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RESEARCH

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Probabilistic Repair Cost Simulation for RC Structures Repaired With Bacteria Coating Material Under Sulfate Attack

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Abstract

Concrete sewage structures are difficult to maintain since they are constructed under the ground and their surfaces inside are exposed to various deteriorations such as acid and sulfate ingress. In this study, their repair costs were evaluated both deterministically and probabilistically considering the extended service life through repairing of conventional repair mortar and a newly developed bacteria repair material. Unlike the conventional deterministic method, the probabilistic manner evaluates repair cost continuously, taking into account variations in the initial service life and extended service life through repair. For the work, variations in the sulfate ion diffusion coefficient and protection parameters (cover depth and repair layer thickness) were obtained experimentally. Based on the target service life (60 years), the repair cost increased to 123% as the maintenance-free period (MFP) decreased by half, and decreased to 77% as the MFP increased to 1.5 times. As the extended service life through repair decreased by half, the repair cost increased to 180% due to the increasing repair frequency. When the repair-extended service life increased to 1.5 times, the repair cost decreased to 73%. Considering exterior sulfate concentrations (120 and 200 ppm) and entire sewage pipelines (3268 m), the bacteria repair material showed the lowest repair cost (1376 K$ and 1498 K$ with the deterministic and probabilistic method, respectively) since the repair-service life increased from 10.4 to 25.3 years and the number of repairs decreased from 9 to 4 due to the low diffusion coefficient of the bacteria repair material.

Keywords: MFP (maintenance-free period), bacteria repair material, service life, repair cost, maintenance

1 Introduction

RC (reinforced concrete) sewage structures are representative national SOC (social overhead capital) structures and serve as key life-line systems. They are difficult to maintain since mostly buried in the ground, and their frequent repairing incurs significant social and economic costs. For such structures that are difficult to maintain and degraded continuously, it is very important to determine the target service life and evaluate the related repair costs (Fenner, 2000; Parande et al., 2006).

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Anaerobic bacteria that live in the sludge sediment inside sewage pipelines decompose and consume deposited organic matter as nutrients during their growth. In the process, they generate a large amount of hydrogen sulfide gas (H_2S) by reducing sulfate ions (SO_4^{2-}) (De belie et al., 2004; Monteny et al., 2000). As the strong acid H_2S gas reduces pH of the concrete surface, the population of sulfur-oxidizing bacteria (e.g., *Thiobacillus thiooxidans* and *Acidithiobacillus thiooxidans*) in neutral environments increases, this allows sulfur-oxidizing bacteria, which generate sulfuric acid (H_2SO_4) and polythionic acid during their metabolic process for further decreasing pH of the concrete surface. In addition, the factors such as the presence of sulfate ions and sulfuric acid deteriorate the internal pore structure through chemical reactions with cement hydrates in the sewage concrete surface (Grengg et al., 2018; Islander et al., 1991; Joseph et al., 2012). These reactions decrease concrete density and aggressively affect physical properties such as pore structure, permeability, and strength.

Because sulfuric acid generally deteriorates the concrete surface, the deterioration can be monitored through surface observation, however the continuous inspection and maintenance of sewage pipelines are difficult due to the generation of toxic hydrogen sulfide gas, presence of effluents, and insufficient oxygen, which can lead to casualties (Oh et al., 2006).

International Design Codes and Specifications on durability design consider carbonation, chloride attack, freezing and thawing, sulfate attack, and the alkali-aggregate reaction as major deterioration factors. However, no clear quantitative design formula for service life for sulfate attack is available. This is because the penetration of the deteriorating agents and concrete cracking due to the expansion of hydrates inside occur simultaneously. Currently several techniques such as the deterioration depth evaluation method (Atkinson & Hearne, 1989; Lee et al., 2013), sulfate diffusion method which considers multiple layers (Yang et al., 2020a), and strength reduction evaluation which considers accelerated testing and strength degradation (Qin et al., 2020; Zhang et al., 2018) are mainly used for service life evaluation under sulfate attack.

Repair cost estimation usually adopts a deterministic life-cycle cost (LCC) method considering the stepwise (step function) repair cost during the period extended with repair to the end of intended service life. Recently, probabilistic repair cost evaluation method has been proposed, where the model probabilistically considers the connection strength between the repair cost and each analysis parameter, however, the deterioration process is not physically modeled. Neural networks (NNs) are employed in several cost estimation models, but the changes in the service life of structures due to deterioration which governs the service life are not considered. The connectivity among influencing parameters is regarded as probabilistic variations (Mulubrhan et al., 2014; Nasir et al., 2015; Rahman & Vanier, 2004; Salem et al., 2003). In addition to NNs, genetic algorithm (GA), and fuzzy logic system (FL) have been used for LCC (Ammar et al., 2013; Firouzi & Rahai, 2012; Sun & Carmichael, 2018). Several studies have proposed adaptive network-based fuzzy inference system (ANFIS), which combined the advantages of NNS and FL systems to process imprecise, uncertainty, and vague data, evaluated the maintenance cost of various structures (Flintsch & Chen, 2004).

Some studies have investigated the repair cost for each process for public housing by analyzing its probabilistic patterns. Although these studies are effective for constructing databases for the maintenance and quantification of probabilistic patterns for the unit repair stage by analyzing variations in the service life of each component, the models cannot provide the actual repair cost considering the intended service life and repair-extended service life (Lee & Ahn, 2018; Park et al., 2018).

The service life of the target structure varies depending on the quality, constructability, and exposure environment. The probabilistic method for repair cost considers variations in the service life which are derived from the actual deterioration model and extended service life through repair. Several researches in this area have extended to repair cost evaluation for each deterioration, sensitivity analysis on service life and repair cost, and various probability-of-service-life function (PSLF) modeling. In particular, some studies attempted the probabilistic method for evaluating the total repair cost of the entire structure during service life as well as the repair cost of each process for public housing (Jung et al., 2018; Kwon, 2017a, 2017b; Yang et al., 2020b; Yoon et al., 2021a). In the case that LCC is evaluated through the probabilistic methods, it is possible to manage the actual repair cost that may occur in the various situations, since the repair cost is evaluated over time with a continuous curve, unlike the stepwise repair cost of the deterministic method (Lee et al., 2020).

In this study, the total repair cost during service life was evaluated for sewage pipelines that have been exposed to sulfate ingress, considering newly developed repair material with bacteria (Rhodobacter capsulatus) and effects of design parameters. The sulfate diffusion coefficient and the coefficient of variation (COV) of the cover depth were derived from the test and measurements, and variations in service life were evaluated using Monte Carlo simulation (MCS). The total repair cost was analyzed using the probabilistic and deterministic methods considering changes in the maintenance-free period (MFP) and the extended service life through the developed bacterial and conventional repair techniques. The differences between the repair costs from the proposed techniques were analyzed, and the effects of design parameters on service life and repair cost are also discussed.

2 Background Theory of Probabilistic Repair Cost Calculation and the Exposure Conditions

2.1 Deterioration of Sewage Pipelines Under Sulfate Attack

RC sewer systems in anaerobic-sulfate environments deteriorate with the growth of sulfate-reducing bacteria and the subsequent generation of hydrogen sulfide gas (Parker, 1945), as explained in Fig. 1. Anaerobic sulfate-reducing bacteria that live in the sediments, introduced into sewer pipes, generate a large amount of hydrogen

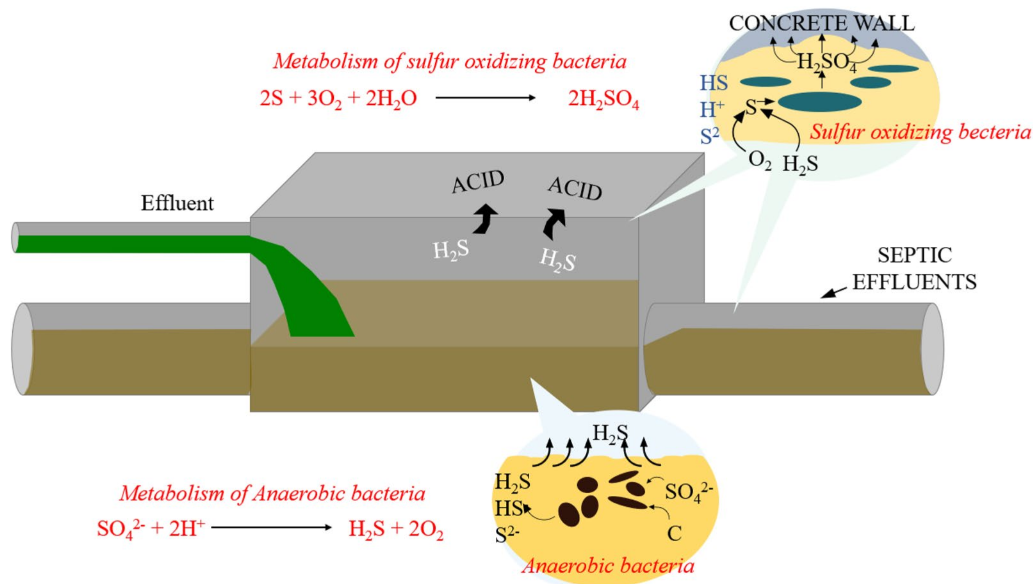


Fig. 1 Deterioration of sewage concrete by sulfate attack.

sulfide (H_2S) gas by reducing sulfate (SO_4^{2-}) when decomposing and consuming organic sediments (De belie et al., 2004). Meanwhile the bacteria oxidize organic matter using the oxygen bonded with sulfur instead of molecular oxygen for protein synthesis and energy acquisition, as shown in Eq. (1). Thiosulfate ($S_2O_3^{2-}$) and tetrathionate ($S_4O_6^{2-}$) are generated together with H_2S, all of which decrease pH of the concrete structure, thereby inducing the reproduction of sulfur-oxidizing bacteria, which exhibit optimal growth efficiency in neutral and acidic environments. The polythionic acid (a sulfur-based chemical) formed during their growth further decreases pH as well. Sulfur-oxidizing bacteria form sulfuric acid by using thiosulfate and elemental sulfur (S) as intermediates in the reduction of the energy acquisition reaction for their growth. The generated sulfuric acid deteriorates the concrete structure through chemical reactions with the cement hydrates on the concrete pipeline surfaces that are in contact with microorganisms. Once an environment dominated by sulfuric acid has been created, the sulfuric acid reacts with cement hydrates and generates gypsum dihydrate ($CaSO_4 \cdot 2H_2O$) and anhydrous gypsum ($CaSO_4$), as shown in Eqs. (2 and 3) (Monteny et al., 2000). Gypsum dihydrate, being water soluble, is easily dissolved from the cement matrix, creating coarse pores in the structure and accelerating the performance degradation of concrete. In addition, anhydrous gypsum expands through forming ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) through reaction with aluminate (C_3A, $3CaO \cdot Al_2O_3$) in cement as listed in Eq. (4), which causes cracking due to the lack of dimensional stability (Aviam et al., 2004).

$$\begin{aligned} & SO_4^{2-} + ATP \rightarrow \text{adenosylphospate - sulfate} \\ & \quad (APS) \rightarrow SO_3^{2-}(+AMP) \\ & S_3O_6^{2-} \rightarrow S_2O_3^{2-}\left(+S_2O_3^{2-}\right) \end{aligned} \tag{1}$$

$$Ca(OH)_2 + H_2SO_4 \rightarrow CaSO_4 \cdot 2H_2O \tag{2}$$

$$CaO \cdot SiO_2 \cdot 2H_2O + H_2SO_4 \rightarrow CaSO_4 + Si(OH_4) + H_2O \tag{3}$$

$$\begin{aligned} & 3CaO \cdot Al_2O_3 + 3(CaSO_4 \cdot 2H_2O) + 26H_2O \\ & \quad \rightarrow 3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O \end{aligned} \tag{4}$$

2.2 Background of Service Life and Repair Cost Evaluation Method

2.2.1 Deterministic and Probabilistic Service Life Evaluation

Several studies on service life prediction under sulfate ingress have been performed and some models have handled complicated chemical reactions of sulfate ion with calcium hydroxide and calcium silicates, which generated gypsum and ettringite, however cracking and simultaneous intrusion of sulfate ion are still difficult for actual durability design in engineering level. As previously mentioned, several service life evaluation methods in engineering level adopt simplified patterns such as multi-layer diffusion in the surface layer (Yang et al., 2020a), the linear deterioration depth with diffusion and cement compositions (Atkinson & Hearne, 1989), and relative strength reduction rate (Zhang et al., 2018). Among the models, the second is predominantly used since it can handle chemical component in cement which reacts with sulfate ion, diffusion characteristics in material, exposure concentration of sulfates, and roughness of surface. This model considers the deterioration depth as a linear function of exposure period by assuming the penetration of sulfate ions into concrete through diffusion, reactions between sulfate and aluminum hydrates, and volumetric expansion confined to the surface. Equation (5) shows the deterioration rate by sulfate (Atkinson & Hearne, 1989; Lee et al., 2013):

$$R = \frac{E \cdot B^2 \cdot c_0 \cdot C_E \cdot D_i}{\alpha \cdot \gamma_f (1 - \nu)}, \tag{5}$$

where E is the elastic modulus of concrete (MPa), B is the linear deformation coefficient by 1 mol of sulfate ions reacting in a unit volume (1.8×10^{-6} m^3/mol), c_0 is the concentration of sulfate ions (mol/m^3), D_i is the sulfate ion diffusion coefficient (m^2/s), α is the roughness coefficient, γ_f is the concrete fracture energy ($= 10$ J/m^2), ν is the Poisson's ratio of concrete, and C_E is the sulfate ion concentration reacting with ettringite (mol/m^3).

In the method, the service life of structure is determined when the increasing deterioration depth with exposure period exceed to the design cover depth. Material reduction factors and environmental factors are considered for marginal durability safety in the design process.

Unlike deterministic durability design, in the probabilistic service life evaluation, the probability of exceeding the critical condition during the target service life is defined and service life is evaluated based on the critical probability. For chloride attacks and carbonation, service life limit conditions and target durability failure probabilities are defined (EN 1991, 2000; Stewart & Mullard, 2007), however, for sulfate attack, no clear target failure probability has been proposed. Assuming that the limit condition is the time for the deterioration depth by sulfate penetration to reach the cover depth, the governing equation can be written as Eq. (6) for probabilistic method:

$$p_f\left[\frac{E \cdot B^2 \cdot c_0(\mu,\sigma) \cdot C_E \cdot D_i(\mu,\sigma)}{\alpha(\mu,\sigma) \cdot \gamma_f (1 - \nu)}(t) > C_d(\mu,\sigma)\right] > p_d, \tag{6}$$

where $p_f(t)$ is the durability failure probability for the deterioration depth, which increases with time, $C_d(\mu,\sigma)$ is the probability distribution for cover depth, and p_d is the target durability probability (maximum allowable probability during intended service life). In Eq. (6), the external sulfate ion concentration (c_0), diffusion coefficient (c_0), roughness coefficient (α), and cover depth (c_d) are random variables.

2.2.2 Deterministic and Probabilistic Repair Cost Evaluation

This section outlines the probabilistic repair cost evaluation based on previous studies. For probabilistic repair cost evaluation, variations in the extended service life through repairing and initial service life (MFP: maintenance-free period) are the primary factors. When the period during which the first deterioration depth reaches the cover depth is assumed to be T_1 (the first service life), the number of repairs becomes zero for the period, which requires no repair. In this case, the initial condition can be given by Eq. (7) (Total Information Service Corporation, 2010; Yang et al., 2020b):

$$T_1 \geq T_{end}, \tag{7}$$

where T_1 is the initial service life, and T_{end} is the final target service life of the structure to be used.

If the average value of the first repair timing is set to $\overline{T_1}$, the safety index (β) and the probability that no repair is required (P_1) can be expressed through Eq. (8) and Eq. (9) (Jung et al., 2018; Kwon, 2017b; Yoon et al., 2021b):

$$\beta = \frac{\left(T_{end} - \overline{T_1}\right)}{\sigma_1}, \tag{8}$$

$$P_1 = \int_{\beta_1}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\beta^2}{2}\right) d\beta, \tag{9}$$

where σ_1 is the standard deviation of $\overline{T_1}$ at the time of the first repair event.

In the theory, the condition for the number of repairs to be N is that T_N is smaller than the target service life (T_{end}), and the sum of T_{N+1} and T_N (N-th repair timing) is larger than T_{end}. In the condition, the safety index can be given by Eq. (10), and the probability (P^*_{N+1}) that the sum of T_N and T_{N+1} is larger than $\overline{T_N}$ is as shown in Eq. (11):

$$\beta_N = \frac{\left(T_{\text{end}} - \left(\overline{T_N} + \overline{T_{N+1}}\right)\right)}{\sqrt{\sigma_N^2 + \sigma_{N+1}^2}}, \tag{10}$$

$$P_{N+1}^{*} = 1 - \int_{-\infty}^{\beta_{N+1}} f(\beta)d\beta = \int_{\beta_{N+1}}^{\infty} f(\beta)d\beta = \int_{\beta_{N+1}}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\beta^2}{2}\right)d\beta, \quad (11)$$

where σ_N is the standard deviation of T_N. The failure probability when the number of repairs is $N(P_N)$ can be generalized as shown in Eq. (12). In addition, if the repair cost for the unit member (i) is constant at C_i, the total repair cost can be shown as Eq. (13).

Details of the equations and conceptual diagrams can be found in previous studies (Jung et al., 2018; Kwon, 2017b; Yang et al., 2020a; Yoon et al., 2021c).

$$P_N = \left(1 - \sum_{k=1}^{N-1} P_N\right) \times P_N^{*}, \quad (12)$$

$$C_T = \sum_{k=1}^{N} (k \times C_i \times P_k), \quad (13)$$

where C_T is the total repair cost which considers the unit repair costs (C_i). Fig. 2 illustrates the schematic diagram of the probabilistic method and comparison with deterministic method for repair cost evaluation.

3 Evaluation of Environmental Conditions and Service Life of Target Structure

3.1 Distribution and Service Life of Target Sewage Pipelines

The distribution of sewage pipelines in the target area is shown in Fig. 3. For evaluation of service life, exterior sulfate concentration was assumed that the section close to pollution sources (public house and facilities) was 200 ppm section and that more than 1.0 km away from pollution sources was 120 ppm. The average sulfate concentration in sewage pipelines is reported to be approximately 120 ppm (Yoon & Yang, 2020), but it varies with flood and rainfalls. The total lengths of the exposure environments for the 120 and 200 ppm sections were found to be 1.425 km and 1.843 km, respectively. The cover depth of sewage concrete structure is usually designed as 30 mm, and the thicknesses of the bacteria repair material and conventional protective mortar are 5 and 10 mm, respectively. Table 1 summarizes design parameters for the service life evaluation, where several results were obtained from the previous study (Yang et al., 2021; Yoon et al., 2021a).

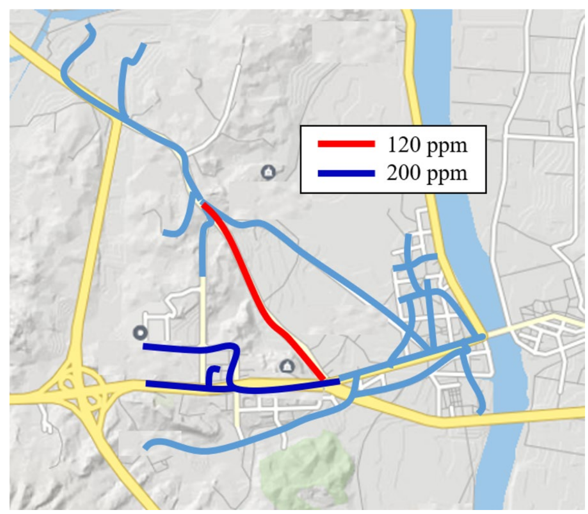


Fig. 3 Sewage pipelines in district A.

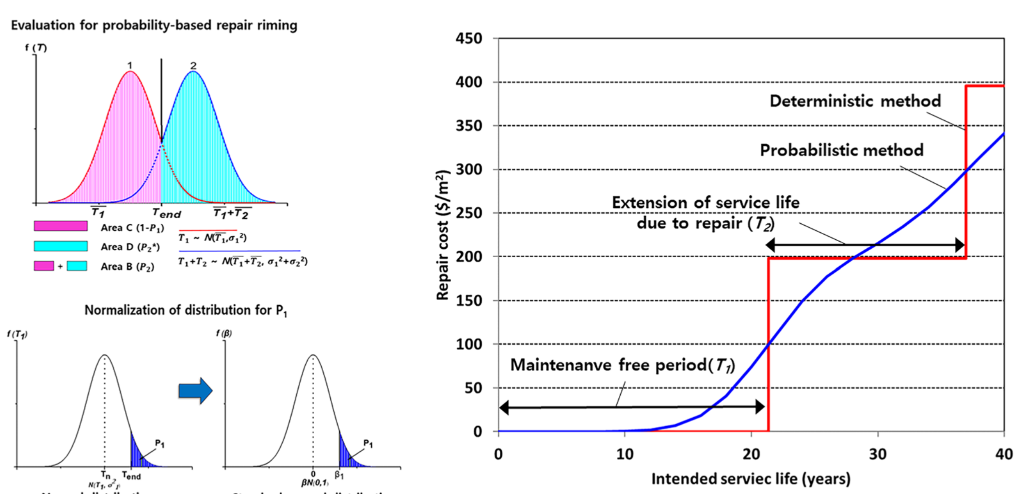


Fig. 2 Conceptual comparison of deterministic and probabilistic repair cost evaluation methods.

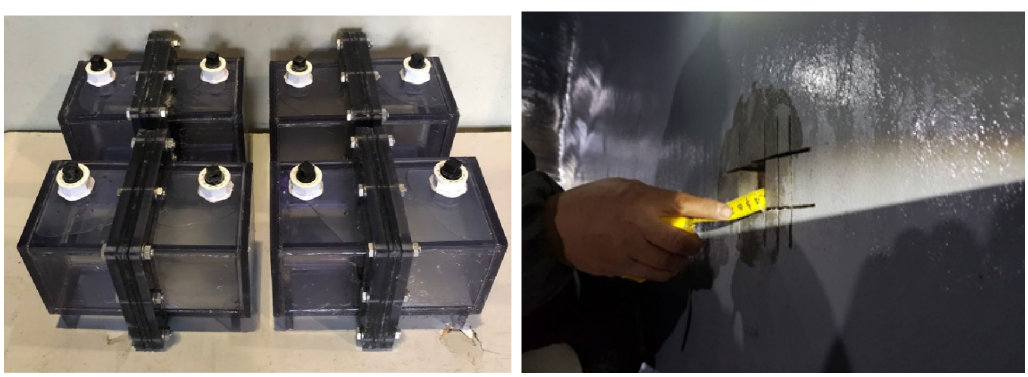
Table 1 Design parameters for sewage concrete, conventional repair, and bacteria repair materials.

Variable	Sewage concrete	Conventional repair mortar	Bacteria repair material
c_0 (ppm)	120/200	120/200	120/200
D_i (m^2/s)	2.12×10^{-12}	2.09×10^{-12}	0.17×10^{-12}
E (MPa)	25700	21500	21500
ν	0.17	0.27	0.27
α	1.5	1.5	1.5
γ_f	10	10	10
Binder weight (kg/m^3)	400	300	300
C_E	207	196	462
Cover depth (mm)	30	10	5

4 Probabilistic Repair Cost Evaluation Considering Exposure Environment

In order to evaluate the repair cost in probabilistic manner, the average and COV of the MFP as well as the service life extended through each repair material and its COV should be given. Variations in the service life were analyzed using the measured cover depth and sulfate ion diffusion coefficient (Yoon et al., 2021b). Assuming normal distribution, random variables were generated considering the average and COV of each design factor, and the service life was derived at each step using Eq. (5), then the average and COV of the evaluated service life were obtained. Regarding concrete, conventional repair mortar, and bacteria repair material, the random variables of them were obtained by 10 time-measurement during construction. Fig. 4(a) shows the test on the sulfate ion diffusion coefficient, and Fig. 4(b) shows the measurement of the cover depth, and these values were observed to follow a normal distribution. The probabilistic variations (average and COV) of the derived design factors are shown in Table 2.

Each service life was evaluated using the information of Table 1 and Eq. (5). The average and COV of the service life obtained from 1000 times random simulations were derived through the process in Fig. 5 and the results are summarized in Table 3 with the conventional unit cost of each repair technique (Dongyang Economic Research Institute, 2021).



(a) Sulfate ion diffusion test (b) Cover depth measurement

Fig. 4 Evaluation of random variable of diffusion coefficient and cover depth.

Table 2 Random variable derivation of diffusion coefficient and cover depth.

Variable	Sewage concrete	Conventional repair mortar	Bacteria repair material
Cover depth/repair thickness (mm)	30.300	10.260	5.120
COV	0.121	0.132	0.108
Diffusion coefficient ($\times 10^{-12}$ m^2/s)	2.120	2.090	0.170
COV	0.135	0.192	0.121

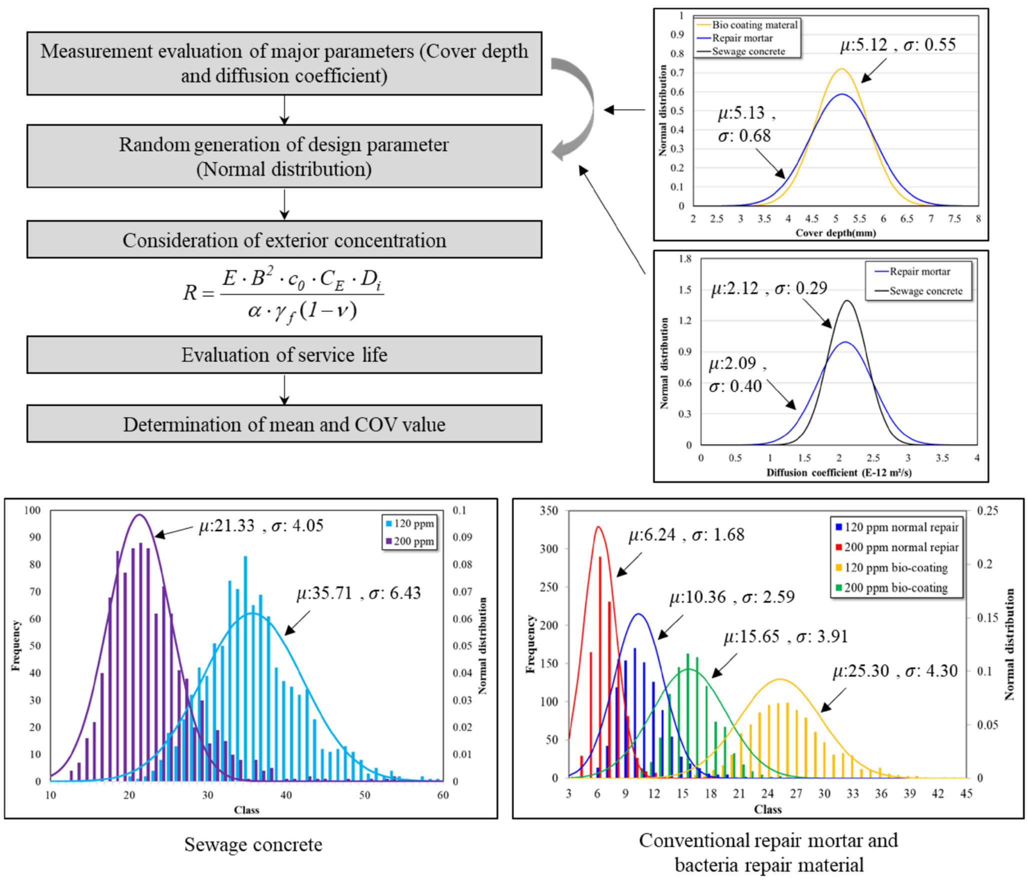


Fig. 5 Flowchart for derivation of service life and COV.

Table 3 Initial and extended service life and their COV with different repair technique.

N = 1000	Concrete		Normal repair		Bio-slime	
	–		294.4 $/m		197.8 $/m	
Service life	**Average**	**COV**	**Average**	**COV**	**Average**	**COV**
200 ppm	21.33	0.19	6.24	0.27	15.65	0.25
120 ppm	35.71	0.18	10.36	0.25	25.30	0.17

Table 4 Simulation of repair cost (control case).

MFP and COV	Changing MFP	Changing extended service life with repair	Changing COV of extended service life
21.3/0.19 15.6/0.25	0.5, 1.0, 1.5 times with constant COV (0.19)	0.5, 1.0, 1.5 times with constant COV (0.25)	0.125, 1.0, 2.0 times with constant extended service life (15.7 years)

5 Probabilistic Repair Cost Calculation and the Factors Influencing Cost

5.1 Simulation on Repair Cost Due to Variations in Design Parameters

In the section, the influence of the average and standard deviation of the design factors in RC sewage concrete was analyzed on the total repair cost. With respect to the simulation conditions, the changes in the repair cost were analyzed while the average and COV varied in the 200 ppm exterior condition. The effect of changing MFP, the service life with repair, and variations in repair materials was analyzed on repair cost. The analysis conditions for the repair cost simulation are listed in Table 4.

Under the given condition, MFP was derived as 21.3 years. The changes in the repair cost were analyzed for 0.5 × MFP and 1.5 × MFP. In this case, the service life extension with repair (15.6 years) and COV (0.25) were fixed. As in the previous studies, when MFP was extended in the early construction stage, the frequency of repairs and the related maintenance cost significantly decreased (Jung et al., 2018; Yang et al., 2020b). After 60 years, the repair cost was evaluated to be $724.40 for 0.5 × MFP, $590.50 for 1.0 × MFP, and $453.30 for 1.5 × MFP, respectively. The extended service life with repair also significantly affects the total repair cost. When the extended service life through repair increased by a factor of 1.5 times to 23.5 years, the repair cost decreased to $428.40. However, when it was shortened to 7.8 years (a half of 15.7 years), the repair cost significantly increased to $1060.70. The COV of extended service life depends on quality of repairing and it shows interesting results. When the COV of the extended service life decreased from the given condition (0.25) to 0.063 and 0.5, the repair costs after 60 years was $590.60 and $582.50, respectively, which showed insignificant effect on repair cost, however the shape of a step function is clearly shown with decreasing COV since the tendency becomes more identical to that of the deterministic method as COV goes to zero (Jung et al., 2018; Kwon, 2017b; Yang et al., 2020a). The repair cost with changing MFP, the extended service life, and affected by COV in

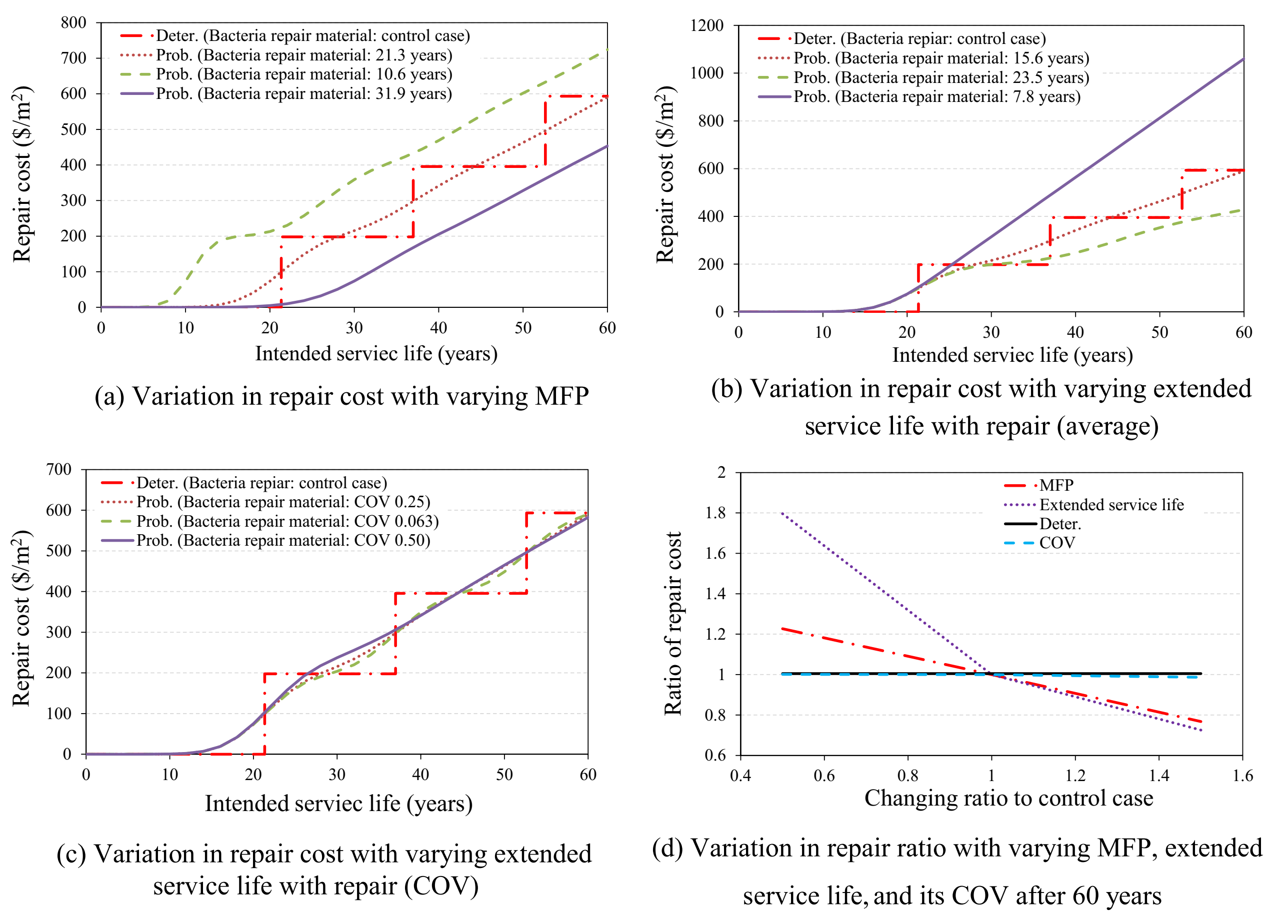


Fig. 6 Repair cost analysis considering changing MFP, extended service life, and COV.

the extended service life are shown in Fig. 6(a–c), respectively. Fig. 6(d) shows the ratio of the repair cost compared with the given condition.

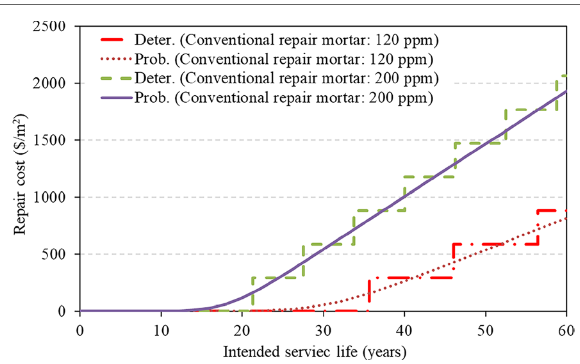
In Fig. 6d, when MFP and extended service life increased to 1.5 times, the repair cost decreased to 77% and 73%, respectively, however when they decreased to 0.5 times, the repair cost increased to 123% and 180%, respectively, which means that it is preferentially required to secure the extended service life with repair and MFP for the limited target service life.

5.2 Evaluation of Total Repair Cost Considering Sewer Networks

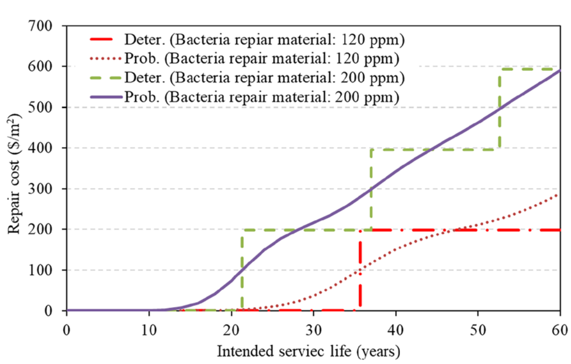
5.2.1 Evaluation of Repair Cost with the Unit Length of the Target Structure

The target service life was determined as 60 years and the repair cost per unit length with the exposure environment was analyzed, as shown in Fig. 7(a) for conventional repair technique. As done in previous studies, the stepwise repair cost was modeled in the deterministic method, but the repair cost with probabilistic method showed a continuous line due to the COV of service life (Jung et al., 2018; Kwon, 2017b). When the exposure environment was 120 ppm, the repair cost was evaluated to be $883.20/m for the deterministic method and $818.30/m for the probabilistic method, respectively. The external sulfate concentration increased from 120 to 200 ppm, the number of repairs increased from three to seven, and the repair cost showed $2060.80/m for the deterministic method and $1931.50/m for the probabilistic method.

Fig. 7b shows the results of evaluating the repair cost for the bacteria repair material derived in this study. In the case of 120 ppm, the number of repairs was one, and the repair cost was $197.8/m for the deterministic method and $287.93/m for the probabilistic method. In the harsh condition (200 ppm), the number of repairs increased to three, and the repair cost was $593.40 for the deterministic method and $590.00 for the probabilistic method. The probabilistic method can reduce the repair cost, but more importantly, it can consider the service life which varies through the repair material, and reasonably reduces the repair cost compared to the deterministic method when the target service life is changed. For example, in the case of a bacteria repair material with a concentration of 120 ppm, the service life has a cycle of 25.3 years for service life for the deterministic method. For the probabilistic method, it is evaluated as a continuous function so that the probabilistic method is economical for 12.2 years after the initial service life (MFP: 35.7 years).



(a) Variation in repair cost with increasing service life for conventional repair mortar



(b) Variation in repair cost with increasing service life for bacteria repair material

Fig. 7 Variation in repair cost with increasing service life for normal and bacteria repair materials.

5.2.2 Evaluation of Total Repair Cost in Target Sewage Network

As described in Sect. 3.1, the length of sewage pipelines was found to be 1425 m for the 120 ppm section and 1843 m for the 200 ppm. With the probabilistic method, the total repair cost could be easily calculated through simple sum of each repair cost with pipe length since the repair cost had a continuous repair cost function. However, for the deterministic method, the repair cost due to the extended service life irregularly varied depending on the repair event and environment. Therefore, the total repair cost was calculated based on the calculation procedure in Fig. 8 and the total repair cost results are plotted in Fig. 9.

As shown in Fig. 9, the repair cost increases alongside the increase in service life, and the stepwise repair cost shows complicated rise depending on the two exposure environments. In the previous study (Jung et al., 2018), the repair cost analysis was performed for chloride ingress of RC structures by probabilistic method. In the work, the probability distributions of design parameters such as diffusion coefficient, surface chloride content,

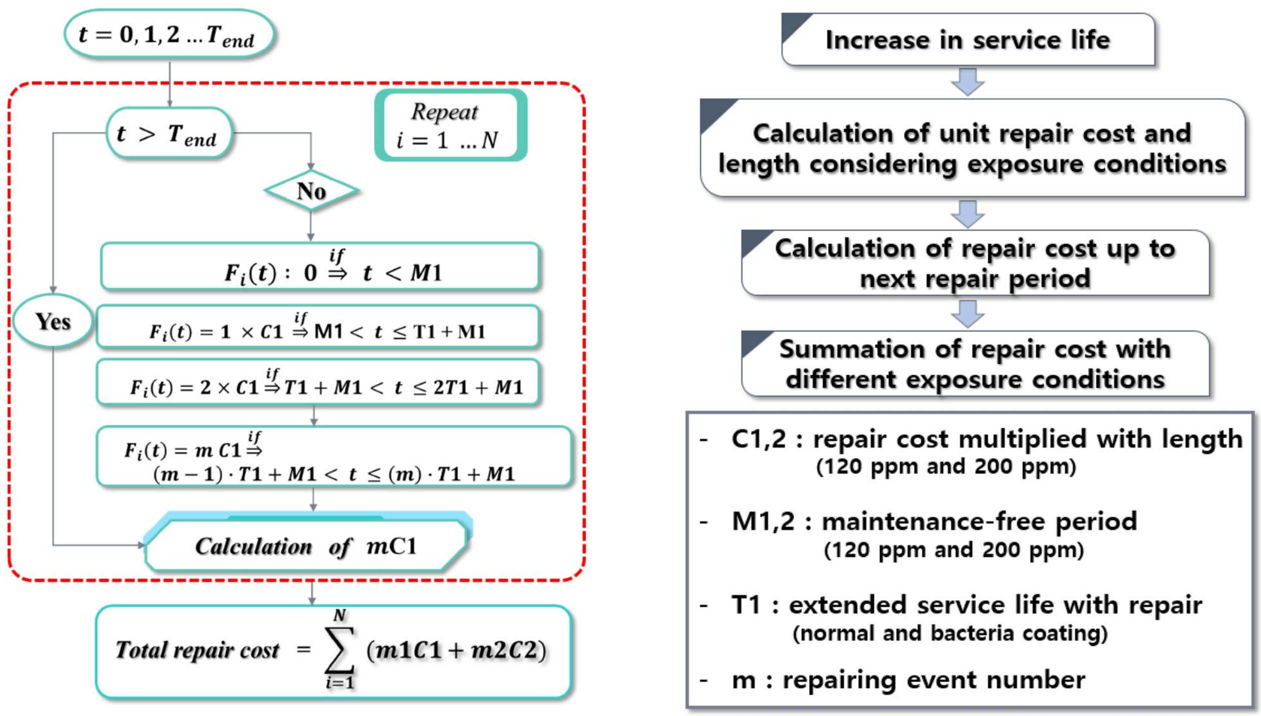


Fig. 8 Flowchart for repair event-based total repair cost with deterministic method.

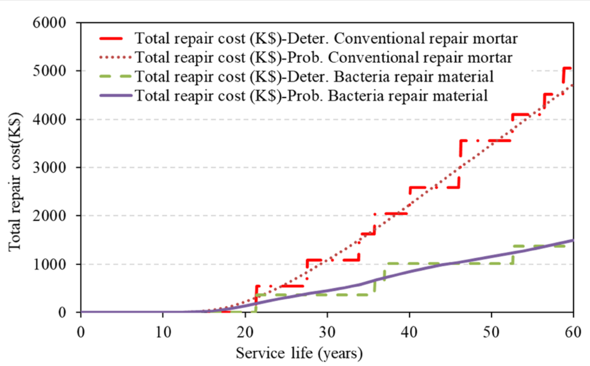


Fig. 9 Variation of total repair cost with varying exposure conditions and repair method (deterministic and probabilistic method).

Table 5 Total repair cost to intended service life.

Conventional repair mortar (*K* $)		Bacteria repair material (*K* $)	
Deterministic method	**Probabilistic method**	**Deterministic method**	**Probabilistic method**
5057.00	4725.80	1376.00	1498.60

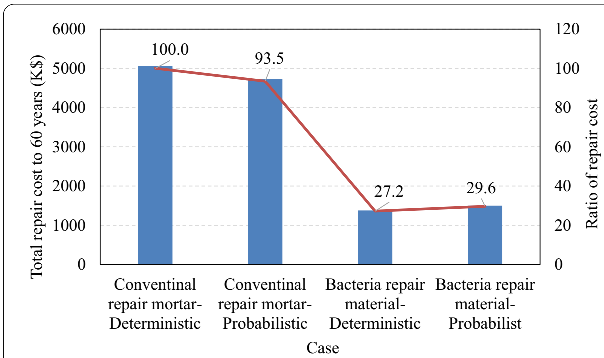


Fig. 10 Total repair cost and its ratios to normal repair cost.

and cover depth were assumed with one repair event. In this study, a sulfate-resistant repair mortar was developed, and the probability distributions the analysis variables were evaluated and defined through lab tests and field survey. In addition, this study has proposed a method for estimating the total repair cost of the sewage system with different exposure conditions and service life.

When the target service life of 60 years arrived, the total repair cost was evaluated to be 5057 K$ for the deterministic method and 4725 K$ for the probabilistic method in the conventional repair method. When the bacteria repair material was used, the repair cost decreased to 1376 K$ for the deterministic method and 1498 K$ for the probabilistic method, respectively. The significant difference from the repair method was caused by the difference in the number of repairs. The number of repairs was nine for the conventional repair material but only four for the bacteria coating. This is because the application of the bacteria coating significantly extended the service life through the low diffusivity of sulfate ions.

Table 5 lists the repair cost results for each method when the target service life of 60 years was reached and the cost-effectiveness is shown in Fig. 10. When the bacteria repair material was used, the repair cost decreased to 27%–31% of that of the conventional repair material.

The newly developed show significantly reduced repair cost, however, it has still limitations. The number of samples for probability distribution characteristics is very limited and the maintenance of quality and performance is not the same as the lab-scaled experiments considering the mass production and construction process (Yang et al., 2021; Yoon et al., 2021c). In addition, the repair cost from probabilistic method may lead to unrealistic and uneconomical results if COVs of MFP and extended service life from repair are too big, so that reasonable PSLF (probability-of-service-life function) and COV are required.

6 Conclusions

In this study, the repair cost for RC sewage pipelines exposed to sulfate ingress was evaluated using deterministic and probabilistic methods. From the measurement of diffusion coefficient and coating thickness, random variables for design parameters were obtained and they were utilized for total repair cost evaluation. The following conclusions are drawn:

1. The probabilistic variations (average and COV) of the bacteria repair material, conventional repair mortar, cover depth, and diffusion coefficient were evaluated through actual measurement and the sulfate ion diffusion test. The exposure environment was classified into two cases (120 and 200 ppm), and the service life and its COV were evaluated considering three variations of design parameters (concrete, conventional repair mortar, and bacteria repair material). Based on COV of extended service life, the probabilistic repair cost was evaluated.
2. In the given condition of target service life of 60 years, the maintenance-free period (MFP) and the extended service life with repair were evaluated to be important factors since MFP and the extended service life with repair increased to 1.5 times, the repair cost decreased to 77% and 73%, respectively.
3. Unlike the deterministic method, the probabilistic repair cost evaluation method can handle service life variations and is implemented as a continuous cost line. It can reduce the repair cost in a reasonable manner by altering the target service life of the structure. For the normal region (120 ppm of sulfate ion) with a length of 1425 m and the harsh region (200 ppm of sulfate ion) with 1843 m, the repair cost for each region and the repair cost for the entire networks were evaluated considering the target service life (60 years). Within the target service life, the total repair cost was evaluated to be 5057 K$ (deterministic method) and 4725 K$ (probabilistic method) for the conventional repair method. However, when the bacteria coating repair material was utilized, it was greatly reduced to 72.8% and 68.3%, respectively, indicating that it is a highly economical repair method. Through changing repair material, the repair frequency was reduced from nine to four since the use of the bacteria repair material significantly extended the service life through the low diffusivity of sulfate ions.

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Authors' contributions
HSY conducted the experiments and collected the data; SJK processed the data, proposed the analytical method, conducted the modeling, and drafted this manuscript; YSY conducted review and investigated previous studies; KHY checked the proposed method and writing and supervised the entire research. All the authors read and approved the final manuscript.

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Availability of data and materials
The experimental data used to support the observations of this study are included in the article.

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

Ammar, M., Zayed, T., & Moselhi, O. (2013). Fuzzy-based life-cycle cost model for decision making under subjectivity. *Journal of Construction Engineering and Management, 139*(5), 556–563.

Atkinson, A., & Hearne, J. A. (1989). Mechanistic model for the durability of concrete barriers exposed to sulphate-bearing groundwaters. *MRS Online Proceeding Library Archive, 176*, 149–156.

Aviam, O., Bar-Nes, G., Zeiri, Y., & Sivan, A. (2004). Accelerated biodegradation of cement by sulfur-oxidizing bacteria as a bioassay for evaluating immobilization of low-level radioactive waste. *Applied and Environmental Microbiology, 70*, 6031–6036.

De Belie, N., Monteny, J., Beeldens, A., Vincke, E., Van Gemert, D., & Verstraete, W. (2004). Experimental research and prediction of the effect of chemical and biogenic sulfuric acid on different types of commercially produced concrete sewer pipes. *Cement and Concrete Research, 34*, 2223–2236.

Dongyang Economic Research Institute (2020). Quantity-per-unit costing of bacteria based deteriorated concrete section repair method. Technical report. Korea: Seoul.

EN 1991. (2000). *Eurocode 1: basis of design and actions on structures*. Brussels: Comité Européen de Normalisation (CEN) 2000

Fenner, R. A. (2000). Approaches to sewer maintenance: A review. *Urban Water, 2*(4), 343–356.

Firouzi, A., & Rahai, A. (2012). An integrated ANN-GA for reliability based inspection of concrete bridge decks considering extent of corrosion-induced cracks and life cycle costs. *Scientia Iranica, 19*(4), 974–981.

Flintsch, G. W., & Chen, C. (2004). Soft computing applications in infrastructure management. *Journal of Infrastructure Systems, 10*, 157–166.

Grengg, C., Mittermayr, F., Ukrainczyk, N., Koraimann, G., Kienesberger, S., & Dietzel, M. (2018). Advances in concrete materials for sewer systems affected by microbial induced concrete corrosion: A review. *Water Research, 134*, 341–352.

Islander, R. L., Devinny, J. S., Mansfeld, F., Postyn, A., & Shih, H. (1991). Microbial ecology of crown corrosion in sewers. *Journal of Environmental Engineering, 177*, 751–770.

Joseph, A. P., Keller, J., Bustamante, H., & Bond, P. L. (2012). Surface neutralization and H2S oxidation at early stages of sewer corrosion: Influence of temperature, relative humidity and H2S concentration. *Water Research, 46*, 4235–4245.

Jung, S. H., Yang, H. M., Yang, K. H., & Kwon, S. J. (2018). Maintenance for repaired RC column exposed to chloride attack based on probability distribution of service life. *International Journal of Concrete Structures and Materials, 12*(1), 1–9.

Kwon, S. J. (2017a). Current trends of durability design and government support in South Korea: Chloride attack. *Sustainability, 9*(3), 417. https://doi.org/10.3390/su9030417

Kwon, S. J. (2017b). Simulation on optimum repairing number of carbonated RC structure based on probabilistic approach. *Journal of the Korean Recycled Construction Resources Institute, 5*(3), 230–238. (in Korean).

Lee, S. H., & Ahn, A. H. (2018). Analyzing the long-term service life of MEP using the probabilistic approach in residential buildings. *Sustainability, 10*(10), 3803. https://doi.org/10.3390/su10103803

Lee, H. J., Cho, M. S., Lee, J. S., & Kim, D. G. (2013). Prediction model of life span degradation under sulfate attack regarding diffusion rate by amount of sulfate ions in seawater. *International Journal of Materials, Mechanics and Manufacturing, 1*, 251–255.

Lee, H. M., Lee, H. S., Suraneni, P., Singh, J. K., & Mandal, S. (2020). Prediction of service life and evaluation of probabilistic life-cycle cost for surface-repaired carbonated concrete. *Journal of Materials in Civil Engineering, 32*(10), 4020297. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003390

Monteny, J., Vincke, E., Beeldens, A., De Belie, N., Taerwe, L., Van Gemert, D., & Verstraete, W. (2000). Chemical, microbiological, and in situ test methods for biogenic sulfuric acid corrosion of concrete. *Cement and Concrete Research, 30*, 623–634.

Mulubrhan, F., Mokhtar, A. A., & Muhammad, M. (2014). Integrating reliability analysis in life cycle cost estimation of heat exchanger and pump. *Advanced Materials Research, 903*, 408–413.

Nasir, M., Chong, H. Y., & Osman, S. (2015). Probabilistic life cycle cost model for repairable system. *IOP Conference Series: Materials Science and Engineering, 78*(2015), 1–8.

Oh, K. J., Ryu, K. J., Bae, T. H., Kim, D. H., & Bae, J. J. (2006). Inspection of chemical attacked sewage concrete structures. *Magazine of the Korea Concrete Institute, 18*(2), 22–26.

Parande, A. K., Ramsamy, P. L., Ethirajan, S., Rao, C. R. K., & Palanisamy, N. (2006). Deterioration of reinforced concrete in sewer environments. *Proceedings of the Institute of Civil Engineers – Municipal Engineer, 159*(1), 11–20.

Park, S. Y., Ahn, Y. H., & Lee, S. H. (2018). Analyzing the finishing works service life pattern of public housing in South Korea by probabilistic approach. *Sustainability, 10*(12), 4469. https://doi.org/10.3390/su10124469

Parker, C. (1945). The corrosion of the concrete, I. the isolation of a species of bacterium associated with the corrosion of concrete exposed to atmospheres containing hydrogen sulfide. *Australian Journal of Experimental Biology and Medical Science, 23*, 81–90.

Qin, S., Zou, D., Liu, T., & Jivkov, A. (2020). A chemo-transport-damage model for concrete under external sulfate attack. *Cement and Concrete Research, 132*, 106048. https://doi.org/10.1016/j.cemconres.2020.106048

Rahman, S., & Vanier, D. J. (2004) Life cycle cost analysis as a decision support tool for managing municipal infrastructure. *Proceedings of the CIB triennial, CIB 2005 Triennial Congress* (pp. 1–11). Toronto: Canada.

Salem, O., Abourizk, S., & Ariaratnam, S. (2003). Risk-based life-cycle costing of infrastructure rehabilitation and construction alternatives. *Journal of Infrastructure Systems, 9*(1), 6–15.

Stewart, M. G., & Mullard, J. A. (2007). Spatial time-dependent reliability analysis of corrosion damage and the timing of first repair for RC structures. *Engineering Structures, 29*(7), 1457–1464.

Sun, Y., & Carmichael, D. G. (2018). Uncertainties related to financial variables within infrastructure life cycle costing: A literature review. *Structure and Infrastructure Engineering, 14*(9), 1233–1243.

Total Information Service Corporation. (2010). TOTAL-LCC, Technical Manual, ver.1.1, 2nd ed., *Total Information Service Corporation* (pp. 24–28).

Yang, K. H., Kwon, S. J., & Yoon, H. S. (2021). Enhancement of strength and resistance to sulfate attack in bio-coating material through negative pressure method for bacteria immobilization. *Applied Science, 11*, 9113. https://doi.org/10.3390/app11199113

Yang, K. H., Lim, H. S., & Kwon, S. J. (2020a). Effective bio-slime coating technique for concrete surfaces under sulfate attack. *Materials, 13*(7), 1512. https://doi.org/10.3390/ma13071512

Yang, K. H., Lim, H. S., Kwon, S. J., & Kim, J. H. (2020b). Repair cost estimation techniques for reinforced concrete structures located at the seashore: Considering various probabilistic service life functions and actual mix proportions. *Construction and Building Materials., 256*, 119469. https://doi.org/10.1016/j.conbuildmat.2020b.119469

Yoon, H. S., & Yang, K. H. (2020). Evaluation of effectiveness of concrete coated with bacterial glycocalyx under simulated sewage environments. *Journal of the Korean Recycled Construction Resources Institute, 8*(1), 97–104. In Korean.

Yoon, Y. S., Ahn, Y. H., Wang, X. Y., & Kwon, S. J. (2021a). Total repair cost simulation considering multiple probabilistic measures and service life. *Sustainability, 13*(4), 2350. https://doi.org/10.3390/su13042350

Yoon, H. S., Yang, K. H., & Kwon, S. J. (2021b). Service life of sewage culvert with bacteria coating from waste sludge and negative pressure. *Journal of Material Cycles and Waste Management,* (Accepted).

Yoon, H. S., Yang, K. H., Lee, K. M., & Kwon, S. J. (2021c). Service life evaluation for RC sewer structure repaired with bacteria mixed coating: Through probabilistic and deterministic method. *Materials, 14*, 5424. https://doi.org/10.3390/ma14185424

Zhang, M., Yang, L. M., Guo, J. J., Liu, W. L., & Chen, H. L. (2018). Mechanical properties and service life prediction of modified concrete attacked by sulfate corrosion. *Advanced in Civil Engineering, 2018*, 1–7.

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