# PROBABILISTIC APPROACH ON THE CARBONATION RATE OF NON-TRANSPORT UNDERGROUND INFRASTRUCTURES

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https://hdl.handle.net/2324/4481617

出版情報：Advances in Construction Materials Proceedings of the ConMat'20, 2020-08-27. 日本コンクリート工学会
バージョン：

# PROBABILISTIC APPROACH ON THE CARBONATION RATE OF NON-TRANSPORT UNDERGROUND INFRASTRUCTURES

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**ABSTRACT**

PCT (Power Cable Tunnel) and UT (Utility Tunnel) are important non-transport infrastructures installed underground to accommodate electricity, gas, water, telecommunications and sewerage facilities in the basement. Most of the PCT and UT are reinforced concrete structures, and the deterioration is intensified due to the increase in duration of use. As a result, the repair and reinforcement costs have increased rapidly, which leads to difficulties in maintenance. In general, carbonation of concrete is known to be a major cause of durability deterioration for PCT and UT. The rate of carbonation should be predicted using a reliable model that considers the materials and mix proportions of concrete and the environmental conditions under which the structure is in service. However, there is insufficient of data on that, and it is difficult to accurately present carbonation prediction models for each structure.

In this study, the carbonation rate of PCT and UT was analyzed for the CDF (Cumulative Distribution Function) of 50% to 95% through probability analysis, and the approximate carbonation rate of PCT and UT operated in Korea was presented. Probability analysis on the carbonation by region of PCT and UT shows that the carbonation rate coefficients at CDF 50% are in the range of 0.249 ~ 2.195mm/√year and 1.000 ~ 3.233mm/√year, respectively. Therefore, there is a significant difference in carbonation rate by region and structure. The results of analysis can be used to predict the progress of carbonation by year of use and can be applied to plan the preventive maintenance for structures.

*Keywords: Non-Transport Infrastructures, Power Cable Tunnel, Utility Tunnel, Durability, Carbonation Rate, Probability Analysis, Preventive Maintenance*

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## 1. INTRODUCTION

Among the infrastructures represented by roads, railways, and ports, there are some underground structures that we often overlook, such as the PCT (Power Cable Tunnel) and UT (Utility Tunnel). As shown in Figure 1, PCT and UT are important non-transport infrastructures installed underground to accommodate electricity, gas, water, telecommunications and sewerage facilities in the basement. This allows the improvement of urban aesthetics, the preservation of road structures, and the smooth communication of traffic. But, most of the PCT and UT are reinforced concrete structures, and the deterioration is intensified due to the increase in duration of use. As a result, the repair and reinforcement costs have increased rapidly, which leads to difficulties in maintenance.

Previous studies have shown that the durability deterioration of underground structures such as PCT and UT is due to carbonation, chloride attack, and chemical attack, among which carbonation has been identified as a major contributor to durability deterioration [1]. In other words, predicting the progression of carbonation for PCT and UT is a key process to evaluate the durability service life of a structure. In general, carbonation has been influenced by internal factors such as concrete mix design, construction quality, and external factors such as atmospheric $CO_2$ concentration, temperature, frequency of precipitation, solar radiation and humidity, etc. [2,3]. In order to predict the durability service life on the carbonation of concrete, many researchers have proposed a carbonation prediction model that predicts the carbonation depth over time from indoor experiments and exposure experiments [4,5,6,7,8]. However, because of the different factors that take into account the rate of carbonation among researchers, the proposed carbonation prediction model will inevitably have a difference in carbonation prediction depth over the intended service life. In addition, the classical carbonation prediction model can be applied when there is construction information such as cement, aggregate, type of admixture, water to binder ratio, curing condition, etc. However, it is practically impossible to obtain construction information for existing underground structures over 20 years of use. At present, PCT and UT are maintained by safety inspection through regular visual inspection and nondestructive test according to the relevant standards. A research was conducted to predict the carbonation of concrete using various actual measurement data obtained from such safety inspection results. However, most of the previous researches were conducted on traffic facilities such as bridges, road tunnels, railway tunnels and subways [9,10,11]. But, PCT and UT are different from the general transport infrastructures in terms of operating environment, it could be supposed that the progress of concrete carbonation is different.

In this study, precision inspection and precision safety diagnosis data performed in six major regions of Korea were collected for carbonation rate analysis on the PCT and UT. The carbonation rate of PCT and UT was analyzed for the CDF (Cumulative Distribution Function) of 50% to 95% through probability analysis, and the approximate carbonation rate of PCT and UT operated in Korea was presented. The analysis results can be used to predict the progress of carbonation according to the years of use. Therefore, it can be applied to plan the preventive maintenance for PCT and UT.

(a) PCT (b) UT

**Figure 1.** Internal view of PCT and UT

# 2. DATA COLLECTION AND INVESTIGATION

## 2.1. Collection of data

The precision inspection and precision safety diagnosis data on the PCT and UT performed in six major regions of Korea as like Seoul, Incheon, Daejeon, Daegu, Gwangju, Busan were collected as shown in Table 1. Most of these reports are managed by the FMS (Facility Management System) of MOLIT (Ministry of Land, Infrastructure and Transport) [12]. The existing underground structures for data collection were constructed between 1978 and 2016, with a total span length of 143km for PCT and 104km for UT. Figure 2 shows the carbonation results of a total of 1,520 sets collected. Results of 1,520 sets on the carbonation depth and cover depth were presented separately by PCT and UT. The 1,520 sets of data consisted of 1,017 sets of PCT and 503 sets of UT.

**Table 1.** Status of data collection

| Division | | Length (km) | Year of const. | Num. of data (set) | Location |
|---|---|---|---|---|---|
| PCT | ⓐ Seoul | 8.488 | 1987~2008 | 302 |  |
| | ⓑ Incheon | 19.441 | 1978~1998 | 61 | |
| | ⓒ Daejeon | 11.092 | 1993~2002 | 60 | |
| | ⓓ Daegu | 37.848 | 1985~2016 | 229 | |
| | ⓔ Gwangju | 24.926 | 1987~2015 | 217 | |
| | ⓕ Busan | 41.604 | 1982~2009 | 148 | |
| UT | ⓐ Seoul | 39.040 | 1978~2003 | 161 | |
| | ⓑ Incheon | 27.562 | 1992~2014 | 116 | |
| | ⓒ Daejeon | 21.671 | 1994~2016 | 77 | |
| | ⓓ Daegu | 6.945 | 1979~1983 | 39 | |
| | ⓔ Gwangju | 1.797 | 1998 | 46 | |
| | ⓕ Busan | 7.270 | 1996 | 64 | |

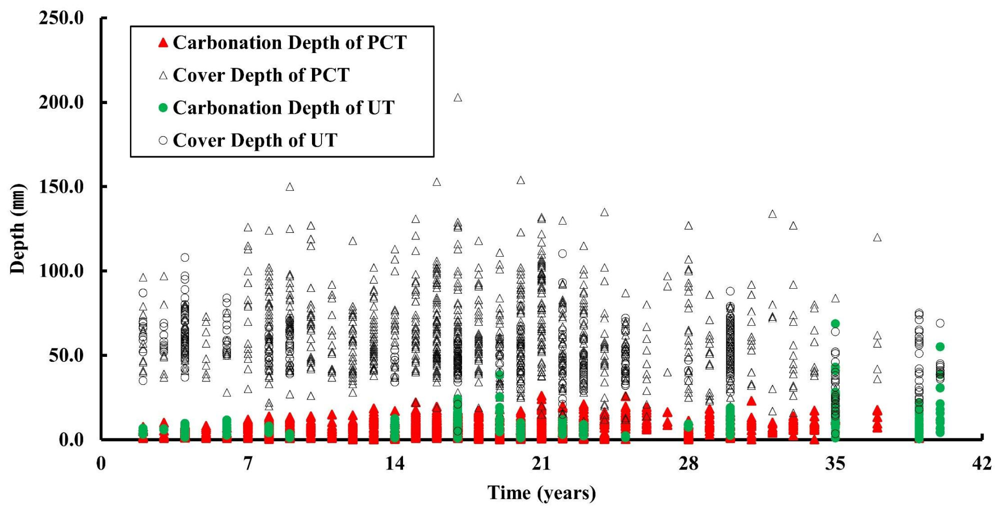
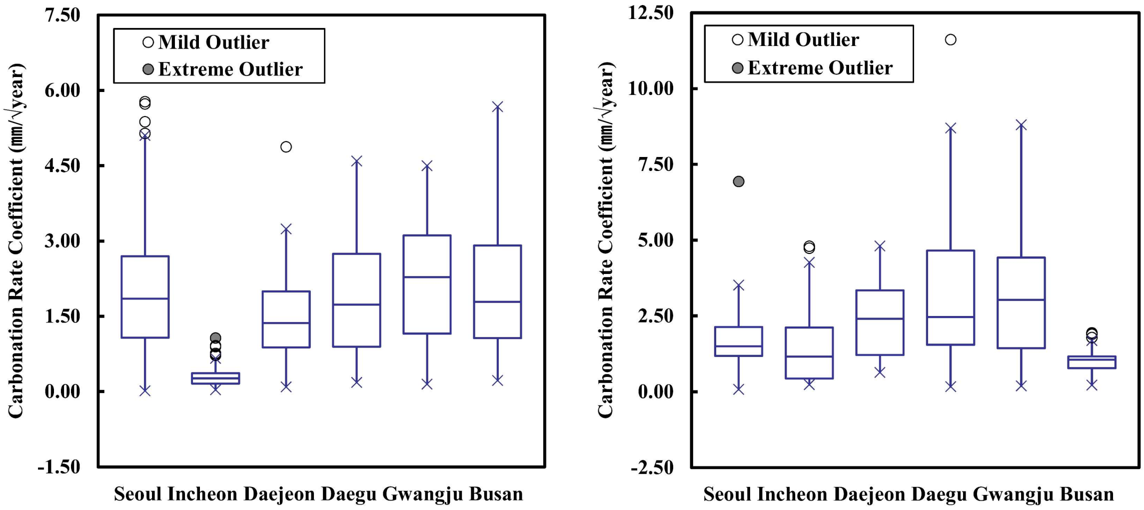



**Figure 2.** Carbonation and cover depth on the PCT and UT

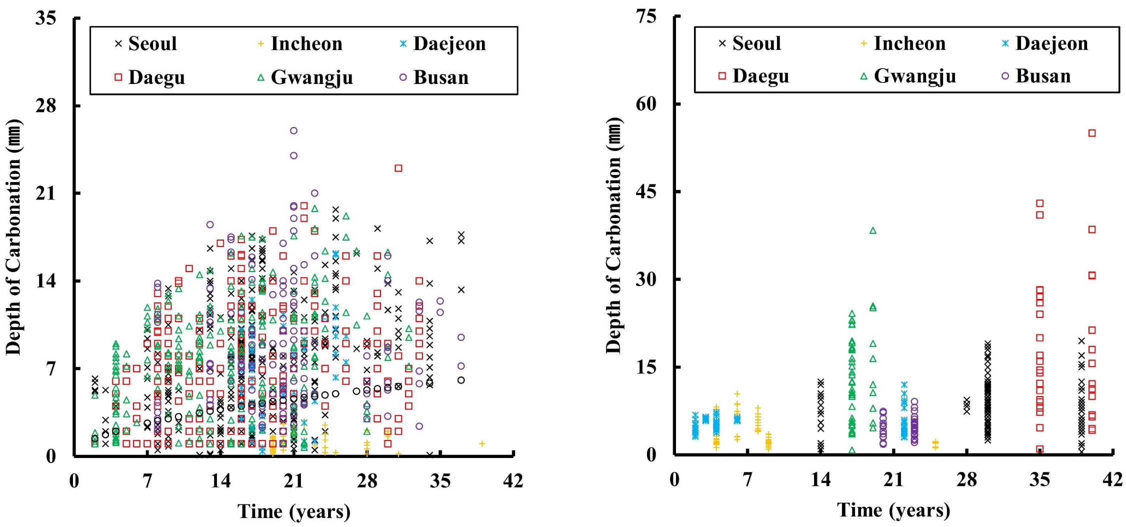
## 2.2. Investigation of data

As a result on the collection of carbonation data, it was found that the carbonation depth dispersion is large enough to be difficult to characterize the pattern. So, an outlier detection was performed that affected the results of the statistics of the regional carbonation rate coefficient for PCT and UT. The partial reasons for the varying depth of carbonation may be human and mechanical errors that inevitably accompany inspecting. Therefore, prior to probability analysis, outlier detection that affects statistical results was performed. Outliers were detected using a box plot of J. W. Tukey on the carbonation rate coefficient of PCT and UT [13]. As shown in Figure 3, the outliers were detected in PCT's data in Seoul, Incheon, Daejeon and UT's data in Seoul, Incheon, Daegu and Busan. Figure 4 shows regional carbonation depth for PCT and UT with outliers removed. In Figure 4 (a), the total carbonation depth of 1,004 sets of PCT with 13 sets of outliers removed is shown by region. The current status of 493 sets of data, with the exception of 10 sets of regional outliers, is drawn in Figure 4 (b) shows the regional carbonation depth of the UT with outliers removed.




(a) PCT (b) UT

**Figure 3.** Outlier analysis of carbonation on the PCT and UT




(a) PCT (b) UT

**Figure 4.** Status of carbonation depth on the PCT and UT after removing outliers

## 3. PROBABILITY ANALYSIS OF CARBONATION

### 3.1. Normality test on the data of PCT and UT

Carbonation data for PCT and UT where outliers have been removed were tested for normality prior to probability analysis. The statistical analysis calculates the test statistic and p value based on the assumption that the data follow a normal distribution, so if the data do not satisfied with the normality assumptions, the validity of the statistical analysis results is lowered. In this study, Q-Q Plot and Kolmogorov-Smirnov test (K-S test) techniques were applied to the normality test on the carbonation data of PCT and UT.

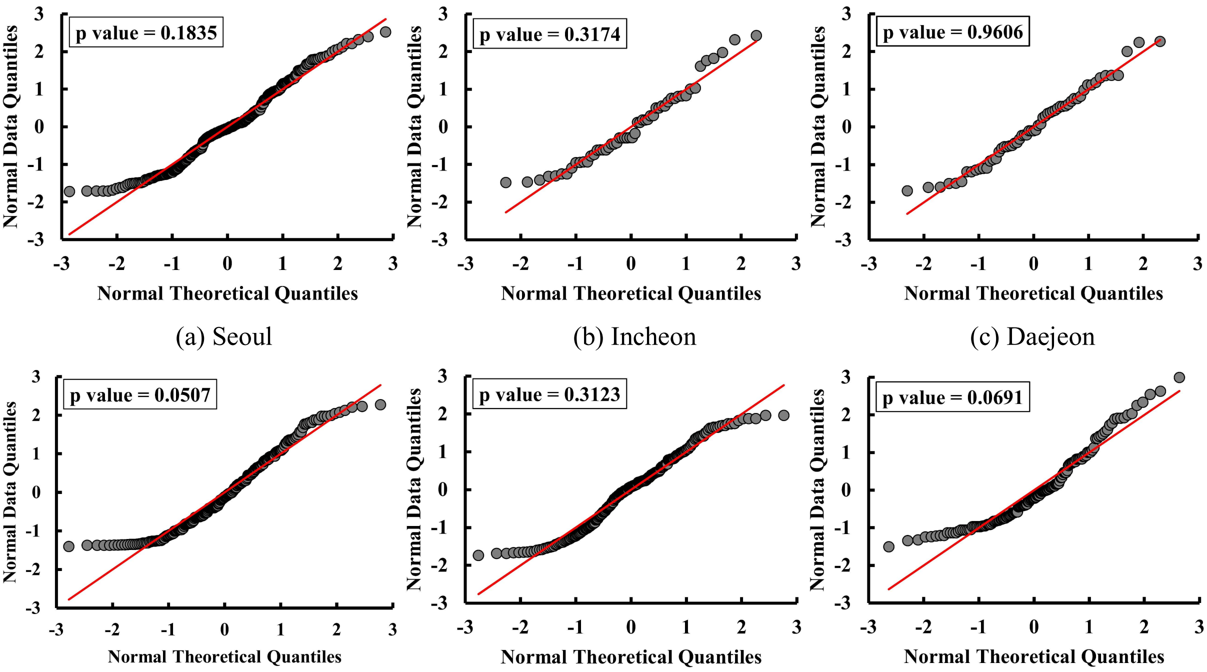
Q-Q Plot is a technique for visually confirming that normality assumptions are satisfied from a graph. If the dots on the scatter plot are located close to a straight line, the data can be assumed to be from a normal population. $\Phi$ indicates the cumulative distribution function of the standard normal distribution, data listed in the order of magnitude are $x_{(1)} \leq \ldots \leq x_{(n)}$, the Q-Q Plot is a scatter plot of the dots of Eq. (1) [14]. Where $p_i$ is $(i\text{-}3/8) / (n\text{+}1/4)$.

$$\left(\Phi^{-1}(p_i), \frac{x_{(i)} - \bar{x}}{s}\right), \qquad i = 1, 2, \cdots, n \tag{1}$$

The Kolmogorov-Smirnov statistic belongs to the supremum class of EDF (Empirical Distribution Function) statistics and this class of statistics is based on the largest vertical difference between the hypothesized and empirical distribution. The Kolmogorov-Smirnov statistic for a given cumulative distribution function $F(x)$ is Eq. (2) [14]. Where *sup* is the supremum which means the greatest, $F_n(x)$ is hypothesized distribution function and $F_o(x)$ is the EDF estimated based on the random sample.

$$Z = sup_x |F_n(x) - F_0(x)| \tag{2}$$

Q-Q plot and K-S test were applied to test the normality of carbonation rate coefficients for PCT and UT. As shown in Figure 5 and Figure 6, calculated p values were more than 0.05 and the test results showed that all carbonation data for PCT and UT where outliers were detected can assume the normality.




(a) Seoul (b) Incheon (c) Daejeon

(d) Daegu (e) Gwangju (f) Busan

**Figure 5.** Q-Q plot and K-S test results on the carbonation data of PCT by region

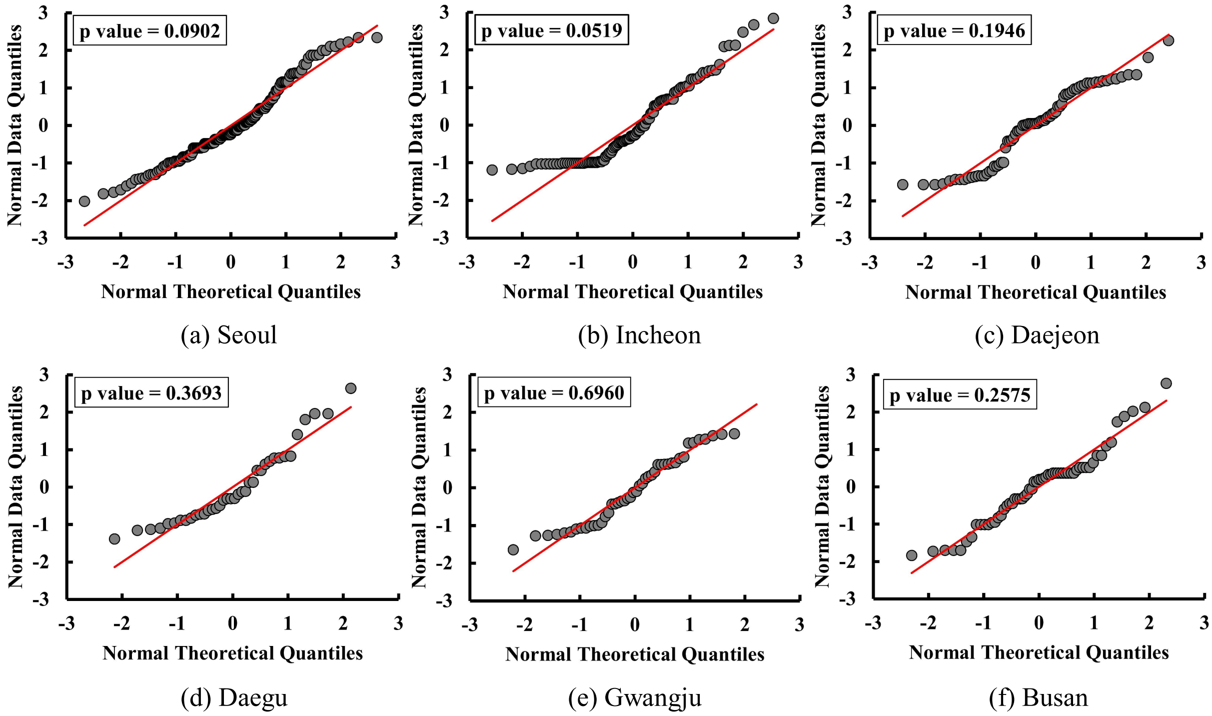



**Figure 6.** Q-Q plot and K-S test results on the carbonation data of UT by region

## 3.2. Probability analysis on the carbonation of PCT and UT

Numerous works have confirmed that the depth of carbonation is in proportion to the square root of the period of carbonation. Generally, Eq. (3) is a used one and it explains that concrete carbonation depth is proportional to exposed time in the air. Where $y$ is the carbonation depth in concrete, $b$ is coefficient for carbonation rate of concrete and $t$ is exposed time in the air.

$$y = b\sqrt{t} \tag{3}$$

In this study, the probability analysis for the carbonation rate coefficients of PCT and UT was performed for 50% ~ 95% probability of non-exceedance using the gaussian probability density function of Eq. (4). Where $\mu$ is the mean of normal distribution, $\sigma$ is the standard deviation of normal distribution, $\pi$ is the ratio of a circle's circumference to its diameter and $x$ is data.

$$P(x) = \frac{1}{\sigma\sqrt{(2\pi)}} exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\} \tag{4}$$

Figure 7 and Figure 8 show the results of histogram and probability analysis on the carbonation rate coefficients of the PCT and UT by region. The CDF 50 ~ 95% analysis results for the carbonation rate coefficients of regional PCT and UT are presented in Table 3. Especially, assuming that the data follow a normal distribution, carbonation rate coefficient at 50% of the CDF represents the mean ($\mu$) value of the data, and 95% of the CDF is less than the probability 97.725% of the cumulative interval from the population mean to $\mu$+2$\sigma$. Analysis of the probability for carbonation by region of PCT showed that at 50% and 95% of CDF, the carbonation rate coefficient was in the range of 0.249 ~ 2.195mm/√year and 0.483 ~ 4.118mm/√year, respectively. Under the condition of CDF 50%, the carbonation rate coefficient of PCT was the lowest in Incheon and the highest in Gwangju. As in the case of PCT, probability analysis for carbonation by region of UT showed that at 50% and 95% of CDF, the carbonation rate coefficient was in the range of 1.000 ~ 3.233mm/√year and 1.528 ~ 6.543mm/√year, respectively. At 50% of CDF, the carbonation rate coefficient of UT was the lowest in Busan and the highest in Gwangju.

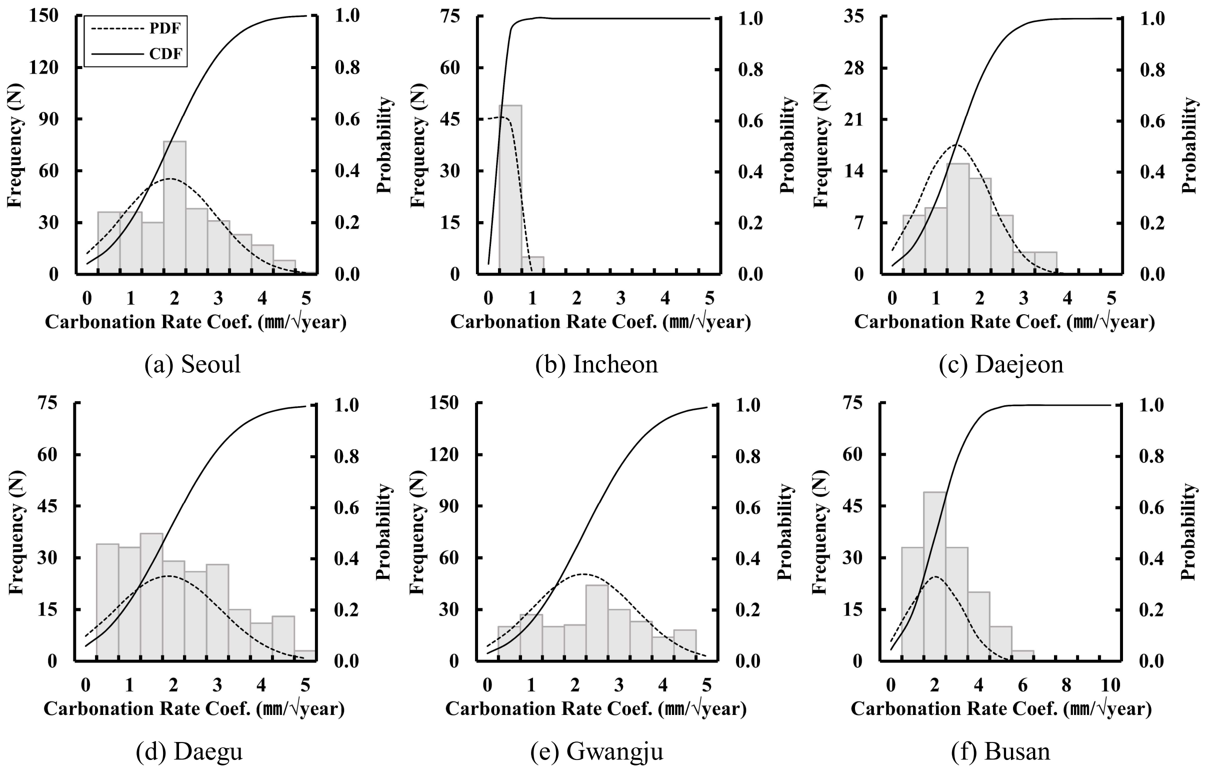



**Figure 7.** Probability analysis on the carbonation rate coefficient of PCT

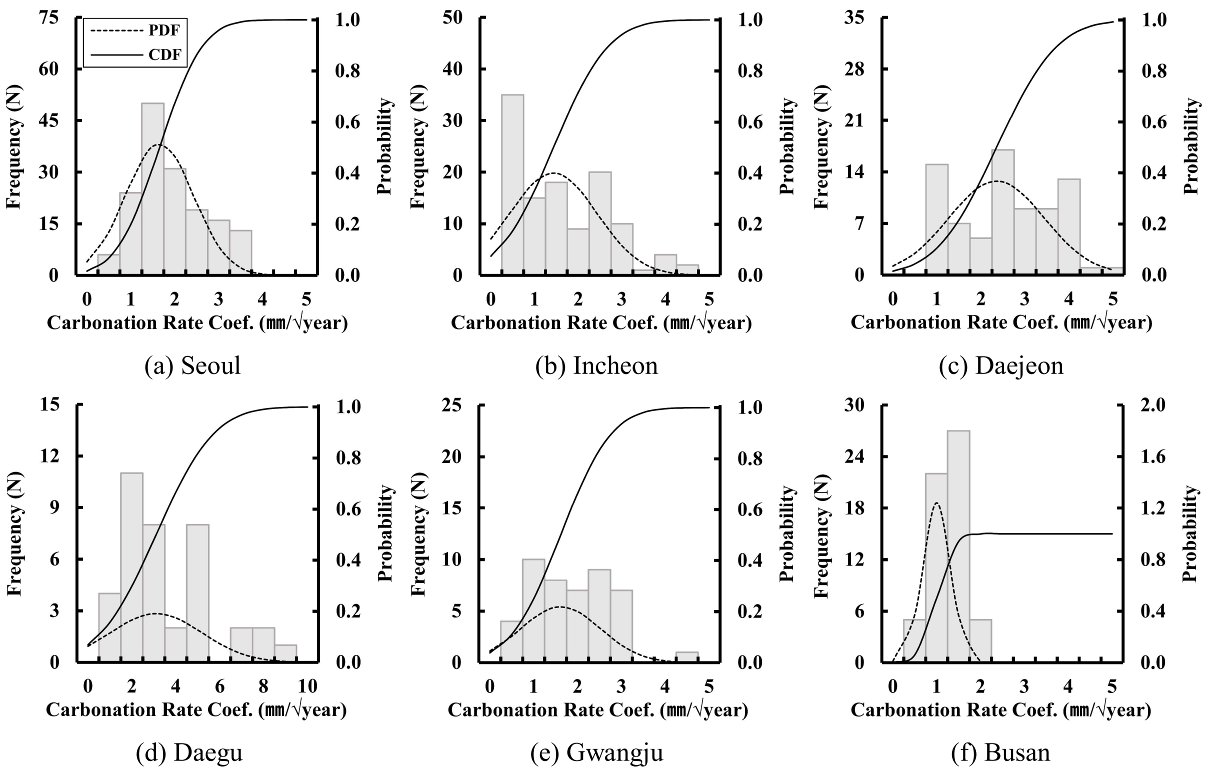



**Figure 8.** Probability analysis on the carbonation rate coefficient of UT

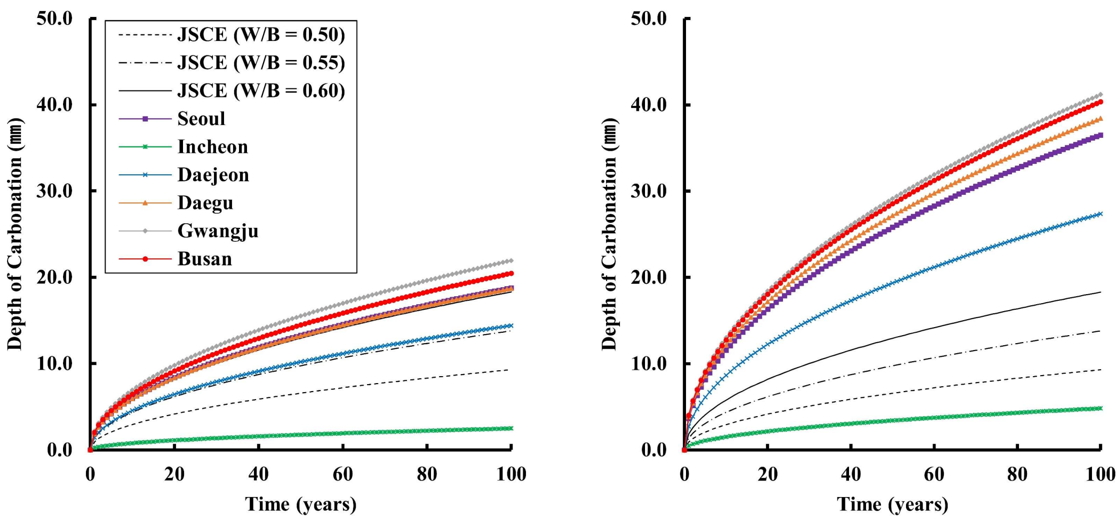
**Table 2.** CDF analysis results on the carbonation rate coefficient for PCT and UT by region

| Division | | Carbonation rate coefficient (mm/√year) | | | | | |
|---|---|---|---|---|---|---|---|
| | | CDF 50% | CDF 60% | CDF 70% | CDF 80% | CDF 90% | CDF 95% |
| PCT | Seoul | 1.880 | 2.151 | 2.443 | 2.785 | 3.260 | 3.652 |
| | Incheon | 0.249 | 0.285 | 0.323 | 0.369 | 0.431 | 0.483 |
| | Daejeon | 1.444 | 1.641 | 1.854 | 2.104 | 2.450 | 2.736 |
| | Daegu | 1.874 | 2.175 | 2.500 | 2.880 | 3.407 | 3.842 |
| | Gwangju | 2.195 | 2.488 | 2.806 | 3.177 | 3.693 | 4.118 |
| | Busan | 2.051 | 2.354 | 2.681 | 3.064 | 3.596 | 4.035 |
| UT | Seoul | 1.654 | 1.848 | 2.058 | 2.303 | 2.644 | 2.926 |
| | Incheon | 1.434 | 1.683 | 1.953 | 2.269 | 2.707 | 3.069 |
| | Daejeon | 2.355 | 2.627 | 2.920 | 3.264 | 3.741 | 4.135 |
| | Daegu | 3.110 | 3.635 | 4.201 | 4.864 | 5.784 | 6.543 |
| | Gwangju | 3.233 | 3.690 | 4.184 | 4.763 | 5.564 | 6.227 |
| | Busan | 1.000 | 1.080 | 1.167 | 1.269 | 1.411 | 1.528 |

## 4. PREDICTION OF CARBONATION BY PROBABILISTIC APPROACH

Based on the carbonation rate coefficient derived through the probability analysis, the depth of carbonation by region was predicted according to the age of use. As shown in Figure 9 and Figure 10, the predicted carbonation depth is compared with JSCE (Japan Society of Civil Engineers)'s carbonation prediction model of Eq. (5) [15]. Where $y$ is the carbonation depth in concrete, $W/B$ is effective water to binder ratio and $t$ is exposed time in the air.

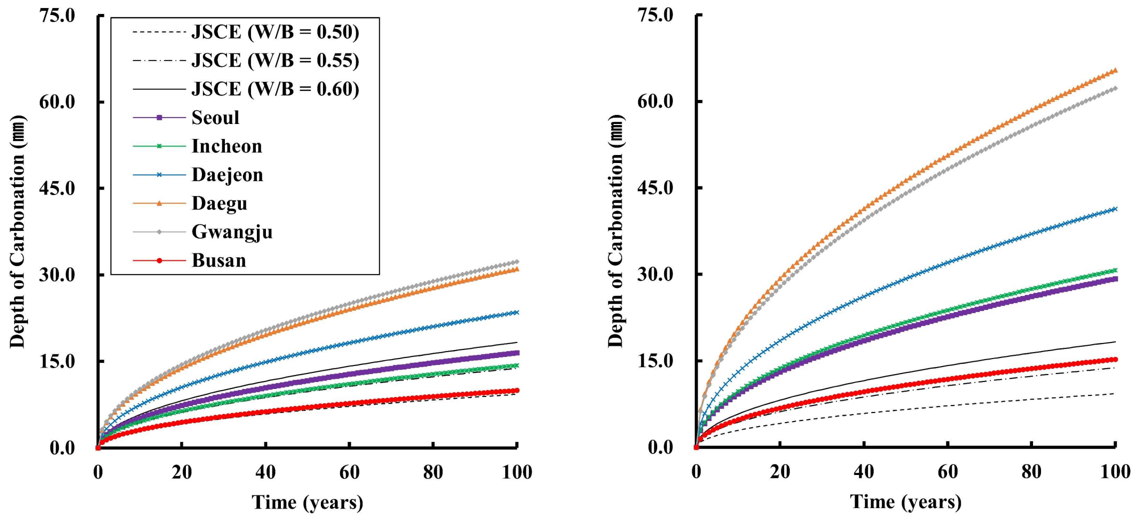
$$y = (-3.57 + 9.0\, W/B)\sqrt{t} \tag{5}$$




(a) CDF 50%

(b) CDF 95%

**Figure 9.** Prediction of carbonation depth on the PCT by probability analysis




(a) CDF 50% (b) CDF 95%

**Figure 10.** Prediction of carbonation depth on the UT by probability analysis

As shown in Eq. (5), JSCE's carbonation prediction model is based on the characteristics of *W/B* and this study assumed *W/B* as 0.50, 0.55 and 0.60 in JSCE's carbonation prediction model. As shown in Figure 9 and Figure 10, some of the predicted carbonation depths for the PCT and UT differ significantly from the predicted values of the JSCE's carbonation prediction model by region. In particular, when considering the results of CDF 95% in terms of conservative maintenance of durability, it was found that the predicted carbonation depth of PCT and UT greatly exceeds the predicted values of JSCE's carbonation prediction model excluding Incheon and Busan, respectively.

## 5. CONCLUSIONS

In this study, precision inspection and precision safety diagnosis data performed in six major regions of Korea were collected for carbonation rate analysis on the PCT and UT. The carbonation rate on the PCT and UT was analyzed by probabilistic approach and the results obtained may be summarized as follows:

1. As a result of test the normality on the carbonation data of PCT and UT by applying the Q-Q plot and the K-S test, the p values were more than 0.05, and all carbonation data for PCT and UT where the outliers were detected could be assumed the normality.
2. Probability analysis on the carbonation by region of PCT and UT shows that the carbonation rate coefficients at CDF 50% are in the range of 0.249 ~ 2.195mm/√year and 1.000 ~ 3.233mm/√year respectively, which is evaluated that Gwangju is the highest of carbonation rate coefficient.
3. These results suggest that PCT and UT of Gwangju are more likely to be disadvantageous than structures of other areas in terms of internal factors, as well as external factors of carbonation such as carbon dioxide concentration, temperature and humidity.
4. The carbonation rate coefficients of PCT and UT at CDF 95% are in the range of 0.483 ~ 4.118mm/√year and 1.528 ~ 6.543mm/√year respectively and the difference in carbonation rate coefficients by region was found to be large. The reason why there were differences on the carbonation rate was the carbonation of PCT and UT by region is reflected the effects of the mix proportions of concrete used, temperature, humidity and carbon dioxide concentration.
5. As a result of comparing the predicted carbonation depths by the probability analysis with the predicted values of JSCE's carbonation prediction model, it was found that there were significant differences. Therefore, in order to manage the carbonation of PCT and UT individually by region and structure, a new type of carbonation prediction model based on each carbonation data is required.

6. Further studies will need to investigate the effect factors of carbonation from restricted precision inspection and precision safety diagnosis data, and research the method of optimization on the predicting carbonation of PCT and UT by region based on the findings.

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