AE Source Location Using Neural Network on AE Evaluation of Floor Conditions in Above-Ground Tank*

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Abstract

Present study reports acoustic emission (AE) technique to evaluate corrosion damages of bottom plates (floor conditions) in above-ground tanks. Artificial AE signals were generated by pencil lead breaks at arbitrary locations on the bottom of a tank (300 kL in capacity) to investigate accuracy of AE source location. Attenuation of AE waves was shown to be very small in liquid. AE source location analysis was conducted, using a neural network (NN). Input and output units of the NN were arrival time differences between four AE sensors and coordinate of the AE source location, respectively. Arrival time differences of AE waves were determined by visual observation of the first signal arrivals and threshold crossing times of the AE signal normalized by its peak amplitude. It was concluded that accurate AE source location can be obtained by the decision process resulted from automated readings of threshold crossing time, based on the NN trained method by theoretical calculation.

Key words: Above-Ground Tank, Acoustic Emission, AE Source Location, Neural Networks

1. Introduction

Development of techniques to evaluate corrosion damages of bottom and annular plates (floor conditions) in above-ground tanks is strongly requested to protect environment from contamination caused by leakage of hazardous products due to the corrosion. Time-based maintenance has been legally required in Japan for tanks with storage capacity greater than 1,000 kL. However, it has been shown that even a strict “intelligent” time-based regime based on past history does not guarantee that no failures will occur in service. Reasons for failure include the inadequacy of the inspection methods used, and change of conditions inside the tank, leading to increased corrosion rates.

It is obvious that the biggest failure of time-based maintenance is that enormous resources are wasted in opening and cleaning tanks for inspection, when there is nothing wrong, and no repairs are needed. Since early 90's a database on Acoustic emission (AE) evaluation has been developed in Europe by opening and inspecting tanks after AE testing

in order to inspect tank floor condition⁽¹⁾. The method uses sensitive AE sensors on the outside of the tank to listen to the sound (AE) resulting from corrosion of the floor. It has been widely used as a cost-effective maintenance tool, proven by its use on more than 10,000 tanks. More than one thousand tanks have been tested annually for these years worldwide.

AE testing based on database consisting of the test procedure and evaluation criteria has been widely used in the world as a standard test method for evaluation of floor conditions in above ground tanks⁽²⁾⁻⁽⁴⁾. The test procedure was introduced to the Japanese industries in 1999. Since then, AE database for data evaluation has been developed to meet the Japanese regulation for tank maintenance. In addition to fundamental studies in laboratory, field applications have been made by several organizations. More than 160 tanks have been tested on the basis of the test procedure. After the AE tests, tanks were opened and thickness data based on discrete point measurements have been collected. Good correlation has been found between AE activity and corrosion risk parameter (CRP), representing corrosion rate, resulted from the statistic analysis of the thickness data. Recommended practice was issued by High Pressure Institute of Japan (HPI) in 2005, based on the AE database and the thickness database⁽⁵⁾.

Present study deals with AE technique to monitor and evaluate the leakage or corrosion. Leakage on bottom plate of a tank was detected using AE by Yang et al.. They suggested that only the stream that is crossing the steep velocity gradient in the vicinity of the hole edge will produce AE bursts⁽⁶⁾. Park et al. confirmed that active corrosion under low pH conditions can be detected using AE technique and there was a positive relation between AE activity and corrosion rate⁽⁷⁾.

Source location gives important information for the evaluation of the AE data. However, accuracy and reliability of the location based on the conventional method have not been discussed much so far. AE sources using punch percussion were located by Cho et al. at the bottom of empty storage tank with diameter of 33 m⁽⁸⁾. Arrival time differences of asymmetric A_0 mode Lamb wave traveling in the bottom plate were used to locate AE sources in their study.

AE source location technique based on a neural network (NN) in bottom plate of an above-ground tank is proposed in the present study. AE signals due to corrosion are often generated on external side of the bottom plate where significant thickness losses are observed. Since source location gives useful and important information for data evaluation, two-dimensional AE source location on the bottom plate has been carried out in this study, using artificial AE sources. Artificial AE signals were generated by pencil lead breaks at several locations on the surface of bottom plate in a tank (300 kL) filled with water to investigate an accuracy of predicted source location. Two dimensional locations of AE sources were calculated using a NN. AE waveforms detected by four AE sensors mounted on side wall of the tank were recorded in an AE equipment. Arrival time differences from an AE source to each sensor were used for input data of the NN. There are some structures (heat pipes and a roof suspension pole) inside tank, which may cause considerable errors in location calculation. The NN, however, may avoid this type of errors, because of robustness of the NN. Therefore, two kinds of arrival time data are used for the NN training: (1) theoretical data calculated by wave velocity in water, (2) experimental data obtained from artificial AE waveforms. In the first analysis, AE source location was made by the use of different training data to investigate the influence of the inside structures on the calculation error in the tank. In the second analysis, arrival times of wave-front were determined by both visual observation (manual) and threshold crossing times resulted from automated readings by the AE equipment for the detected waveforms normalized by its peak amplitude. The results are compared in order to discuss source location errors.

2. Acoustic Emission Measurement

2.1 Experimental Procedure

An above-ground tank out of service was prepared by Japan Energy Corporation (Fig.1). Diameter, height, capacity, thickness of the bottom and wall are 7.60 m, 7.43 m, 300 kL, 8 mm and 6mm, respectively. Water was placed to 45cm in height to insure propagation of longitudinal AE waves (P-waves) in water. Artificial AE sources by pencil lead breaks were produced on the internal surface of the bottom plate of the tank. Sensor arrangement and AE source locations are shown in Figs. 2 and 3. Four PAC R3I AE sensors (resonant frequency: 30 kHz.) were attached with magnet holders on the side wall of the tank at 0.35 m in height from annular plate. Couplant (Silicon grease) was placed between the sensor surface and the tank surface to insure a good contact for wave transfer. An AE equipment (μ DISPTM, PAC) was used to record acoustic emission signals detected by the AE sensors. AE was generated by pencil lead breaks at 73 locations on the surface of bottom plate in the tank to investigate accuracy of predicted locations. In some sources, a sensor was mounted on the bottom plate beside the source as a trigger sensor to investigate wave modes (ch 5 in Fig. 2).

Fig. 1 Above-ground tank.

Fig. 2 Sensor arrangement.

Fig. 3 Artificial AE source.

2.2 Propagation of AE Waves in Tank

Since AE waves must be detectable and arrival times of the waves must be readable for AE source location, the attenuation of AE waves during propagation in tank must be small to obtain meaningful data. AE waves due to pencil lead breaks propagate both in the

bottom plate and liquid. The AE waves traveling in the bottom plate exhibit three types of waves (P-wave, S-wave and A_0 mode of lamb waves in thin plate (first mode of anti-plane lamb wave)), while only one wave (P-wave with less attenuation) in liquid, respectively (Fig. 4).

A trigger sensor was mounted near the artificial AE source. AE signals were acquired at the locations of ch 1 - ch 4 (Figs.2 and 3). Arrival times of the waves traveling from an AE source to each sensor were calculated by theoretical wave velocities for the waves that propagate in the bottom plate and side wall, and for those that propagate in water. To investigate effect of the attenuation on AE waves, propagation characteristics of AE waves in both empty tank and one filled with water were compared.

2.3 Acoustic Emission Source Location

It is known that there are two methods to locate AE sources. One is to use arrival time differences between AE sensors ⁽⁸⁾⁻⁽¹³⁾. The time differences are obtained by reading arrival times of detected AE signal at each sensor in the same event set. The other one is based on the dispersive nature of Lamb waves ⁽¹⁴⁾⁽¹⁵⁾. Estimation of source location is possible since predominant Lamb wave modes are proved to propagate in different velocities. This method is only applicable under low noise environment with small attenuation during the wave propagation.

It has been shown experimentally that the attenuation of AE waves during propagation is smaller in liquid than in the bottom plate. Thus AE waves that propagate in liquid have been focused in this study for AE source location based on the arrival time differences. Two-dimensional AE source location using arrival time differences was proposed by Venkatesh et al. using a NN approach ⁽¹¹⁾. In our previous research, errors in AE source location were evaluated. It has been confirmed that the NN approach provides better solution than that based on theoretical and iterative operation using least-square methods ⁽¹²⁾. Moreover, it was shown in our previous work that corrosion sources can be located by the use of the NN ⁽¹³⁾. Thus the NN is applied to locate AE sources on the bottom plate of a tank filled with water.

3. Neural Network

3.1 Architecture of Neural Network

In the proposed source location using the NN, a multilayer feed-forward NN trained by a back-propagation algorithm was used and a sigmoid function was applied as the activate function of each node. Preliminary experiments were conducted to find suitable network architecture. The NN consists of four input nodes corresponding to the time differences arrived to each sensor and two output nodes corresponding to location on the bottom plate of the tank (Fig. 5). Hidden nodes and layers were empirically set to 5 and 4, respectively. Thirty-seven and thirty-six location points were used for the NN training and non-training location, respectively. Both trained and non-trained location points are shown in Fig. 6.

3.2 Training Data Set Preparation

Heating pipes (diameter : 48.6 mm) for circulation of heated oil are installed at the 20 cm - 26 cm in height on the bottom plate of the tank. A center pole (channel steels (150x75x6.5 and 125x65x6 mm) intersecting each other by tack welding) is installed in the tank to support the roof, as shown in Fig. 7. Investigation of influence of the heating pipes and the center pole on the arrival time is necessary in addition to the analysis of wave path in water. The arrival time of the wave can be easily obtained by the use of the theoretical wave velocity in water and the actual distance between an AE source and each sensor if the existence of the pipes and the pole has no influence on the wave path. To confirm this, the AE sources were generated at different locations and the results were compared using the NN training data prepared by different way of training. Arrival time differences for the

NN training were prepared as follows: (1) Arrival time differences between an AE source and each sensor were calculated by using the theoretical wave velocity and the distance mentioned above; (2) Arrival time differences between an AE source and each sensor were calculated by the use of the arrival times of artificial AE waveforms with visual observation. In order to train a network, normalized arrival time differences and normalized two-dimensional coordinates were used for input data and output data, respectively. Thirty-seven NN training location points are shown in Fig. 6 (a).

3.3 Input Data

Input data for the NN to locate AE sources from arrival times of AE waves were determined from rise time of artificial AE waveforms in the following manners: (1) using visual observation, (2) using predetermined threshold value for normalized AE waveforms. A suitable threshold level was determined by preliminary experiments. Thirty-six non-training location points are shown in Fig. 6 (b). Both training and non-training points were used as validation data for the location to evaluate accuracy of the source location based on the NN.

3.4 Evaluation of Acoustic Emission Location Error

The output coordinate data are evaluated in terms of deviation of distance from the actual location. The equations are described in Eqs. (1), (2).

$$\text{Deviation of distance [m]} = \sqrt{(x-X)^2 + (y-Y)^2} \dots (1)$$

$$\text{Error [\%]} = \frac{\sqrt{(x-X)^2 + (y-Y)^2}}{D} \times 100 \dots (2)$$

Where, (x, y), (X,Y) and D are predicted location, location of an AE source, and the maximum distance between sensors, respectively.

4. Results and Discussion

4.1 Acoustic Emission Waveform traveling in Empty Tank and Water Filled Tank

Figures 8 (a), (b) and Figs. 8 (c), (d) show detected AE waveforms at ch 1 and ch 3 due to the artificial AE source at point A in Fig. 3 for the empty tank and the tank filled with water. The distances between the AE source (source A) to ch1 and ch3 are about 2m and 6m, respectively. Arrival times of waves traveling each path shown in Fig. 4 were calculated from theoretical velocities of P-wave (5950 m/s), S-wave (3240 m/s), A_0 mode of lamb wave (2500 m/s) in steel and P-wave in water (1500 m/s). P-wave, S-wave, and A_0 mode of lamb wave might be discernable in the empty tank. The amplitude of A_0 mode should be detected if the distance between the AE source and a sensor is small. However, it should be difficult if the distance is great (Fig. 8 (a), (b)). In the RMS amplitudes for

Fig. 4 Wave path of AE Propagation.

Fig. 5 NN structure for AE source location.

Fig. 6 Location points.

Fig. 7 Position of heating pipes to circulate oil and a center pole.

duration of 3 msec from rise up time, the amplitude ratio of ch3 to ch1 was 0.15. On the contrary, the amplitude ratio of ch3 to ch1 in the water filled tank was 0.71 (Fig. 8 (c), (d)). The amplitude of any waves traveling in the bottom plate of the tank filled with water decrease significantly in comparison to the empty tank because of dispersion of AE energy into water. Since P-wave propagating is dominant over all the other waves in water, RMS amplitudes of P-waves for duration of 3 msec from rise up time were extracted to the analysis.

These results suggest that the AE source location can be performed in above-ground tanks in service by applying the technique of measuring the P-wave in oil, insofar as the AE waves can be detected clearly at each sensor placed on the side wall.

4.2 Effect of Neural Network Training on the Location of Acoustic Emission Source

The training procedure of the NN is discussed to investigate the influence of structures installed inside the tank. Arrival time differences for training data were provided by: (1) theoretical calculation using physical properties and geometry of the tank, (2) experimentally obtained arrival times of P-wave propagating in water. Arrival time differences by visual observation due to artificial AE waveforms were used for validation of NN input data. Arrival time by visual observation was determined as the arrival time of wave front with large amplitude because P-wave in water is greater than any other waves as shown in Fig. 8.

Results of the NN location for both deviation from the actual location and its error resulted from the NN are shown in Table 1. (a), (b), (c) and (d) in Table 1 correspond to (training : theory in Fig. 6-(a) and validation : experiment in Fig. 6-(a)), (training : experiment in Fig. 6-(a) and validation : experiment in Fig. 6-(a)), (training : theory in Fig.

6-(a) and validation : experiment in Fig. 6-(b)), and (training : experiment in Fig. 6-(a) and validation : experiment in Fig. 6-(b)), respectively.

Error in the case of (b) in Table 1 was smaller than that in the case of (a) for trained location points, because the case of (b) includes the training data. As for non-trained location points, maximum error in the case of (c) is larger than in the case of (d). Minimum error and average error in the case of (c), however, are smaller than that in the case of (d). Frequency of deviation for distance from the actual location is shown in Fig. 9. The distance data in Fig. 9 exhibits the summation for each 10 cm. The location error less than 0.4 m, resulted from arrival times of AE waveforms, is larger than the error resulted from theoretical calculation. However, the ratio of number less than 0.6 m from arrival times calculated theoretically, and that resulted from the arrival times by AE waveform are 93.2 % and 95.9 %, respectively. Thus the ratios of number for less than 0.6m are almost the same in the theoretical calculation and experimental results based on waveforms. In practical use, this range of accuracy (60 cm x 60 cm) in source location should be good enough to perform further follow-up inspection for detailed information of the damaged area. It is because floor scan inspection, for instance, is usually performed for larger than this size of area during internal inspection. These results indicate that it is unnecessary to take the influence of the internal pipes and poles on the arrival time into account. It can be also concluded that theoretical calculation of arrival time differences is effective as training data of a NN.

4.3 Comparison of AE Source Location using Different Threshold Level of Amplitude

Arrival time differences resulted from theoretical calculation have been used as training data of the NN. Arrival times for the validation data without training were obtained using the trigger time at different three threshold levels for normalized AE waveforms. The maximum, minimum and average errors of source location are listed in Table 2. From these results, it is obvious that error deviations are influenced by the threshold levels. The minimum value for the average error is obtained at 0.5 threshold value. Note that it corresponds to the ratio of the threshold level to the maximum wave amplitude. Taking the diameter of the tank (7.60 m) into account, the average error distance (0.41 m) is small enough for identification of the damaged area. Frequency of deviation from the actual location for three threshold levels is shown in Fig. 10. Precise data analysis revealed that the location errors for the distance over 2 m were due to the detection of unknown high noise (in the case of threshold 0.3) and the detection of reflected P-wave from opposite side of wall (in the case of threshold 0.8), respectively. The frequency distribution demonstrates the importance of selection of the threshold level. From these results, it is concluded that the threshold level of 0.5 is the most effective for accurate source location.

4.4 Comparison of AE source Location using Different Arrival Time Detection

The NN training data of arrival time differences are same as section 4.3. Arrival times for validation data were obtained from artificial AE waveforms. Both the time resulted from arrivals of the AE waveform by visual observation and that from the threshold crossing (threshold 0.5) were used. Validation data for evaluation were provided with all training and non-training location points. Differences between actual and predicted AE source locations are shown in Fig. 11. The maximum, minimum and average errors are given in Table 3. Frequency of distance error deviations is shown in Fig. 12. Accuracies of predicted location by visual observation are slightly higher than that from data acquisition by optimum threshold level. It is quite probable that the error from the measurement of threshold crossing time should be due to unexpected reflections of waves by surrounded boundaries except for reflection from the wall. Though visual observation

(b) Waveform recorded at ch3 in the empty tank.

(d) Waveform recorded at ch3 in the tank filled with water.

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Table 1 Deviation for distance from the actual location and its error: (a) Results for trained location based on the theoretical calculation using physical properties, (b) Results for trained location using P-wave arrival obtained experimentally, (c) Results for non-trained location based on the theoretical calculation using physical properties, (d) Results for non-trained location using P-wave arrival obtained experimentally.

Method	Maximum		Minimum		Average	
	Error (%)	Distance (m)	Error (%)	Distance (m)	Error (%)	Distance (m)
(a)	17.4	1.32	1.0	0.08	5.0	0.38
(b)	15.8	1.20	0.2	0.01	3.6	0.27
(c)	7.0	0.53	0.5	0.04	3.7	0.28
(d)	6.7	0.51	0.9	0.07	3.8	0.29

Fig. 9 Frequency of deviation for distance from the actual location.

Fig. 10 Frequency of deviation for distance from the actual location for different three threshold levels. Location errors over 2m are summarized at the 2m loci of abscissa.

Table 2 Errors of source location obtained by three different threshold levels.

Threshold	Maximum		Minimum		Average	
	Error (%)	Distance (m)	Error (%)	Distance (m)	Error (%)	Distance (m)
0.3	75.2	5.72	0.3	0.02	13.5	1.03
0.5	19.3	1.47	0.3	0.02	5.4	0.41
0.8	35.7	2.71	0.1	0.01	10.7	0.80

Table 3 Deviation of distance from the actual location and its error: (a) Results for all location points using arrival times obtained by visual observation, (b) Results for all location points using arrival times obtained by setting threshold to 0.5.

Method	Maximum		Minimum		Average	
	Error (%)	Distance (m)	Error (%)	Distance (m)	Error (%)	Distance (m)
(a)	17.4	1.32	0.6	0.04	4.3	0.32
(b)	19.3	1.47	0.3	0.02	5.4	0.41

Fig. 11 Results of AE source location for all location points.

Fig. 12 Frequency of deviation for distance from the actual location.

5. Summary

Artificial AE waves generated on the surface of the bottom plate of the tank propagate in two different media. P-wave, S-wave and the lamb wave propagate in the bottom plate, while P-wave released into liquid propagates in liquid. The present study has revealed that the amplitude of A_0 mode of lamb wave traveling in the tank filled with water is small, as compared with that of empty tank. It has been also found that the P-wave with less attenuation during traveling in water is easy to detect even for long traveling distance. This indicates that P-wave propagating in liquid is proper wave mode for determining the arrival time in the tank filled with liquid. Influence of structures (pipes and a pole installed inside the tank) on the arrival time has been examined in the present source location analysis. It was confirmed that the influence of the structures was small, and arrival time differences calculated theoretically are effective as training data of a NN. This fact indicates that practical training of the NN can be made theoretically before testing without experimental AE data. Accuracy of source locations was compared between arrival times resulted from visual observation and those from threshold crossing of AE waves normalized by its peak amplitude. It has been concluded that accurate AE source location can be made by automated reading of threshold crossing time, using the NN trained method based on the theoretical calculation.

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