed rock formation and, therefore, the location error is very small and amounts about 20 cm.
The sites of the AE activity from a time period of about 9 months between four excavation levels are shown in a top view in Fig. 3. The extension in vertical direction amounts to approximately 120 m. Each AE event is plotted as a point. Only strong events (696,278 events), which were precisely located using at least 16 P- and S-wave arrival times are included in this figure. The locations of the AE borehole sensors are plotted as open circles.

![Fig. 3 Location of AE events between November 15, 2004 and August 23, 2005 (696,728 events) in top view.](image)

The events can be roughly separated into two Regions I and II (marked by ovals). The highest density of AE events was observed in Region I outside the AE network above the backfilled cavity. The AE network is only able to monitor the roof of the cavity, not the floor and the walls, because all sensors are located at levels higher than the cavity. The events in Region II were preferably located along walls of open cavities, which will be backfilled in the future. Compared with Region I, most of the events of Region II occurred 50 m to 100 m higher than in Region I. The AE activity in this area is interpreted as ongoing damage in the immediate vicinity of mine cavities and rock boundaries due to dilatancy under deviatoric stress conditions.

**Determination of AE Magnitude and Attenuation Length**

The maximum amplitudes $A$ of all sensors in a network and the distances $r$ of an AE source to the sensors are used to determine a measure of signal strength in an analogous way as with magnitude determination in seismology using a relation, which considers geometric wave attenuation as well as attenuation by damping:

$$A(r) \propto \frac{1}{r} \cdot \exp(-\alpha \cdot r)$$

where $\alpha$ means the damping coefficient. The amplitudes are specified in the logarithmic decibel (dB) scale. In a semi-logarithmic plot (Fig. 4) of the product $A \cdot r$ versus $r$ of all transducers a linear relationship is obtained by a straight-line fit to the data. The value of the straight line at the reference distance $r_0 = 50$ m is determined and regarded as the magnitude of the AE event.
The slope of the straight line corresponds to the damping coefficient. Generally, damping of high-frequency AE waves is caused by scattering and intrinsic absorption, which will mainly occur at grain boundaries or microcracks, by small inclusions of other rock materials, gas, or water, which are embedded in many rock formations, and by reflection, refraction, and mode conversion at boundaries between different rock materials.

![Graph](image)

Fig. 4 AE amplitudes of one event measured with 28 sensors corrected for geometric wave dispersion versus distance.

It can be seen from Fig. 4 that travel paths of the signals range from 25 to 140 m. The slope of the line corresponds to a damping coefficient of 3.9 dB per 10 m which corresponds to an attenuation length of approximately 22 m. The attenuation length, in which the peak amplitude corrected for geometric wave dispersion, $A/r/r_0$, is reduced to 37% (or 1/e), is a reciprocal measure of the damping coefficient. The value of this straight line corresponds to a magnitude of 56.35 dB at the reference distance $r_0 = 50$ m. It should be mentioned, that the damping coefficient and the magnitude are mean values which are determined at various travel paths from the source to the 28 sensors and in various directions.

**Results**

Figure 5 displays the distribution of the mean attenuation length of the events in a gray-scale density plot. The plot shows the attenuation length within horizontal cells of 5 x 5 m; cells containing less than 10 events are displayed as white areas. Again, as in Fig. 3, Regions I and II are marked by ovals.

The lowest mean attenuation length of about 25 m occurred in Region II in a small zone between $y = 250$ m and $y = 290$ m (light grey cells). In this area microcracking still takes place at the contours of closely spaced cavities even a long time after excavation. On the other hand, the highest attenuation length of about 510 m was obtained in Region I outside the sensor network (northwest direction). The highest and lowest attenuation lengths of 25 m and 510 m correspond to damping coefficients of 3.47 dB per 10 m and 0.17 dB per 10 m, respectively.
Scattering at microcracks occurs in regions of deviatoric stress, e.g. in the excavation disturbed zone (EDZ) with thickness of a few meters at the contour of underground cavities. That may be the reason for the high damping values found in regions of closely spaced cavities like Region II. On the other hand, in Region I with the lowest attenuation, the AE signals mainly propagate through undisturbed rock salt to the AE sensors. It should be mentioned, that this kind of analysis assumes implicitly no correlation between the radiation pattern and the orientation of the fracture plane of the source. However, this effect does not seem statistically important because of averaging over many events located in the whole monitored area.

![Fig. 5 Attenuation length obtained from AE events between November 15, 2004 and August 23, 2005 (696,278 events) in top view.](image)

**Conclusion**

Apart from geometrical attenuation, intrinsic absorption, and shadowing effects by cavities and drifts, high-frequency acoustic waves are attenuated by scattering at small inclusions of anhydrite, clay, gas, or water, which are embedded in most salt rock formations. On the other hand, in regions of deviatoric stress, e.g., in the EDZ with thickness of a few meters at the contour of underground cavities, scattering at microcracks is the limiting factor of the attenuation length. Most of the AE signals partly travel through these zones because all sensors are installed in flat boreholes, which were drilled from the gallery walls. That may be the reason for the low attenuation lengths in regions of closely spaced cavities like Region II. A comparison of our estimated attenuation lengths with the calculated one, which Price published [4] seems doubtful. We assume that the main reason for scattering is microcracks in the EDZ. When measuring in very large volumes of homogeneous rock salt, the attenuation lengths should be even larger than 500 m. The critical point seems to be over which distances a salt dome is homogeneous enough.

Difficulties are to be presumed at boundaries between different rock materials like rock salt, anhydrite, or clay because of reflection, refraction, and mode conversion of acoustic waves.
Even under very slow creep conditions, microcracking and consequently AE activity may be induced at these geological boundaries. These interfering signals are to be possibly discriminated from neutrino generated events by careful source analysis.

References