AE Monitoring Corrosion-induced Deterioration of Reinforced Concrete Piles in The Simulated Marine Environment

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Abstract. An experiment study was conducted to assess the effectiveness of acoustic emission (AE) technique monitoring the corrosion-induced damage in the marine environment. Three reinforced concrete (RC) piles of 1600 mm long by 200 mm square were casted and then were exposed in a simulated marine environment to reach 5%, 10% and 20% of steel rebar mass loss respectively. Throughout the whole test period, all specimen was monitored by three AE sensors installed at two different heights of the concrete surface and at the end of the steel rebar, respectively. The AE activities were analyzed to determine corrosion-induced deterioration at different corrosion levels. Based on the finding, the effectiveness of AE technique on monitoring of RC piles of high-pile under aggressive marine environmental conditions was established.

1. Introduction
Damage induced by corrosion in reinforcing steel rebar is the main source of degradation of high-pile wharves exposed to marine environment [1]. In marine engineering, the most severely deteriorated segments of the wharves (Figure. 1) are the tidal and underwater zones of the piles that are supplied with adequate chloride, water and oxygen [2]. When active corrosion of reinforcement is initiated, the corrosion product (rust) started to expand leading to the reduced tensile strength of the piles [3]. This damage could further accelerate the corrosion process and decrease the bond effect of steel rebars with their surrounding concrete, which eventually may result in the problems of serviceability and the destruction of structural integrity [4].

Consequently, many researchers have made efforts to develop novel methods that have the potential to detect active corrosion in reinforced structures. Moreover, it is urgent to develop the quantitative non-destructive testing (NDT) methods in order to detect the corrosion degrees to assess remaining structural capacity of RC piles of existing marine structures [5].

Traditionally, corrosion monitoring based on half-cell potential and concrete resistivity are the most popular qualitative techniques to indicate the probability of active corrosion in marine RC structures [6]. Quantitatively, electrical data received from the NDT method such as LPR and AC impedance spectroscopy were used for estimating the corroded condition for a higher resolution [7]. These methods are assumed to be capable of identifying the corrosion process in an early corrosion stage. [8] However, factors including temperature, concrete resistivity, oxygen availability etc. would affect the accuracy of corrosion measurement. Additionally, these techniques need to be electrically or physically contacted with steel rebar, which is unavailable in real marine structures. Also, the aforementioned NDT methods are neither suitable for real-time monitoring or typically intrusive [9].
Recent years, the AE technique has been developed to be a powerful non-destructive monitoring method capable of providing early warning in comparison with the electrochemical techniques. The premise of corrosion monitoring by AE technique refers to that the release of generated elastic wave due to fracture of concrete induced by the corrosion activity in reinforcement can be effectively detected by AE transducers attached on the surface of concrete. There are several unique advantages of AE technique including the capability of real time and global monitoring, high sensitivity to the processes or mechanisms that generate stress waves and easy to employment. In addition, the characteristic of AE monitoring of utilizing energy generated by damage source does not need any supplying of external energy. These features enable AE technique as a non-destructive and reliable online monitoring method for localized corrosion induced damage of large-scale reinforced concrete piles in the marine environment.

To this end, extensive researches has been published on corrosion evaluation in RC structures. For instance, Li et al. [10] and Ohtsu et al. [11] utilized AE technique to monitor the corrosion initiation and cover cracks due to the expansion of rust in small-scale RC specimens. Similarly, plenty of experimental investigations exploited AE technique of RC specimens subjected to accelerated corrosion to monitor the corrosion process. Fewer studies focused on utilizing AE monitoring of corrosion in large-scale concrete components. Calabrese et al. [12] applied AE monitoring to identifying the progression of different damage induced by corrosion in large-scale prestressed concrete beams. Likewise, Vélez et al. [13] achieved an early recognition of corrosion in large-scale portions of prestressed concrete piles exposed to saltwater. The aforementioned literature, however, lacks investigations concerned with the AE monitoring of corrosion damage in large-scale RC piles. Moreover, the quantitative data about AE monitoring of corrosion damage progression in existing RC piles exposed to marine harsh environment are extremely limited. This research aims to evaluate the effects of AE technique of detecting localized corrosion in the large-scale piles subjected to the coupling effect between wet-dry cycle of artificial seawater and accelerated corrosion. The research also aimed at investing the influence of attached AE transducer location on the efficiency of corrosion damage detection. The outcomes from this research established a generalized frame for localized corrosion assessment of RC piles under the typical harsh marine environment using AE technique.

Figure 1. Corrosion zones of marine piles.

2. Experimental Test

2.1. Preparation of Specimens
Three reinforced concrete piles of 1,600 mm long and 180 mm square were cast to represent actual piles of the wharves widely used in coastal port engineering (Figure 2). In this study, compression reinforcement was made by four 8mm-diameter longitudinal steel bars and the depths of concrete cover was 20 mm with a space of 100 mm for the 6 mm-diameter plain stirrups. Each specimen is divided into
three zones among which the tidal zone is set with a range of 400 mm in the middle. The internal cathode was proved by a stainless hollow steel rebar mounted in the middle of the cross section to accelerate the corrosion process. All specimens were made from the same source of concrete with a mix proportion of 1: 1.13: 2.67: 0.41 by weight (cement: sand: gravel: w/c), which had a compressive strength (28 days) of $32 \pm 1.1$ MPa. The yield strength and ultimate strength of the compression reinforcement made by 10mm-diameter steel were 335 MPa and 445 MPa respectively. The yield strength and ultimate strength of the 6 mm stirrups were 240MPa and 380 MPa respectively. The specimen coded as A, B and C were corroded to reach 5%, 10% and 20% of the steel mass loss in a simulated marine environment respectively. Throughout the whole test period, three sensors were situated on each specimen with one transducer on the end of the intruded steel rebar and the other two on different positions of the concrete surface, the exact position of the sensors are shown in figure 2.

![Figure 2. Specimen geometry (mm).](image)

### 2.2. Accelerated Corrosion Technique

The accelerated corrosion technique used in this study was based on the Faraday’s law, aiming to reduce the time of the corrosion process to an acceptable time span. The designed electricity current in the test was $180 \mu A/cm^2$, which was provided by a constant-current system consisted of a direct current galvanostatic power supply. The time to different specimens with varied mass loss of reinforcement (degree of corrosions) was calculated by the Faraday’s law, for instance, the test time of specimen reaching 10% mass loss (pile B) was 40 days. In the accelerated corrosion test, all specimens were mounted in a tank full of manufactured sea water to create the artificial wet-dry cycles (tidal action). The water level in this test was fluctuated with a range of 40 to 80mm for every 6 hours to simulate the tidal action of the actual marine environment. Additionally, a heater was provided over the tank to change the environment temperature, varying from 24℃ to 41℃ in a single day, to simulate the varied temperatures in an actual marine environment.

### 2.3. Setup of Monitoring Systems

The AE instrumentation included AE sensor and preamplifiers that were connected by an AE system made by the Physical Acoustic Corp. (PAC) of USA. The used R15 transducers have a resonated frequency of 150 kHz. In the test, the sampling frequency and threshold level were set at 5 MHz and 40dB respectively, which are sensitive enough to attain corrosion-induced signals. The AE waveforms was amplified by a preamplifier with 40 dB.

### 3. Results and Discussion

#### 3.1. Classification of AE Sources
Peak frequency, which has the maximum magnitude of the frequency and is determined by the signals in frequency domain by fast Fourier transform (FFT) [10], was adopted herein as criteria to classify the raw AE sources. The peak frequency can be used to distinguish various AE sources resulting from reinforcement corrosion. Figure 3-4 represent the peak frequency of all raw AE hits throughout all the corrosion test from Sensor A3 (installed on the concrete surface of beam A) and A1 (installed at the end of the reinforcement of beam A), respectively, as an example for other sensors. Four major parts can be noticed: one bellow 30 kHz (type I), one around 50 kHz (type II), one near 150 kHz (type III) and another part higher than 200 (type IV). To be specific, for sensor A3, the majority of peaks (78%) frequency is lower than 50 kHz (type I and type II), while the proportions of type III and type IV are 12% and 9% respectively. The percentages of AE signals of type I-II, type III and type IV from sensor A1 are 39%, 53% and 8% respectively.

These four frequency bands are closely related to various AE source due to reinforcement corrosion. In this study, only the AE hits with peak frequency bellow 30 kHz were observed before the electrically accelerated corrosion test, meanwhile the only sources of AE events were the noises induced by the varied water level. Thus, signals of type I can be attributed to the influence of water level fluctuation. Weijie1 and Mazile [14] revealed that the AE hits with peak frequency of around 50 kHz were caused by the bubble evolution in the liquid medium. Thus, type II could be related the with the hydrogen bubbles from electrochemical reaction. Li et al [15] concluded that the typical signal from concrete crack had a peak frequency ranging from 275-350 kHz and Yoon’s work suggested that AE signals induced by both micro-cracking and macro-cracking have relatively high frequency with a range from 180 kHz to 350 kHz. In addition, Weijie [10] concluded that the AE hits with around 110kHz peak frequency were associated with corrosion products and Yoon [16] suggested AE signals from debonding were related to longer duration and frequency peak at 120 kHz. According to above references, it is reasonable to speculate that type III come from the movement and generation of corrosion products and reinforcement-concrete interface debonding while type IV was connected to the crack development and propagation.

3.2. Corrosion-induced Damage Identification
The curves of cumulative signal strength (CSS) were compared with a typical steel corrosion loss model in the marine environment (Figure.5). In this model, Phase 1 was the first part where the corrosion initiated. At Phase 2, inhibition of oxygen flow and reduction of the corrosion rate occurred because of the building up of corrosion products on the corrosion surface of steel rebar. Further corrosion loss caused by anaerobic corrosion involved in Phase 3 and Phase 4. The curves of CSS and Sr attained by all the sensors seemed to be consistent with the trend of the aforementioned phenomenological model, as shown in Figure.5. Similarly, a four-stages feature can be also distinguished from these curves:

![Figure 3. Peak frequency of Sensor A3.](image)

![Figure 4. Peak frequency of Sensor A1.](image)
(a) Phase 1 is characterized by low values of current density and steady increase of CSS curves, during which the concrete medium was modified because of the chloride ions diffusing and accumulating in the pore of concrete. The slow increasing of CSS values over this period means the de-passivation in the surrounding layer of steel rebar and the onset of corrosion. Additionally, it is noticeable there was a sudden rise at a later stage of this phase (around the 3rd day in the accelerated corrosion test) indicating the dramatic corrosion activities, which was confirmed by the observation of oozing of corrosion products.

(b) In phase 2, the corrosion products fractioned against the concrete pores accompanied with the development of micro-cracks. Moreover, the generation of the first visual crack resulted in another sudden rise of CSS curve at the end this stage. This phenomenon was confirmed by an apparent crack and many oozing of corrosion production distributing on the surface of the specimen.

(c) Phase 3 and 4 were the repetition of phase 2, during which further corrosion activities and more severe deterioration of the pile specimen happened.

4. Conclusion

In this study, the localized corrosion process of reinforced steel in three reinforced concrete piles was investigated in the simulated marine environment through acoustic emission technique. The feasibility of AE technique to detect the corrosion-induced concrete cracking is studied in a artificial marine environment.

It was found that the raw AE materials can be classified into four types according to the analysis of peak frequency which has the potential to distinguish various AE sources resulting from reinforcement corrosion. In addition, the curves of CSS attained by all the sensors seemed to be similar with the trends of the classical corrosion mode. What’s more, sudden changes in CSS curves at a particular locations can be a good indicator to detect the corrosion-induced damage of the piles (initiation of corrosion and generation of the first visual crack). This shows that AE is a powerful technique to monitor corrosion-induced deterioration of reinforced concrete piles under harsh marine environment.

References

[1] Kwon, Seung Jun, et al. (2009) Service life prediction of concrete wharves with early-aged crack: Probabilistic approach for chloride diffusion. Structural Safety, 31.1: 75-83.

[2] Suh, Kwangsuk, et al. (2007) Effectiveness of fiber-reinforced polymer in reducing corrosion in marine environment. ACI Structural Journal, 104.1: 76.

[3] Xia, Jin, Wei-liang Jin, and Long-yuan Li. (2011) Shear performance of reinforced concrete beams with corroded stirrups in chloride environment. Corrosion Science, 53.5: 1794-1805.

[4] Stewart, Mark G., and David V. Rosowsky. (1998) Structural safety and serviceability of concrete bridges subject to corrosion. Journal of Infrastructure systems, 4.4: 146-155.
[5] Abouhussien, Ahmed A., and Assem AA Hassan (2017). Acoustic emission monitoring of corrosion damage propagation in large-scale reinforced concrete beams. Journal of Performance of Constructed Facilities, 32.2: 04017133.

[6] Liang, Hongjun, et al. (2019) Electrochemical performance of corroded reinforced concrete columns strengthened with fiber reinforced polymer. Composite Structures, 207: 576-588.

[7] Luo, Dong, et al. (2019) A Recent Progress of Steel Bar Corrosion Diagnostic Techniques in RC Structures. Sensors, 19.1: 34.

[8] Kawasaki, Yuma, Yuichi Tomoda, and Masayasu Ohtsu (2010). AE monitoring of corrosion process in cyclic wet–dry test. Construction and Building Materials, 24.12: 2353-2357.

[9] Di Benedetti, Matteo, et al. (2013) Acoustic emission historic index and frequency spectrum of reinforced concrete under accelerated corrosion. Journal of Materials in Civil Engineering, 26.9: 04014059.

[10] Li, Weijie, et al. (2017) Monitoring concrete deterioration due to reinforcement corrosion by integrating acoustic emission and FBG strain measurements. Sensors, 17.3: 657.

[11] Ohtsu, M., K. Mori, and Y. Kawasaki. (2011) Corrosion Process and Mechanisms of Corrosion-Induced Cracks in Reinforced Concrete identified by AE Analysis. Strain, 47: 179-186.

[12] Vélez, William, Fabio Matta, and Paul Ziehl. (2015) Acoustic emission monitoring of early corrosion in prestressed concrete piles. Structural Control and Health Monitoring, 22.5: 873-887.

[13] Zhuang, Ning, et al. (2018) Cracking behavior of reinforced concrete piles externally bonded with carbon fiber reinforced polymer in a marine environment. Construction and Building Materials, 190: 1154-1162.

[14] Mazille H and Rothea R. (1994) The use of acoustic emission for the study and monitoring of localized corrosion phenomenon. In Modeling Aqueous Corrosion: From Individual Pits to System Management. Springer: Dordrecht, The Netherland. Volume 266, pp. 103-127.

[15] Li Z, Li F and Zdunek A, et al. (1998) Application of acoustic emission technique to detection of rebar corrosion in concrete. ACI Mater. J., 95: 68-81.

[16] Yoon D.-J, Wei W.J and Shah S.P. (2000) Assessing damage in corroded reinforced concrete using acoustic emission. J. Eng. Mech., 126, 273-283.

[17] M Ohtsu, Y Tomoda. (2008) Phenomenological model of corrosion process in reinforced concrete identified by acoustic emission. ACI Mater. J., 10: 5194-5199.