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Leak Detection In Large Storage Tanks Using Seismic Boundary Waves

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Synopsis

This paper describes a field evaluation of a technique for detecting leaks in large above-ground storage tanks. The technique detects leaking tank products in the foundation material by sensing anomalies in seismic boundary waves transmitted across the tank bottom. The evaluation consisted of three steps: (1) investigation of surface (Rayleigh) wave anomalies due to surface soil saturation in linear arrays; (2) evaluation of boundary waves propagated across the bottom of typical tanks; and (3) a surface (Rayleigh) wave experiment using tomography to locate velocity changes due to surface soil saturation. The results of these tests have shown that boundary waves can be easily propagated along a tank bottom and received by conventional geophones, and that soil saturation anomalies can be detected and located using boundary waves and tomographic reconstruction.

INTRODUCTION

Leakage of fuels and other chemical substances from storage tanks is a problem of great concern to both tank owners as well as the public in general. This problem applies to the large number of relatively small underground tanks, as well as to the smaller number of extremely large tanks that are generally found at fuel depots, tank farms, and petrochemical facilities. While the possibility of leakage in these large tanks has not received much public attention, it is of concern to tank owners. Leak detection methods are available but most of these require emptying the tank, and introducing inspection personnel into a hazardous environment. These are very expensive, and result in a loss of productivity. Non-intrusive acoustic emission techniques have been introduced in recent years, but their reliability is still in question.

The reported work deals with the development of a non-intrusive method for leak detection in large storage tanks. The method is based on the detection of transmission anomalies in seismic boundary waves which are propagated along the tank bottom (Maser, 1987). These anomalies result from the effect of soil saturation (due to leakage) on the boundary wave propagating along the tank bottom/soil boundary. The boundary waves utilized in this work are generated using a three pound hammer. These waves propagate along the boundary created by the soil, the tank bottom, and the tank fluid (see Figure 1). Their behavior is very similar to the more familiar Rayleigh waves. These propagating waves are picked up by an array of geophones on the opposite side of the tank. Wave fronts encountering soil which has been exposed to tank products will be delayed and reduced in amplitude due to the changed soil properties. These changes will be picked up by the receiving geophones.

The principle for leak detection using these boundary waves is tomography, similar to that used in X-rays. Wave transmission paths which encounter tank products in the soil will have different arrival characteristics than those which do not. Any change involving the presence of tank products over time in the earth under the tank will produce changes in these arrival characteristics.

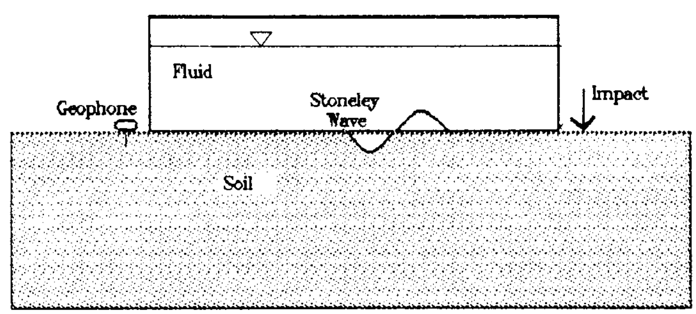

Figure 1 - Boundary (Stoneley) Waves Under an Above-Ground Storage Tank

A two-dimensional image of the zone of material under the tank which has been affected by tank products can be produced using tomography. The boundary waves are initiated at several locations around the perimeter of the tank, and are received by geophone arrays opposite the various initiation points (see Figure 2). The location of an affected zone is then computed from these multiple ray paths, as is done with a CAT Scan.

The objective of this work was to verify a seismic boundary wave technique for detecting leaks in large above-ground storage tanks. The three issues which have been addressed were: (1) can waves be propagated under a tank and clearly be detected on the opposite side; (2) does the saturation of the foundation soil produce an anomaly significant enough to be measured; and (3) can the anomaly be detected and located using multiple source/receiver arrays?

The following sections describe the physical principals which underlie this measurement concept. This will be followed by a description of preliminary tests which were conducted to verify aspects of the measurement concept, and tests which were conducted to verify the use of tomography for detecting leak locations.

UNDERLYING PHYSICAL PRINCIPLES

Seismic Boundary Waves

Mechanical waves propagate along the boundary between two media when a suitable contrast between the material properties occurs across the boundary. The amplitude of particle motion in these boundary waves decays rapidly away from the interface over a distance of approximately one wavelength. Thus the boundary provides a wave guide along which waves

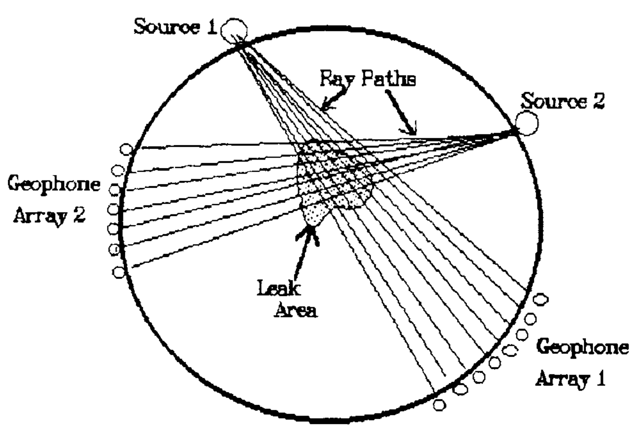

Figure 2 - Detection of Leakage using Multiple Geophone Arrays

propagate with a minimum loss of energy into the surrounding media. Waves propagating along a liquid/solid boundary are referred to as Stoneley waves. As with Rayleigh waves, their propagation velocity is slightly less than the shear wave velocity of the solid material. Stoneley waves propagating at the interface of liquid-solid or solid-solid boundary between two homogeneous half-spaces are non-dispersive, that is, the propagation velocity is frequency independent. However, Stoneley waves propagating along an interface between media whose properties vary with distance from the interface are dispersive.

Equations for Stoneley wave propagation along liquid-solid or solid-solid boundary are available in a number of textbooks (Ewing et.al 1957, Miklowitz 1978). Some researchers have proposed more advanced models to represent more complex boundaries. For example, a model has been developed for wave propagation within a fluid layer surrounded by elastic half spaces (Staecker and Wang 1973). Another model (Krey, 1963) represents a low velocity elastic seam which is surrounded by elastic half-spaces with higher velocities. This model was originally proposed for wave propagation in coal seams. An extensive study has been conducted by Kaelin (1986) using the above two models for evaluation of underground slurry liners and barriers using guided seismic waves.

The basic Stoneley wave formulation has been modified to include a thin structural plate (tank bottom) sandwiched between the liquid and solid half spaces (Madanat et. al, 1987). The behavior of the plate is represented using conventional plate theory. This plate theory model produced good agreement with results from a more detailed three layer model (Halabe, 1987). The plate model showed that the boundary waves were non-dispersive when wavelengths were greater than 20 times the plate thickness for concrete and 50 times the plate thickness for steel. The boundary wave behavior in this regime is insensitive to the plate properties, and dependent primarily on the shear and P-wave velocities in the underlying soil.

The amplitude of boundary wave motion decays exponentially in the direction perpendicular to the boundary, with the decay proportional to the wavelength. For frequencies of interest to this study (50 to 100 Hz), the wavelengths of the waves propagating under tanks range from 2 to 6 meters. Thus, property changes in a thin soil layer in the neighborhood of the boundary cause a significant effect on boundary wave propagation. Such property changes take place in the presence of a leak.

The most significant effect of leakage on boundary wave propagation is due to the change in physical properties of the foundation material around the region where leakage takes place. The following section describes this effect in further detail.

Influence of Moisture on Wave Propagation

Moisture influences wave propagation velocities in soil by increasing the effective mass and changing the resistance to deformation. The nature of these effects depend on the type of wave motion (shear vs. dilatational), the type of soil, the particle acceleration (related to the frequency content of the wave), and the degree of saturation. When tank products other than water are considered, their effects will be similar to those of water unless there are significant differences in their density and viscosity. The following paragraphs describe the nature of the effect of water on boundary wave propagation.

As with Rayleigh waves, Stoneley waves depend primarily on the shear wave velocity (V_s) and to a lesser extent on the pressure wave velocity (V_p). The following describes the influence of moisture on these two body wave velocities for both granular and cohesive materials.

P-waves propagate in granular material by inducing volume change. As the percent saturation increases, the mass increases (reducing the velocity), but resistance to volume change does not occur until close to 100% saturation. At that point the P-wave velocity dramatically increases to close to the P-wave velocity in water.

Shear waves propagate in granular material by inducing shear deformation. As the degree of saturation increases, the effective mass increases but in a manner which depends on the participation of the water in the motion. This, in turn, depends on the particle size, the particle acceleration, and the fluid viscosity (Whitman, 1970). In general, the presence of fluid has little effect on the resistance to motion.

In fine granular materials such as fine silty sands with a degree of saturation in the range of 5 to 20 percent, capillarity produces an artificial cohesion between the solid particles thus increasing the shear modulus of the material. Beyond 20% saturation, this effect gradually diminishes and becomes negligible beyond 50%. (Wu et.al. 1984).

For clay and sand/clay mixtures, the P- wave velocity increases and the shear wave velocity decreases continuously with degree of saturation (Whitman, 1970).

Based on the above discussion, the effect of saturation on boundary wave propagation will depend on the nature of the foundation material. For granular material, one would expect the effect to be due primarily to the sharp increase in P-wave velocity due to saturation. For cohesive material, the effect would be due primarily to the reduction in shear velocity, which results in a direct reduction in boundary wave velocity.

Physical Characteristics of Storage Tanks

The effects of tank leakage, and the ability to measure these effects, will depend on the tank dimensions and its construction. Large aboveground storage tanks are typically cylindrical, flat bottomed and resting on ground. The tanks of interest here have diameters ranging from 30 to 200 ft., and heights ranging from 24 to 64 ft. Tanks are typically concrete or steel. Steel tank bottoms are made of rectangular plates with a minimum thickness of 1/4 inch. Concrete tank bottoms range in thickness from 6 to 15 inches, and are reinforced.

Tank bottoms are supported by a sand pad and/or a base of compacted granular material. The sand may be oiled, and a layer of asphalt paving mix may be placed immediately below the tank bottom. More sophisticated foundations are used to accommodate large tanks and weak soil conditions. A common feature is a ringwall to support high loads under the tank shell. Other possibilities include use of compacted rock fill, a concrete slab, and pile foundations.

The leak detection concept evaluated in this paper is based on the effects of leakage on the tank foundation materials. Leaks from the bottom of a storage tank are caused by corrosion and weld failure. Leaking tank products flow through the permeable foundation material into the less permeable fill or native material, where they establish a saturation plume whose shape depends on the nature of the material. This saturation plume is an anomaly which can be detected by measuring its influence on boundary waves propagated across the tank bottom.

The following section describes field experiments which verify the basic premises of this leak detection concept.

PRELIMINARY EXPERIMENTS

Preliminary field experiments were carried out to investigate two aspects of the leak detection concept: (1) the influence of soil moisture on boundary wave propagation; and (2) the ability to generate and propagate boundary waves under storage tanks. The following paragraphs describe these tests and their results.

Instrumentation

Seismic waves were generated during this study using the blow of a 3 lb. hammer against a circular steel plate (8 in. in diameter and with a thickness of 3/4 in.) resting on the ground. Other sources were investigated during this study in an effort to maximize the signal and its repeatability, and to generate the highest frequencies. The choice of these sources was based on studies by Pullan et. al. (1986). The investigation of sources revealed that the hammer blow on the metal plate provided convenience along with the highest frequency content and a high level of repeatability (correlations ~0.96).

A string of twelve 28 Hz vertical axis geophones were used as receivers. The seismic signals were triggered by a hammer switch, transmitted through a multiconductor cable and conditioned through a custom-made bank of PC controlled amplifiers and filters. The conditioned signals were then acquired and digitized using a PC based A/D board. The digitized data was saved and used subsequently in the computational analysis. Figure 3 shows the components of the data acquisition system used in this work.

Figure 3 - Components of the Geophone Data Acquisition System

Linear Array Tests

A series of field experiments were conducted to investigate the effect of water infiltration on boundary wave propagation. These experiments were conducted on open fields using a linear array of geophones, and water was introduced into the ground midway in the array. The waves generated under these conditions are Rayleigh waves, but their sensitivity to soil conditions is similar to that of the boundary waves that would be generated under a tank. For these tests the geophones were placed in a straight line and 5 feet apart. The source was placed 20 to 30 feet away from the first geophone and a area between two geophones (eg. 5 and 6) was chosen for saturation. Data was collected before and after the addition and penetration of water into the ground. The following is a description of a typical experimental procedure.

An area for water infiltration was prepared. This preparation included building a 4 ft. diameter berm to contain the water, and, drilling holes in the ground with a power auger to expedite water infiltration. Seismic wave propagation measurements were made after this preparation, but, before the introduction of water. The bermed area was then flooded with water after the initial measurement, and the water was allowed to permeate into the ground. The effect of progressive saturation was monitored by subsequent seismic measurements carried out after the penetration of 15, 30, and 40 gallons of water.

A comparison of the data acquired before and after water infiltration indicates a delay in the waves arrivals produced by the water. The effect was quantified by correlating the waves arrivals generated before and after the water addition. Figure 4 presents the superposition of typical Before and After linear array data, along with the results of the Before and After correlation. Note that the correlation coefficients decrease for the geophones beyond the water saturated area.

Figure 5 shows a typical results for a linear array test. The Figure represents the change ir correlation coefficients between the seismic data before and after water was added to the ground. The correlation was measured by comparing these cases with the control case, representing the repeatability of the measurement before any water was added. The percent change in correlation coefficient was computed as

$$\% \text{ Change} = [(CC_{bb} - CC_{ba})/CC_{bb}] \times 100 \qquad (1)$$

where CC_{bb} represents the repeatability of the measurement in the before condition as waveform correlations on repeated measurements, and CC_{ba} represents the correlation of the "after" waveforms with the "before" waveforms. This measure was used to separate the repeatability issue from the influence of the addition of water. The results in Figure 5 show a sharp divergence in the % change after the saturated spot. The effect is quite evident in the data collected up to 25 feet beyond the saturated spot. Beyond

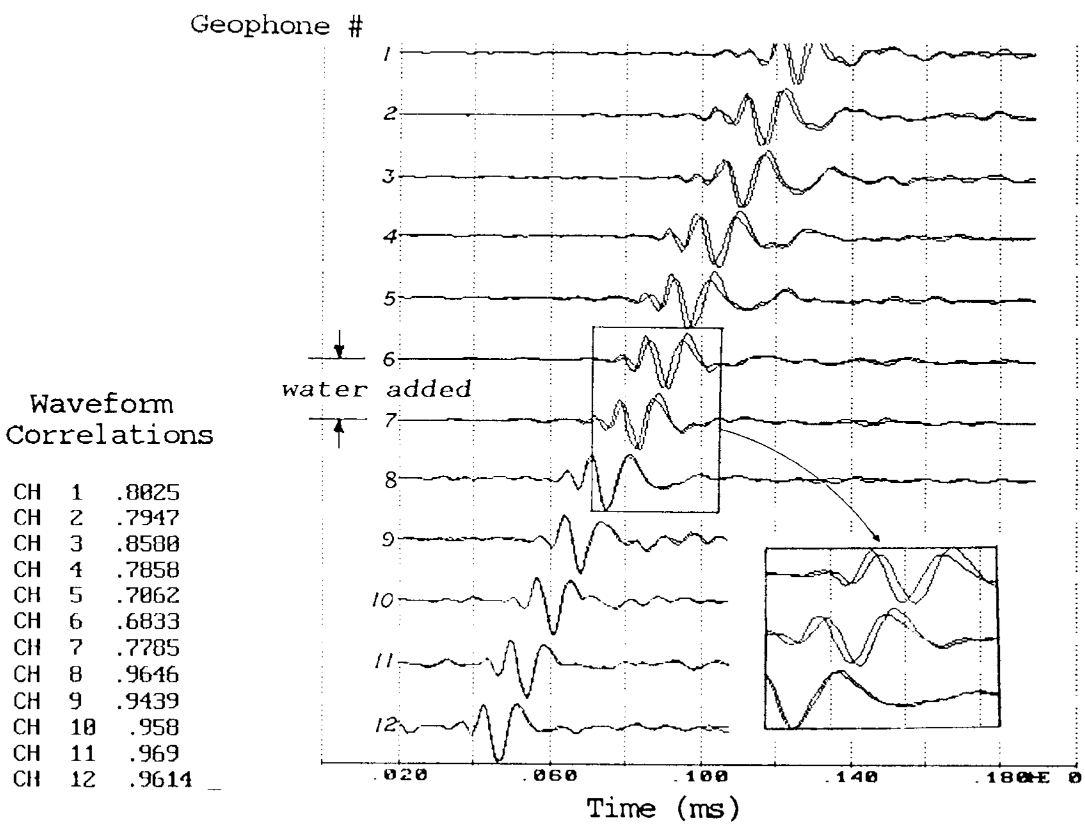

Figure 4 - Linear Array Data Showing Results Before and After Water Addition

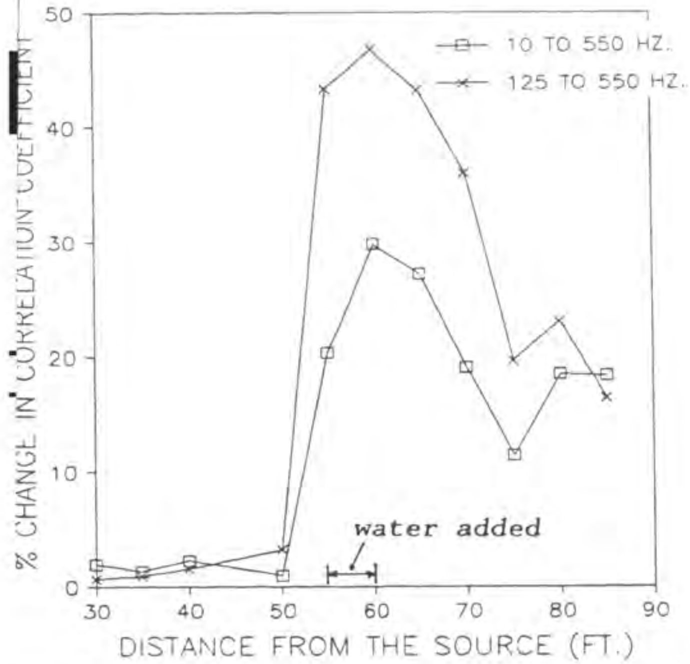

Figure 5 - Change in Waveform Correlation Due to Water Addition

that, a process of wavefront healing appears to take place. This can potentially be a problem in tanks exceeding 60 ft. in diameter, where the leak area is far from the measurement location.

Tank Tests

The objective of these experiments was to assess the ability to generate and propagate boundary waves considering variations in design, material, size, and substructure of storage tanks. The tests were carried out on four in-service storage tanks. The measurement technique is described below.

The circumference of the tank was divided into 36 stations, each station 10 degrees apart from the other. A string of 12 geophones was placed at 12 adjacent stations. The metal plate (source) was placed at a station opposite the middle of the geophone string at the opposite side of the tank bottom. After collection of the data at this location the source was moved to each of the 3 adjacent stations on either side and the test was repeated. To completely cover the tank bottom, the geophone string was relocated around the tank bottom. A description of the tanks and their foundations are given in table 1.

Figure 6 shows the hammer blow initiation of the boundary waves. Figure 7 shows the plot of typical data collected using this storage tank array.

Based on the above experiments, it was concluded that it is possible to propagate waves under the tank and variation in sub-structure design is not a limiting factor for the test.

Table 1 - Properties of Field Tested Tanks

Tank #	Content	Diameter (ft.)	Wall & Bottom Material	Foundation
1	Water	118	Concrete	Crushed Stone
2	Water	93	Steel	Concrete ring wall, 1" sand on 4" asphalt imp. sand
3	Gasoline	60	Steel	10" sand on 15" concrete pile cap
4	Diesel Fuel	48	Steel	Compacted Crushed Stone

Figure 6 - Hammer Blow Wave Initiation

LEAK DETECTION USING TOMOGRAPHY

Results presented in the previous section confirm the ability to propagate and detect Stoneley type boundary waves along the bottom of above-ground storage tanks. They also confirm that waves of this type will be significantly affected by the localized infiltration of fluid into the soil adjacent to the boundary. The following sections present the methodology behind the non-intrusive tank leak detection system using seismic imaging or tomography.

Tomography Algorithm

Researchers, especially in medicine, have developed algorithms to construct images of objects from "projections" of electromagnetic and ultrasonic waves. Projections represent the accumulated physical properties (ie., propagation velocity, attenuation, etc...) along the wave propagation path from source to receiver. Iterative algorithms are used to solve the large systems of linear equations that arise in reconstructing an image from these projections.

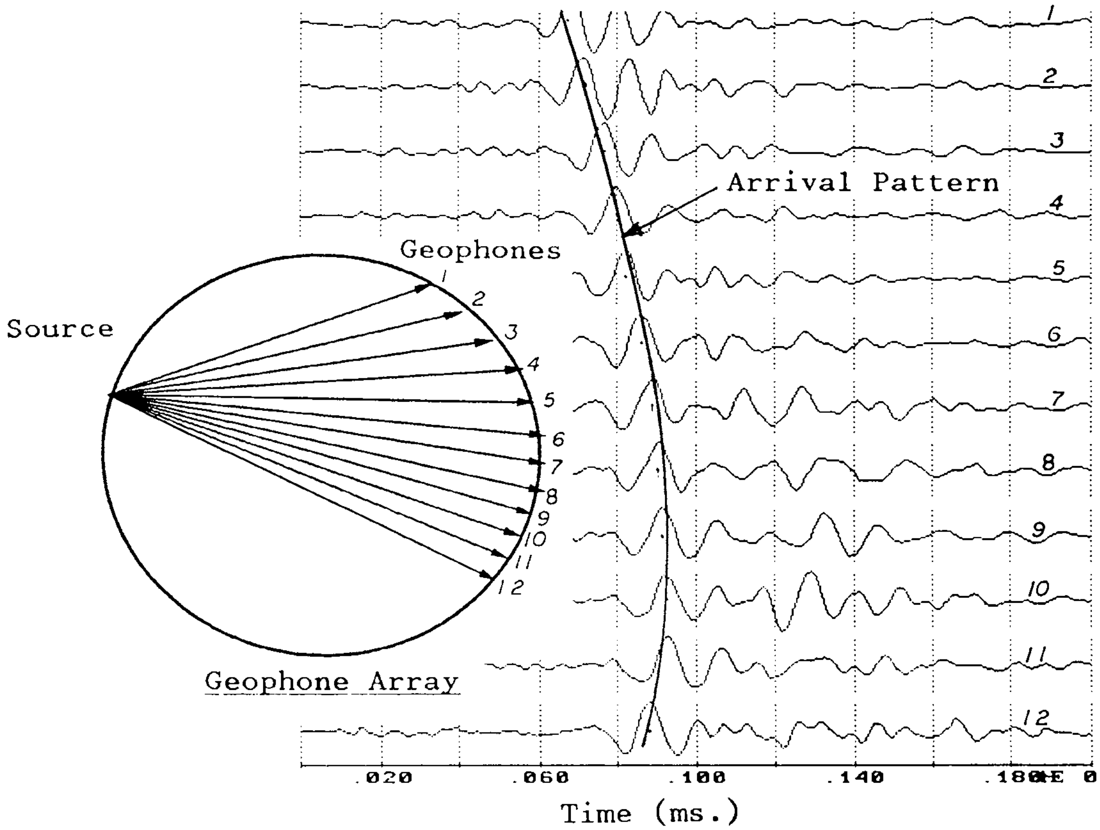

Figure 7 - Wave Arrival Pattern for Typical Geophone Array

Similar image reconstructions can be made with seismic waves, as described in the literature (Carrion 1987, Noelt 1987). The following summarizes those aspects of seismic tomography which are directly related to the leak detection problem using boundary waves.

The most commonly employed parameter in reconstructing an image using seismic tomography is the relative delay of a seismic wave. Using ray theory, the travel time or delay of the ray as a line integral over the ray path can be predicted.

The proposed tank tomographic system incorporates linear ray tracing algorithms in conjunction with a network of square cells. The velocity of the wave in each cell is calculated from the arrival time of the rays traversing these cells as described below.

Figure 2 presented earlier, shows the typical geometry used for the tomographic survey of tanks. The seismic source is located at various positions at the perimeter of the tank, while the receivers are deployed in an array around the tank. The source/receiver layout results in a characteristic fan-geometry. As discussed earlier a hammer can provide a signal with adequate power to conduct such a tomographic survey.

Let s(j) be the unknown "slowness" function (slowness is the inverse of velocity) for each cell j. Suppose there are i data values, ie., first arrival times, which we denote using the vector T(i). They are obtained for different source/receiver locations. Assuming linear ray paths, and ignoring the effects of diffraction, each T may be calculated using the following relationship:

$$As=T \qquad (2)$$

where A is an i x j matrix whose elements A(ij) denote the path lengths of the ith ray in the jth cell. The above system of linear equations may be inverted to uniquely determine individual slowness in each cell.

Under real conditions, the assumption is that instead of T, a vector b is available, which represents measured arrival times including measurement errors. Therefore, the problem, is then to determine a vector x from the set of equations, where x is an approximation of the slowness vector s.

$$Ax=b \qquad (3)$$

Usually, this set of equations is sparse, strongly overdetermined, and inconsistent. Since there is no exact solution, a least squares solution is sought after, which would minimize the least square error associated with

$$||Ax-b|| \qquad (4)$$

A standard FORTRAN mathematical library routine was used to determine the least squares solutions required to invert the above system of equations.

Field Procedure

The tank tomography method was tested in an open field in Lawrence, Massachusetts. The experiment was performed on a 36' diameter circular area simulating the area under a tank (see Figure 8). The site was chosen because of its favorable surface wave propagation characteristics, ie., minimum amount of dispersion and little overlap of reflected P and S waves on top of the desired surface wave. As with the linear array experiments, Rayleigh waves were used to represent the more general boundary waves which would be present under a tank.

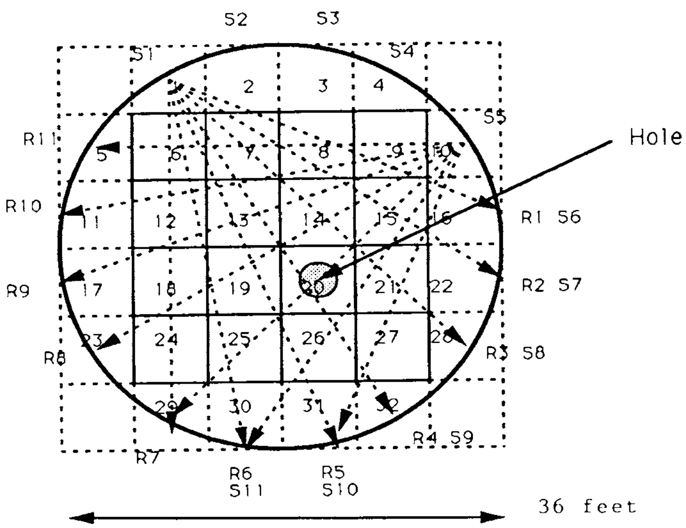

Figure 8 - Tomographic Layout for Field Test

The receiver/source locations (R1-11,S1-11) were carefully marked and the receivers were placed at the locations indicated in Figure 8 on the perimeter of the area. A three pound hammer was used to excite seismic signals. The geophones (11 were used here) and data acquisition system was the same as that described earlier for the linear array and tank tests. Each tomographic survey consisted of recordings obtained from 33 hammer blows (stacking 3 hammer blows per source location). The signals were recorded at a sampling rate of 4kHz. The data from each of the 54 ray paths was analyzed to determine the surface wave arrival times.

The tomographic survey was repeated five times as follows: (1) prior to any disturbance; (2) after a 5 x 5 x 0.5 ft. deep hole was then dug at cell 20; (3) after 50 gallons of water were placed in the hole, and about 20 gallons had penetrated into the ground; (4) after 100 gallons had been poured into the hole, and about 40 gallons had penetrated into the ground; and (5) after the 100 gallons had permeated through the ground, leaving an empty hole.

The above surveys were conducted over a 5 day time span. To measure environmentally induced variations in the surface wave velocity, the velocity of a propagating surface wave was measured with a linear array. These tests revealed a 5% change in wave velocity over the 5 day span, probably due to time variations in moisture content of the surface soil. This variation introduces errors in the tomographic analysis which is seeking to identify temporal changes due to leakage in an otherwise uniform condition. It was assumed, however, that the "noise" associated with this background variation would not drown out the pertinent results.

Detection of Arrival Times

Arrival times were determined by noting the arrival time of the first significant peak in the seismic records. 1.5 ms was subtracted from the arrival time of this peak to compensate for the electronic delay associated with triggering the data acquisition system. This was because the surface wave arrives 1/4 cycle before the onset of the first significant peak. The shape of the initial pulse did change from receiver to receiver due to dispersion. However, it was determined that over the distances involved, the arrival times could still be measured relatively accurately (+/- 1 ms) by noting the arrival time of the first peak.

Summary of Results and Discussion

The velocity profiles were calculated for each of the cells using equation (4). The calculated velocity for each cell changes randomly between the surveys due to measurement error and the mean velocity change mentioned above. However, the velocity of cell 20 shows a distinct reduction associated with the introduction of water into the hole at cell 20 (see Figure 9). Results from the intermediate surveys show that this velocity reduction becomes more pronounced as more water penetrates into the ground.

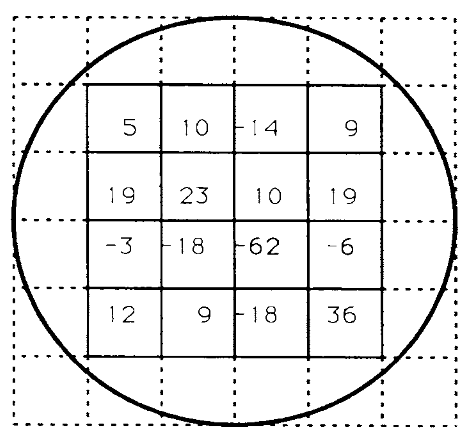

Figure 9 - Computed Change in Cell Velocities (ft./sec.) Due to Water Infiltration

The results presented above indicate that a simple tomographic model applied to surface wave arrivals is capable of detecting surface moisture anomalies in soils. When applied to leak detection in tanks, the procedure can be used to detect leaks by conducting tomographic surveys at regular time intervals. Because of the presence of the tank, changes in foundation properties related to weather, as experienced in this test, would not be of concern.

The simple ray model exploited in this research ignores the effect of ray-bending, dispersion, and diffraction as the seismic waves propagate through soil. For example, the determination of arrival times is complicated by a combination of random errors associated with the measuring process and errors related to the inadequacy of the ray model. Numerical calculations conducted by Wielandt (Wielandt, 1987) show that diffraction effects become more pronounced as the receiving transducer is separated by a larger distance from the anomaly. This phenomenon was confirmed in the linear array experiments conducted herein. For the 36 ft. diameter tomographic experiment conducted in this research, the anomaly was reasonably close to the receivers. Therefore, the diffraction effects described by Wielandt did not significantly distort the measured arrival times. However, for large tanks, with diameters greater than 60 feet, these effects may become significant requiring more robust modelling.

CONCLUSIONS

The objective of this work was to verify a seismic boundary wave technique for detecting leaks in large above-ground storage tanks. The three issues addressed were: (1) can the waves be propagated under a tank and clearly detected on the opposite side; (2) does the saturation of the foundation soil produce an anomaly significant enough to be measured; and (3) can the anomaly be detected and located using multiple source/receiver arrays? The answers to these questions have all been positive. Specifically, the work has produced the following conclusions:

1) Seismic boundary waves can be propagated along the bottom of typical storage tanks using a simple hammer blow source, and can be clearly sensed using conventional geophones.

2) Surface soil saturation causes a transmission anomaly in boundary (Rayleigh) wave propagation which can be clearly detected.

3) The location of a saturated area in a circular tank bottom geometry can be determined using tomographic reconstruction based on multiple source/receiver data.

These conclusions confirm the feasibility of the proposed leak detection technique. Certain complications may arise when dealing with leaks in real tanks, such as the potential loss of resolution with larger size tanks. This and other issues can only be resolved with further evaluation on tanks with known leakage.

ACKNOWLEDGEMENTS

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REFERENCES

Carrion, Phillip, Inverse Problems and Tomography in Acoustics and Seismology, Penn Publishing Co., Atlanta, GA, 1987.

Ewing, W.M., Jardetzky, W.S., and Press, F., Elastic Waves in Layered Media, McGraw-Hill, 1957.

Halabe U. B., "Detection of Leakage From Large Storage Tanks Using Seismic Boundary waves", thesis submitted for the degree of Master of Science in the Dept. of Civil Eng. MIT, 1987.

Kaelin, J.J., "Evaluation of underground Liners and Barriers Using Guided Seismic Waves," thesis submitted for the degree of Master of Science in the Department of Civil Engineering, MIT, May, 1986.

Krey, T.C. "Channel Waves as a Tool of Applied Geophysics in Coal Mining," Geophysics, Volume 28, Number 5, 1963.

Madanat, S., Halabe, U.B., and Maser, K.R., "Leak Detection in Large Storage Tanks" Massachusetts Institute of Technology, Center for Construction Research and Education, 1987.

Maser, K.R. "Leak Test for Liquid Containment" U.S. Patent No. 4,000,621, October, 1987.

Miklowitz, J., Elastic Waves and Waveguides , North-Holland Publishing Company, 1978.

Pullan, S.E., Miller, R. D., Waldner, J. S., "Field comparison of shallow seismic sources", Geophysics Vol. 51,, No. 11, Nov. 1986.

Staecker,P.W. and Wang, W.C., " Propagation of Elastic Waves Bound to a Fluid Layer Between Two Solids, " Journal of the Acoustical Society of America, Volume 53, Number 1, 1973.

Wielandt, E., "On the validity of the ray approximation for interpreting delay times" in Seismic Tomography With Applications in Global Seismology and Exploration Geophysics. Noelt, Guust (Ed.), D. Reidel Publishing Co., Dordrecht, Holland, 1987.

Wu S., Gray D.H., Richart F.E., Capillary Effect on Dynamic Modulus of Sands and Silts", Journal of Geotechnical Engineering, Vol. 110, No. 9, Sep. 1984, PP. 1188-1203.

Yoder E.J., and Witczak M.W., "Principles of Pavement Design", 2nd. Ed. 1975.