Ultrasonic Nondestructive Testing Method for Evaluation of Annular Seals

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Introduction

Drilling boreholes is common practice in geotechnical and geoenvironmental investigations and in various other exploration, testing, and monitoring applications. When a casing is placed in a borehole an annular space is created between the casing and the surrounding soil. If not properly sealed, this annular space can be a potential path for transport of contaminants in the subsurface environment. Cross-contamination due to mixing of clean and contaminated groundwater can occur (Fig. 1). A poor annular seal can also result in loss of groundwater.

There exist a number of methods to evaluate the integrity of annular seals. The most common methods used for in situ evaluation of seals around casings are: water level monitoring, pressure testing, and cement logging (Driscoll 1986). Two other less frequently used methods for evaluating cement seals are temperature logging and radioactive logging (Driscoll 1986). A summary of existing in situ seal evaluation methods and their advantages and disadvantages is presented in Table 1.

The limitations of the existing methods (Table 1) indicate that there is need for a simple, yet sensitive testing method to evaluate the wide range of commonly used casings and sealants. The method should also allow for repetitive testing after seal placement to monitor the performance of a seal over time. For this reason, a nondestructive testing method that uses ultrasonic principles was developed.

Ultrasonic Test Method

Methods used for ultrasonic nondestructive testing of materials were adapted for evaluating the integrity of seals around a casing. The pulse-echo inspection technique was used (Ensminger 1988). A testing method was developed to assess the nature of materials

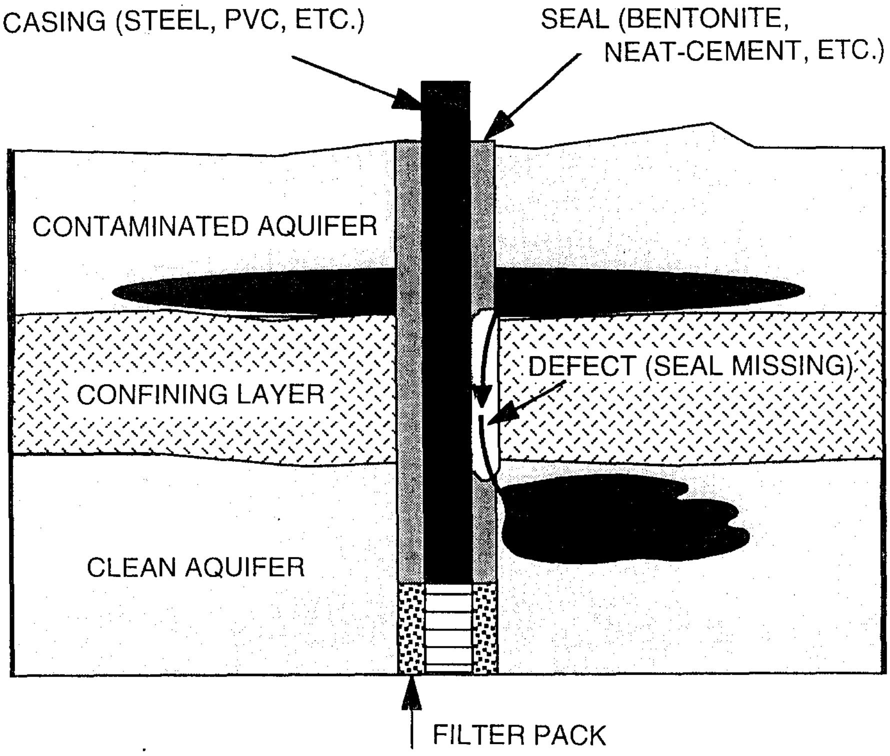

Fig. 1 Cross-contamination through a defective well seal

Table 1 Advantages and Disadvantages of In Situ Seal Evaluation Methods

Method	Advantages	Disadvantages
Level Monitoring (Water level inside casing monitored)	•Simple •Can be conducted repeatedly after seal placement	•Crude •Location of defects cannot be identified
Pressure Testing (Casing pressurized against seal)	•Can be conducted repeatedly after seal placement	•Only cement seals in rock formations can be tested •Location of defects cannot be identified
Cement Logging (Condition of seal evaluated from inside a casing by sending and receiving sonic waves)	•Both casing-seal and seal-formation bonds can be evaluated •Exact location of defects can be identified •Can be conducted repeatedly after seal placement	•High cost •Services provided by a limited number of companies using specialty equipment •Only cement seals around steel casings are tested
Temperature Logging (Curing temperature of cement monitored to determine amount of seal)	•Simple	•Only cement seals can be tested •Must be conducted within 12-24 hours after placement of seal •Location of defects cannot be identified
Radioactive Logging (Radioactive tracer mixed into seal prior to placement monitored)	•Location of defects can be identified •Can be conducted repeatedly after seal placement	•High cost •Special procedures required for handling of radioactive material

(seal or defects filled with air or water) in contact with casings placed in boreholes.

A probe was designed and constructed for downhole testing (Fig. 2). An evaluation is conducted by sending and receiving ultrasonic waves using a single transducer and commercially available hardware (Fig. 2). The method was initially developed and evaluated in the laboratory (Yesiller 1994). Its effectiveness was then evaluated in the field.

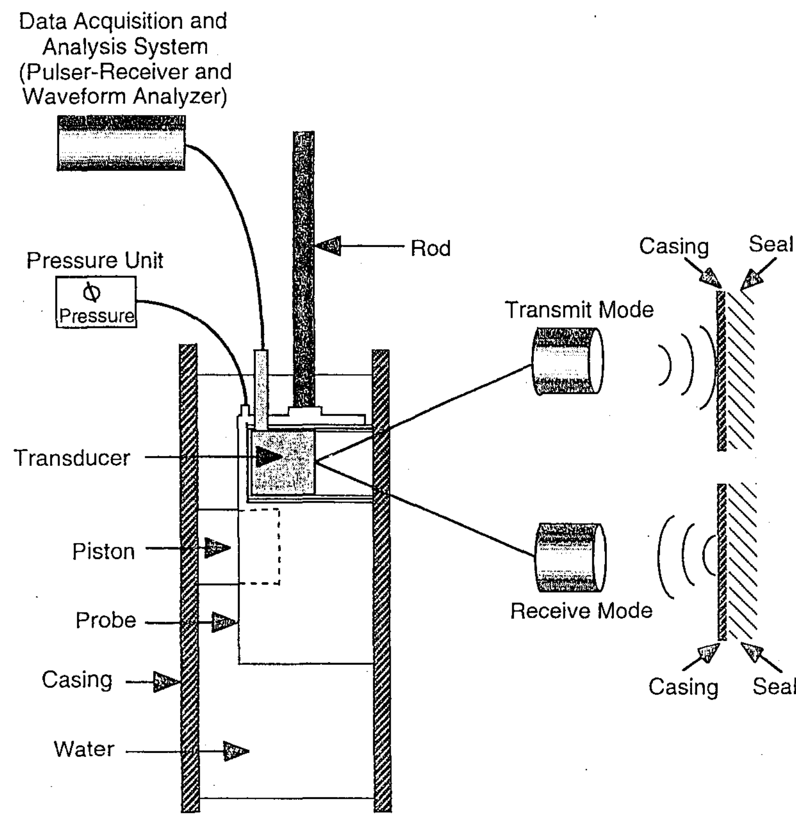

Fig. 2 Probe deployed in a casing

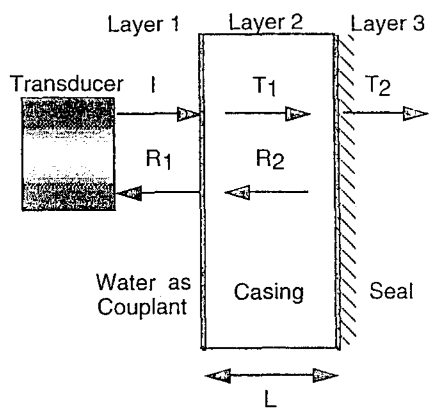

Fig. 3 Three layered system used in the tests

The electronic equipment used for seal evaluation consists of three units: a piezoelectric transducer, a pulser-receiver, and a waveform analyzer (Fig. 2). The transducer is used to transmit and receive ultrasonic waves. The transducer is actuated by the pulser-receiver, which is connected to the waveform analyzer for digitization of data.

The probe is a cylindrical unit constructed from Delrin® (a plastic) that houses the transducer. A solid piston that can move in and out of the probe is used to fix the probe at a certain location inside a casing. The probe is lowered inside the casing via a set of rigid aluminum rods to the desired depth of measurement. The probe is pressed against the casing by applying a pressure of 240 kPa to the piston. In this configuration, the face of the transducer is orthogonal to the casing wall, which permits the maximum amount of ultrasonic energy to be transmitted into the casing (Fig. 2). Also, a fixed thickness of water (12.7 mm) is maintained in front of the transducer to act as a couplant.

A test is conducted at the measurement location after the probe has been pressed against the casing wall. After data collection at a given location, the probe is retracted by releasing the pressure. The probe is then lowered to the next measurement location or rotated horizontally to conduct measurements along different directions.

Data Acquisition and Analysis

The seal around a casing is conceptualized as a three-layered system (Fig. 3). Ultrasonic waves sent by the transducer travel through the coupling medium (water), the casing, and the seal. When the incident wave (i.e., I) encounters the boundaries between layers, its energy is distributed between reflected (i.e., R_1, R_2) and transmitted waves (i.e., T_1, T_2). Reflections from the boundary between the casing and seal (i.e., R_2) are received by the same transducer. Differences in the acoustic properties of media present behind the casing cause differences in the reflected wave energies. Analysis of these reflected waves indicates the presence of different media (seal or defects filled with air or water in a seal) behind a casing.

The waveforms shown in Fig. 4 are typical of waveforms obtained using steel casings. When there is no-backing (air), the initial high amplitude reflection from the water-casing interface is followed by multiple sharp reflections from the casing-air interface. When a sealant such as a neat-cement is present behind the steel casing, the initial high amplitude reflection from the water-casing interface is followed by low-amplitude reflections from the casing-cement interface that decay quickly. This difference in the waveforms is used to discriminate between intact and defective seals.

A measure of energy, ENG, is used to quantify characteristics of the reflections from the casing-seal interface. Different values for ENG are obtained depending on whether the seal is intact

or defective. ENG is a measure of the area under the amplitude-time plot over a specified time interval (Fig. 4). The presence of different materials behind the casing causes changes in the amplitudes of reflections from the casing-seal interface and thus changes in ENG.

Depth and ENG are recorded at each measurement location along the length of a casing. To discriminate quantitatively between an "intact" seal and a "defective" seal, a measured profile of ENG is compared statistically to the profile expected for a defective seal (Yesiller 1994). A seal that is in full contact with the casing is an "intact" seal, whereas defects consisting of water or air around the casing correspond to a "defective" seal. A low value of ENG is indicative of an "intact" seal, whereas a high value for ENG indicates a "defective" seal.

Field Tests

Results from field tests conducted in Fall 1994 and in Summer 1995 are shown in Fig. 5. The tests were conducted in a borehole that was 152 mm in diameter and was installed using a hollow stem auger. The casing placed in the borehole was a 50-mm-diameter Sch. 40 steel pipe, that simulated a monitoring well casing. The casing was 3-m long, 2.7 m being below ground and the remaining 0.3 m above ground. Seals and defects placed in the borehole, from top to bottom, consisted of a 0.46-m-thick neat-cement seal (2 kg Type-I Portland cement to 1 L of water) at the surface, a 1.3-m-thick sand layer simulating a defect, and another neat-cement seal 1.75-m-thick at the bottom (Fig. 4).

Results of tests conducted in 1994 and in 1995 are shown in Fig. 5 with average ENG for air and water backing (reference measurements for comparison) around the casing. The ultrasonic responses obtained from the seal and sand layers were different. The upper cement layer was intact except for the mid-point (Fig. 4). This point was persistently detected as defective (high ENG) in the tests. The borehole was excavated in Summer 1995 after the tests were completed. It was observed that there was a cavity in the seal between the depths of 0.15 m to 0.20 m (Fig. 6). The cavity extended from the casing to the surrounding soil along the entire width of the seal. The lower neat-cement seal was intact except for the mid-section (Fig. 5). This section was persistently detected as defective in the tests. High ENG was obtained for the sand layer both in Fall 1994 and Summer 1995 which indicated that there was a defect.

Summary

An ultrasonic nondestructive testing method employing the pulse-echo inspection technique was developed to evaluate the integrity of annular seals surrounding casings in boreholes. The test equipment consists of readily available and non-proprietary components. The testing and analysis procedures are reasonably simple to use. A single piezoelectric transducer along with commercially available hardware (a pulser-receiver and a waveform analyzer) are used for data acquisition and analysis. A probe that houses the transducer was designed and constructed for downhole testing. A data acquisition and analysis method was developed for seal evaluation.

The ultrasonic method is effective for detecting the presence of bentonite and cement-based seals and defects composed of air, water, or coarse-grained formation materials such as sand that are in contact with a casing. Measurements can be conducted along any direction in a casing by rotating the probe horizontally. Seals around steel and PVC casings can be evaluated, but the algorithm can be modified easily to test other metallic or plastic casings. The probe is designed to fit into 50-mm-diameter casings, but can be modified to fit into casings having smaller or larger diameters.

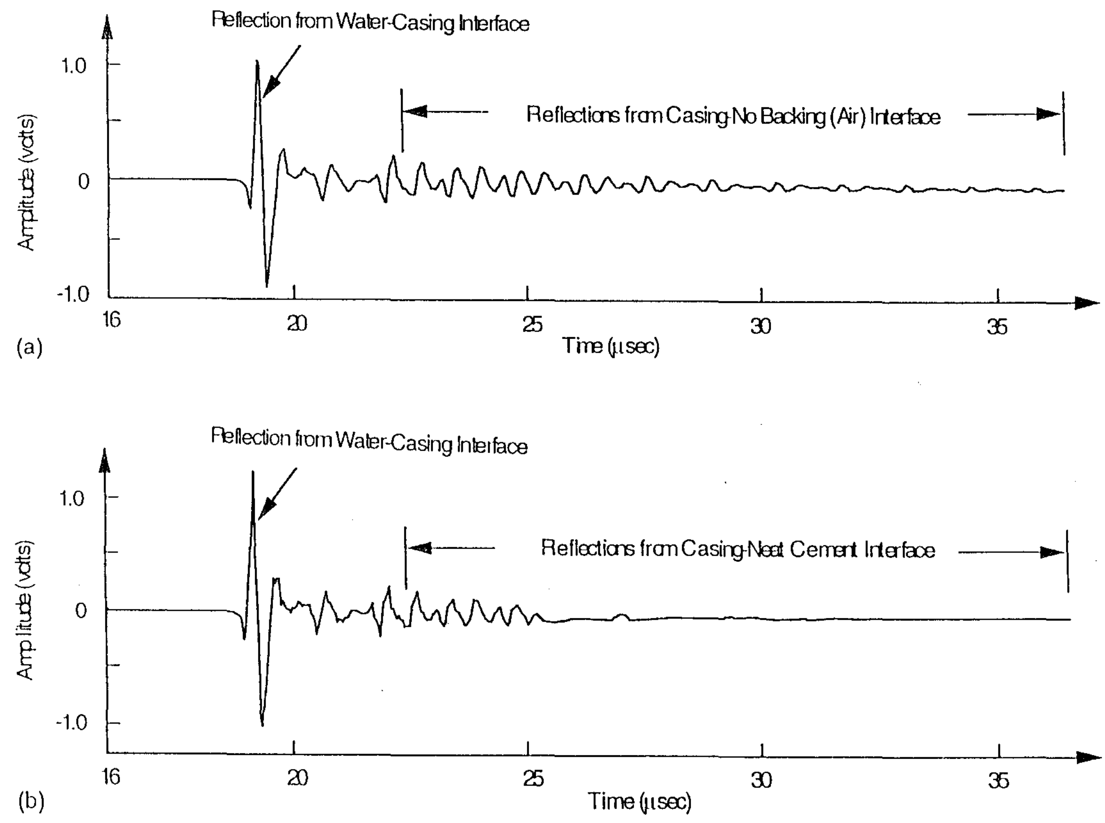

Fig. 4 Two typical waveforms obtained from tests with steel casings: (a) no backing (air), (b)neat-cement backing

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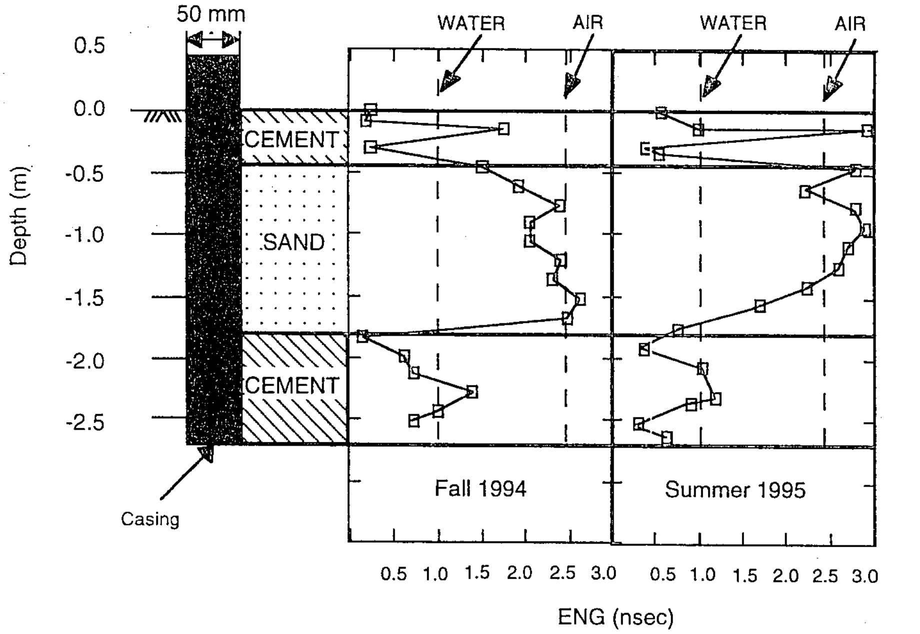

Fig. 5 Results of field tests

Fig. 6. Cavity in the neat-cement seal