Field Evaluation of Ultrasonic Method for Assessing Well Seals

by Nazli Yesiller, Craig H. Benson, and Tuncer B. Edil

Abstract

Field tests were conducted in three boreholes using an ultrasonic testing method to evaluate its ability to assess contact between the seal and riser (casing). The ultrasonic method is used inside the riser without disturbing the riser, seal, or formation soil. The risers were 50-mm-diameter (2-inch) Schedule 40 steel pipes that are used for ground water monitoring wells. Different types of seals were placed around the risers and defects were purposely introduced in the seals to test the ultrasonic method. The ultrasonic response changed as the neat-cement seals cured or hydration of the bentonite seals changed. When adequate moisture was not available, the bentonite seals deteriorated, losing contact with the riser. When adequate moisture was available, however, the seals swelled into contact with the riser. Both conditions were detected with the ultrasonic method. The method also detected the intentional defects, as well as defects that were not intended. The boreholes were excavated to compare results of the ultrasonic tests with the actual condition of the seals. The condition of the seals agreed well with the results of the ultrasonic tests.

Introduction

When a riser (also commonly called a well casing) is placed in a borehole, an annular space is created between the riser and the surrounding soil. If not properly sealed, the annular space can be a potential pathway for transport of contaminants in the subsurface (Meiri 1989; Pekarun 1995; Lacombe et al. 1995; Pankow and Cherry 1996). Contamination can occur due to mixing of adjacent bodies of clean and contaminated ground water or from intrusion of contaminated surface water (Riewe 1996). A poor annular seal can also result in loss of ground water. A properly placed seal protects the riser against corrosion and chemical degradation (Nielsen and Schalla 1991).

An ultrasonic testing method was recently developed for in situ evaluation of annular seals surrounding risers used for water supply and monitoring wells. The ultrasonic method is used to detect differences in the ultrasonic response of materials in contact with a riser and to determine what material (seal or defects filled with air or water) exists outside the riser (Yesiller et al. 1997). The ultrasonic method is a simple, yet sensitive, testing method to assess seals without disturbing the riser, seal, or formation. Separations on the order of micrometers between the seal and the riser can be detected, and defects having an area as small as 250 mm² (0.4 in²) can be located (Yesiller et al. 1997). Ultrasonic tests can be conducted repeatedly after seal placement to monitor the performance of the seal with time.

This paper describes ultrasonic tests conducted in three boreholes to assess whether the ultrasonic technique could detect defects in the field, as had previously been shown in laboratory model borehole tests (Yesiller et al. 1997). The type of sealant (e.g., bentonite chips or neat-cement) was varied to determine if different types of seals could be distinguished using the ultrasonic method. In addition, defects were purposely introduced in the seals to see if they could be detected. The condition of the seals was evaluated in the fall of 1994 and summer of 1995. Subsequently, the boreholes were excavated. The ultrasonic responses compared well with the visual condition of seals.

Method

The ultrasonic seal evaluation method is described in detail in Yesiller (1994) and Yesiller et al. (1997). A brief summary describing the equipment, data acquisition, and data analysis follows.

Equipment

The ultrasonic pulse-echo inspection technique is employed to assess the nature of materials (seal or defects filled with air or water) in contact with the riser. A piezoelectric transducer is used to send and receive ultrasonic waves into the riser and seal (Figure 1). The transducer is actuated by a pulser-receiver, which is connected to a waveform analyzer for digitization of data. Reflections generated as the waves pass into the riser and seal are analyzed to evaluate the integrity of the seal. A detailed description of the equipment can be found in Yesiller (1994). All of the equipment is available at reasonable cost.

A downhole probe that houses the transducer is used for conducting tests in a riser (Figure 1). The cylindrical probe is constructed of Delrin® plastic. The transducer is placed inside a cylindrical space in the probe. The probe is lowered inside the riser via a set of rigid aluminum rods to the desired depth of measurement (Figure 1). A solid piston, which moves in and out of the probe, is used to fix the probe against the riser wall (Yesiller et al. 1997). The probe can be deployed to any depth, although measurements at great depth may require the use of amplifiers. In addition, the riser need not be plumb, because the piston pushes the probe against the casing wall, ensuring that the signal is transmitted orthogonal to the riser.

After collecting data at a given location, the piston is retracted by releasing the pressure. The probe is then lowered to the next measurement location or rotated horizontally to conduct measurements along different orientations.

Presence of water is required in front of the transducer to act as a couplant for the transmission of ultrasonic waves into a riser. A mechanism to supply water in front of the transducer was designed for use in risers above the ground water level (Figure 1). A soft rubber ball is lowered inside the riser and the ball is pressurized at the desired depth. The inflated ball plugs the

Figure 1. Schematic of probe deployed in riser.

riser, allowing the part of the riser above the rubber ball to be filled with water. After data acquisition is complete, pressure in the rubber ball is released and the ball is retracted from the riser (Figure 1). Rubber balls of various diameters are commercially available from plumbing supply companies for use in various diameter risers.

Because the probe is immersed in water, the signal is insensitive to variations in relative humidity and is protected from large temperature fluctuations. In addition, the signal is not affected by contaminants or suspended solids, unless the solids concentration is high (e.g., mud consistency).

Data Acquisition and Analysis

The data are analyzed assuming ultrasonic transmission occurs through a three-layered system (Figure 2). In the three-layered system, ultrasonic waves sent by

Figure 2. Three-layered system assumed in analysis.

the transducer travel through the coupling medium (water), the riser, and the seal. When the incident wave (I) encounters boundaries between layers, its energy is distributed between reflected waves (R_1 , R_2) and transmitted waves (T_1 , T_2). Reflections from the boundary between the riser and seal (R_2) are received by the same transducer used for transmission. Differences in the acoustic properties of media present behind the riser cause differences in the amplitude of the reflected wave. Analysis of the reflected waves are used to detect the presence of different media (seal or defects filled with air or water in a seal) behind a riser (Yesiller 1994; Yesiller et al. 1997).

The waveforms shown in Figure 3 are typical of waveforms obtained using steel risers. When there is no backing (i.e., the defect is air), the initial high-amplitude reflection from the water-riser interface is followed by multiple sharp reflections from the riser-air interface. When a sealant such as neat-cement is present behind the riser, the initial high-amplitude reflection from the water-riser interface is followed by decaying lower-amplitude reflections from the riser-cement interface. This difference in waveforms is used to discriminate between intact and defective seals.

A measure of energy, E , is used to quantify characteristics of the reflections from the riser-seal interface (Yesiller 1994). E is defined as:

$$E = \int_{t_0}^{t_f} V_r dt \quad (1)$$

where V_r is the voltage amplitude of the reflected signal normalized to a reference voltage (V_r is dimensionless); t is time; and t_0 and t_f are the lower and upper boundaries of the time interval (Figure 3). Equation 1 is evaluated numerically using a program in the waveform analyzer (Yesiller 1994). The reference voltage is the peak-to-peak amplitude of the first reflection in the waveform from the water-casing interface. The presence of different materials behind the riser causes changes in the amplitudes of reflections from the riser-seal interface and thus changes in E . A high value for E is obtained when the backing material provides little attenuation (e.g., water, air, formation materials), and a low value for E is obtained when the backing material provides significant attenuation (e.g., sealants such as neat-cement and hydrated bentonite). Examples of E for different materials in contact with a steel riser are shown in Figure 4.

To evaluate a seal, depth and E are recorded at a series of points along the length of the riser. A seal that is in full contact with the riser is an "intact seal," whereas a seal containing defects consisting of water or air around the riser corresponds to a "defective" seal. A low value for E is indicative of an intact seal, whereas a high value for E indicates a defective seal. To discriminate quantitatively between an intact seal and a defective seal, a measured profile of E is compared statistically to the profile expected for a defective seal (Yesiller 1994). Prior to placement of a seal, conditions

Figure 3. Typical waveforms obtained from tests with steel risers: (a) no backing (air) and (b) neat-cement backing.

Figure 4. Profiles of E from risers with different backings.

corresponding to a defective seal (air or water adjacent to riser) are defined by making reference measurements around a riser using air and water as the backing. Average values for E corresponding to air (E_a) and water (E_w) around a riser are shown with the E profile for the seal on a plot of E vs. depth (Figure 4). The profile for the sealed riser is compared with the profiles for no backing (air) and water backing using a t -statistic under the null hypothesis that the seal is defective. When the difference between the measured E and E_a and/or E_w is not statistically significant, the seal is defective. Intact and defective seal locations are marked on the E profile using results of the statistical analysis.

Field Tests

Field tests were conducted in three risers installed at two locations in Wisconsin: Madison (Boreholes 1 and 2) and Columbus (Borehole 3). Various seals and defects were placed around the risers in the boreholes.

Ultrasonic testing of the seals was initially conducted in the fall of 1994. Additional testing was conducted in the summer of 1995, approximately 10 months after installation. Bentonite and neat-cement were used for the seals, and defects were introduced intentionally using dry sand. The boreholes were 152 mm (6 inches) in diameter, and the risers were Schedule 40 steel pipes 50 mm (2 inches) in diameter. Although only 50-mm-diameter stainless steel risers were evaluated in this study, a recent study by Klima (1996) shows that the method can also be used to evaluate seals surrounding PVC risers and risers with diameters of at least 15 cm. The method is also equally applicable to carbon steel risers, because the difference in acoustic impedance of stainless and carbon steels is not significant (McIntire 1991).

Seal and Defect Materials

Bentonite seals were prepared with bentonite and water using procedures employed by the Wisconsin Department of Transportation. The seal was composed of 50 percent bentonite and 50 percent water, by weight. Pure Gold[®] Medium Chips (9.5 mm diameter) manufactured by Colloid Environmental Technologies Co. (CETCO) were used.

Neat-cement seals were prepared using a ratio of 42.6 kg (94 pounds) Type-I Portland cement to 20.8 L (5.5 gallons) of water. This neat-cement seal is used commonly in field applications for sealing risers (Strata Engineering Corp. 1991; Edil et al. 1992; Wisconsin Department of Transportation 1994).

Defects were constructed using Portage sand, a clean, medium, uniformly graded sand classified as SP according to the Unified Soil Classification System. Laboratory model borehole tests showed that E for dry sand is similar to E for air, and E for wet sand is similar to E for water (Yesiller 1994).

Installation and Sealing of Risers

Boreholes 1 and 2 were installed on the University of Wisconsin–Madison campus. Seals consisting of a single material (bentonite only or neat-cement only) and “defects” consisting of sand were placed around the risers. Borehole 3 was installed near Columbus, Wisconsin, with assistance from the Wisconsin Department of Transportation. Bentonite and cement seals were placed around the riser in Borehole 3. Sand was used to construct the defect layer around the riser in Borehole 3. All boreholes were drilled using a hollow stem auger. The seals and defects were placed in the boreholes immediately following drilling. Placement of seals and defects was completed within two to three hours.

Boreholes 1 and 2 extended 2.7 m (9 feet) below the surface (Figure 5). The risers were 3 m (10 feet) long, 2.7 m (9 feet) being below the surface and 0.3 m (1 foot) remaining above the surface. The stratigraphy of the site consisted of a 0.6-m-thick (2-foot) topsoil layer and an underlying silty sand layer. Ground water was not encountered. Arrangements of the seals and “defects” in Boreholes 1 and 2 are shown in Figure 5. The bottommost layer of neat-cement (cement and water) in

Figure 5. Schematics of (a) Borehole 1, (b) Borehole 2, and (c) Borehole 3.

Borehole 1 was placed using a tremie pipe. The topmost layer of neat-cement in Borehole 1 was placed by pouring the seal into the hole from the surface. Bentonite seals were placed in Borehole 2 by filling the annulus with water to a specified depth and then dropping bentonite chips into the water. The bentonite chips were expected to gradually hydrate and form a seal. Sand defects were placed in both boreholes by pouring the sand from the ground surface.

Borehole 3 extended 4.5 m (15 feet) below the surface (Figure 5c). The riser placed in the borehole was 6 m (20 feet) long, 4.5 m (15 feet) being below the surface and 1.5 m (5 feet) remaining above the surface. The riser left above the surface was used to determine E for air (E_a) and water (E_w) backings (Yesiller 1994). The E for air (E_a) was determined without anything around the pipe. To determine E_w , large-diameter pipe (30 cm diameter) was temporarily placed around the riser above the ground surface. The large pipe was sealed so that the annulus could be filled with water, and measurements for water backing (E_w) were made. Seals made with neat-cement, bentonite slurry, or bentonite chips and water and defects consisting of dry sand were placed in the borehole by pouring the materials into the annulus from the ground surface. Ground water was encountered at a depth of 4.5 m.

Results of Ultrasonic Tests

Borehole 1 — Madison, Wisconsin

Results of the tests conducted in Borehole 1 are shown in Figure 6. Measurements of E were conducted at the same depths and orientations in all of the tests. The riser for Borehole 1 was tested in air inside the borehole prior to placement of the seals and defects. This provided an average E for air backing (E_a) to be used in the data analysis (Figure 6). E_w for water backing was obtained from tests on Borehole 3.

Results of tests conducted one day after placement (Figure 6) show the different ultrasonic responses of the seal and defect layers. The upper neat-cement seal was intact near the surface and defective near the mid-section and base of the layer. E for the lower neat-cement seal was significantly different from E_a and E_w , indicating the presence of an intact seal at all locations (Figure 6).

E for the sand layer was between E_a and E_w . Dry sand was placed in the borehole as the defect layer, but some of the water used to prepare the adjacent cement seals seeped into the sand, which resulted in E lower than E_a . Nevertheless, all of the locations in the sand layer were found to be defective. Similar behavior was observed when saturating sand defects in laboratory model borehole tests (Yesiller 1994).

By seven days, E for the upper neat-cement seal decreased below E_w except for one location, indicating that most, but not all, of the upper layer was intact (Figure 6). A similar condition was observed throughout the monitoring period. The high E near the middle

Figure 6. Results from ultrasonic evaluations of Borehole 1.

Figure 7a. Unintended defect in neat-cement seal in Borehole 1: cavity in seal.

Figure 7b. Unintended defect in neat-cement seal in Borehole 1: soil-stained riser.

of the upper neat-cement layer was obtained at the same location in the one-, seven-, and 16-day tests and the 10-month test.

The ultrasonic response of the sand layer changed in time (Figure 6). E for the sand layer increased and became close to E_a (except for one location) at the end of seven days due to drainage of water, which is consistent with the response of dry and wet sands in laboratory tests (Yesiller 1994; Yesiller et al. 1997). A response consistent with dry sand was also obtained during the 16-day and 10-month tests.

After 10 months, the upper neat-cement seal surrounding the riser in Borehole 1 was retrieved to determine why a "defect" was indicated by the ultrasonic assessment when the seal was intended to be fully intact. A cavity was found in the seal between depths of 0.15 m (6 inches) to 0.20 m (8 inches), and soil near the cavity stained the riser (Figure 7). The cavity extended from the riser to the surrounding soil along the entire width of the seal. The location of this defect agreed exactly with the location that was repeatedly detected as defective using the ultrasonic method (Figure 6). During excavation of the borehole, the sand layer was examined and found to be dry. Thus, the condition of the sand also agreed with the results of the ultrasonic test (Figure 6).

Borehole 2 — Madison, Wisconsin

Results of the tests conducted in Borehole 2 are shown in Figure 8. Measurements of E were conducted at the same depths and orientations in all of the tests. The riser placed in Borehole 2 was tested inside the borehole prior to placement of the seals and defects. This provided an average E_a for air backing to be used in the data analysis. The E profile for water backing was obtained from the riser in Borehole 3.

One day after placement, E near the top of the upper bentonite layer was high, indicating the presence of a defective seal (Figure 8). Desiccation and cracking of the bentonite seal was visually observed at the ground surface, which is consistent with the ultrasonic response. In contrast, E for the bottom portion of the upper bentonite seal was low, indicating the presence of an intact seal. E for the entire lower bentonite seal was also significantly lower than E_w , indicating the presence of an intact seal (Figure 8). At the end of seven days, E near the surface was still high, indicating the continued presence of a defective seal. Desiccation cracks were still visible in the seal at the ground surface.

Lower E was obtained during the 17-day test for the top portion of upper bentonite seal (Figure 8). Between the seven-day and 17-day measurements, rain water seeped into the upper bentonite layer, resulting in rehydration and swelling of the bentonite and a subsequent reduction in E . Nevertheless, the ultrasonic response of this portion of the seal indicated a defect at 17 days (Figure 8). In contrast, the entire upper bentonite layer was found defective during the 10-month test.

The ultrasonic response of the lower bentonite seal also varied over time. E for this layer increased to val-

Figure 8. Results from ultrasonic evaluations of Borehole 2.

ues between E_w and E_a by seven days after installation (Figure 8), indicating that the seal was defective. Apparently, water from the bentonite was removed by the adjacent dry formation soil, resulting in desiccation and shrinkage of the bentonite and separation of the bentonite and the riser. Similar responses were obtained in the 17-day and 10-month tests.

E for the sand layer was close to that of water (E_w) one day after placement (Figure 8), even though dry sand was placed in the borehole as the defect layer. Water used to hydrate the upper bentonite seal seeped into the sand, as occurred in Borehole 1. Subsequently, E for the sand defect increased as water drained into the surrounding soil. At seven days, E was close to E_a and all results from the sand layer indicated that it was a defect. Similar behavior was observed in Boreholes 1 and 2. At 17 days, E for the sand layer was again close to E_w , because water seeped into this layer after heavy rains on Day 16. Similar decreases in E due to water were detected in the bentonite layers.

The upper bentonite seal surrounding Borehole 2 was unearthed in the summer of 1995. The bentonite seal was dry and cracked and, at some locations, the bentonite appeared powder-like (Figure 9). The formation soils around the borehole were dry. It was also observed that the bentonite chips had never fully hydrated. The outer surface of the chips appeared to have hydrated at one point; however, the center of the

Figure 9. Dry and cracked bentonite from Borehole 2.

Figure 10. Results from ultrasonic evaluations of Borehole 3.

chips remained dry. These observations are consistent with the high E obtained for the upper bentonite seal, which indicated the seal was defective.

Borehole 3 — Columbus, Wisconsin

Results of tests conducted in Borehole 3 are shown in Figure 10 with the average E for air or water backings shown for comparison. Measurements were conducted at the same depths and orientations in all of the tests. The average E for air (E_a) and water (E_w) backings were determined by preliminary tests conducted using the portion of the riser above the surface.

During testing after installation, only a slight difference was evident between the ultrasonic responses of the seals and the defect. E values from the fresh neat-cement and bentonite seals were close to E_w or between E_a and E_w at all depths (Figure 10). E near E_a close to the ground surface was probably caused by air entrapped in the neat-cement mix. In contrast, the lower portion of the neat-cement layer was uncured cement, which was in a viscous fluid state and thus yielded E near E_w . The fresh bentonite also had an ultrasonic response similar to water which is consistent with the behavior of hydrating and consolidating bentonite slurry observed in laboratory model borehole tests (Yesiller 1994). That is, E for bentonite drops below E_w after the bentonite fully hydrates and/or consolidates.

Curing of the cement resulted in a decrease in E over time (Figure 10, three- and 16-day tests). E obtained for the cement seal reached a low value at the top and bottom of the cement layer 31 days after installation, indicating the presence of an intact seal. However, in the mid-section of the cement layer, the E was consistently between E_w and E_a , which is indicative of a defect. A similar response was obtained in the long-term condition (10 months after installation). During excavation, it was found that a polyethylene tube installed for saturating the sand defect was in direct contact with the riser near mid-depth of the cement seal. Thus, the polyethylene tube prevented contact between the seal and riser, which was reflected as a defect in the ultrasonic evaluation.

Hydration and consolidation of the bentonite also

resulted in a reduction in E . By 16 days after installation, the E s for both bentonite layers were significantly different from E_w and E_a (Figure 10). Low E values were also obtained in both bentonite layers 31 days and 10 months after installation.

As occurred in Boreholes 1 and 2, E for the sand defect was close to E_w after installation (Figure 10), which was probably due to water seeping into the sand. Also, as was observed in Boreholes 1 and 2, the ultrasonic response of the sand defect varied over time. E of the sand layer increased and was close to E_a during the three- and 16-day tests apparently as the sand became drier. In contrast, E for most of the sand layer was similar to E_w during the long-term test. This test was conducted after a rainy day, and pooled water existed in the area surrounding the borehole. Apparently, rain water seeped into the sand layer around the riser. Nevertheless, the presence of the sand layer was detected as a defect with the ultrasonic method.

Summary and Conclusions

Tests were conducted using an ultrasonic method in three boreholes containing sealed risers to evaluate the ability of the method to assess contact between seals and risers. Seals composed of neat-cement or bentonite were used. Defects were introduced intentionally in the seals around the pipes using dry sand. The risers were 50-mm-diameter (2-inch) Schedule 40 steel casings used for ground water monitoring wells. The risers were installed and sealed in the fall of 1994. Ultrasonic testing was conducted in the fall of 1994 and summer of 1995.

Results of the tests showed that the ultrasonic device is capable of differentiating between different sealants in contact with a riser, and that it will detect regions devoid of sealant. Intentional defects consisting of clean sand placed in each borehole were readily detected by the device. In addition, the device also detected defects that were not intended, such as desiccation cracking of bentonite sealants and a cavity in a neat-cement seal.

The ultrasonic responses also show that the condition of a seal changes over time, due to curing of cement or hydration/desiccation of bentonite. Thus, periodic seal evaluations may prove useful in ensuring that ground water resources are adequately protected.

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Biographical Sketches

Nazli Yesiller received her B.S. and M.S. degrees from Bogazici University, Turkey, and a Ph.D. from the University of Wisconsin–Madison, all in civil engineering. She is an assistant professor in the Department of Civil and Environmental Engineering at Wayne State University (Detroit, MI 48202). Her research interests are in geoenvironmental engineering, particularly in the use of nondestructive testing for analysis of earthen materials. Her research is experimental (both laboratory and field). She teaches courses in geotechnical engineering, design of waste containment facilities, and geosynthetic engineering.

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