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Predicting Damage in a Concrete Structure Using Acoustic Emission and Electrical Resistivity for a Low and Intermediate Level Nuclear Waste Repository

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In this study, the well-known non-destructive acoustic emission (AE) and electrical resistivity methods were employed to predict quantitative damage in the silo structure of the Wolsong Low and Intermediate Level Radioactive Waste Disposal Center (WLDC), Gyeongju, South Korea. Brazilian tensile test was conducted with a fully saturated specimen with a composition identical to that of the WLDC silo concrete. Bi-axial strain gauges, AE sensors, and electrodes were attached to the surface of the specimen to monitor changes. Both the AE hit and electrical resistance values helped in the anticipation of imminent specimen failure, which was further confirmed using a strain gauge. The quantitative damage (or damage variable) was defined according to the AE hits and electrical resistance and analyzed with stress ratio variations. Approximately 75% of the damage occurred when the stress ratio exceeded 0.5. Quantitative damage from AE hits and electrical resistance showed a good correlation (R = 0.988, RMSE = 0.044). This implies that AE and electrical resistivity can be complementarily used for damage assessment of the structure. In future, damage to dry and heated specimens will be examined using AE hits and electrical resistance, and the results will be compared with those from this study.

Keywords: Damage, Wolsong Low and Intermediate Level Radioactive Waste Disposal Center, Silo, Acoustic emission, Electrical resistivity

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1. Introduction

Of the twenty six nuclear reactors constructed in South Korea, twenty four are still in operation. Approximately 532,000 assemblies of spent fuel are being temporarily stored in the boundaries of the nuclear power plants, and 35,200 m^3 of low and intermediate level nuclear waste is stored in the Wolsong Low-and Intermediate-Level Waste Disposal Center (WLDC), which has been open since 2015 [1-2]. The WLDC consists of six silos and connecting tunnels and is made of high-strength concrete with rebar. This huge underground concrete structure will be operated for more than thirty years and maintained for over a hundred years [3]. The WLDC plays an important role in keeping radioactive waste safe, and maintaining public acceptance. Therefore, its structural safety and damage need to be strictly monitored, not only during operation but after disposal.

The common monitoring method is visual inspection. However, most parts of the underground structures are hidden by soils and rock mass and visual inspection cannot give a continuous and quantitative damage of the structures. Thus, it is necessary to employ non-destructive monitoring methods, so called geophysical methods, to ensure there is no crack initiation inside the structures and between ground and the structures. Previous researchers have conducted tests using acoustic emission (AE) to estimate the location of crack generation, and to evaluate the damage to the structures [4-6]. However, since the high frequency AE signals tend to attenuate rapidly compared to low frequency signals, it is necessary to install many AE sensors for ensuring the accuracy.

In this study, well-known geophysical method, electrical resistivity, is adopted to assess the damage caused to the structure during Brazilian test. The measured geophysical data sets from the AE and electrical resistivity analyses were compared with strain gauge and load cell data to analyze the potential use of geophysical methods for damage prediction.

2. Experimental program

2.1 Acoustic emission and electrical resistivity

Acoustic emission (AE) is one of the mechanical wave detection methods, using frequencies that generally range from 50 kHz to 1 MHz [7]. Once the structures are damaged, seismic wave is generated from the damaged structures. The AE method is commonly used to detect crack generation and evolution using the AE parameters depicted in Fig. 1 [8]. Well-known AE parameters are AE count, AE hit, AE energy, peak amplitude, duration, average and dominant frequency. An AE hit was determined to be the representative AE parameter, because AE counts drastically increase before failure, and therefore cannot show the precursor of failure, while frequency related parameters are closely dependent on the damping and failure modes [9-10].

Electrical resistivity is one of the most well-known geophysical survey methods. The electrical resistivity method is commonly used to determine the groundwater level or a highly conductive clay layer [11-12]. Electrical resistivity is an inherent characteristic that shows the degree of disturbance of current flow. A current (or potential) is applied to one electrode and the potential drop (or current) is measured at an opposite electrode. If a crack occurs between the measuring electrodes, the measured electrical resistivity will be increased because the current flow path is extended, and the cross-sectional area is reduced. AE signals are passively de-

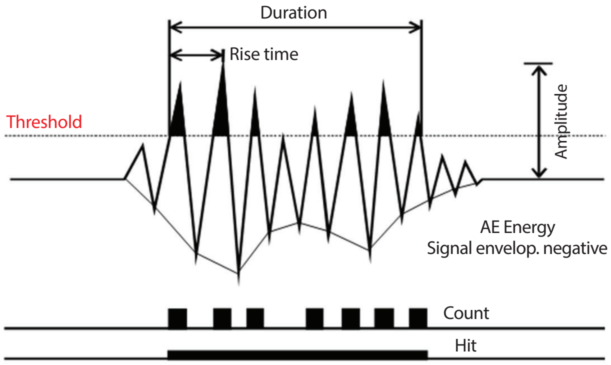


Fig. 1. Definitions of AE parameters [8].

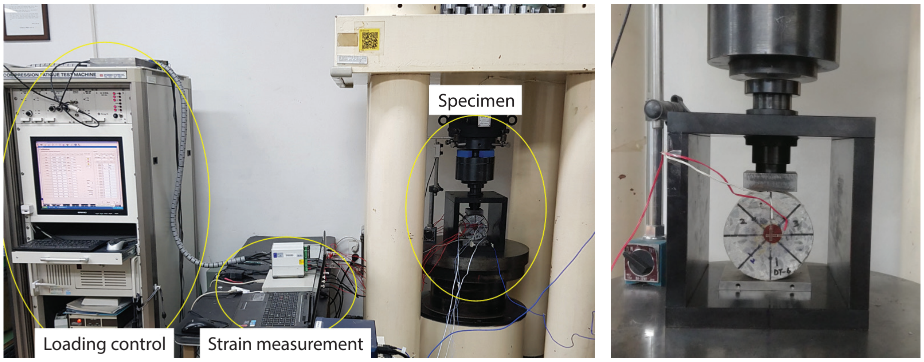
tected (not controlled by the researcher), however, electrical resistivity is actively obtained and controlled by the researcher [13]. Therefore, the electrical resistivity method can be utilized together with the AE method to identify damage.

2.2 Specimen preparation and Test setup

Brazilian tests were conducted with a universal testing machine (KDU-200, maximum load: 100 tons, Fig. 2) to generate tensile oriented cracks. Saturated specimens whose diameter and height were 100 mm and 60 mm, respectively, were prepared for the Brazilian test using the same concrete silo recipe employed to construct the WLDC (Table 1). Eight acoustic emission sensors (Nano-30, MISTRAS), two alumina electrodes, and a bi-axial strain gauge were attached to the surface of the specimens, as shown in Fig. 3. The loading rate was controlled within 0.1–0.2 mm·min^{-1} to prevent rapid failure of the specimens. Acoustic emission signals from the generated cracks were detected each 0.001 second with a MISTRAS 8ch AE system. Electrical resistance was obtained by applying 1 V and the resultant current gain in each 5 seconds measured with a HIOKI IM3533-01.

Table 1. Silo concrete recipe used in the Kyeongju low and intermediate nuclear waste repository [14]

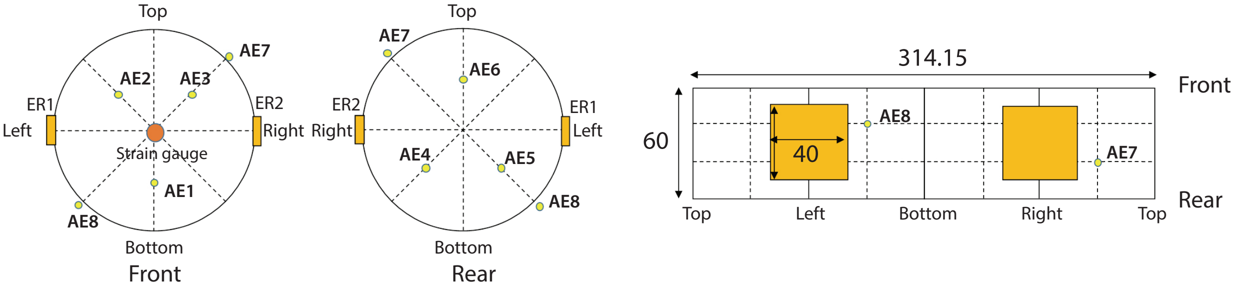
Proportion (kg·m^{-3})									
Water	Cement	Fly ash	20 mm Coarse aggregate	Coarse sand	Fine sand	Water reduction agent	Air entraining agent	High rate water reduction agent	Total
185	375	94	961	414	278	0.7059	0.084	2.551	2,310.3



(a) Test setup

(b) Specimen and Brazilian Jig

Fig. 2. Test setup for Brazilian test.



(a) Front and rear view

(b) Exploded view

Fig. 3. Arrangement of attached sensors (in mm).

Axial and lateral strains were measured every 0.2 second with a KYOWA PCD 320 data logger, and amplified using CAS LCT-PRO. The three measurements were simultaneously obtained and compared with the load cell data.

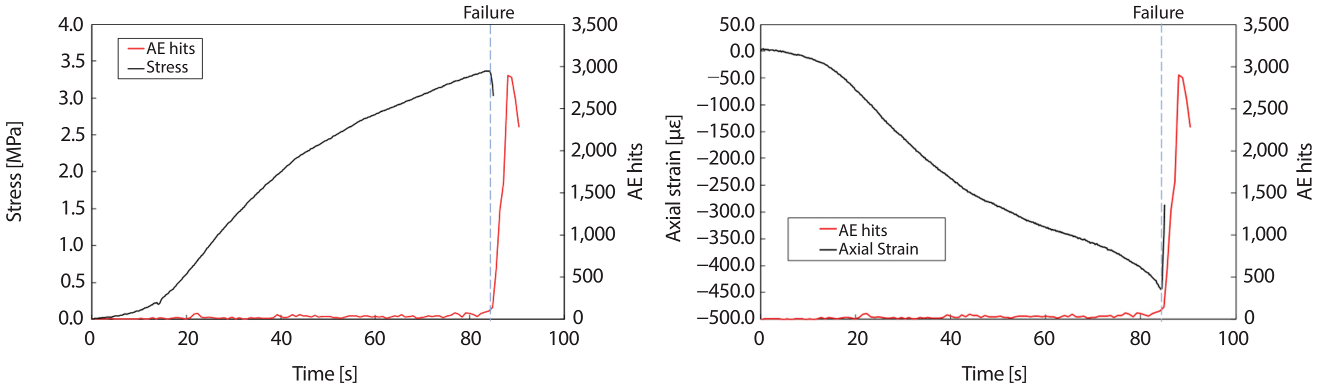
3. Results

3.1 Relationship between stress/strain and AE hits

Eight AE sensors are attached on the surface of the specimen and continuously measure the signals whose threshold is 50 dB. Tensile strength of the specimen is 3.37 MPa and tensile modulus is 26.31 GPa. Axial strain is marked as negative when the specimen is compressed and lateral strain is marked as positive when the specimen suffers tension to the outer direction. Fig. 4 shows the relationship between stress, axial strain and lateral strain obtained from the data logger and load cell, and AE hits with time variation. Stress and strains smoothly increased in early stage because the loading rate is controlled between 0.1–0.2 mm·min^{-1}. Axial strain and cumulative AE hits show a similar trend which give rapid increments when the specimen has almost failed.

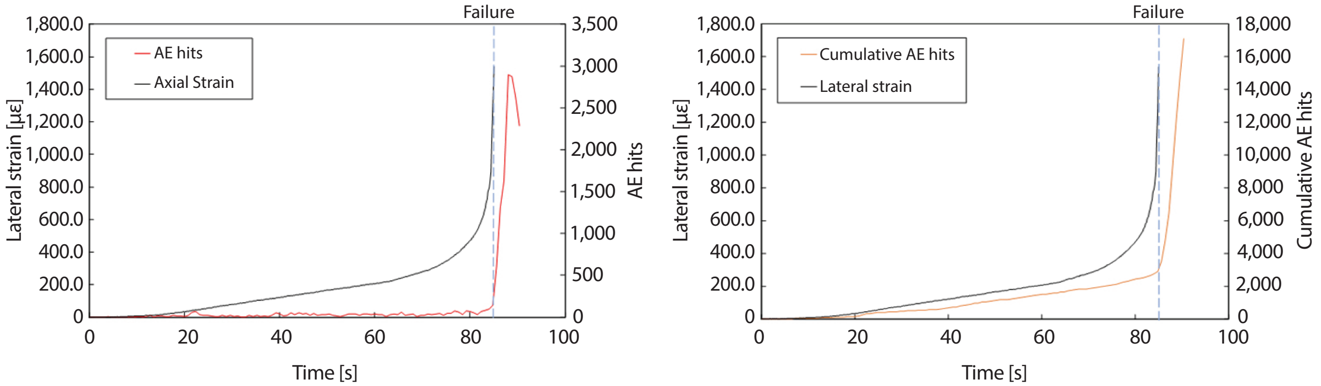
3.2 Relationship between stress/strain and electrical resistance

The electrical resistivity of a solid material cannot be directly obtained, however, the shape factor of the speci-



(a) Stress and AE hits

(b) Axial strain and AE hits



(c) Lateral strain and AE hits

(d) Lateral strain and cumulative AE hits

Fig. 4. Relationship between stress-strain and AE hits: (a) Stress-AE hits, (b) Axial strain-AE hits, (c) Lateral strain-AE hits, and (d) Lateral strain-cumulative AE hits.

men can be obtained using brine and a conductivity meter [15]. When the electrode position and size are determined, the shape factor is given as a constant. Therefore, the measured electrical resistance has the same trend as the electrical resistivity in the same experimental setup. The relationship between stress, axial strain and lateral strain obtained from the data logger and load cell, and the measured electrical resistance were compared with time variation (Fig. 5). The increase in electrical resistance can be explained using Archie's law, as the decrease in pore space due to elastic deformation, and the decrease in cross-sectional area where current flows due to cracks [13, 16]. The decrease in electrical resistance might be oriented the broken parts being re-stocked after failure, and excess pore water fills the crack.

3.3 Damage of specimen

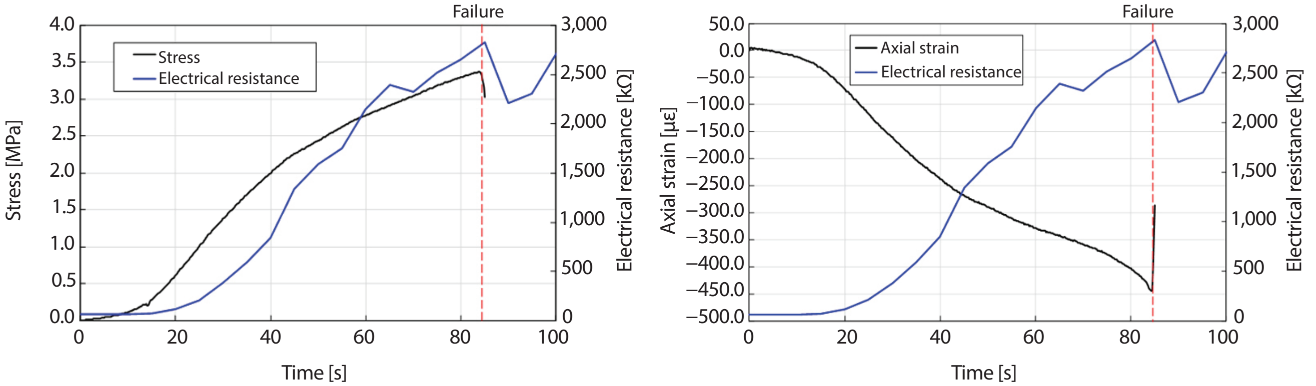
Quantitative damage of the structure (D) is generally represented in terms of modulus (E) as follows [17-18]:

$$E = E_o\,(1 - D) \rightarrow D = \frac{E_o - E}{E_o} \tag{1}$$

where E_o is initial modulus of the structure.

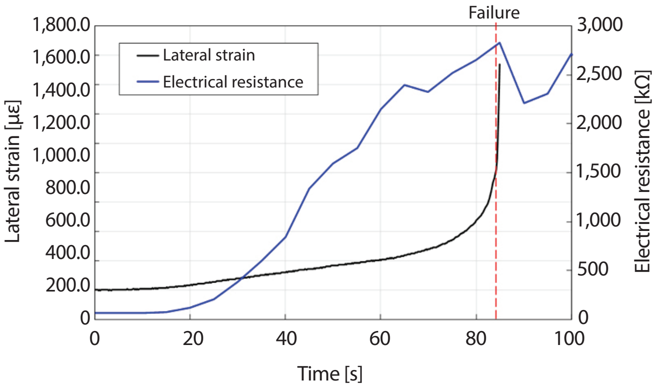
The quantitative damage can be treated as a normalized value of specific measured data, such as cumulative AE hits or electrical resistance. In this study, the damage variable for AE (D_{AE}) is defined as follows:

$$D_{AE} = \frac{H_{\max} - H}{H_{\max}} \tag{2}$$



(a) Stress and electrical resistance

(b) Axial strain and electrical resistance



(c) Lateral strain and electrical resistance

Fig. 5. Relationship between electrical resistance and (a) Stress, (b) Axial strain, (c) Lateral strain.

where $H_{\max}$ is the cumulative number of AE hits when the specimen fails.

The damage variable for electrical resistance (D_{ER}) is defined as follows:

$$D_{ER} = \frac{ER_{\max} - ER}{ER_{\max}} \tag{3}$$

where $ER_{\max}$ is electrical resistance when the specimen fails.

Quantitative damage in the Kyeongju low and intermediate radioactive waste disposal silo structure was obtained, and is depicted in Fig. 6 for cumulative AE hits using Eq. (1) and for electrical resistance using Eq. (2). The damages obtained from AE hits and electrical resistance give a similar trend near failure, however, damage from AE hits overestimate compared to the damage from electrical resistance. This might be oriented because in initial stage of the loading, inherent cracks in the specimen is closing and this closure of the crack generates the AE hits. The damage in the structure exponentially increases as the stress ratio (=σ/σ_{max}) increases. In both methods, damage to the structure is less than 25%, when a half of the maximum strength of the structure is applied.

Damage with stress ratio from AE hits and electrical resistance are compared using statistical methods, R and root mean square error (RMSE). R and RMSE are defined as follows:

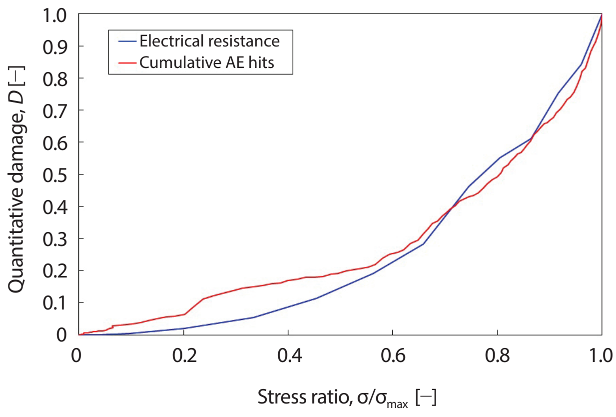


Fig. 6. Quantitative damage derived from AE and electrical resistance (stress ratio= $\sigma/\sigma_{\max}$).

$$R = \sqrt{1 - \frac{\sum_{i=1}^{n}\left(D_{AE}^{i} - D_{ER}^{i}\right)^2}{\sum_{i=1}^{n}\left(D_{AE}^{i} - \overline{D_{AE}^{i}}\right)^2}} \tag{4}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(D_{AE}^{i} - D_{ER}^{i}\right)^2}{n}} \tag{5}$$

where D_{AE}^{i} is the quantitative damage from cumulative AE hits, $\overline{D_{AE}^{i}}$ is the mean of quantitative damage from cumulative AE hits, and D_{AE}^{i} is the quantitative damage from electrical resistance.

If two data sets become identical, R goes unity and RMSE goes zero. R and RMSE between two types of damage is 0.988 and 0.044, respectively. Quantitative damage assessment has been studied using acoustic emission [19]. However, AE method has a limitation in detection range due to its high frequency oriented damping. This result shows that electrical resistance can be utilized compensatively with acoustic emission to assess the damage of the structure.

4. Conclusions

This study tried to estimate the quantitative damage in the concrete structure of WLDC using acoustic emission and electrical resistivity. A Brazilian tensile test was conducted to generate cracks in the structure. Data from strain gauges and load cells attached to the specimen were compared with (cumulative) AE hits from eight sensors, and electrical resistance from two electrodes attached to the specimen. The failure of the specimen was identified using the strain gauge and load cell data. The AE hits and electrical resistance drastically changed when the specimen failed. Quantitative damage for AE hits and electrical resistance was defined and derived with changes in stress ratio. The quantitative damage to the concrete silo structure was about 25% when the first half of the maximum stress was applied. The last 75% of damage occurred when the stress ratio was larger than 0.5. Quantitative damage from cumulative AE hits and electrical resistance is almost identical along stress ratio (*R*: 0.988, *RMSE*: 0.044). The results of this study confirmed that acoustic emission and electrical resistivity can be utilized compensatively for sustainable monitoring of WLDC structure.

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